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INTEGREEN

Action 3: System design

D.3.2.2

On-board traffic and environment monitoring units

Project Coordinating Beneficiary	Municipality of Bolzano
Project Associated Beneficiary n.2	TIS innovation park (TIS)
Project Associated Beneficiary n.3	Austrian Institute of Technology (AIT)
Project Associated Beneficiary n.4	Österreichisches Forschungs- und Prüfzentral Arsenal (ÖFPZ)

Città di Bolzano
Stadt Bozen

TIS innovation park

AIT AUSTRIAN INSTITUTE OF TECHNOLOGY

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1 Introduction

The System Design action aims primarily at producing the technical specifications for the Supervisory Centre and for the Mobile Systems. It follows directly after the Requirements phase which is the main input to this Action as it can be seen in Figure 1 here below.

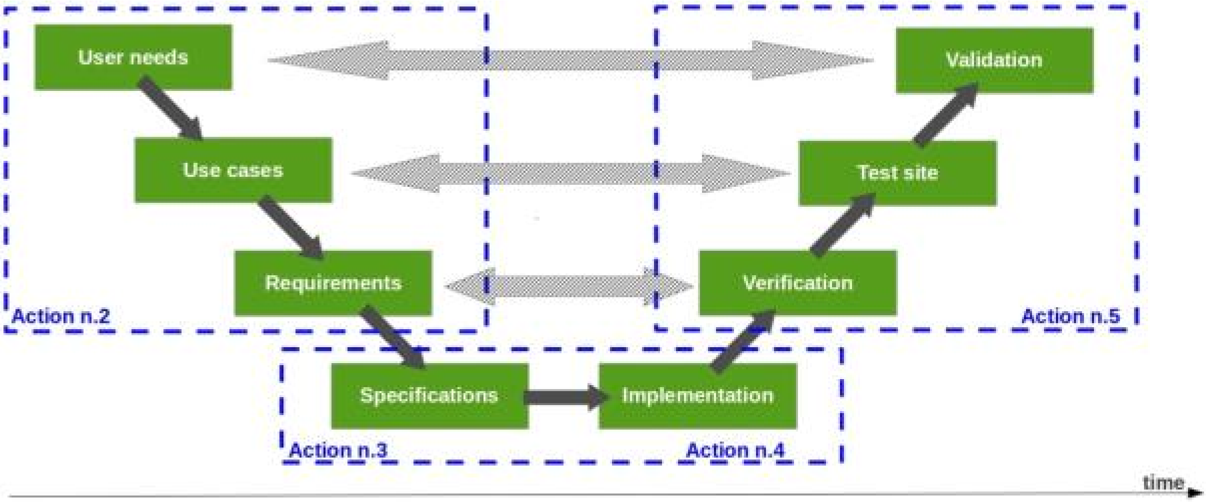


Figure 1: The V-model approach applied in the INTEGREEN project

1.1 Purpose of the document

This document Deliverable D.3.2.2 is the second of the two AIT deliverables of Action 3: System Design.

AIT is the responsible beneficiary for the activities in Action 3 and directly responsible for the execution of Task 3.2 Mobile System Design, while the execution of Task 3.1 Supervisory Centre design is under the responsibility of TIS.

In Task 3.2 the Mobile System Design activities are divided in three subsystems as follows:

- On-board telematic unit
- On-board traffic monitoring unit
- On-board environmental monitoring unit

The three subsystems are clearly visible in Figure 2 here below.

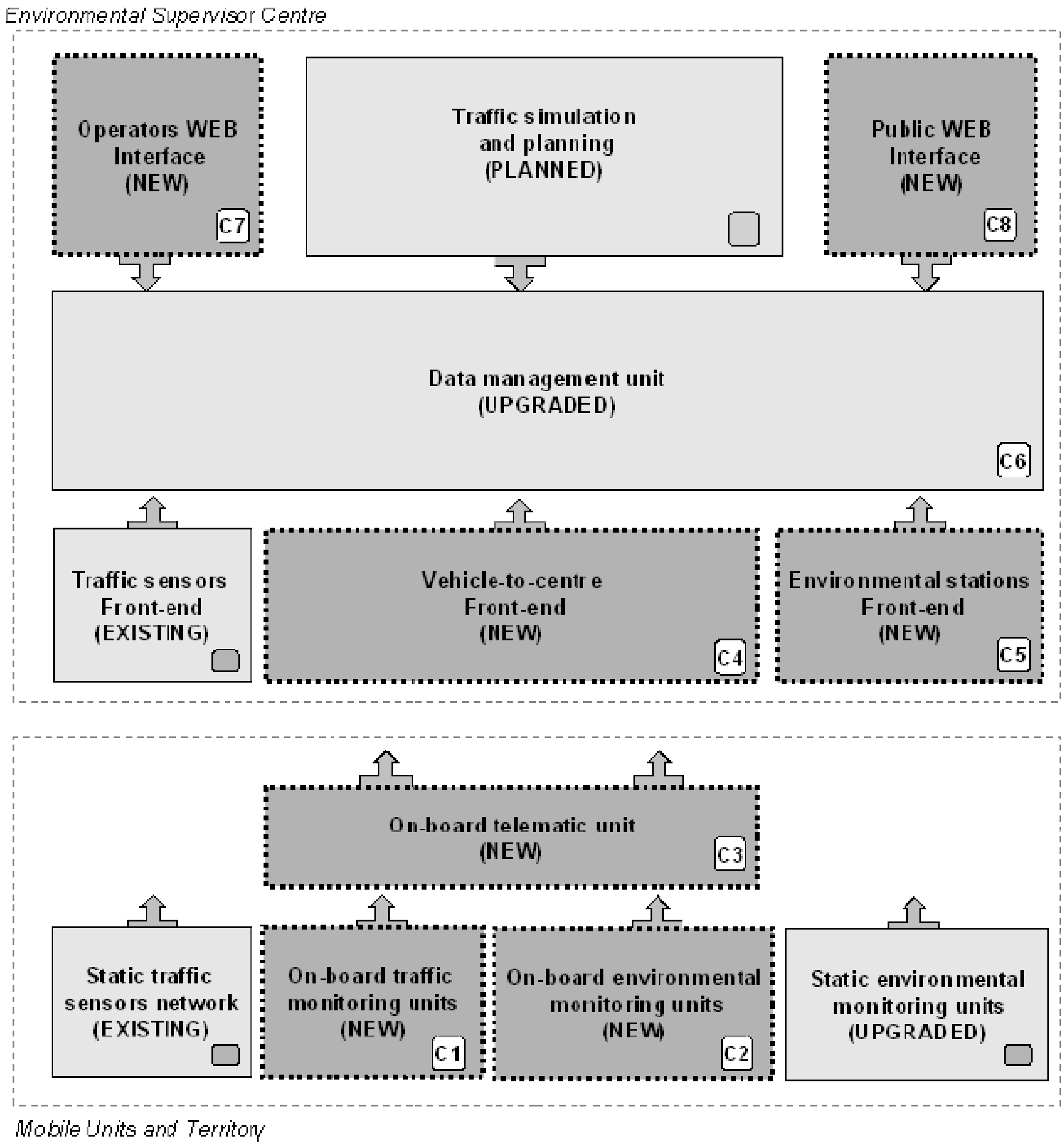


Figure 2: INTEGREEN system architecture

The design activities of the On-board telematic unit are described in deliverable D.3.2.1 while the design activities of the On-board traffic monitoring unit and of the On-board environmental monitoring unit are described in this deliverable document D.3.2.2.

The overall design objective has been to achieve a solution based on selecting sensors and modules which are already present on the market. Basic research has not been considered as the final prototype system will have to be suitable for commercialisation after INGEGREEN.

In Task 3.2 a complete mobile system suitable for automotive application has been designed. The system design will be the input for the next Action to implement and build a prototype with full functionalities which will allow vehicles to have traffic and environmental detection capabilities, as well as real-time communication functionalities, in particular between the On-board telematic unit and the Vehicle front-end and subsequently to the Supervisor Center system.

This document deliverable contains the main output of Task 3.2 as the On-board traffic monitoring unit and the On-board environmental monitoring unit have been designed ad-hoc for the INTEGREEN solution. These two units have the highest level of functional complexity and at the same time, in their design the latest assembly and production technological advancements have been taken into account.

1.2 Specification definition methodology

The methodology that has been applied in the design activity is illustrated in Figure 3. It is composed by three initial sequential activities and subsequently by parallel activities for the Environmental and Traffic monitoring unit. The aim has been (i) to assess and evaluate the critical requirements that most influence the High-level architecture, (ii) to design a modular system where single units can be easily reused in the future and (iii) to produce a set of design specifications that are ready for commercialisation after INTEGREEN.

1.2.1 Requirements

The output from Action 2 defined and documented in deliverable D.2.2.1 have been analysed, assessed and prioritised.

1.2.2 Frame design

The INTEGREEN Mobile System has been modelled in a FRAME ITS architecture. This activity is described in deliverable D.3.1.1 (Data management unit and environmental stations front-end design).

1.2.3 High level architecture design

Analysis of different modules and options that would have fulfilled the requirements.

1.1.1 Investigation of sensor modules and sensors

Evaluation and selection of suitable Off-the-Shelf miniature traffic and gas sensors modules or chips. This has been especially important for the environmental sensors investigation because their characteristics and behaviour for fast mobile measurements were less known.

1.1.2 Test of selected sensors in measurement campaigns

Selection of most suitable sensors after field test verification and validation measurements. Like in 0 above, this has been an especially important step for the environmental sensors.

1.1.3 Detailed design specifications

A detailed HW and FW design of the two units has been completed and documented.

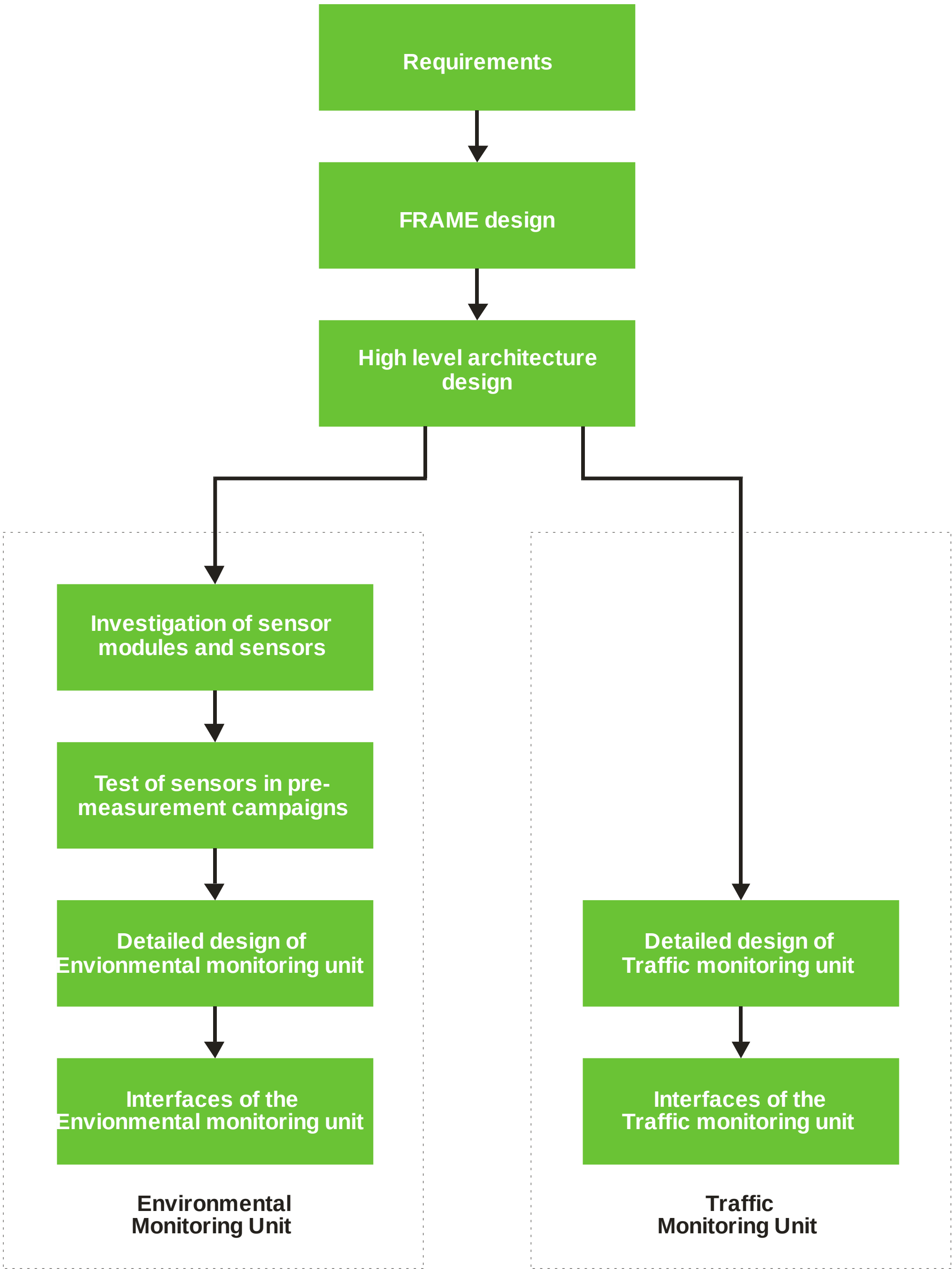


Figure 3: Methodology for the design of the On-board monitoring units

1.1.4 Interface specifications

All HW and FW interfaces to external components (GPS, Power supply, CAN-bus, air interface, data interface, expansion interfaces) have been completed and documented.

2 Requirements

2.1 Mobile System Requirements from previous Action

The complete set of mobile system requirements taken from deliverable D.2.2.1 is listed here below in Table 1. It is worth noting that no requirements are defined for the vehicle front-end, as its functionality is dependent by the requirements defined for the Vehicle data-source described in deliverable D.2.1.1 Supervisor Centre components requirements.

Components	ID	Name	Type	Priority
On-board telematic unit	OBU_1	Computing capacity	F	M
	OBU_2	Storage capacity	P	M
	OBU_3	Storage capacity (optional)	P	C
Communication unit	CU_1	Communication technology	NF	M
	CU_2	Communication protocols	NF	M
	CU_3	Communication load	P	M
HMI	HMI_1	HMI - Information content	F	M
	HMI_2	GUI - Information content	F	C
On-board traffic monitoring unit	OBTU_1	Kinematic sensors	F	M
	OBTU_2	Kinematic sensors plus	F	M
	OBTU_3	Kinematic sensor quality	F	S
On-board environmental monitoring unit	OBEU_1	Environmental sensors	F	M
	OBEU_2	Meteorological sensors	F	M
	OBEU_3	Environmental sensors plus	F	C
	OBEU_4	Environmental sensor quality	F	S

Table 1: Mobile System Requirements list.

The requirements for the On-board telematics unit (OBTU), for the Communication unit (CU) and for the HMI are related to the design activity of the On-board telematics unit and consequently are described in Deliverable D.3.2.1. The requirements for the On-board traffic monitoring unit and for the On-board environmental monitoring unit described here below are the main input for the design activity described in this deliverable document.

2.1.1 On-board environmental monitoring unit

The following tables summarise the specific requirements of the On-board environmental monitoring unit.

ID	OBEU_1
Name	Environmental sensors
Description	The environmental data unit has to deliver at least pollutant sensor data composing of: • NO_2 • O_3
Rationale	System design - air pollutants are selected according to (i) specific monitoring needs within the city of Bolzano and (ii) technological constraints.
Type	Functional
Priority	Must

Table 2: Requirement OBEU_1 (environmental sensors).

ID	OBEU_2

Name	Meteorological sensors
Description	The environmental data unit has to deliver meteorological data, related in particular to the following parameters: • air temperature ; • humidity.
Rationale	System design – the online calibration of pollutant measurements require meteorological data
Type	Functional
Priority	Must

Table 3: Requirement OBEU_2 (meteorological sensors).

ID	OBEU_3
Name	Environmental sensors plus
Description	The environmental data unit can deliver additional pollutant sensor data: • NO_X • PM_{10} • VOC • CO • SO_2
Rationale	System design – although these pollutants are difficult to measure they are of high interest for the urban air quality
Type	Functional
Priority	Could

Table 4: Requirement OBEU_3 (environmental sensors plus).

ID	OBEU_4
Name	Environmental sensor quality
Description	The pollutant and meteorological sensors together with the first data stream filtering should deliver additional quality and accuracy information.
Rationale	System design – data quality is essential for the fusion of different data sources to achieve a reliable concentration estimation.
Type	Functional
Priority	Should

Table 5: Requirement OBEU_3 (environmental sensors plus).

The above requirements imply that the environmental sensors don't have to be able to measure the annual average air pollution levels in the city of Bolzano (see D2.1.1, Supervisor Centre components requirements, section 2.1.3 Air pollution levels) but to be able to quickly detect the peak levels in hot-spots due to climate conditions as well as to traffic conditions.

2.1.2 On-board traffic monitoring unit

The following tables summarise the specific requirements of the On-board traffic monitoring unit.

ID	OBTU_1
Name	Kinematic sensors
Description	The on-board traffic monitoring unit has to deliver at least GPS sensor data composing of: • position; • heading ;

	• speed.
Rationale	System design – minimum requirements for traffic state estimations
Type	Functional
Priority	Must

Table 6: Requirement OBTU_1 (kinematic sensors).

ID	OBTU_1
Name	Kinematic sensors plus
Descriptio n	The traffic data unit must also deliver acceleration sensor data
Rationale	System design – acceleration data increases the quality of traffic based emission calculations
Type	Functional
Priority	Must

Table 7: Requirement OBTU_2 (kinematic sensors plus).

ID	OBTU_3
Name	Kinematic sensor quality
Description	The GPS and acceleration sensor together with the first data stream filtering should deliver additional quality and accuracy information.
Rationale	System design – data quality is essential for the fusion of different data sources to achieve a reliable traffic status estimation.
Type	Functional
Priority	Should

Table 8: Requirement OBTU_1 (kinematic sensors).

2.2 Automotive considerations

The two units (Environmental and Traffic monitoring unit) should be mounted on vehicles for real-time mobile data collection. The configuration for a specific vehicle should be flexible in the sense that in one vehicle it is possible to mount

- only the Traffic monitoring unit
- only the Environmental monitoring unit
- both monitoring units.

In the project a test phase with two different cars is planned:

- AIT test car (Ford Focus)
- TIS test car

In each of these two vehicles the prototypes of both types of monitoring units should be tested.

For a mobile in-vehicles use there are different considerations to be taken into account:

<u>Physical dimension:</u>

The space in private vehicles is limited and consequently the units should be as small as possible. The whole system should be placed inside the vehicles, only necessary parts like antennas or air inlet could be outside the vehicle.

Power supply:

The power supply in cars is typical 12V but on trucks or busses it can be also 24V. Furthermore the voltage is not really constant. In the phase of starting the engine there can be a voltage drop of several volts (depending on the vehicle, type of battery and condition of the battery).

The units should be functioning when the engine of the vehicle is running. So it is reasonable to use the power supply after the ignition lock. Some parts of the electronic should be powered continuously (from the vehicle battery), so both power supply lines can be used:

- +12 V ignition
- +12V continuous

In particular for the +12V continuous power supply the power consumption should be very low.

Temperature range:

The temperature in a vehicle can be varying in a wide range. For use in European countries a possible temperature range of -20 °C to 70 °C should be considered.

Vibration:

The vibration in vehicles can damage electronic or mechanical parts. So in the design care should be taken to avoid larger electronic and mechanical components as well as fix them in an adequate way.

3 High level Architecture of the mobile system

The INTEGREEN mobile system includes all functions and modules of the Mobile probe system and the stationary Vehicle front-end including its interface to the Supervisor Center (see Figure 4).

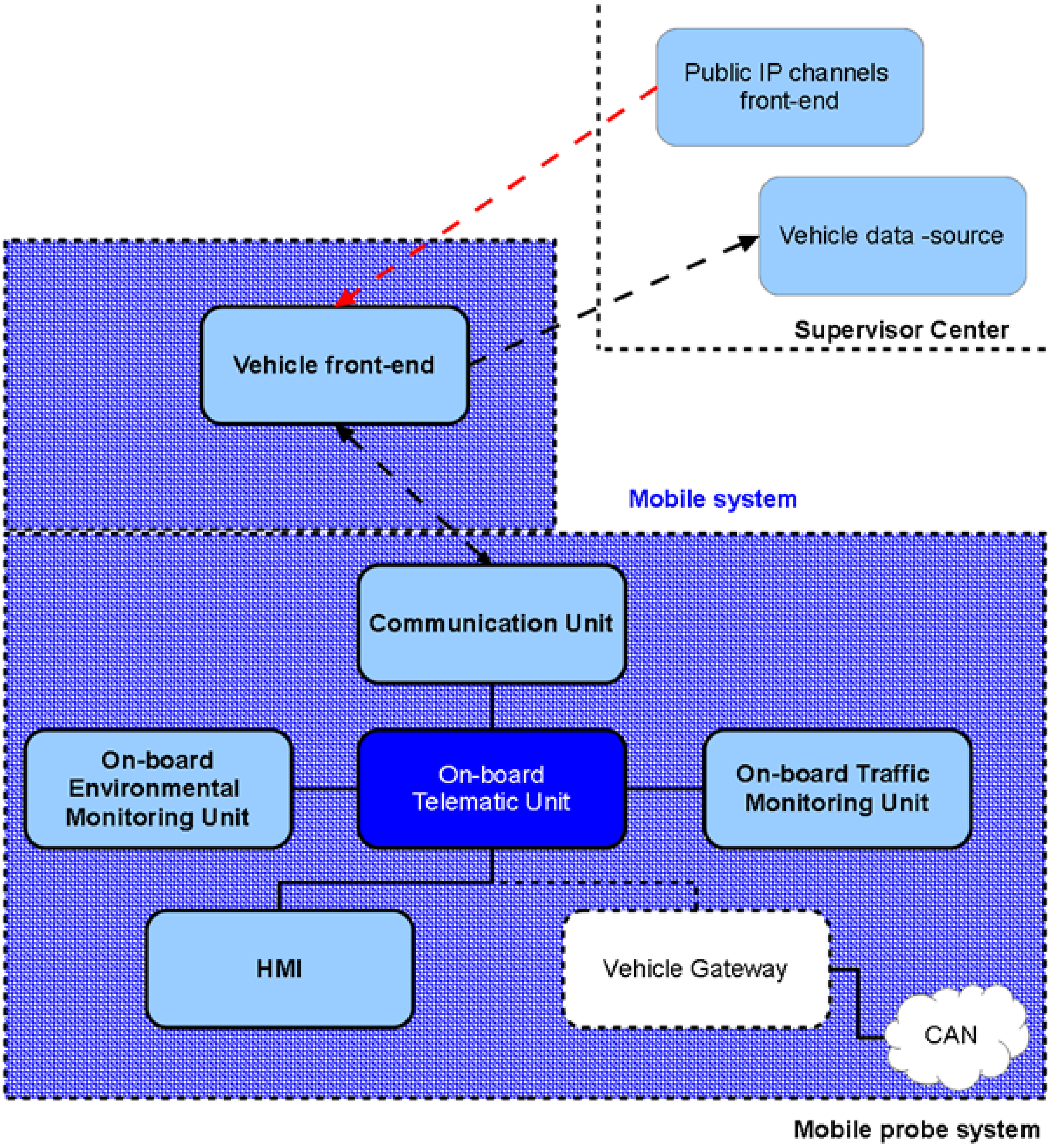


Figure 4: The reference architecture of the INTEGREEN mobile system

The mobile probe system can be mounted on vehicles like cars, busses or trucks and is fully supplied with electrical power from the vehicle itself. Data communication is only possible via radio communication.

3.1 Functional blocks of the mobile system

The main functional blocks of the mobile probe system are:

- **On-board Environmental monitoring unit**: it collects environmental data, in particular air pollution data and meteorological data as well as GPS position data. This data is then transferred to the On-board Telematic unit. The detailed design of this unit will be described in this document.

- **On board Traffic monitoring unit**: it collects traffic related data, in particular vehicle speed, kinematic data of the vehicle and GPS position data. This data is also transferred to the On-board Telematic unit. The detailed design of this unit will be described in this document.

- **On-board Telematic unit**: it receives the data from the On-board Environmental monitoring unit and from the On-board Traffic monitoring unit. The data will be elaborated and then transmitted to the communication unit. To avoid a continuous on-the-air transmission the data will be transmitted in blocks (one minute of data blocks). Therefore the Telematic unit must be able to save data (the Communication unit don't save data). The detailed design of this unit will be described in the deliverable D.3.2.1.

- **Communication unit**: this unit communicate fully automatic via an air interface with the vehicle front-end in a bidirectional way. It transmits environmental, traffic and vehicle specific data to the vehicle front-end and can receive information data for the driver. The detailed design of this unit will be described in the deliverable D.3.2.1.

- **HMI**: the Human-Machine Interface is the interface for the driver of the vehicle. The information from the Supervisor Center will be illustrated to the driver. The detailed design of this unit will be described in the deliverable D.3.2.1.

- **CAN-bus access**: data from the vehicle like speed and acceleration can be directly collected by the On-board Telematic unit or via the On-board traffic monitoring unit. The detailed design of this unit will be described later in this document.

The functional block of the stationary part of the mobile system:

- **Vehicle front-end**: this unit is connected via an air interface to one or more vehicle(s). The data received from the mobile probes are collected and transferred via the Vehicle front-end to the Supervisor Center Vehicle data-source and subsequently to the Supervisor Center. In the other direction it can receive information data for the drivers from the Supervisor Center and transfers it to the mobile probe. The detailed design of this unit is described in the deliverable D.3.2.1.

3.2 Interfaces between the functional blocks of the mobile system

- Interface between **On-board Environmental monitoring unit** and **On-board Telematic unit:**

  It should be implemented as physical USB-Interface. The main data direction is from the On-board Environmental monitoring unit to the On-board Telematic unit. Configuration data can be sent in the other direction.

- Interface between **On-board Traffic monitoring unit** and **On-board Telematic unit:**

Also this interface should be implemented as physical USB-Interface. The main data direction is also in this case from the On-board Traffic monitoring unit to the On-board Telematic unit. Configuration data can be sent in the other direction.

- Interface between **On-board Telematic unit** and **Communication unit:**

  The communication unit can be physically integrated in the Telematic unit or can be a separate module. If a separate module is chosen then the interface can be USB or LAN.

- Interface between **On-board Telematic unit** and **HMI:**

  The HMI can be connected via a cable interface (VGA, HMI, Display Port …) to the telematics unit or alternately it can be equipped with its own communication unit such as a smart phone that can be used for this function.

- Interface to the **CAN-bus:**

  As mentioned in chapter 3.1 above the CAN-bus access can be implemented either via the Telematic unit or via the Traffic monitoring unit. The design will be described in chapter 5.1.2 of this document.

- Interface between **Communication unit** and **Vehicle front-end:**

  As described above this interface is an air interface between the moving vehicle and the stationary Vehicle front-end. This interface will be described in in the deliverable D.3.2.1.

- Interface between **Vehicle front-end** and **Supervisor Center:**

  This is a crucial interface between the project partner AIT and TIS and will be described in the deliverable D.3.2.1.

4 Design of Environmental monitoring system

4.1 Physical description of environmental sensors

Environmental sensors are sensors to measure different kinds of environmental load that influence humans, animals and plants.

For street traffic environment the most important pollution can be divided in

- Gas pollution
- Particulate matter
- Physical properties

4.1.1 Gas pollution

The most important environmental gases in respect to road traffic are:

- Carbon dioxide (CO_2)
- Nitrogen oxides (NO_x: NO, NO_2)
- Carbon monoxide (CO)
- Sulfur dioxide (SO_2)
- Ozone (O_3)

The concentration of many gases is not constant and changes with the influence of other gases and/or with sun radiation. For this reason and for the relative small concentrations in traffic environment it is difficult to take measurements with small and economic sensors.

Gas sensors have typically response times between a few seconds and a few minutes. This is another problem for mobile sensors moving with typical urban vehicle speed.

Important characteristics for gas sensors are:

- Selectivity: the sensor should only be sensible for the desired gas
- Sensitivity: the gas concentration in ambient air is frequently in the range from parts per billion (ppb) up to parts percent
- Stability: in the sense of chemical, electrical and mechanical influences
- Long life time
- Short reaction time

- Low power consumption
- Simple calibration
- Low price

The goal is to convert a gas concentration in an electrical value that can be memorised, digitally processed and transferred as well as represented in a proper manner.

Principles for electrical measurement of gas concentrations are:

- Chemo resistive sensors, Metal oxide semiconductor (MOX)
  The measured gas affects the resistive property of a sensor. The change in conductivity can be measured electrically
- Capacitive
  The dielectric medium of a capacitor is influenced by the gas. The capacitance can be measured electrically
- Electrometric
  The sensor generate an electric potential as a function of the gas concentration which can be measured with electronic devices, i.e. lambda probe
- Amperometric
  The sensor generates an electrical current. The measurements from the electrode originate from an oxidizing reaction, i.e. electro chemic cell, fuel cell
- Thermic (Pellistor)
  Increase of temperature due to chemical reaction of the measured gas on the sensor surface. This increase of temperature can be measured
- Optical
  The optical characteristics of a probe volume with the measured gas are influenced. The optical characteristics can be measured.

The most important measurement principles for the selected gases are MOX, Electrochemical and Optical.

MOX-gas sensors:

The structure of a **M**etal **Ox**ide (MOX) sensor is shown in Figure 5. On a substrate with 2 metal electrodes an active material (i.e. SnO_2) is deposed. This active material changes its conductivity with the concentration of a gas. On the two metal electrodes the conductivity can be measured. In order to create the operation temperature of typically 300°C – 400°C below the substrate, an electrical resistive heating (i.e. platinum) has been positioned. This temperature promotes the chemical reactions on the surface of the active layer.

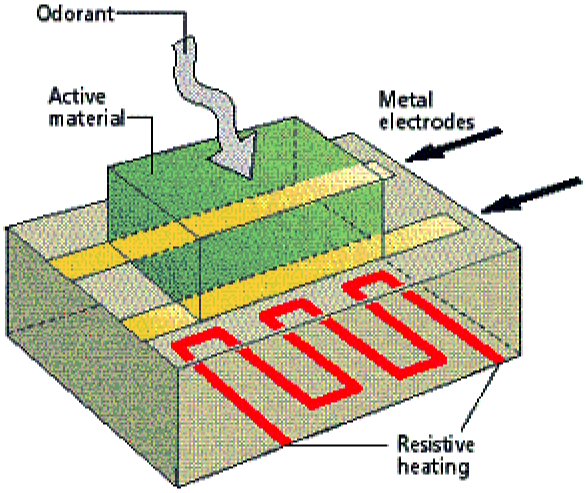


Figure 5: MOX-structure[2]

The working principle is based on the variation of conductivity in the presence of oxidizing and reducing gases. The electron density changes with the adsorption and desorption of oxygen (O, O_2). Adsorbed oxygen gives rise to potential barriers at grain boundaries and thus increases the resistance of the sensor surface.

The sensing material is a semiconductor of n-type or p-type. N-type semiconductors for example are SnO_2, ZnO, Fe_2O_3, TiO2 and WO_3. These materials respond to reducing compounds like H_2, CH_4, CO, C_2H_5 or H_2S. On the other side, p-type semiconductors (CuO, NiO or CoO) respond to oxidising compounds like O_2, NO_2 and Cl_2. These sensors can be optimised with the thickness of the material or doping with other metals.

A disadvantage of this sensor type is the nonlinearity characteristic. Due to the heating energy the sensors are not low power devices and they need a certain time to reach the operating temperature in order to reach the desired sensitivity.

Optical gas sensors:

The basis for many types of optical gas sensors is the Beer – Lambert law. It relates the absorption of light to the properties of the material through which the light travels.

The gas density is calculated from the number of gas molecules and the mass of the gas molecule:

$$\rho = N \cdot M$$

ρ… gas density [kg·m^{-3}]
N… concentration of gas molecules [m^{-3}]
M… mass of the gas molecule [kg]

[2] Soure: Università degli Studi di Siena (http://www.dii.unisi.it/~electron/lab/Ricerca/MOX%20Sensors.htm)

The light absorption of the light travelling through a homogenous medium is described by the Beer – Lambert law:

$$I(z) = I_0 \cdot e^{-\alpha \cdot z}$$

I(z) ... light intensity at the position z [W·m^{-2}]
I_0 ... light intensity at the position z = 0 [W·m^{-2}]
α ... absorption coefficient [m^{-1}]
z ... distance [m]

The absorption coefficient depends on the material, the wave length of the light, the air pressure and the temperature. We now consider a volume concentration *C* in terms of volume of the interested gas in relation to the total gas volume. If *α* is known at the pressure p_0 and the temperature T_0, the light intensity at other gas pressures and temperatures can be calculated:

$$I(C) = I_0 \cdot e^{-\alpha_0 \cdot C \cdot z \cdot \frac{T_0}{T} \cdot \frac{p}{p_0}}$$

I(C) ... light intensity [W·m^{-2}]
I_0 ... light intensity at the position z = 0 [W·m^{-2}]
α_0 ... absorption coefficient at p_0 and T_0 [µm^{-1}]
z ... distance [m]
T ... absolute real gas temperature [K]
T_0 ... absolute standard gas temperature [K]
p ... absolute real gas pressure [hPa]
p_0 ... absolute standard gas pressure [1013 hPa]
C ... relative gas concentration [ppm]

The light intensity decreases with the increasing gas concentration. From this equation the gas concentration can be calculated:

$$C = \frac{1}{\alpha_0 \cdot z} \cdot \frac{T}{T_0} \cdot \frac{p}{p_0} \cdot \ln \frac{I}{I_0}$$

The sensor can be designed in a way that the logarithm can approximately be linearised:

$$C \approx -\frac{1}{\alpha_0 \cdot z} \cdot \frac{T}{T_0} \cdot \frac{p}{p_0} \cdot \left(1 - \frac{I}{I_0}\right)$$

Many gases have a strong absorption in the infrared or ultraviolet spectrum.

Spectral range	Gas
IR	CO, CO_2, CH_4, NH_3
UV	O_3, H_2S, SO_2, NO, NO_2

Table 9: Spectral absorption range of some gases

Different absorption-based sensing techniques:

- UV absorption:
  The electrons of the atom or molecule can absorbe energy in the form of ultraviolet light to excite these electrons to higher molecular orbits.The wavelength of the light is very characteristic for the molecule.

- NDIR (Non-dispersive infrared sensor):
  In contrast to UV absorption not the electrons but the dipole elements are activated. The IR-light is absorbed by the target gas in the path between the source and the target. To detect a specific gas a dedicated wavelenth for this gas is necesary.

- UV fluorescence:
  With the UV light at wavelenth v the molecule is beeing excited from its normal state to an excited state. When it returns to the normal state a light with a different characteristic wavelength v_1 is emitted. The emitted wavelength v_1 is typically longer than v.

- Chemiluminescence:
  During a chemical reaction from one molecule to another molecule excess energy will be freed and a photon will be emitted. The emitted light energy is proportional to the number of reactions.

- Photometrie
  A light soure emittes radiation of a certain wavelength (i.e. mercury vapour lamp, heating wire). The light will be absorbed according to the law of Beer – Lambert. With optical filters only the wavelength of the interested gas arrives at the photo sensor. With two consecutive measurements (one with the interested gas and one with the interested gas filtered) the absorption of this specific gas can be measured.

Used units for gas environmental measurements and conversion of units:

The general used units for gas environmental measurements are:

- milligram per cubic metre (mg/m^3)
- microgram per cubic metre ($\mu g/m^3$)
- parts per million (ppm, 10^{-6} volume/volume)
- parts per billion (ppb, 10^{-9} volume/volume)

where:

- $1\ mg/m^3 = 1000\ \mu g/m^3$

- 1 ppm = 1000 ppb

Also mass per cubic metre can be converted in volume per volume and vice versa with the use of the ideal gas law:

$$C_i = C_j \cdot \frac{M \cdot u}{k} \cdot \frac{p}{T} = C_j \cdot A_{temp}$$

$$A_{temp} = \frac{M \cdot u}{k} \cdot \frac{p}{T}$$

C_i ... gas concentration in mg/m^3
C_j ... gas concentration in ppm
p ... absolute real gas pressure [Pa]
T ... absolute real gas temperature [K]
k ... Boltzmann constant ($1.380658 \cdot 10^{-23}$ J/K)
u ... unified atomic mass unit ($1.66 \cdot 10^{-27}$ kg)
M ... molecular mass in multiple of u

In Table 10 the conversion from volume concentration to mass concentration at standard pressure (p = 1013 hPa) and 20 °C (293.15 K) is illustrated. On the other hand in *Table 11* the conversion from mass concentration to volume concentration is displayed.

gas	volume concentration	mass concentration
SO_2	1 µg/m^3	0.3753 ppb
NO	1 µg/m^3	0.8019 ppb
NO_2	1 µg/m^3	0.5229 ppb
CO	1 µg/m^3	0.8591 ppm
O_3	1 µg/m^3	0.5012 ppb

Table 10: Conversion from mass concentration to volume concentration

gas	mass concentration	volume concentration
SO_2	1 ppb	2.665 µg/m^3
NO	1 ppb	1.247 µg/m^3
NO_2	1 ppb	1.912 µg/m^3
CO	1 ppm	1.164 mg/m^3
O_3	1 ppb	1.995 µg/m^3

Table 11: Conversion from mass concentration to volume concentration

Typical errors of environmental gas measurement:

An accurate measurement of typical gas concentrations in urban traffic environment is very difficult. The following are the main reasons:

- The gas concentrations are relatively low (typical 1 – 100 µg/m^3)
- The gas sensor needs relatively long time for one measurement (typically 1 – 100 s). In this time frame the vehicle with the measurement device moves from several meters up to km in an urban environment
- The sensor value depends on the temperature
- The sensor value depends on the pressure
- Nonlinearity of the sensors
- Zero drift of the sensor
- Cross sensitivity: the sensor responds also to other gases

Sensor data interfaces:

An environmental gas sensor converts a gas concentration into an electrical value, which can be measured with the measurement device. Depending on the sensor type many different electrical analogue or digital interfaces can be found. The most important interfaces are:

- Analogue electric voltage
- Analogue electric current
- Analogue electric resistance
- Digital I2C (Inter-Integrated Circuit) Interface
- Digital SPI (Serial Peripheral Interface)
- UART (Universal Asynchronous Receiver Transmitter) like RS-232
- LAN (Local Area Network) Interface

4.1.2 Particulate matter

Atmospheric particulate matters (PM) are small pieces of solid or liquid particles in the air. Due to the small size of particles smaller than 10 µm, the particles when inhaled from humans or animals can penetrate in the small parts of the lung like the bronchia and can affect the health. Larger particles are filtered from the nose.

For environmental measurements the following PM categories are of interest:

- PM_{10}: particles smaller than 10 µm
- $PM_{2.5}$: particles smaller than 2.5 µm
- UP: ultrafine particles smaller than 0.1 µm

An accurate measurement of particulate matter is done with manual measurements and subsequent laboratory analysis. This means that a defined quantity of air is filtered and then the particles in the filter are weighed and analysed. Therefore gravimetric principles are used. With x-Ray Fluorescence spectroscopy, Atomic Absorption Spectroscopy or Mass Spectroscopy, the total mass, the sizes and the composition is determined.

This method is very complex and cannot be used for a real time measurement in terms of minutes.

A different measurement principle is used by the German company Grimm Aerosol. A laser light is scattered on each particle and the scattered light is measured with light photometry. Through a counter the number of particles and also their size is determined. The principle is shown in Figure 6.

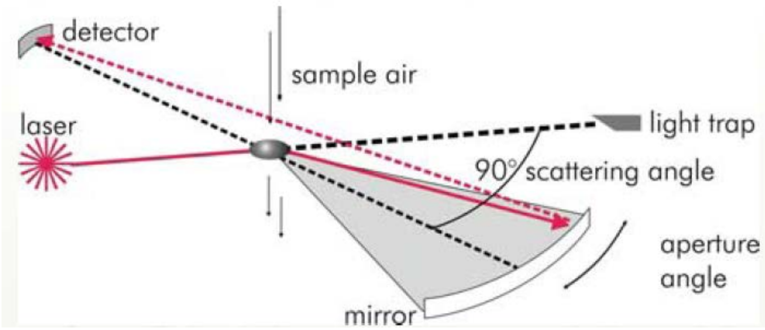


Figure 6: Measurement principle of the GRIMM indoor air monitor

4.1.3 Physical properties

The physical properties of the environment are accurately measured by stationary environmental stations in the city of Bolzano and the city surroundings. The main weather parameters are:

- Air temperature
- Air pressure
- Humidity
- Wind speed and direction

- Precipitation (type, intensity)
- Sun radiation

These parameters are not of particular interest for traffic analysis and traffic data processing in a fine spatial resolution and consequently they are not part of the must requirement list of the INTEGREEN mobile system.

However, the accuracy of many sensors depends on air temperature, air pressure and humidity and for this reason these parameters are measured anyway for compensation of these effects. Some intelligent sensors have already integrated multiple sensors for the air temperature and/or humidity and air pressure.

4.2 Sensor types

For the environmental sensors many properties of the sensors have to be considered. Some characteristics are already described in the previous section. Environmental sensors can be found in a very large scale of electrical, physical and economical range.

To design a mobile environmental unit the following parameters have to be analysed:

- Accuracy of the measurement value
- Response time of the sensor on the measurement gas
- Drift of the measurement value with time (short range and long term)
- Cross reference characteristics of the sensor
- Environmental interface (gas aspiration)
- Power consumption
- Electrical data interface (analogue/digital, type)
- Physical dimension of the sensor module
- Weight of the sensor module
- Price and availability
- Duration of life

4.3 Market analysis of environmental sensors and systems

4.3.1 Stationary measurement devices

The most accurate sensors can be found in stationary measurement devices. These environmental stations are designed for stationary mode with high precision measurement and medium to long sample period. The size and weight of the stations are large and the price is also high (> 10k€).

Here are two examples of stationary measurement platforms:

<u>AQM 60 from aeroqual:</u>

Aeroqual was formed in 2001 to commercialise gas sensitive semiconductor (GSS) technology developed over three decades by researchers in the UK and New Zealand.

Aeroqual primarily uses Gas Sensitive Semi-conductor (GSS) sensor technology because of their quick response, long life, wide operating temperatures and sensitivity. The principle of the sensor technology is illustrated in Figure 7.

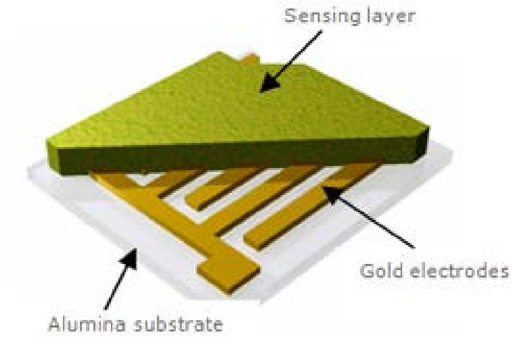


Figure 7: Aeroqual sensor technology[3]

The AQM 60 unit is designed for outdoor measurement. Typical applications are urban monitoring, near road monitoring, perimeter monitoring (power generation plants, petrochemical refineries…) and open space monitoring. In Figure 8 the AQM 60 is shown. The lower part is the thermal management system which is responsible for a constant temperature of the measurement sensors. At the upper part there are the air inlets, the left inlet is for the gas concentration measurement and the right inlet is for the particle measurement.

[3] Source: Aeroqual (www.aeroqual.com)

Figure 8: AQM 60 from aeroqual

In Figure 9 the measurement, control and communication devices are illustrated. A complex gas flow is necessary for the accurate measurement.

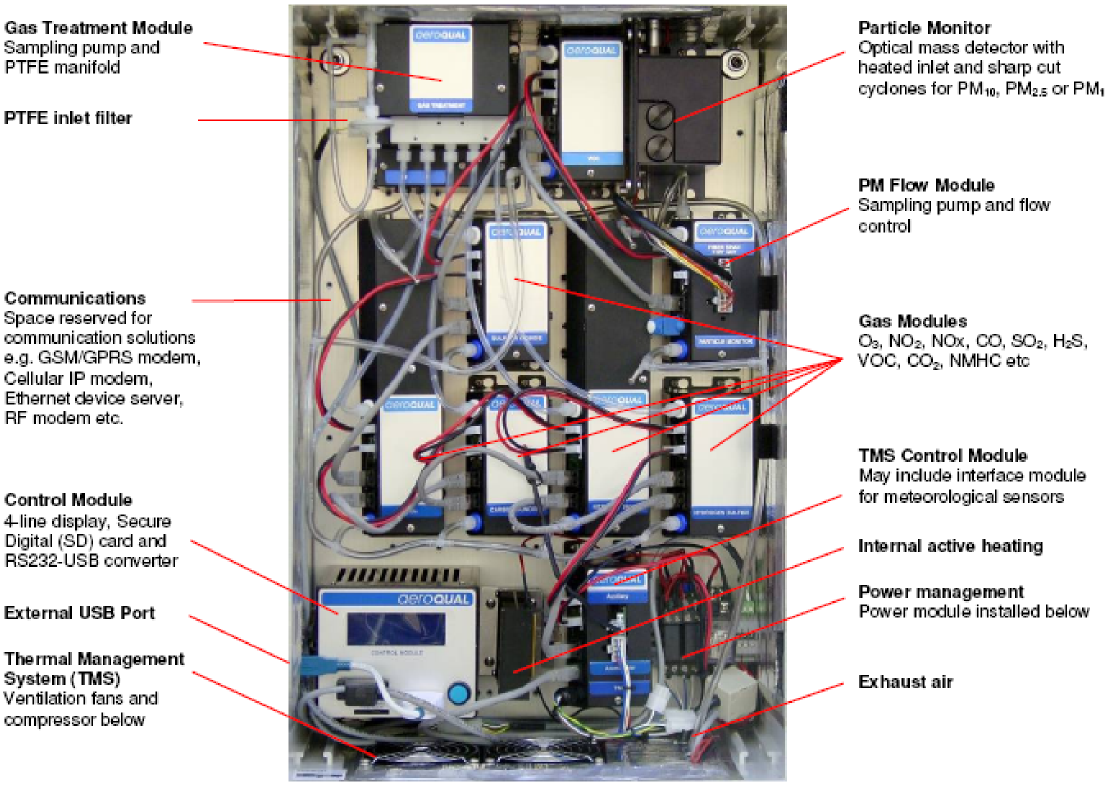


Figure 9: Inside the AQM 60

Overview of the main characteristics of the AQM 60 (for more information see the Detailed Specification from aeroqual [1]):

- Dimension (with inlets and thermal management system): 1300mm x 555mm x 400mm
- Weight: 10 – 50kg (depending on instrument configuration)
- Temperature: -20°C to 55°C with thermal management system
- Power requirement: 100 – 240V AC or 12V DC, 80 – 160W (depending on instrument configuration)
- Measurement modules Ozone (O_3):
    - Calibrated range: 0 – 0.5 ppm O_3
    - Resolution: 0.001 ppm O_3
    - Precision : 0.005 ppm O_3
- Measurement modules Nitrogen Dioxide (NO_2):
    - Calibrated range: 0 – 0.2 ppm NO_2

- Resolution: 0.001 ppm NO_2
- Precision : 0.005 ppm NO_2

- Measurement modules Nitrogen Dioxide (NO_x):
  - Calibrated range: 0 – 0.5 ppm NO_x
  - Resolution: 0.001 ppm NO_x
  - Precision : 0.005 ppm NO_x
- Measurement modules Carbon Monoxide (CO):
  - Calibrated range: 0 – 25 ppm CO
  - Resolution: 0.1 ppm CO
  - Precision : 0.2 ppm CO
- Measurement modules Carbon Dioxide (CO_2):
  - Calibrated range: 0 – 2000 ppm CO_2
  - Resolution: 1 ppm CO2
  - Precision : 10 ppm CO2
- Measurement modules Particle Monitor (PM_{10}, $PM_{2.5}$, PM_1, TSP):
  - Calibrated range: 0 – 2000 µg/m^3
  - Resolution: 1 µg/m^3
  - Precision: 3 µg/m^3
  - Sample period: 1 s
- Different weather modules (wind speed and direction, rainfall, barometric pressure, air temperature, relative humidity, dew point)
- Noise meter and calibrator
- RF and Ethernet modules

Airpointer® from recordum:

The airpointer® from the Austrian company recordum is the world's first "out-of-the-box plug and play" compact multi gas air quality monitoring system and offers unique opportunities due to its compact dimensions and its modular platform.

In Figure 10 the Airpointer is illustrated.

Figure 10: Airpointer from recordum

The Base Unit can be equipped with up to seven ambient air measurement modules. The measurement modules work typically with optical gas sensors and therefore they cannot be miniaturised.

The principal pollutant measurement modules are:

- Ozone (O_3)
- Carbon Monoxide (CO)
- Sulfur Dioxide (SO_2) and Hydrogen Sulfide (H_2S)
- Nitrogen Oxides (NO, NO_2, NO_x)
- Particulate Matter (PM_{10}, $PM_{2.5}$)

Following are illustrated the main characteristics of the Airpointer (for more information see the Detailed Specification from recordum)

- Dimension:
    - Base Unit 2D (up to two drawers): 831mm x 740mm x 352mm
    - Base Unit 4D (up to four drawers): 1067mm x 740mm x 352mm

- Weight:
    - Base Unit 2D: 65.8 kg
    - Base Unit 4D: 73.9 kg
    - Measurement module: 4 – 12 kg
- Temperature: -20 to +40 °C
- Power requirement: 110 – 230V AC, 500 W, peak up to 670 W
- Measurement modules Ozone (O_3):
    - Measuring Principle: Ultraviolet Photometry
    - Range: dynamic up to 20 ppm
    - Lowest detectable limit: circa 0.5 ppb
- Measurement modules Nitrogen Oxide (NO, NO_2, NO_x):
    - Measuring Principle: Chemiluminescence
    - Range: dynamic up to 20 ppm
    - Lowest detectable limit: circa 0.4 ppb
- Measurement modules Carbon Monoxid (CO):
    - Measuring Principle: NDIR
    - Range: dynamic up to 10000 ppm
    - Lowest detectable limit: circa 0.04 ppm
- Measurement modules Particulate Matter (PM_{10}, $PM_{2.5}$):
    - Range: dynamic, up to 2500 µg/m^3
    - Lowest detectable limit: < 1µg/m^3
- Response time of gas sensor modules: circa 60 s
- Weather modules are possible (wind speed, wind direction, humidity, barometric pressure, temperature)
- Other sensors are possible (sound level, pedestrian counter, UV-radiation, illumination, ...

- Communication by modem (GSM, GPRS, UMTS) or LAN (cable and wireless)

4.3.2 Mobile pollutant measurement laboratory (MOSQUITA)

The Paul Scherrer Institute (PSI) in Switzerland developed in the year 2000 a first version of a mobile pollutant measurement laboratory which allows "Measurements Of Spatial Quantitative Imissions of Trace gases and Aerosols" (MOSQUITA). In 2009 the mobile laboratory was expanded with an aerosol mass spectrometry. MOSQUITA is equipped with a suite of instruments to characterize the chemical composition and physical properties of aerosols as well as trace gases at high time-resolution.

Figure 11: The PSI mobile laboratory (MOSQUITA)[4]

The mobile laboratory was developed to measure pollutants both near traffic (i.e. in urban area, highway) and at rural locations far away from traffic with short sample time and on different times of day and year.

Different measurement projects have been conducted with the mobile pollutant measurement laboratory, for example in Minneapolis, Switzerland, Barcelona and Paris.

A schematic picture of the Mobile Pollutant Measurement Laboratory is given in Figure 12. To catch the measurement air with the driving vehicle before it is influence of the own exhaust the air inlet was placed on the top of the vehicle above the van front end (see Figure 12).

[4] Source: Paul Scherrer Institut (www.psi.ch)

A: Inlet tip

B: SMPS sampling line branching

C: OPC sampling line branching

D: Flow distribution cylinder

E: Blower

F: Wind direction, relative humidity, global radiation

G: Gas inlet

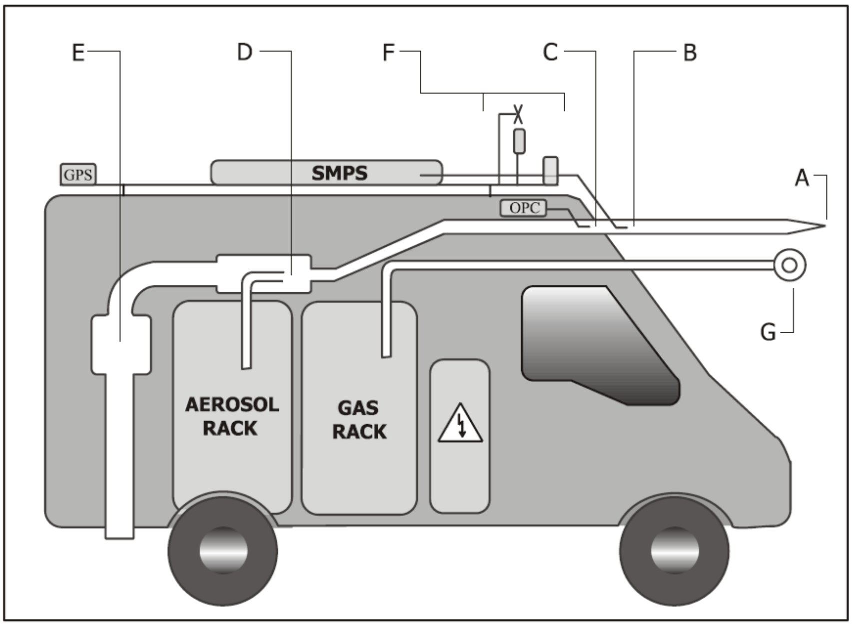


Figure 12: Schematic setup of the PSI Mobile Pollutant Measurement Laboratory[4]

The complete set of measurement equipment has a total weight of approximately 1000 kg and a total power consumption of 1600 W. For the delivery of the energy a second alternator was built in the van engine system.

In Figure 13 the gas measurement equipment and the power supply are shown.

Figure 13: Racks for gas phase measurements (left rack) and power supply (right rack)[4]

In Table 12 the measurement parameters are listed. The indicated time resolutions represent the instrument time resolutions. The system time resolution for the aerosol and gas phase instruments is 10 ± 3 s.

	Parameter	Instrument Method / Type	Time Resolution	Detection Limit
Aerosols	Size Distribution D = 7-310 nm	SMPS (Scanning Mobility Particle Sizer) /TSI DMA 3071, CPC 3010	3 min	not defined
	Number Concentration D > 3 nm	CPC (Condensation Particle Counter) /TSI UCPC 3025	1 s	0.5 cm-3 (1s)
	Size Distribution D = 0.3-20 µm	OPC (Optical Particle Counter) /Grimm Dustmonitor 1.108	6 s	1 particle/l (6s)
	Active Surface Area	DC (Diffusion Charging Sensor) / Matter Engineering LQ1-DC	1 s	10 µm2 cm-3
	Black Carbon Mass Concentration	Aethalometer (Visible Light Absorption) /Magee AE-10	1 min	40 ng m-3 (5 lpm, 5 min)
	$PM_{2.5}$	Betameter (Beta radiation absorption) / Eberline FH 62 I-R	½ h	3 µg m-3 (½ h)
Gas Phase	O_3	Ozone-Monitor (UV absorption) / constructed by PSI	2 s	1 ppb
	CO	CO – Monitor (Vacuum UV resonance fluorescence) /Aerolaser AL-5002	1 s	2 ppb
	CO_2	CO_2 –Monitor (IR absorption) / LI-COR	1 s	0.1 ppm
	NO_x, NO_y, HNO_3, PAN	NOxTOy (Chemiluminescence) /constructed by MetAir / PSI / Juelich	1 s	200 ppt
	H_2O_2, total peroxide	Peroxide Monitor (Fluorescence) / Aerolaser AL-2002	120-180 s	200 ppt
	HCHO	Formaldehyde Monitor (Fluorescence) IFU Garmisch	120-180 s	200 ppt
Other	Geographical information	GPS/Garmin IIplus	2 s	common standard
	Temperature	Thermilinear Thermistor Network/YSI 44203	< 1 min	common standard
	Pressure	constructedbyPSI	< 1 min	common standard
	Relative humidity	HUMICAP sensor/Vaisala HMP 31UT	< 1 min	common standard
	Wind direction	constructed by PSI	1 s	common standard
	Global radiation	Pyranometer/Kipp&Zonen “Solarimeter” CM10	< 1 min	common standard

Table 12: Instrumentation of the PSI mobile pollutant measurement laboratory[4]

4.3.3 DUVAS

DUVAS is an acronym for **D**ifferential **U**ltra**V**iolet **A**bsorption **S**pectroscopy. It is a highly flexible cost effective family of intelligent portable, mobile and fixed sensors using closed path spectroscopy, capable of detecting multiple pollutants simultaneously at ppb level.

The technology was developed from Duvas Technologies Ltd, a start-up company which was founded with the objective to commercialise the result of the MESSAGE project (see deliverable D.2.2.1 chapter 1.2.12 and chapter 1.2.13).

Duvas is also a newly created entity that sits within the Imperial Innovations Incubator that combines the academic and engineering excellence of Imperial College London with the commerciality of the real world.

The principle of DUVAS is illustrated in Figure 14. It is an optical gas sensor and measures the light attenuation at different wavelength at the basis of the Beer – Lambert law.

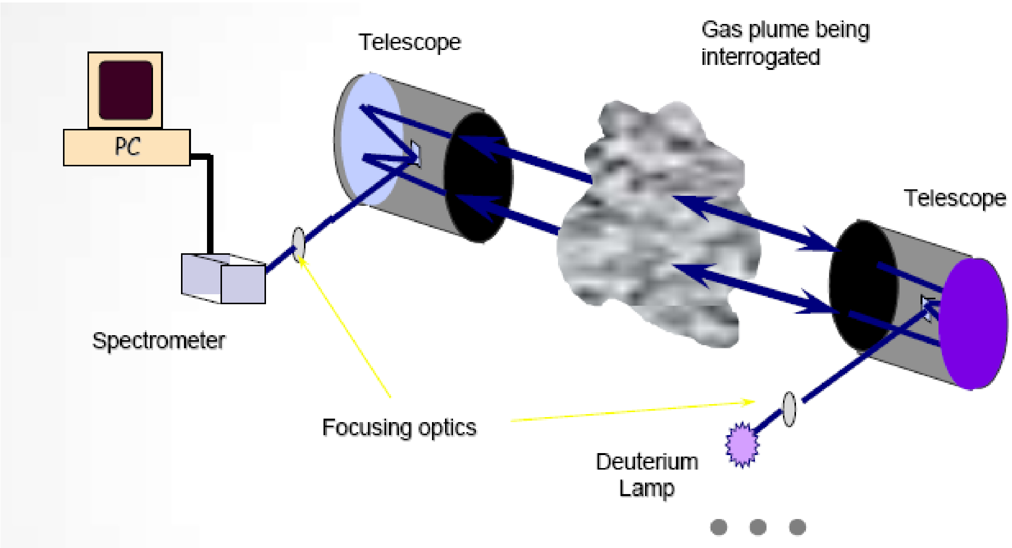


Figure 14: Principle of DUVAS

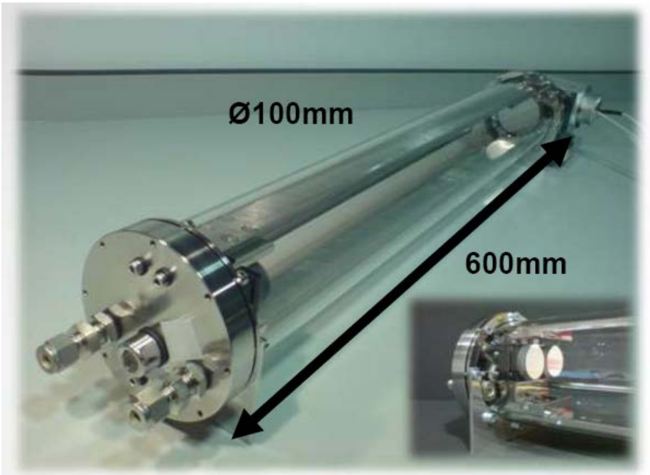


Figure 15: Tube of the DUVAS sensor

A specification of the Air Quality Monitoring device D100AQM is available. Here are the main characteristics:

- Measuring Principle: Ultraviolet Absorption Spectroscopy
- Performance: Simultaneous Analysis of Multiple Gases in ppb concentration

- Current Species: SO_2, NO_2, NO, O_3, C_6H_6 (Benzene)
- Optional Species: Toluene, Ethyl Benzene, (m-, o-, p-) Xylene, Ammonia, 1-3 Butadiene
- UV light source: Deuterium Lamp
- Sample Flow: 90 lpm
- Range 0 – 2 ppm
- Detection Limit 1 - 40 ppb [1]
- Accuracy: better than 5% [5]
- Linearity: within 5%[5] up to 2 ppm
- Precision: better than 2% [5]
- Drift: less than 3% / month
- Response Time: <10 s
- Mains Power: 110-240V AC; 50-60Hz
- Power Consumption: 88.2 W max
- Physical Characteristics:
  - Size (L W H): 805mm x 214mm x 207mm
  - Weight: <20 kg
- Environmental:
  - Humidity non-condensing
  - Temperature operating –0°C to 45°C
  - Storage temperature -10°C to 60°C
- Connectivity: PC, LAN, USB, GPRS
- Optional sensors: Humidity sensor, Temperature sensor

The product is not yet available on the market and currently there are only a few devices in the test phase. The commercialisation of this technology was planned for the early part of

[5] Depending upon pollutant

2013 but then postponed to the following year. The price is expected to be quite high in the region of 40 k€.

4.3.4 AQMesh

The AQMesh (Figure 16) is an air pollution monitoring system from the british company “Air Monitors” (http://www.airmonitors.co.uk). The Air Monitors are working in a partnership between the University of Cambridge and Geotech.

Figure 16: AQMesh

The AQMesh is developed as a “low cost” environmental air pollution monitoring solution for stationary measurement. Typical applications are site perimeter monitoring, traffic hot spot monitoring and fugitive emission monitoring. It works with an integrated battery with up to 2 years life. The data communication is done per wireless communication via GPRS.

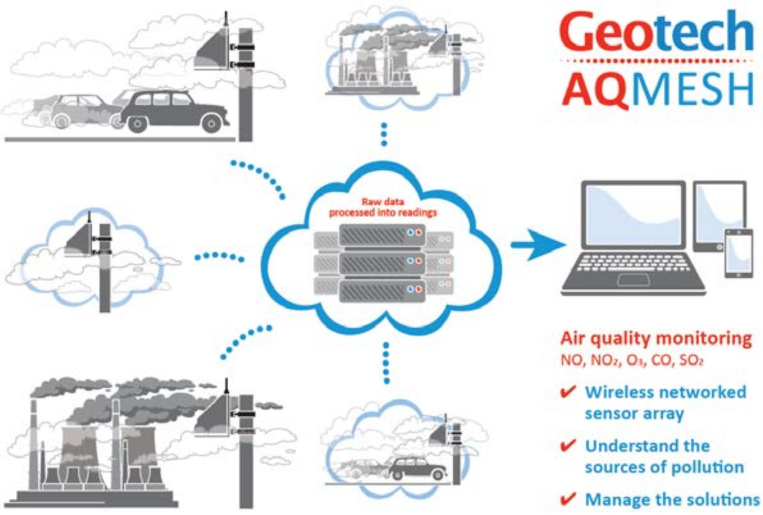


Figure 17: Typical Applications of the AQMesh

To allow a long life with batteries the AQMesh device has low calculation capacity inside. The system is centrally managed as there are a number of real time corrections needed to be made on the data in order to achieve the desired accuracy. The data of all "pods" is processed on central servers.

The response time of the system is 20 to 30 seconds. The device is developed for stationary use.

GENERAL SPECIFICATIONS			
Gases measured	Up to five gases - NO, NO2, O3, CO, SO2		
Ranges and accuracy	NO	0-2ppm	(±10% of reading)
	NO_2	0-200ppb	(±10% of reading)
	O_3	0-200ppb	(±10% of reading)
	CO	0-5ppm	(±10% of reading)
	SO_2	0-10ppm	(±10% of reading)
Lower detectable limits	NO	5ppb	
	NO_2	5ppb	
	O_3	5ppb	
	CO	20ppb	
	SO_2	5ppb	
Sensor life	2 years		
Power	Primary batteries, up to 2 years operation (dependant upon measurement strategy)		
Communications	GPRS communications, multi-band worldwide operation		
Enclosure	Material	Polyurethane moulded enclosure	
	Size	Approximately 170 x 180 x 140mm	
	Weight	< 2kg	
	IP rating	IP65	
Environmental temperature range	-20°C to 50°C		
Environmental humidity	0-95% RH		
Server software	Data sent to remote server		

Table 13: Specifications of the AQMesh

The commercial availability of the AQMesh is not clear. From the brochures released now by AQMesh the product seems to be available on the market.

4.3.5 Solid state sensors

There are many companies offering commercial solid state gas sensors. To have a good overview about possible sensors for the INTEGREEN mobile environmental unit we have analysed the exhibitor list of the "Sensor + Test 2012". This event is the leading forum for sensorics, measuring and testing technologies worldwide. The 2012 trade fair with its 536 exhibitors from 29 nations imposingly presented the entire spectrum of measuring and testing system expertise from sensors to computers.

In addition a general Internet search for solid state sensors was conducted.

Sensor for NO_2:

Many companies offer miniature NO_x sensors and sensor systems to measure concentration of 10 to 100 ppm. The following are a few examples of such sensor:

- Nano Environmental Technology (http://www.nenvitech.com) 0 – 30 ppm, 0 – 300 ppm

- Nemotech (www.nemototech.it) 0 – 20 ppm

- SolidsenSe (www.solidsense.de/) 0 – 100 ppm

- J. Dittrich (www.dittrich-systeme.de/) 0 - 50 ppm

- arteos GmbH (www.arteos.com/) 0 – 20 ppm

For traffic environmental condition pollution concentrations of about 10 to 1000 ppb of NO_x are of interest.

Sensors with lower detection limit and detailed specifications:

- Alphasense (http://www.alphasense.com)

The NO2-B4 Sensor (Figure 18) from Alphasense has a measurement range from 0 – 20 ppm of NO_2. It has a small case (Figure 19) and a good sensitivity.

Figure 18: Alphasense NO2-B4 sensor

Figure 19: Dimension of the NO2-B4 sensor

The NO2-B4 is an electrochemical gas sensor. It works in the amperometric mode. This means it creates a current that is linearly proportional to the fractional volume of the toxic gas. The structure of the sensor is illustrated in Figure 20.

The main characteristics of the NO2-B4 sensor can be found in Table 14.

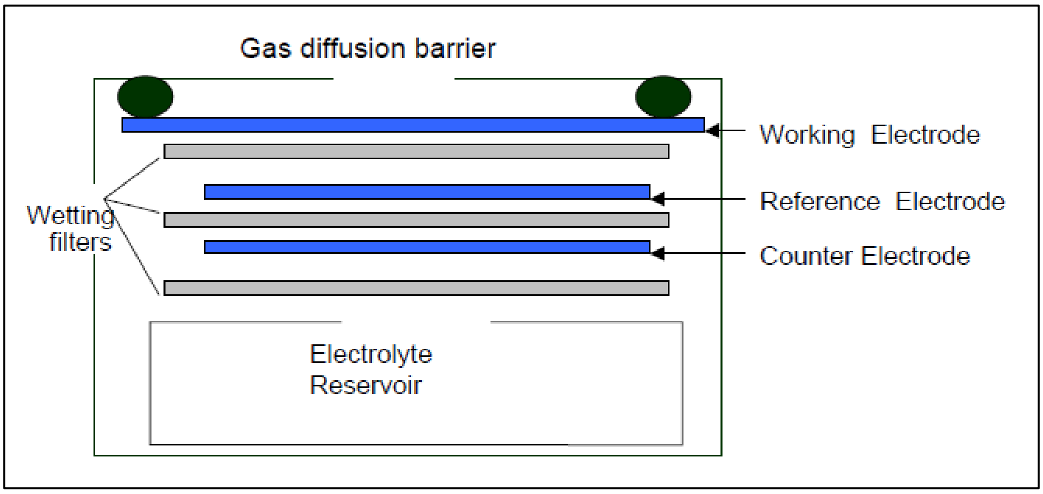


Figure 20: Schematic diagram of electrochemical toxic gas sensor.

PERFORMANCE			
	Sensitivity	nA/ppm at 2ppm NO_2	-250 to -600
	Response time	t_{90} (s) from zero to 2ppm NO_2	< 25
	Zero current	nA in zero air at 20°C	-15 to 20
	Noise*	±2 standard deviations (ppb equivalent)	12
	Range	ppm NO_2 limit of performance warranty	20
	Linearity	ppb error at full scale, linear at zero and 5ppm NO_2	< ±1
	Overgas limit	maximum ppm for stable response to gas pulse	50
	*** Tested with Alphasense ISB low noise circuit**		
LIFETIME	Zero drift	ppb equivalent change/year in lab air	0 to 20
	Sensitivity drift	% change/year in lab air, monthly test	-20 to -40
	Operating life	months until 50% original signal (12 month warranted)	> 18
ENVIRONMENTAL			
	Sensitivity @ -20°C	(% output @ -20°C/output @ 20°C) @ 2ppm NO_2	40 to 70
	Sensitivity @ 50°C	(% output @ 50°C/output @ 20°C) @ 2ppm NO_2	120 to 135
	Zero @ -20°C	nA change from 20°C	±10
	Zero @ 50°C	nA change from 20°C	60 to 380
CROSS SENSITIVITY	H_2S sensitivity	% measured gas @ 5ppm H_2S	< -130
	NO sensitivity	% measured gas @ 5ppm NO	< 4
	Cl_2 sensitivity	% measured gas @ 5ppm Cl_2	< 100
	SO_2 sensitivity	% measured gas @ 5ppm SO_2	< -20
	CO sensitivity	% measured gas @ 5ppm CO	< 0.1
	H_2 sensitivity	% measured gas @ 100ppm H_2	< 0.1
	C_2H_4 sensitivity	% measured gas @ 100ppm C_2H_4	< 0.1
	NH_3 sensitivity	% measured gas @ 20ppm NH_3	< 0.1
	CO_2 sensitivity	% measured gas @ 5% Vol CO_2	< 0.1
	O_3 sensitivity	% measured gas @ 100ppb O_3	30 to 65
	Halothane sensitivity	% measured gas @ 100ppm Halothane	< 0.1
KEY SPECIFICATIONS			
	Temperature range	°C	-30 to 50
	Pressure range	kPa	80 to 120
	Humidity range	% rh continuous	15 to 85
	Storage period	months @ 3 to 20°C (stored in sealed pot)	6
	Load resistor	Ω (ISB circuit is recommended)	33 to 100
	Weight	g	< 13

Table 14: Main characteristics of NO2-B4 Sensor

The zero current is with -15 up to 20 nA (25 to 80 ppb equivalent NO_2) high but can be calibrated to nearly 0 with a offset correction. Nevertheless, the zero drift with time and dependency of temperature can be a problem. Also the cross sensitivity with O_3 can be a problem in outdoor environment (ozone varies over the time of the day and with sun radiation). For a single calibration the sensor gives a good response also at very low concentrations between 0 and 200 ppb (Figure 21).

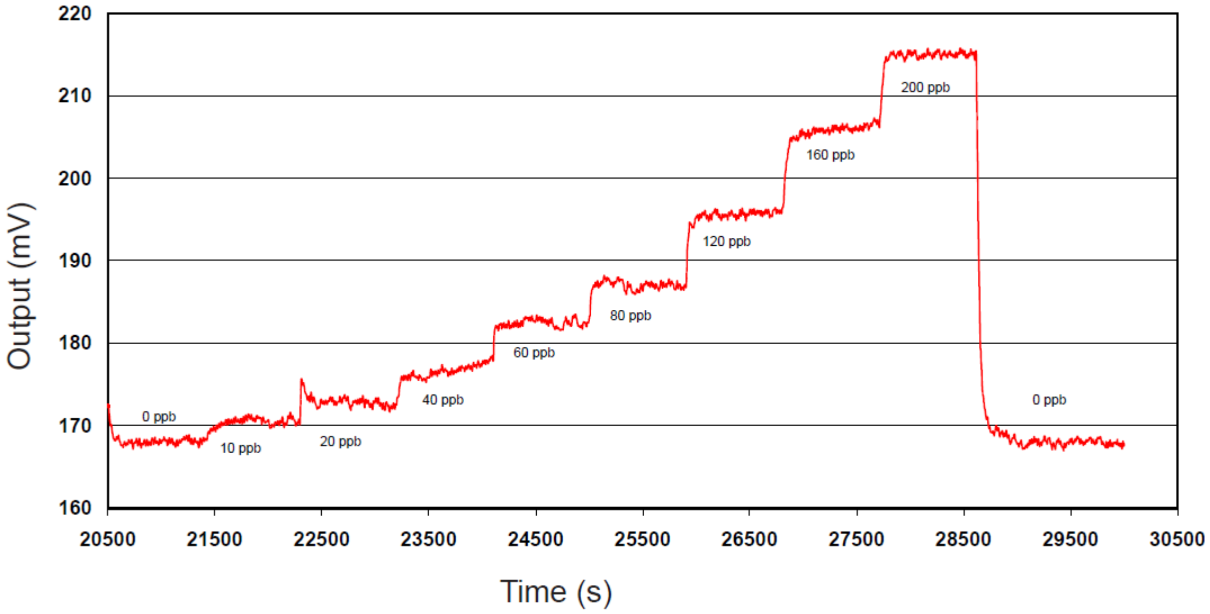
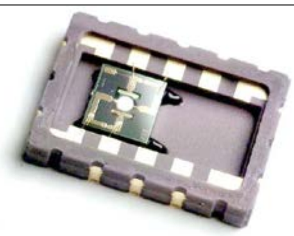
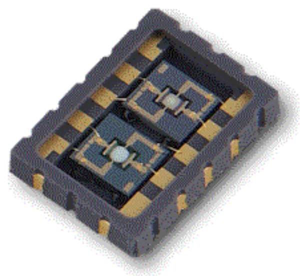


Figure 21: Response of the NO2-B4 to 200 ppb NO_2

- e2v (http://www.e2v.com/ , www.sgxsensortech.com)

The British company e2v (previously known as EEV) purchased Gresham Scientific Instruments (then renamed e2v scientific instruments), and sold the non-core business e2v Scientific Instruments, the industrial gas sensing business and e2v microsensors SA in May 2012 to SGX Sensortech Limited. Now SGX Sensortech continues the business with the sensors. The commercial brand of the sensors is still e2v.

SGX Sensortech now offers 4 interesting types of high sensitive NO_2-Sensors:

Sensor	EC4-20-NO2	MICS-2710	MICS-2714	MICS-4514
Picture				

Sensor Principle	Electrochemical Sensor	Metal Oxide Semiconductor	Metal Oxide Semiconductor	Metal Oxide Semiconductor
Gas	NO_2	NO_2	NO_2	Combined CO and NO_2
Range	0 – 20 ppm NO_2	50 – 5000 ppb NO_2	50 – 5000 ppb NO_2	50 – 5000 ppb NO_2 10 – 1000 ppm CO
Operation Temperature	.-20 - +50 °C	-30 – 85 °C	-30 – 85 °C	-30 – 85 °C
Heating power	-	Max. 50 mW	Max. 50 mW	Max. 50 mW (NO_2) Max. 81 mW (CO)
Sensor Case (approx...)	D.: 20 mm H: 17 mm	D.: 9 mm H: 4 mm	Miniature dimensions SMD case 7 x 5 mm	Miniature dimensions SMD case 7 x 5 mm
Other characteristics	Zero in air: < 0.9 ppm NO_2 Resolution: 0.1 ppm NO_2 Long-term output drift: < 2% signal/month Response time, t90 <35 s			

Table 15: Characteristics of SGX (e2v) Sensors

- <u>Nano Environmental Technology (www.nenvitech.com)</u>

The Italian company Nano Environmental Technology (n.e.t.) offers nemototech NO_2 sensors.

Figure 22: nemototech NT-NO2 sensor

The NT-NO2 sensor is offered with two different measurement levels:

- NT-NO2-PL30 with a detection range 0 – 30 ppm
- NT-NO2-PL05 with a detection range 0 – 5 ppm

Each of these two sensors has similar technical specifications (see Table 16). The only differences are the detection range and the maximum overload.

	NT-NO2-PL30	NT-NO2-PL05
Detection Range	0 – 30 ppm	0 – 5 ppm
Maximum Overload	150 ppm	50 ppm
Output signal	600± 150 nA/ppm	600± 150 nA/ppm
Resolution	0.1 ppm	0.1 ppm
Repeatability	± 2 %	± 2 %
Typical Baseline Range (pure air):	< ± 0.2 ppm	< ± 0.2 ppm
Typical Response Time (t90):	< 25 sec	< 25 sec
Baseline Shift (-20 ~ 40 °C):	< 0.2 ppm	< 0.2 ppm

Table 16: Technical specifications of n.e.t. sensors

4.4 Selection of NO_2 sensors

The selection of a suitable sensor for the project has been a quite difficult process because the datasheets of the sensor manufacturer are not very detailed. The specification data frequently have a wide range or only an upper or lower limit of the value. The cross sensitivity is not always specified. When the manufactures were directly contacted they frequently refused to give more information other than the published datasheets. About mobile use of sensors and measurement characteristics with moving vehicles also no information has been found. [2], [3], [4]

To have a better understanding of the sensor quality for a mobile measurement it was decided to buy some sensors and to test them in pre-measurement campaigns.

The sensors manufacturer offer test boards for sensor validation. These test boards are very different in size, power supply and data interface.

A first selection activity was planned to be executed with the following sensors systems:

- NO2-B4 from the company Alphasense: NO_2 sensor
- NT-NO2-PL05 from the company n.e.t.: NO_2 sensor

- MICS-4514 from the company SGX (formerly e2v): combined NO_2 / CO sensor

4.5 Pre-measurement campaign with gas sensors

4.5.1 First pre-measurement campaign

A first pre-measurement campaign was executed with the AIT test vehicle (Ford Focus) with the sensor boards installed inside (see Figure 23).

Used sensors:

- NT-NO2-PL05
    - Supplier: n.e.t. (Nano Environmental Technology)
    - Calibrated sensor T = 2237 for NO_2
    - Calibration date: 13.3.2013
    - Output: analogue 0.8 V (0 ppb) – 4.0 V (5000 ppb)
    - Concentration <100 ppb → output 0
    - Output measured with oscilloscope, 100 Sample/s
- MiCS-4514
    - Supplier: SGX (e2v technologies)
    - Combined non calibrated sensor for CO and NO_2
    - Output: electrical resistance of CO and NO_2 sensor
    - Output data from evaluation software 1 Sample/s

Figure 23: Installation of sensors for the first pre-measurement campaign

Test route overview: Different test cases were executed where the time is logged in elapsed number of seconds. The seconds are the same appearing in the x-axis of the test results charts shown here below.

The following test cases can be observed in Figure 24 and in Figure 25, by looking at the curves corresponding to the elapsed seconds on the x-axis.

- Vehicle parking
  - [1906 … 2782]
- Drive on urban road
  - [0 … 712]
  - [799 … 985]
  - [1274 … 1732]
  - [1818 … 1860]
  - [2783 … 3343]
  - [3344 … 3800]
- Drive on a highway
  - [1109 … 1273]
  - [1733 … 1817]
- Drive through a tunnel
  - [713 … 798] (Kaisermühlentunnel)
  - [986 … 1108] (Kaisermühlentunnel)
  - [1861 … 1905]
- Measurement near a car exhaust pipe
  - [3799 … 4436]

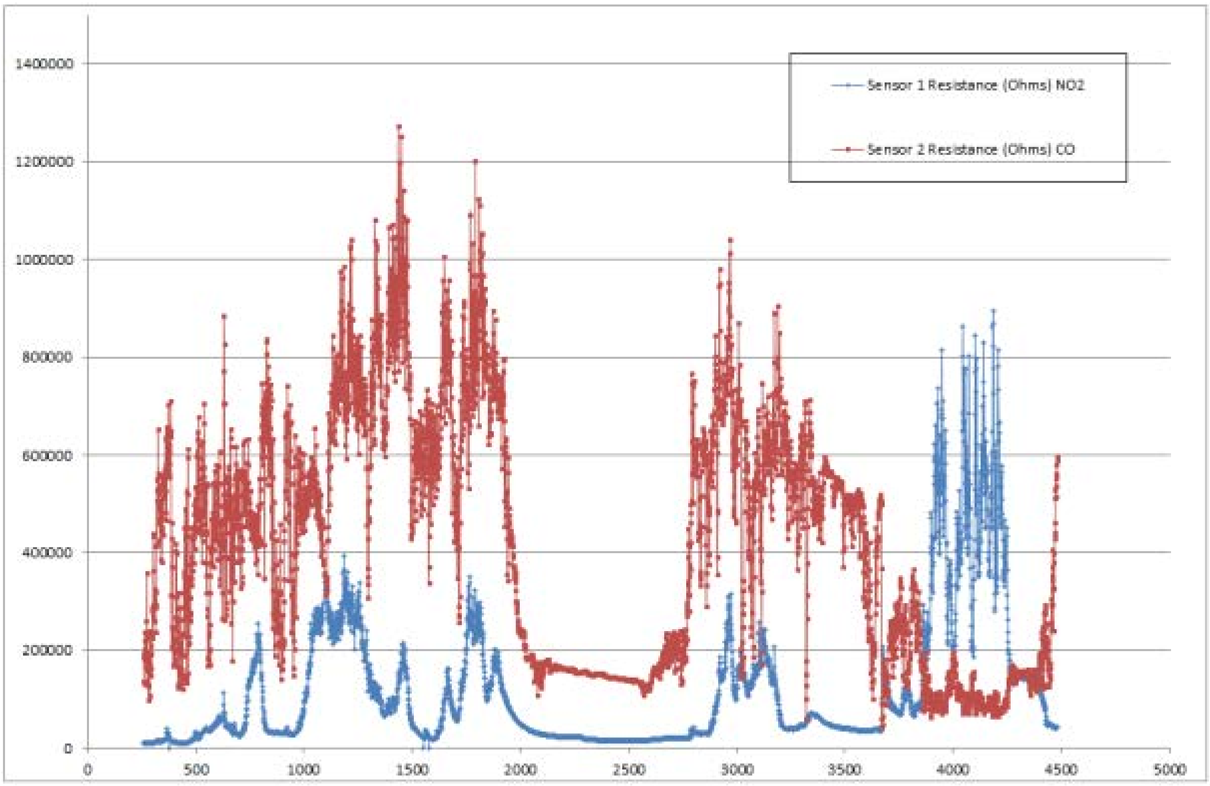


Figure 24: Test result of MiCS-4514

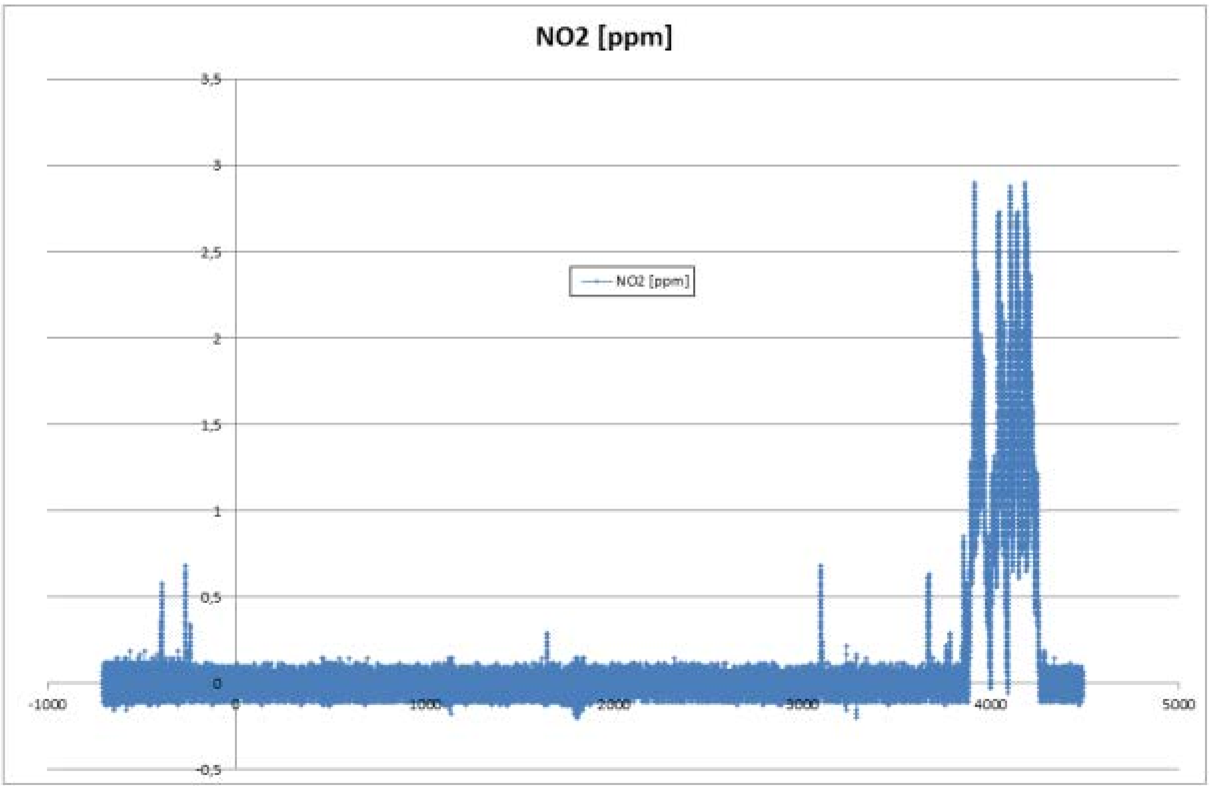


Figure 25: Test result of NT-NO2-PL05

The analysis of the measured data gave very different results from the two sensors:

The NT-NO2-PL05 measures only in a few situations pollution levels higher than his defined resolution of 0.1 ppm. Sometime single peaks which were caused from trucks or busses near our test vehicle were seen. The rest is noise. But on the other hand, this sensor is calibrated from the supplier and therefore the higher pollution levels measured can be considered as correct.

The NO_2 sensor of the MiCS-4514 shows very well the increase of pollution in the tunnels (Kaisermühlentunnel in Vienna). On urban roads measures medium values and in parking situations (away from roads with high traffic loads) measures low levels.

The CO sensor of the MiCS-4514 (resistance is inverse to the concentration level) shows also an increase in tunnels. It seems that also in the parking situation the CO level increase. But the reason was due to the different air flow. So we deducted one important consequence: a constant air flow on the sensors is needed for the whole measurement time.

4.5.2 Second pre-measurement campaign

To achieve a stationary air flow on the gas sensors we mounted the sensor boards in a box and designed an air flow tube only through the sensors surfaces. To get a constant air flow a membrane air pump was used. Also a second electrochemical gas sensor from Alphasense (similar to the NT-NO2-PL05) without this 0.1 ppm threshold was added. For the sampling of the analogue signal outputs a USB-Logger with high resolution ADC was selected. The box with the air flow system and the sensors installed is shown in Figure 26 and Figure 27.

After the air pump the air flows through a flow meter (mesurement of air flow) and then through the Alphasens sensor (out of the box).

The n.e.t. sensor, the SGX sensor and the temperature/humidity sensor are mounted in the box. With a tube of about 30mm diameter the measured air passes only this three sensors in the box. For this test system this tube is not perfectly tight, but the main part of the measurement air leaves the box after passing over the sensors.

Figure 26: Air sensor test box inside

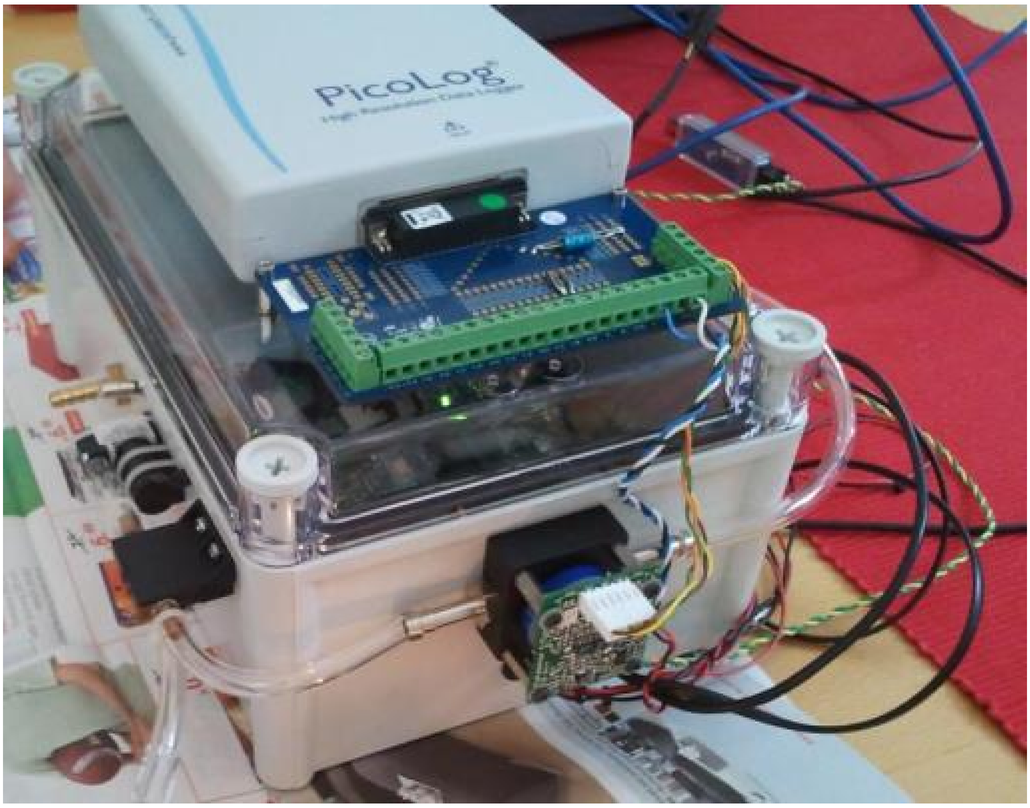


Figure 27: Air sensor test box with air flow system

Figure 28: Air inlet of the test vehicle

The air is aspirated from an air pump through a long inlet tube. This tube ends at the roof of the car near the left back light of the car (Figure 28).

<u>Used sensors:</u>

- NT-NO2-PL05
  - Supplier: n.e.t. (Nano Environmental Technology)
  - Calibrated sensor T = 2237 for NO_2
  - Calibration date: 13.3.2013
  - Output: analog 0.8V (0 ppb) – 4.0V (5000 ppb)
  - Concentration <100 ppb → output 0
  - Output measured with high precision sampler, 10 Sample/s
- MiCS-4514
  - Supplier: SGX (e2v technologies)
  - Combined non calibrated sensor for CO and NO_2
  - Output: electrical resistance of CO and NO_2 sensor
  - Output data from evaluation software 1 Sample/s
- NO2-B4
  - Supplier: Alphasense
  - Calibration data from the supplier
  - Output: analogue WE and Aux
  - Output measured with high precision sampler, 10 Sample/s
- Temperature and Humidity

- Supplier: Sensiron
- High resolution sensor (0.01 °C, 0.01 % RH)
- Output: digital output
- Output data from evaluation software

- Air flow sensor
  - Analogue output
  - Output measured with high precision sampler, 10 Sample/s

Track in Vienna (see also Figure 29):

- First point: GPS-time 8:41:26
- Last point: GPS-time 10:24:00
- Interpretation of track:
  - 8:51:40 start of travel to stationary environmental station
  - 9:04:17 arrive at environmental station "Stadlau"
  - 9:18:44 start from environmental station, drive to Techgate and to the Kaisermühlentunnel.
  - 9:35:10 entrance in Kaisermühlentunnel (middle of the tunnel)
  - 9:36:38 exit Kaisermühlentunnel
  - 9:36:51 entrance in Kaisermühlentunnel (direction nord-west)
  - Circa 9:39:30 exit from Kaisermühlentunnel
  - Circa 9:48:00 entrance in Techgate garage
  - Circa 9:57:00 exit from Techgate garage
  - 10:05:46 entrance in medium-small garage
  - 10:20:17 exit from medium-small garage
  - 10:23:59 End of GPS-track.

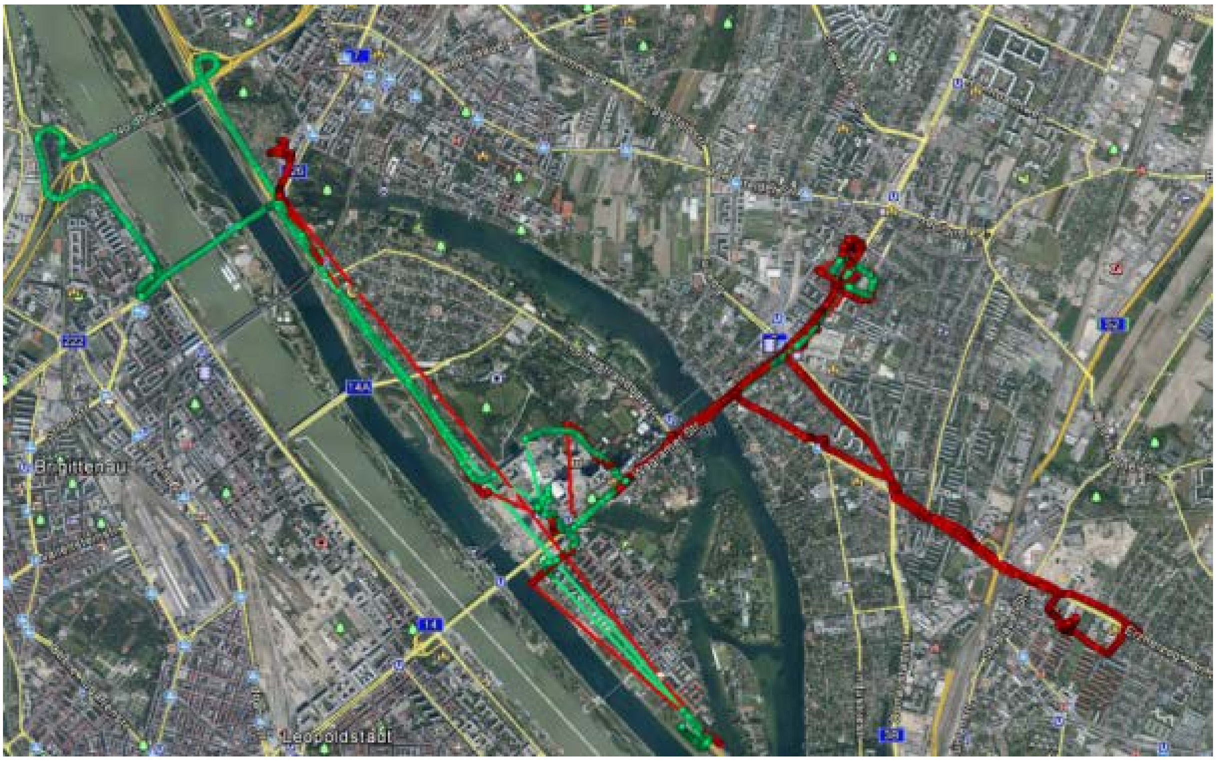


Figure 29: Track of Pre-measurement campaign 2 (red and green)

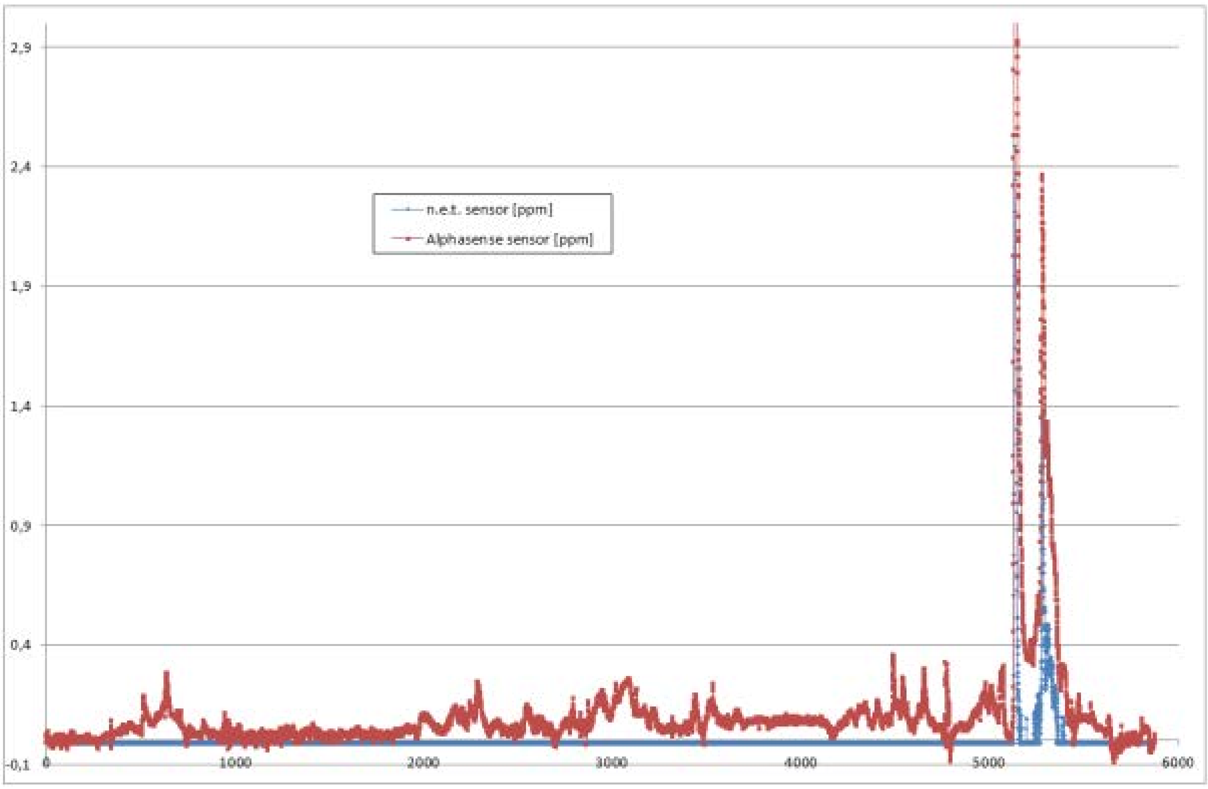


Figure 30: Result of n.e.t. sensor and Alphasense sensor at pre-measurement campaign 2

Observations and Interpretations of the measurement:

- The software of the SGX sensor had different crashes, so we don't have good data.

- The calibration values of the Alphasense sensor given from the supplier don't give a reasonable concentration. So we used the amplification factor from the supplier (-647 nA/ppm) and selected an offset that makes sense (lowest measured value near 0 ppb) because we saw a drift of this offset value. This is also the recommended procedure from the manufacturer when a sensor is purchased without the sensor board). The measured offset is given by the sum of the sensor offset and the sensor-board offset. In a first approximation from the sensor-board we used only OP1 output (working electrode) and not OP2 (compensation electrode). OP2 output was nearly constant and gave only a small deviations of the offset

- From the measured maximum values of net-Sensor and Alphasense we notice that there still was an absolute error of about 40 %. This error should decrease with a better calibration.

- The maximum measured values of 50 to 100 ppb detected on the street if a big vehicle is driving (or starting) near the sensors seem to be in the right dimension.

- The measured temperature and humidity were nearly constant through the whole measurement.

- The air flow is very constant due to the air pump. Small fluctuation of the air flow due to different vehicle speeds was not observed with the air flow meter (the air flow meter has a very short response time of about 3 ms).

- The air flow drops at second 5143 and 5462 were caused intentionally. We tested the air flow with closed tube to see if the aspiration tube is tight.

- In the "Kaisermühlentunnel" NO_2 pollution clearly increased on the sensors (near second 4888 and 4537).

- The time synchronisation of the different registration devices were aligned before the measurement campaign (precision of 1 second).

- The measurement of the n.e.t. - sensor gave during the whole drive a value 0 (< 100 ppb).

- At the end of the test drive we put the aspiration tube near the exhaust of the vehicle to measure high pollution concentrations. In this way we caused the net-sensor to measure values different from 0 (> 100 ppb). The data of the SGX sensor increased also very strong but due to another crash of the SW the data could not be saved.

- The aspirating tube has a length of about 1.5 m and the air flow with this type of air pump was slow. Consequently we noticed a time delay from changing the air mixture value and the change of the reading on the sensors. This time delay was of about 20 seconds and must be considered for the matching of the pollution value with the corresponding GPS-position! The same time delay was also observed with the temperature/humidity sensor. An improvement can be achieved with a stronger air pump (and perhaps a smaller tube).

- The NO_2 concentration peaks at second 4488, 4536, 4647 and 4768 were caused by commercial road vehicles and city-busses near our vehicle (we measured this peaks with circa 20 seconds delay (see point above).

- The pollution in the TechGate garage was low and constant in the whole garage where we drove.

4.5.3 Third pre-measurement campaign

For the third pre-measurement campaign a stronger air pump was used to achieve a smaller time delay between the real position from the GPS receiver and the measured pollution concentration due to the air-flow of the aspiration tube.

The used sensors and sensor readout system are the same as in the second pre-measurement campaign.

Also the measurement route in Vienna is very similar (see Figure 31):

- First point: GPS-time 11:59:18 (13:59:18 MEZ)
- Last point: GPS-time 15:25:15 (17:25:15 MEZ)
- Interpretation of track:
  - 11:59:18 start of system for stabilization of sensors and drive to startpoint
  - 12:59:31 start of testdrive, drive to environmental station “Stadlau”
  - 13:18:00 – 13:30:21 stop near environmental station “Stadlau”
  - 13:30:22 – 13:18:45 drive to Kaisermühlentunnel
  - 13:18:46 – 14:00:09 part of the Kaisermühlentunnel
  - 14:00:10 – 14:02:16 return to Kaisermühlentunnel
  - 14:02:17 – 14:04:17 Kaisermühlentunnel
  - 14:04:18 – 14:24:50 testdrive
  - 14:24:50 end of testdrive
  - 14:37:31 – 14:47:16 drive to environmental station “Stadlau”

- o 14:48:17 – 15:08:06 stop near environmental station “Stadlau”
- o 18:08:07 - 15:25:15 return drive to start point, End of GPS-track
- o Tests with high pollution levels

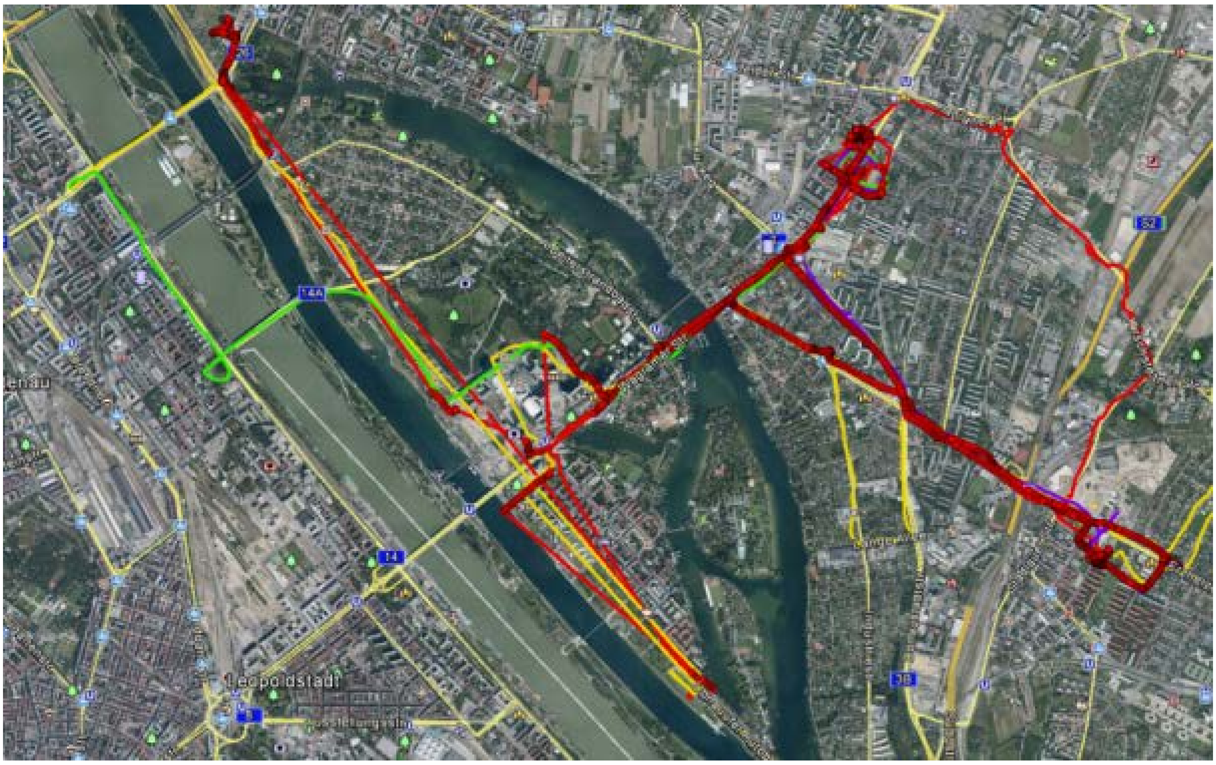


Figure 31: Track of Pre-measurement campaign 3 (colours are not relevant)

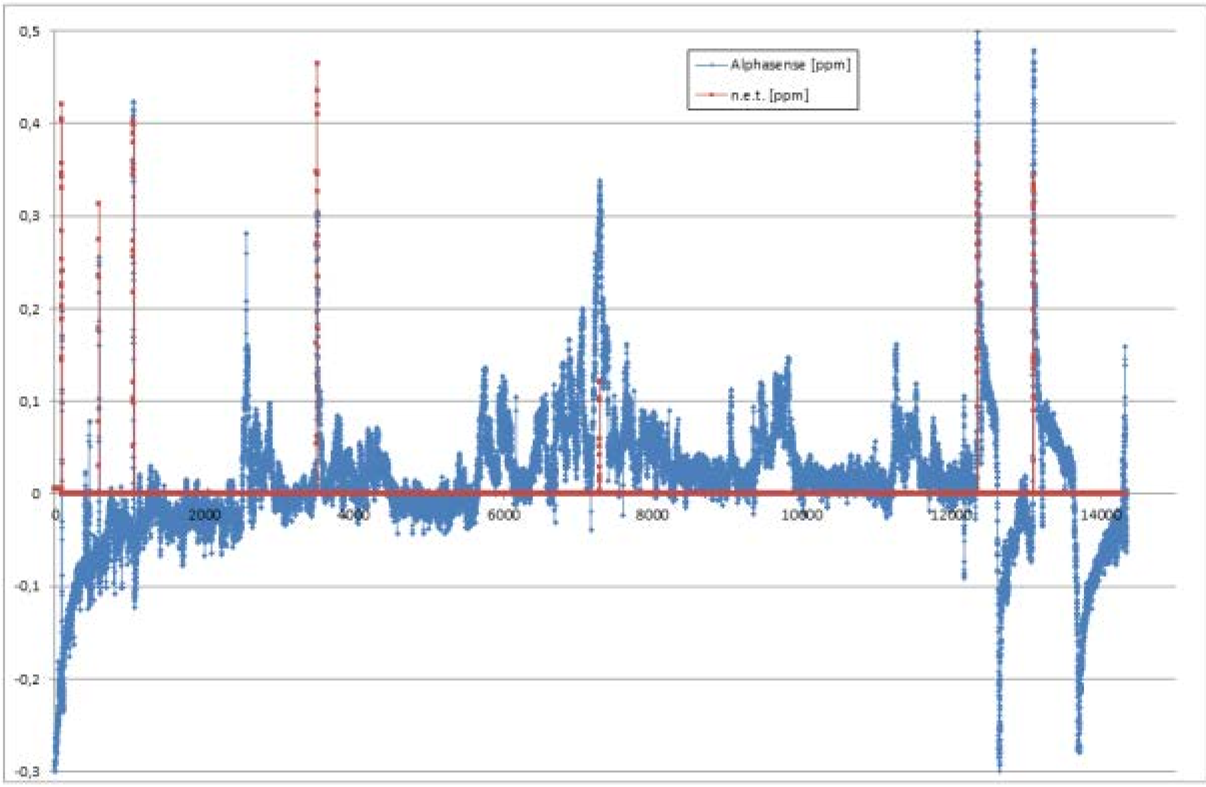


Figure 32: Result of n.e.t. sensor and Alphasense sensor at pre-measurement campaign 3

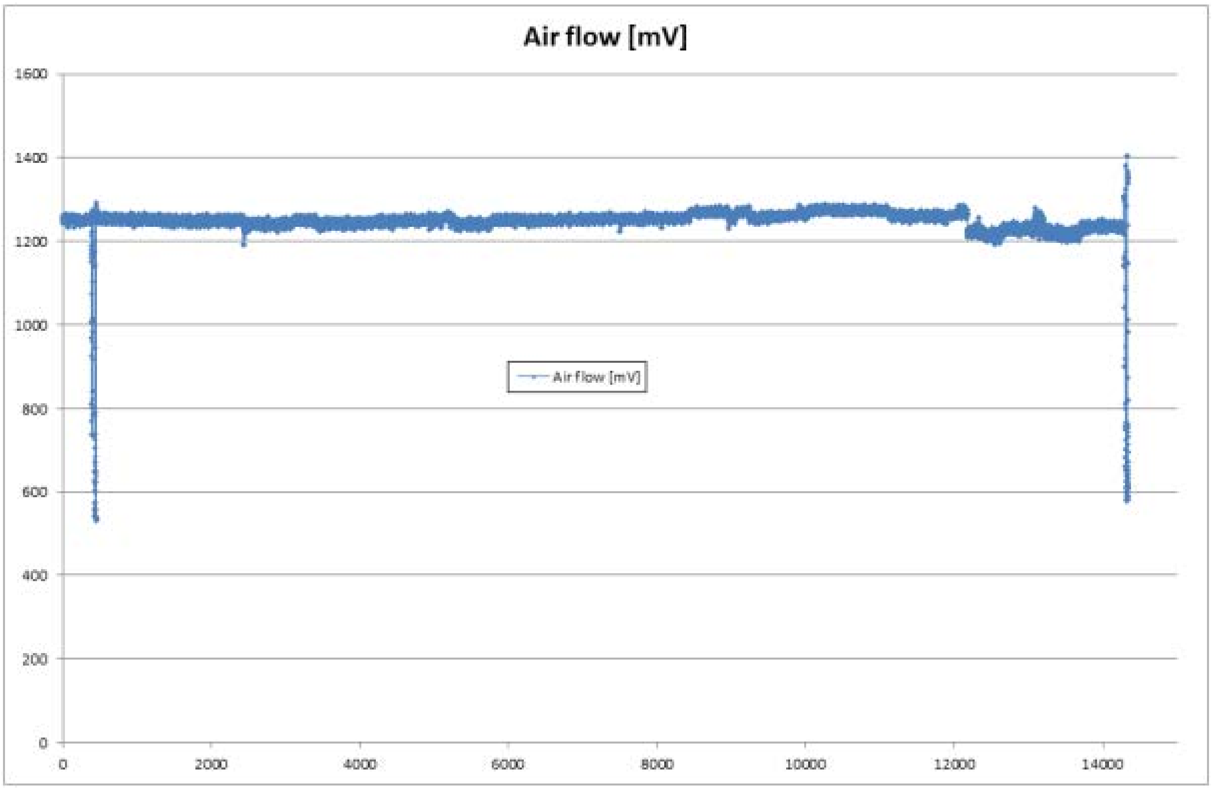


Figure 33: Air flow

Observations and Interpretations of measurement:

- The SGX NO_2 / CO sensor had first contact problems and after repair soldering this sensor was damaged.

- The Alphasense sensor was not well calibrated in this test session. In different periods the value was zero or negative which doesn't make sense from a physics point of view.

- The Alphasense sensor needed very long time to stabilize. 1500 s after power-on the measured value is negative. In the 4 hour measurement time the sensor has a small drift.

- During the two periods near the stationary environmental station, the measured concentration gave two different values due to the drift of the Alphasense sensor.

- Measured peaks due to other vehicles on the street gave higher concentration values than the drift of the Alphasense sensor.

- The higher pollution in the Kaisermühlentunnel is also in this measurement campaign clearly visible with the Alphasense sensor.

- The measured temperature and humidity were nearly constant through the whole measurement period.

- The air flow drops were caused intentionally. We tested the air flow with closed tube to see if the aspiration tube is tight.

- The n.e.t. sensor measured a few times concentrations higher than 100 ppb.

- To measure the response time of the Alphasense NO_2 sensors we put the aspiration tube near the exhaust of the vehicle to measure high pollution concentrations. At time 12337 s to 12397 s the sensor was exposed for 60 s to a high pollution level and at time 13086 s to 13206 s the sensor was exposed for 120 s to a similar but a little bit higher pollution level. The output of the sensor is quite complex as at first we measured a fast increase of the sensor output (overshoot), and then the output value decreased. After 190 s and 408 s respectively we measured a delayed undershoot of the sensor output.

- The aspirating tube has a length of about 1.5 m and the air flow with the new air pump was faster (stronger air pump in relation to the last measurement campaign). So we noticed a time delay between the change of the air pollution and the change of the sensors measurement value. This time is about 15 seconds and must be considered for the matching of the pollution value with the GPS-position!

- The pollution near the fixed environmental station of the city of Vienna was 23 µg/m³. This value was taken from the official web-site of the municipality of Vienna.

Due to the long stabilizing time of some sensors a continuous power supply should be considered for the HW design.

4.6 Detailed design of environmental monitoring unit

From the previous chapter we have the following specifications for the HW:

- Compact enclosure which includes all possible functions including sensors, air flow system, and the whole electronic
- Flexible design for further extensions
- MECU (Miniature Electronic Control Unit) for real time collection of all sensor data
- GPS receiver for location detection
- Sensors with all amplifiers, filter and converter on a single sensor board
- Closed air guide system for the sensors with controlled air flow

Air pollution sensors:

The pre-measurement campaigns gave good indications about the possible air pollution sensors.

The decision of the pollution sensors to be used for the design of the mobile system is the following:

- Nitron dioxide (NO_2):
  - NO2-B4 from Alphasense: this electrochemical sensor is small and optimised for low ppb concentration and designed for environmental measurement. The cost is about 75 €.
  - MiCS-4514 from SGX: this Metal Oxide Semiconductor sensor is very small and cheap (about 5 €). It needs a heating power for the operation and detects also very low pollution concentrations.
- Ozone (O_3):
  - O3-B4 from Alphasense: this electrochemical sensor has similar characteristics like the NO2-B4 sensor. It has the same mechanical characteristics and need a very similar electronic circuit like the NO_2 sensor.
- Carbon monoxide (CO):
  - MiCS-4514 from SGX: this Metal Oxide Semiconductor sensor has already the NO_2 sensor and the CO sensor in one case. It needs also a very similar electronic circuit like the NO_2 sensor.

All the electronic for these sensors can be designed with low-cost components and placed near the sensor to avoid electrical disturbance.

Analog-to-digital converter (ADC):

The selected air pollution sensors are analogue sensors. To save and transmit the value the analogue signal will be converted into a digital signal. The analogue output signal of the sensors is quite low (-200 to -800 nA/ppm) so first the signal must be amplified (low noise and low drift), filtered and converted into an electrical voltage. For the conversion a high precision ADC should be used (better than the noise and drift of the sensor itself). We select a high resolution ADC from Texas Instruments with AFE (Analog-Front-End) and True Continuous Background Calibration with a sufficient number of analogue inputs. The sample rate can be in the 100 ms range because with these gas sensors higher rates of measurement are not possible.

Temperature and humidity sensor:

For the selection of the air temperature and relative humidity (RH) sensors there is a wide range of different sensors on the market. The most important considerations are:

- Small size
- Temperature range at least -20 °C to +70 °C
- Temperature accuracy at least 1 °C
- RH range possible 0% to 100%
- RH accuracy at least 5%
- Possibly digital interface for simple connection and calibration
- Ideal a combined temperature / RH sensor
- Low power consumption
- Fast response time
- Low prise

A big supplier for this type of sensors is “Sensirion” in Switzerland.

This sensor should be placed inside the air flow system.

Sensor Control Unit:

An intelligent Miniature Electronic Control Unit (MECU) should be designed to set-up the sensors, read-out the sensors at least once per second and communicate with the INTEGREEN On-board Telematic Unit. This MECU should be programmable and have the capabilities to read different types of sensors.

GPS receiver:

A GPS (Global Positioning System) receiver should be integrated in the system. The receiver calculates the geographic position and associates the sensor values with this position. Additionally, GPS receivers deliver also the precise GPS global time (which is correlated with the UPC time).

The whole on-board system should be integrated in a vehicle and therefore the need an external GPS antenna is reasonable. For a good receive quality the use of an external active antenna should be possible, this means the electronic will have to provide the power supply needed by the active GPS antenna. In the INTEGREEN configuration the use of a passive GPS antenna is also possible.

Air guide for sensors:

Restricted Information.

For further information please contact the appropriate specialists of AIT Austrian Institute of Technology GmbH.

4.7 Interfaces of the Environmental monitoring unit

The front side of the Environmental unit is shown in Figure 39.

Figure 34: Front view of the Environmental Unit with Connectors

The connectors from left to right are:

- USB-connector type B: for connection to the Telematic unit
- GPS antenna connector SMA: for connection to an active or passive GPS antenna
- Power supply connector: to connect to the vehicle power supply

The power supply connector of the Environmental unit is shown in Figure 40.

The line “12V continuous” powers the sensors continuously and can be connected to the battery supply of the vehicle.

The line “+12V ignition” powers the rest of the unit. It should be active only during measurements.

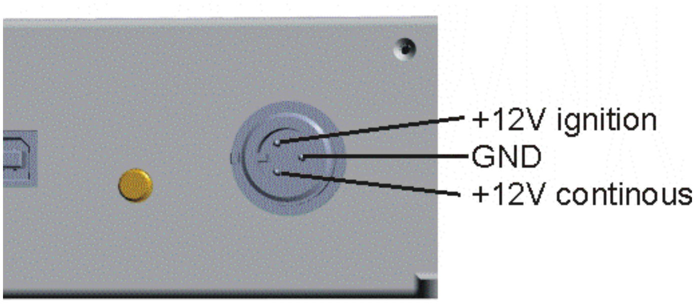


Figure 35: Power supply of the Environmental Unit

The side view of the Environmental Unit is shown in Figure 41.

Figure 36: Side view of the Environmental Unit with Connectors

The connectors from left to right are:

- Expansion connector D-Sub 9 pol
- Air inlet for air tube with 5 mm inner diameter
- Air outlet for air tube with 5 mm inner diameter

5 Design of Traffic monitoring unit

From the requirements for the Traffic unit (chapter 2) there are two main categories of data:

- Geographic position of the vehicle
- Kinematic of the vehicle

5.1 Sensors of the Traffic monitoring unit

5.1.1 Geographic position detection

The geographic position of a vehicle can be detected in different ways:

- Global position detection
    - GPS, official name: NAVSTAR GPS (USA), popular global location system
    - GALILEO (EU), still under construction
    - GLONASS: (Russia), operating
    - COMPASS: (China), still under construction
- GSM/UMTS location detection: with the aid of cellular communication the position can be estimated. A database of all the communication cells in the network is necessary.
- WLAN location detection: similar like GSM/UMTS cell information also with the visible WLAN hotspots and a database the location can be estimated.
- Information from the vehicle driver or operator: the driver or the operator of the vehicle communicates the location.

Only the GPS localisation system can work fully automatically without databases. GPS receivers provide directly the absolute coordinates. Additionally to the position, the GPS receivers provide also speed and heading.

One of the leading suppliers for GPS receiver chips is the Switzerland company u-blox. They offer miniature GPS receiver chips, GPS systems and GPS antennas (active and passive).

5.1.2 CAN-Bus access

In modern vehicles the different electronic control units inside the vehicle are connected via serial busses for data exchange.

The most common automotive busses are [5]:

- CAN-bus (controller area network), widely-used, max. 1 Mbit/s

- FlexRay bus: 10 Mbit/s, used in some new cars
- LIN-bus (Local Interconnect Network), max. 20 Kbit/s, cheap serial bus
- MOST (Media Oriented Systems Transport), a high speed multimedia bus

In the AIT test vehicle an access to the CAN-bus is possible.

The amount of different data types exchanged on the CAN-bus is wide. Some examples are:

- Speed data
- Steering wheel data
- Pedal data (acceleration pedal, clutch pedal, brake pedal)
- Engine data
- Fuel data
- ABS data

In this project mainly speed data and acceleration data are of interest.

To protect the vehicle from accidental written commando from the traffic monitoring unit (SW-bugs, crash of the FW) a HW write protection in the CAN-driver component from the traffic monitoring unit has been designed.

In the AIT test vehicle there is a HW protection unit against writing to the CAN-bus permanently present. To activate the CAN-bus reading and the CAN-bus write protection, a special signal must be provided to the protection unit (see Figure 44, pin +5V (Write Protection)).

5.1.3 Motion sensor

If the access to the CAN-bus of the vehicle is not possible the kinetic characteristics of the vehicle can be detected with motion sensors.

With inertial sensors like accelerometers and gyroscopes the linear acceleration and circular speed of an object can be measured. With 3 orthogonal linear accelerometers and 3 orthogonal gyros the motion of the object can be tracked [6].

In the INTEGREEN Traffic monitoring unit a Six Degrees of Freedom Inertial Sensor system is implemented.

5.2 Detailed design of traffic monitoring unit

The design of the traffic monitoring unit is similar to the design of the Environmental Unit (chapter 4.6):

- Compact box which includes all possible function including sensors and the whole electronic
- Flexible design for further extensions
- MECU (Miniature Electronic Control Unit) for real time collection of all sensor data
- GPS receiver for location detection
- Sensors with all electronics (amplifiers, filter and converter) on a single sensor board

MECU

An MECU is already used in the Environmental monitoring unit. The same MECU is used for the Traffic monitoring unit.

GPS

Because a GPS information is needed for the Environmental monitoring unit and for the traffic monitoring unit, it is a better design choice to place the GPS receiver components on the MECU and not on two different sensor boards (only one PCB development has to be done). With this architecture the Traffic and the Environmental monitoring units can be used independently. In a configuration where both units are used it is possible to mount the GPS components only on one of the two MECUs to save costs.

Housing:

The housing of the Traffic monitoring system is similar to the housing of the Environmental system. The physical dimension of the box is the same (see Figure 37).

In Figure 42 the Traffic monitoring unit with housing but without electronic components is shown.

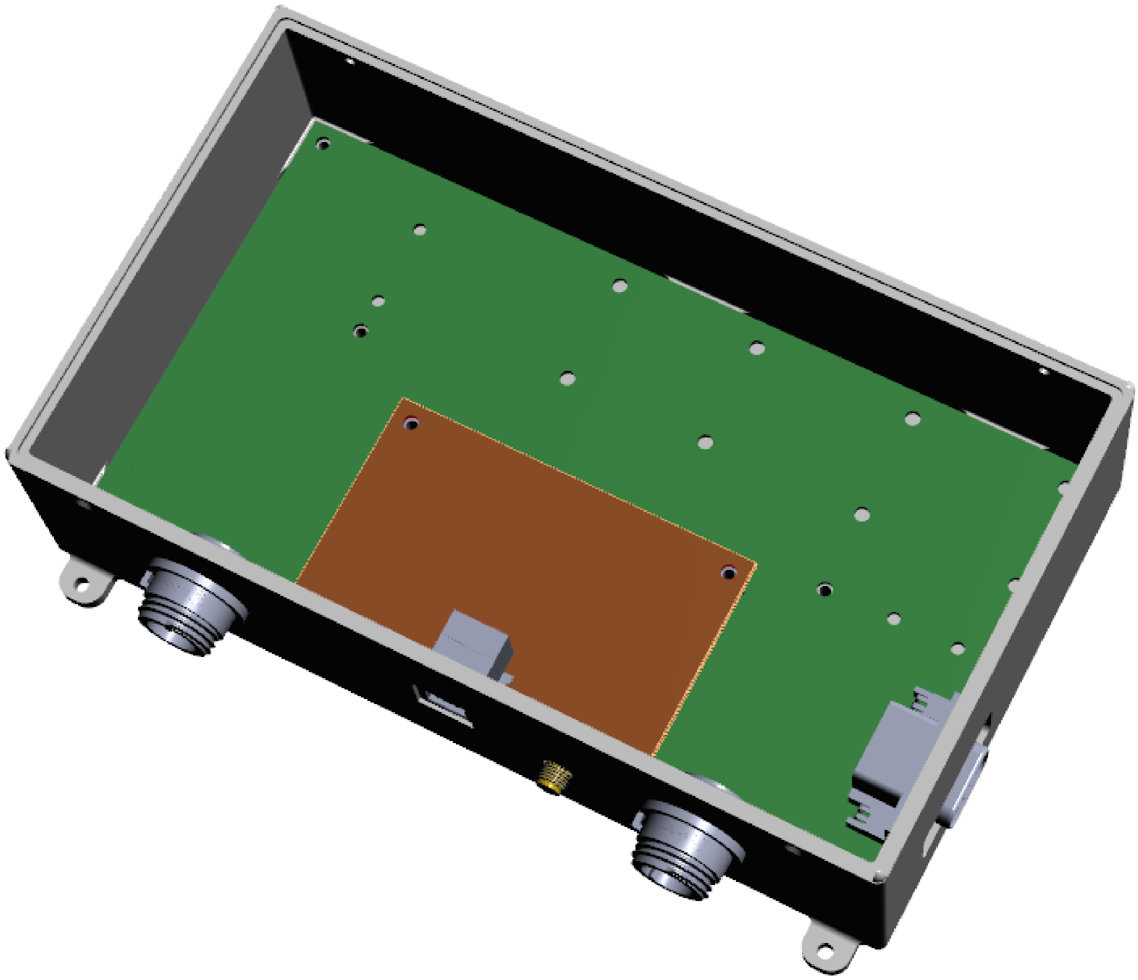


Figure 37: Traffic monitoring unit with housing

The green board is the sensor board and the brown board is the MECU (with GPS receiver).

The interfaces of the Traffic monitoring unit are descried in the next chapter 5.3.

For the Firmware of the MECU the same points like for the Environmental monitoring unit are valid (chapter 4.6).

5.3 Interfaces of the traffic monitoring unit

In Figure 43 the front view of the Traffic monitoring unit is shown.

Figure 38: Front view of the Traffic monitoring unit with connectos

The connectors from left to right are:

- CAN-bus connector: for connection to the vehicle CAN-bus
- USB-connector type B: for connection to the Telematic unit
- GPS antenna connector SMA: for connection to an active or passive GPS antenna
- Power supply connector: to connect to the vehicle power supply

The power supply connector is the same as the power supply connector of the Environmental monitoring unit (see Figure 40).

The CAN-bus connector is illustrated in Figure 44. The pin “+5 (Write protection)” is only used for the AIT Test vehicle.

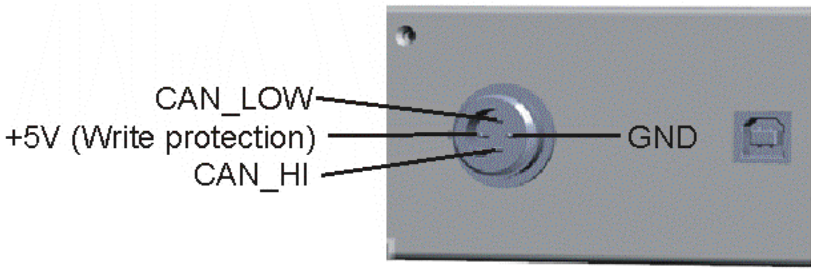


Figure 39: CAN-bus connector of the Traffic monitoring unit

Figure 40: Side view of the Traffic monitoring unit with connector

On the side there is only one connector:

- Expansion connector D-Sub 9 po

Conclusions

In this section the key objectives and achievements of the design phase for the On-board Environmental monitoring unit and of the On-board Traffic monitoring unit are summarised.

The following have been the main steps of the design phase: High level architecture design, Investigation of sensor modules and sensors, Test of selected sensors in measurement campaigns, Selection of most suitable sensors after field test verification and validation, Detailed design specifications and the Interface specifications.

The **On-board Environmental monitoring unit** collects environmental data, in particular air pollution data and meteorological data as well as GPS position data. This data is then transferred to the On-board Telematic unit.

To select the suitable air pollution sensors three measurement campaigns with the AIT test vehicle have been conducted in Vienna. Following the results of evaluation of environmental sensors available on the market and the results of the measurements for the 3 pollution gases defined in the requirements, the decision of the pollution sensors to be used for the design of the mobile system has been the following:

- Nitron dioxide (NO_2): NO2-B4 from the company Alphasense
- Nitron dioxide (NO_2): MICS-4514 from the company SGX (formerly e2v); combined NO_2 / CO sensor
- Ozone (O_3): O3-B4 from Alphasense
- Carbon monoxide (CO): MICS-4514 from SGX; combined NO2 / CO sensor

An intelligent Miniature Electronic Control Unit (MECU) has been designed to set-up the sensors, read-out the sensors and communicate with the INTEGREEN On-board Telematic Unit. This MECU should be programmable and have the capabilities to read different types of sensors. In addition a GPS (Global Positioning System) receiver has been integrated in the system. The whole on-board system should be integrated in a vehicle and therefore a design with an external GPS antenna chosen. Temperature and humidity sensors have also been included in the design.

All the electronics for these sensors have been designed with low-cost components and placed near the sensor to avoid electrical disturbance.

The **On board Traffic monitoring unit** collects traffic related data, in particular vehicle speed, kinematic data of the vehicle and GPS position data. The data is then transferred to the On-board Telematic unit.

From the requirements for the Traffic unit (chapter 2) two main categories of data, the Geographic position of the vehicle and the Kinematic of the vehicle have been taken into account in the design phase. The design of the traffic monitoring unit is similar to the design of the Environmental Unit where the MECU is the same and a GPS receiver is also included such that Traffic and the Environmental monitoring units can be used independently from one another. A CAN-bus access is foreseen and with the AIT test vehicle an access to the CAN-bus is possible where speed data and acceleration data will be read and transferred to the Telematic Unit.

All the designs including HW and FW as well as interfaces to external components (GPS, Power supply, CAN-bus, air interface, data interface, expansion interfaces) have been completed and documented.

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Appendix A: Acronyms and Definitions

CO_2: carbon dioxide

CO: carbon monoxide

C_6H_6: benzene

FW: Firmware

HW: Hardware

lpm: litre per minute

NO: nitrogen oxide

NO_2: nitrogen dioxide

NO_X: nitrogen oxides, which include NO and NO_2

O_3: ozone

Pb: lead

PM_{10}: particles with diameter inferior to 10 [µm]

$PM_{2.5}$: particles with diameter inferior to 2.5 [µm]

ppb: parts per billion

ppm: parts per million

ppt: parts per trillion

SO_2: sulphur dioxide

SW: Software

TSP: Total Suspended Particulates