SIXTH FRAMEWORK PROGRAMME

PRIORITY 6

"SUSTAINABLE DEVELOPMENT, GLOBAL CHANGE AND ECOSYSTEMS"

Project acronym: OPTO-EMI-SENSE

Project full title:
An Optical Fibre Sensor Based Intelligent System for Monitoring and Control of Exhaust Emissions from Road Vehicles

Contract no. TST3-CT2003-506592

Instrument: STREP

Thematic Priority: 1.6.2 Surface Transport

Publishable Technical Summary Report

Start date of project: 1st January 2004. Duration: 36 Months

SUMMARY

Summary of Project Objectives

The project addressed the problem of pollution of the environment by road vehicles as defined under the Thematic Priority 1.6.2, Sustainable Surface Transport relating to the Work Programme "Integrating and strengthening the European Research Area". The research activities of the consortium will be based around state of the art developments in the area of optical fibre sensor and intelligent instrumentation technology to formulate a system for on line monitoring of exhaust emissions from road vehicles. The application of this technology to resolving the problems of atmospheric pollutants and their regional impacts is therefore highly appropriate to the issue identified in the thematic roadmap i.e. "*New technologies and concepts for all surface transport modes".*

The project's technical objectives were as follows: -

- To set up laboratory based test facilities such that the sensor systems may be characterised in a precisely controlled and reproducible manner. Therefore, individual parameters such as optical absorption and scattering may be studied in isolation as well as collectively.
- To isolate and identify the optical signals arising from contaminants present in the complex mixtures of exhaust systems of a wide range of vehicles using advanced and novel optical fibre based spectroscopic interrogation techniques
- To develop novel optical fibre sensors which are miniature and robust in their construction and may be integrated in an optical network and fitted and/or retro-fitted to the exhaust systems of a wide range of vehicles
- To interface and fully integrate the novel sensor systems into the existing data network of the vehicle, thus providing the driver with clear and unambiguous in-car information on contaminant levels of exhaust emissions. This may take the form of alarm levels or analogue display as well as enabling emission minimisation through accessing the vehicle's engine control unit.

The Consortium

The consortium which successfully undertook the research programme comprises six members from four EC member states. They include four academic institutions, an SME and an end user (a major European car manufacturer). They are identified as follows

1 University of Limerick Ireland (LIM)
2 City University, London, UK (CU)
3 University of Liverpool, UK (LIV)
4 Fiberware GmbH, Germany (FIB)
5 Centro Ricerche Fiat, Italy (CRF)
6 University of Rostock, Germany (ROS)

The Coordinator and Contact Details

The project is co-ordinated by the University of Limerick, Ireland and the co-ordinator's contact details are provided below

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Their combined expertise and knowledge of the technological and business issues has facilitated the rapid development of the technology into a demonstratable prototype within the three year lifetime of the project. The project has been divided into ten workpackages as defined below

Work-package No	Workpackage title	Start month	End month	Deliverable No
1	Design of optical Fibre Sensor Network &Temperature Sensors	0	12	D1.1, D1.2
2	Design of Optical Fibre Gas Sensors	0	12	D2.1
3	Development of Data Acquisition and Signal Processing Software incl. Configuration Neural Networks	0	16	D3.1, D3.2
4	Coupling and Housing of Fibre Sources and Detectors to sensors	12	20	D4.1, D4.2
5	Commissioning of the Test and Calibration Facility	12	22	D5.1, D5.2
6	Calibration, Testing and Characterisation of Sensors	23	29	D6.1, D6.2
7	Development of Microcontroller based System	24	30	D7.1
8	Commissioning of the Full Systems Test Facility and testing	20	33	D8.1, D8.2
9	Integration into Production Vehicle	27	36	D9.1, D9.2
10	Dissemination and Reporting	10	36	D10.1, D10.2

Table 1. Workpakages of the Project

1. Introduction

The Physical location of the sensors within the exhaust system of the Fiat Croma is shown in Fig.1 below

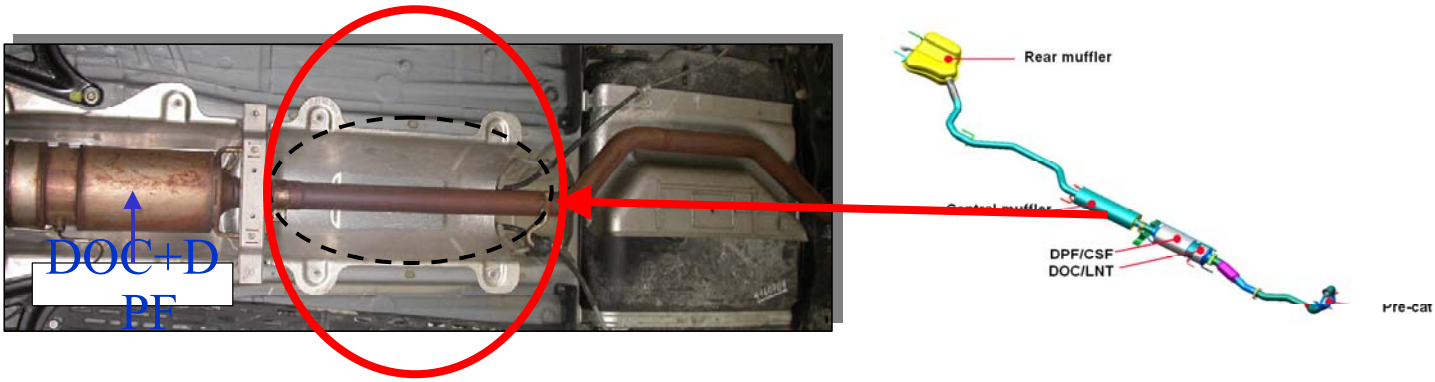


Figure 1: Location of Sensors and Exhaust Line Layout For A Diesel Common Rail Engine.

The work performed in the project has been to research the use of optical fibre sensors for the measurement of exhaust gas emissions and temperature in the exhaust system of road vehicles. The gases identified as being of interest under successive EC emission control standards (currently Euro IV) are as follows

Nitric Oxide (NO)
Nitrogen dioxide (NO2)
Carbon dioxide (CO2)
Carbon Monoxide (CO)
Sulphur Dioxide (SO2)
Hydrocarbons (Many, including Methane, Benzene, Toluene)
Water Vapour (Interfering Parameter)

The work performed to implement these sensors was initiated as sensor design in WP 1 (Temperature sensor) and WP 2 (Gas sensors) during the first 12 month period of the project. These designs were initially tested in University of Liverpool and system integration performed during the second 12 month period. The integrated systems were comprehensively tested on the demonstrator vehicle, the Fiat Croma in the testing centre of CRF during the final 12 month (extended to 18 month) period..

2. Initial Specification

The specification for the sensors of the project was supplied by the end user, CRF at the beginning of the project and the functional requirements and related specified performance are detailed below: -

- ✓ Wide concentration range measuring capability
- ✓ High sensitivity, accuracy and resolution
- ✓ High selectivity
- ✓ No post-production calibration for sensor or control unit
- ✓ Compact packaging and low power consumption
- ✓ Short power-on stabilization time
- ✓ Short response time
- ✓ Insensitiveness to fuel and oil additives and impurities
- ✓ Output signal independency from gas-flow / pressure
- ✓ Good temperature endurance and signal linearity
- ✓ Good vibration resistance
- ✓ Long operating life
- ✓ Low cost

2.1 Concentration range sensitivity

During the normal engine operation the raw gas concentration are subjected to wide and fast changes; moreover, in particular engine conditions (i.e.: post injection, rich spike for DeNOx system, etc.) the exhaust pollutants concentration increase up to thousand ppm. For these reason exhaust gas sensors are necessary capable to measure from few ppm to high pollutants concentration. In the following list the needed concentration ranges are reported for the different gaseous species: -

- ➢ CO $\Rightarrow$ 20 – 2000 ppm
- ➢ $NO_x \Rightarrow$ 20 – 2000 ppm
- ➢ $SO_x \Rightarrow$ 2 – 200 ppm
- ➢ HC $\Rightarrow$ 50 – 5000 ppm

The minimum values indicated above correspond to mandatory thresholds in terms of g per km emissions values as defined for the various Euro standards

Tier	Date	CO	HC	HC+NOx	NOx	PM
Diesel		**g/Km**				
Euro 1†	1992.07	2.72 (3.16)	-	0.97 (1.13)	-	0.14 (0.18)
Euro 2, IDI	1996.01	1.0	-	0.7	-	0.08
Euro 2, DI	1996.01[a]	1.0	-	0.9	-	0.10
Euro 3	2000.01	0.64	-	0.56	0.50	0.05
Euro 4	2005.01	0.50	-	0.30	0.25	0.025
Euro 5‡	mid-2008	0.50	-	0.25	0.20	0.005
Petrol (Gasoline)		**g/Km**				
Euro 1†	1992.07	2.72 (3.16)	-	0.97 (1.13)	-	-
Euro 2	1996.01	2.2	-	0.5	-	-
Euro 3	2000.01	2.30	0.20	-	0.15	-
Euro 4	2005.01	1.0	0.10	-	0.08	-
Euro 5‡	mid-2008	1.0	0.075	-	0.06	0.005[b]

* Before Euro 5, passenger vehicles > 2,500 kg were type approved as Category N_1 vehicles
† Values in brackets are conformity of production (COP) limits
‡ Draft proposal, July 2005
a - until 1999.09.30 (after that date DI engines must meet the IDI limits)
b - applicable only to vehicles using lean burn DI engines

Table 1.1. The Mandatory threshold levels as defined in successive Euro Standards for the various exhaust line pollutants.

2.2. Sensitivity, Accuracy and Resolution

In order to comply with the new European legislation (EURO IV) the emission limit control will be very tight and accurate; the only way to achieve a good control of the exhaust gases is to adopt a gas sensor capable to detect the concentration of pollutants with a great accuracy and resolution: -

- Lower detectable limit: ~ 1 % f.s.
- Repeatability: +/- 0.5 % f.s.
- Resolution: ~ 0.5 % f.s.

2.3. High selectivity

A very important characteristic of a gas sensor is its selectivity. In the case of the exhaust there exist many different chemical species which can interfere with the different sensor signals. Also the λ ratio variation and the presence of H_2 and H_2O can be possible interference sources. As a consequence, highly selective sensors are desirable in order to avoid any signal cross-interference. Possible influences must be taken into account through appropriate sensor calibration.

2.4. Post-production calibration for sensor or control unit

The principal requirement for an automotive sensor is the ease of management; after the installation on-board the sensor must not need re-calibration procedures; also, the control unit must be maintenance free.

2.5 Power-on stabilization time

Such parameter must be as short as possible. In any case the power-on stabilization time is a common issue in sensors which need a defined temperature range for the correct measurement operation (e.g.: λ sensor). In case of an optical fiber sensor the stabilization time due to temperature is not a problem as there is no requirement for temperature attainment of the sensing element before starting the measurement.

2.6 Response time

There are two aspects related to response time depending on the application:

- Exhaust Aftertreatment System Control. For these systems, a data sampling frequency from 2 to 5 Hz can be sufficient to properly monitor the exhaust gas composition.
- Combustion control: in this case, the feedback of the system must be performed in real-time. (bandwidth >30 Hz needed for closed loop control).

The first priority in terms of the objectives of OPTO EMI SENSE project is concerned with emission monitoring and exhaust control.

2.7. Packaging and low power consumption

The feasibility of a gas sensor application directly on the exhaust pipe is strongly related to its housing dimensions. An initial specification for constraints on the sensor dimensions due to availability of space under the car was presented as follows

- Sensor mounted inside exhaust pipe: $\phi \sim 10$ mm – L ~ 30 mm
- Sensor mounted outside exhaust pipe $\phi \sim 20$ mm – L ~ 50 mm

Another important parameter is the maximum power consumption, but as mentioned above, such problem is much more important when an internal sensor heater is needed for the heating up of the sensing element. The target in terms of power consumption should not exceed 10 W (continuous).

2.8. Output signal independency from gas flow / pressure

Pressure and flow rate in the exhaust pipe are very variable and are close correlated to the engine working point; the typical flow rate and pressure values in a Diesel common rail exhaust pipe are the following:

- Exhaust gas flow range from 50 m^3/h to 800 m^3/h.
- Maximum continuous pressure up to 2.5 bar.
- Pressure peaks (max. 250 h cumulated over lifetime) ≤ 4 bar.

In order to have a reliable measurement of the exhaust gas pollutant concentration the output sensor signal must be independent from both the flow rate and the pressure variations.

2.9 Insensitiveness to fuel, oil additives and impurities

The exhaust gas environment is a very complex mixture of gas which carry many different types of particles coming from the combustion of the fuel and the oil, along with a little fraction of particles coming from the pipe corrosion. The main impurity elements contained into the exhaust gas could be: Fe, P, S, Si, C, Ca, K. If the sensor is mounted downstream of

the Diesel Particle Filter (DPF) then interference from such particles can be avoided in an effective manner.

2.10 Temperature endurance and signal linearity

The sensor operating temperature is critically dependent on the mounting position within the exhaust system; in general the maximum temperature of the exhaust gas is about 300°C in normal operation but in some circumstances can climb to 750 ^{o}C e.g. when the DPF is being recycled.

2.11 Permissible vibrations

The exhaust line is subject to a continuously vibration due to the engine operation and the road asperity; an exhaust gas sensor is subject to the same type of vibration. The typical permissible vibration for a sensor are the following:

- vibration displacement up to 0.3 mm
- vibration acceleration up to 300 m/s^2

2.12 Operating life

The minimum operating life time for an exhaust gas sensor is at least 10 years and 250.000 km.

2.13 Target costs

the normal target costs for a mass production exhaust gas sensor is in the range €10 - 30

3. The Sensing Approach

The fundamental approach used in this investigation was to use an open path gas cell as the gas sensor and either a fluorescence decay time or Bragg grating base temperature sensor.

3.1. Gas Sensing

There was an enormous range of materials and devices available from which to construct the optical fibre gas sensor. These are summarised in table 3.1.1 below

Sensor principle	Fibre	Fibre Window Of Transmission	Absorption lines	Transmitters
Evanescent Field Sensor	Silica (gcf)*	<0.8 - >1.8µm	NO2=0.4 µm CO=1.567µm CO2=1.573µm CH4=1.67µm NO=1.78µm NO2=1.98nm	DFB<2.4 µm GlowBar
Evanescent Field Sensor	Saphire (pcf)*	0.6(1)-3.7µm	NO2=0.8 µm CO=1.567µm CO2=1.573µm NO=1.78µm NO2=1.98µm CO=2.3µm CH4=1.67µm NO=2.7 µm CO2=2.7 µm NO2=3.4 µm SO2=3.98 um	DFB<2.4 µm MIR LEDs (2.7- 4.7 µm) QCL GlowBar
Reflection Sensor	(Silica) (Chalgogenide) Saphire(pcf)** ZBLAN (gcf)*	0.6(1)-3.7µm	NO2=0.8 µm CO=1.567 µm CO2=1.573 µm CH4=1.67µm NO=1.78µm NO2=1.98µm CO=2.3 µm NO=2.7 µm CO2=2.7 µm NO2=3.4 µm	DFB<2.4 µm MIR LEDs (2.7- 4.7 µm) QCL Lead-Salt>3.4 µm GlowBar
Reflection Sensor	Chalgogenide PIR Hollow Core	2-6µm	CO=2.3 µm NO=2.7? CO2=2.7? NO2=3.4 µm SO2=3.98 um CO2=4.2 µm CO=4.6-7 µm NO=5.25 µm NO2=6.1 µm	DFB<2.4 µm QCL/Lead-Salt MIR LEDs (2.7- 4.7 µm) GlowBar
Reflection Sensor	Hollow Core	190-500	NO=195, 225 nm SO2=206, 212 nm NO2= 300-500 nm	Xenon flash lamp / Deuterium/ LED
Reflection Sensor	Silica	225-900	NO=225 µm NO2=300-500 nm	Xenon flash lamp / Deuterium/ LED
Evanescent Field Sensor	Silica (gcf)	225-900	NO=225 nm NO2=300-500 nm	Xenon flash lamp / Deuterium

*gcf – glass cladding fibre **pcf – plastic cladding fibre

Table 3.1.1. Summary of Fibre Technologies and Available Techniques With Respect to the Specific Absorption Lines of the Exhaust Emission Species Concerned

It was beyond the remit of this project to test all combinations of the above components and the table was drastically reduced following completion of the first 12 month period. The table is presented below as Table 3.1.2: -

Sensor principle	Fibre	Fibre Window Of Transmission	Absorption lines	Transmitters
Evanescent Field Sensor	Saphire (pcf)*	0.6(1)-3.7μm	NO=2.7 μm CO2=2.7 μm NO2=3.4 μm SO2=3.98 um	DFB<2.4 μm Filament (1- 11 μm) QCL GlowBar
Reflection or Transmission Sensor	(Silica) (Chalgogenide) Saphire(pcf)** ZBLAN (gcf)*	0.6(1)-3.7μm	CO=2.3 μm NO=2.7 μm CO2=2.7 μm NO2=3.4 μm	DFB<2.4 μm Filament (1- 11 μm) QCL Lead-Salt>3.4 μm GlowBar
Reflection or Transmission Sensor	Chalcogenide PIR	2-6μm	CO=2.3 μm NO2=3.4 μm SO2=3.98 um CO2=4.2 μm CO=4.6-7 μm NO=5.25 μm NO2=6.1 μm	DFB<2.4 μm QCL/Lead-Salt Filament (1- 11 μm) GlowBar
Reflection or Transmission Sensor	Silica (UV Enhanced)	210-900	NO=225 μm NO2=300-500 nm	Xenon flash lamp / Deuterium/ LEDs
Evanescent Field Sensor	Silica (UV Enhanced)	210-900	NO=225 nm NO2=300-500 nm	Xenon flash lamp / Deuterium/ LEDs

*gcf – glass cladding fibre **pcf – plastic cladding fibre

Table 3.1.2. Summary of Fibre Technologies and Available Techniques With Respect to the Specific Absorption Lines of the Exhaust Emission Species Concerned

From Table 3.1.2. gas sensors were constructed which fundamentally operated in the Ultra Violet (to measure NO, NO_2 and SO_2) and Mid Infra Red (to measure CO, HCs and CO_2) ranges of the optical spectrum. The operating principle of each sensor is described in Fig 3.1.1and 3.1.2. below

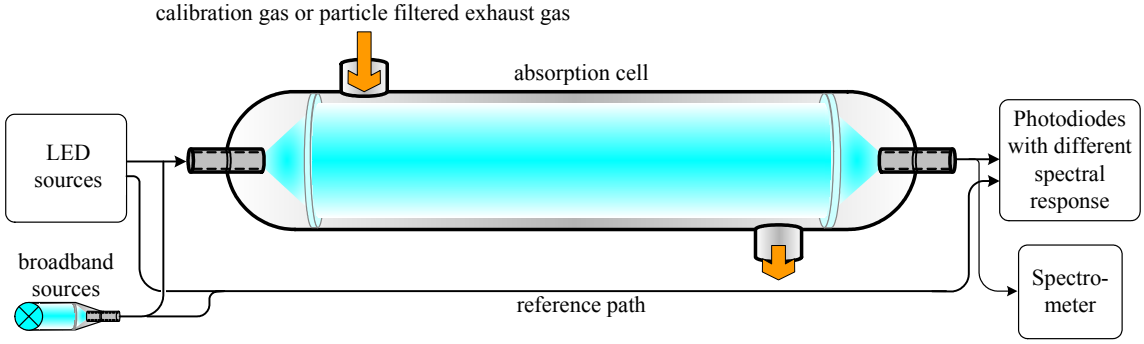


Fig 3.1.1 Schematic Outline of Gas Cell Used in UV Experimental Tests.

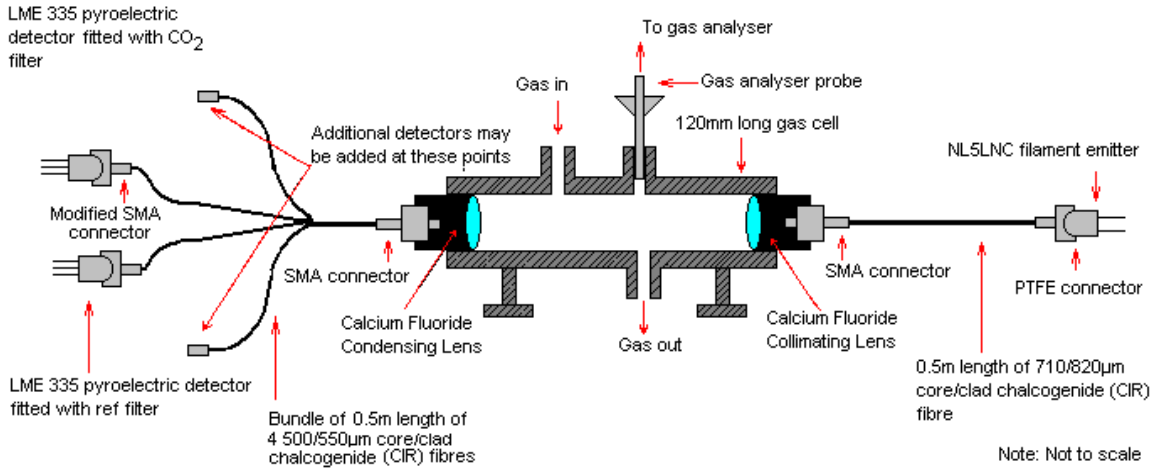


Fig 3.1.2. Schematic Outline of Gas Cell Used in Mid IR Experimental Tests.

The gases absorb optical radiation in each of the above wavelength ranges. The optical absorption spectrum for the UV gases (NO, NO_2 and SO_2) is shown in Fig 3.1.3. and the Mid IR gases in Fig 3.1.4.

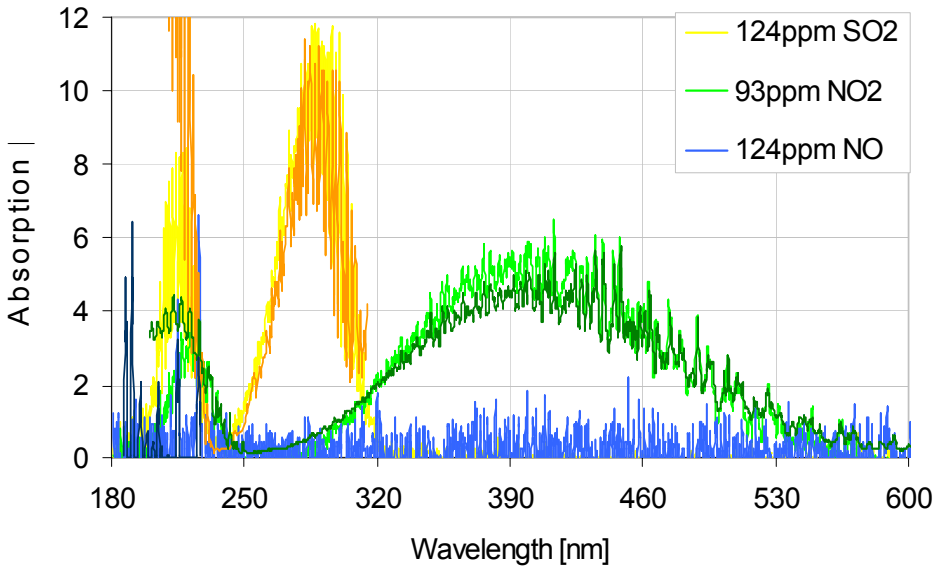
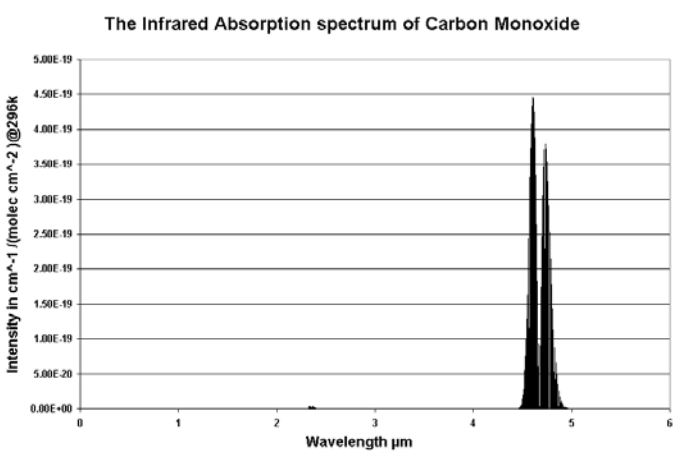
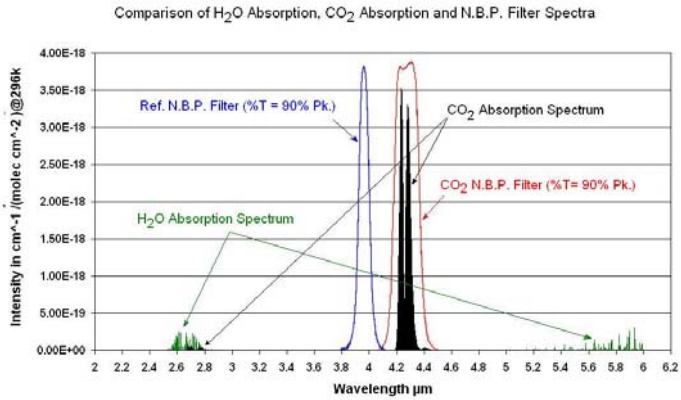
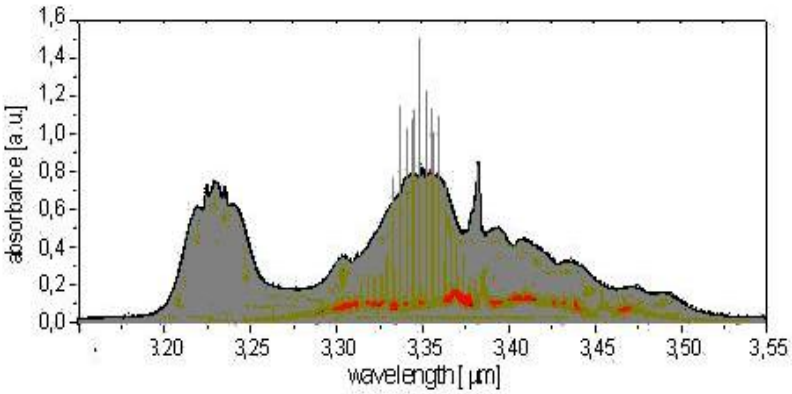


Fig 3.1.3. Spectral absorption data of single measured calibration gases (light colour) compared with database ones (dark colour)





(a) **(b)**



(c)

Fig 3.1.4. Spectral absorption data for (a) CO (b) CO2 and (c) HCs

3.2. Temperature Sensor

During this project two separate optical fibre temperature sensors were developed and evaluated namely the fluorescence decay time and in-fibre Bragg grating versions. These were both evaluated in terms of their performance at the laboratory of University of Liverpool. The Bragg Grating Sensor was found to be the more robust in terms of its immunity to vibration. Its principle of operation is described in Fig 3.2.1 below

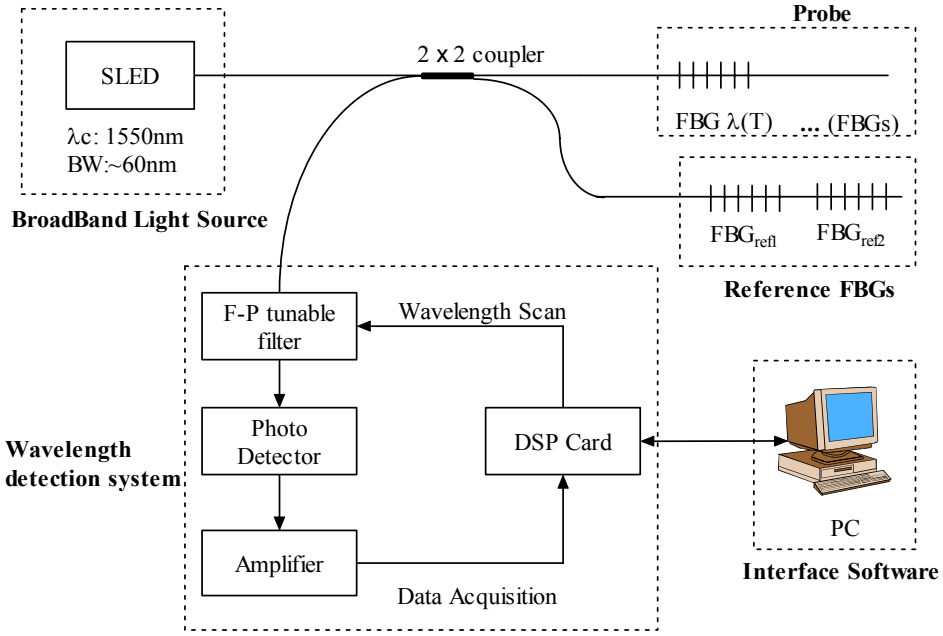


Fig 3.2.1 Schematic representation of the Optical Fibre Bragg Grating Temperature Sensor

The system configuration for testing the Optical Fibre Bragg Grating temperature sensor is shown in Fig 3.2.1. A broadband optical source (SLED) is used to illuminate the system. The returned (reflected) optical signal from the FBG is effectively scanned using a tuneable Fabry Perot (FP) filter. The scanned signal is further amplified and acquired and processed using a DSP card and transmitted to a laptop PC for display and storage.

4. Sensor Testing and System Integration at University of Liverpool

The sensor systems were rigorously tested at the test laboratory of Liverpool University prior to locating at the test facilities of CRF in Turin. The data gathered and analysed at Liverpool provided vital information for development of the sensor systems to be mounted on the Fiat Croma. These were reported at the 24 Month stage and were detailed in the activity report of that period. This section comprises a synthesis of activities in the workpackages relating to this phase of the work (WP3,WP4,WP5 and WP 6 (partially)) and the results from those activities. Fig. 4.1. shows a photograph of the Kubota Diesel Engine used for tests in this phase of the work

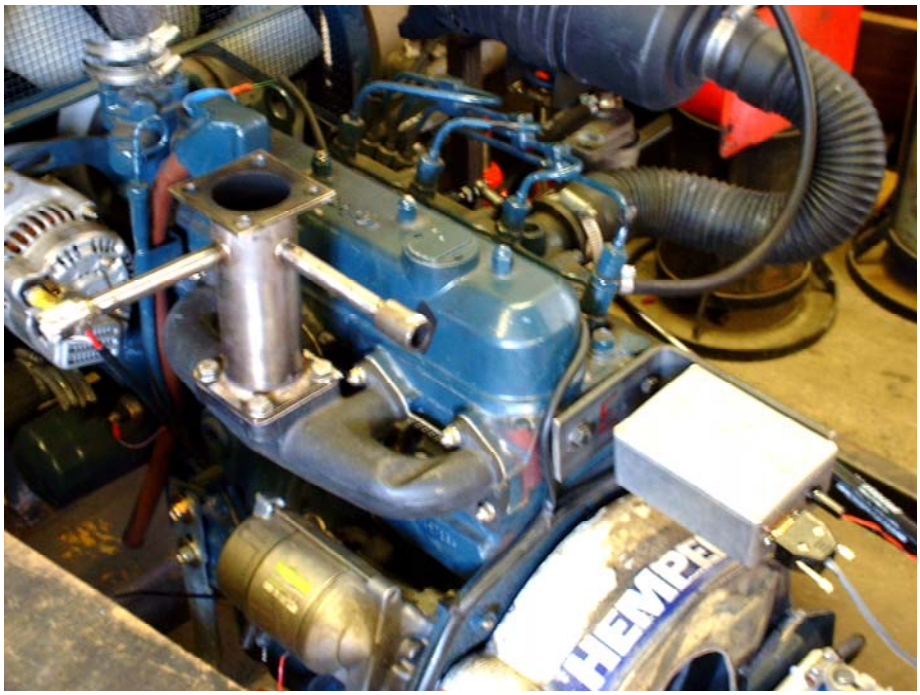


Fig 4.1 The Kubota D1105 diesel Engine

4.1. The Experimental Test System

The tests conducted at University of Liverpool allowed an opportunity for the sensors to be interfaced to the respective data acquisition units and integrated. Initially, the sensor outputs were recorded on a National Instruments PXI system interfaced to a PC running LabVIEW. AS much of the data being recorded were spectra (from the gas sensors), the Graphical User Interface of LabVIEW allowed these results to be displayed and stored in an optimum manner for ease of recording and analysis. An example of the output from the LabView programme is shown in Fig 4.1.1.

Having established the PC based system for capturing data in the laboratory it was also necessary to develop a microcontroller or embedded system to host the software developed for capturing the data and show that it was possible to do so as this would be the target system for incorporation on a road vehicle. This development led (during the final reporting period) to a fully operational embedded processor based system (DSP TI 6713 EVM) to acquire and

process the data from the sensors is shown in Figure 4.1.2 as a schematic (a) and photographically (b). The system is capable of real time data acquisition and processing and is connected via interface electronics components to the gas sensors.

(a)

(b)

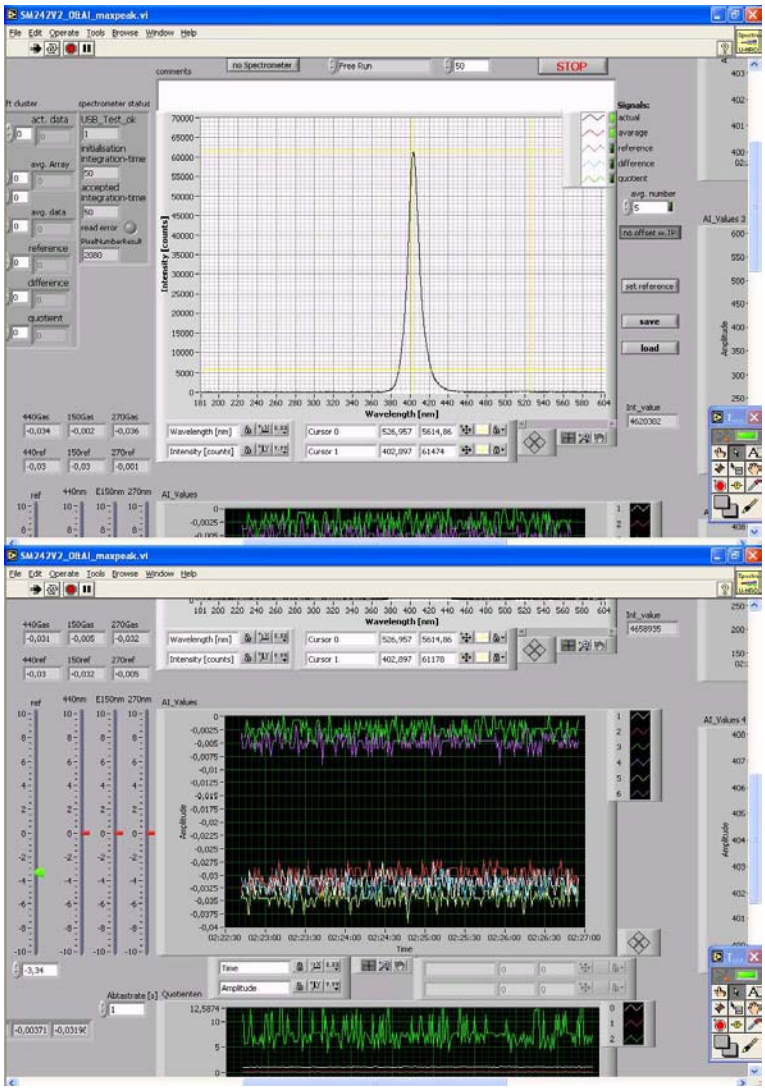
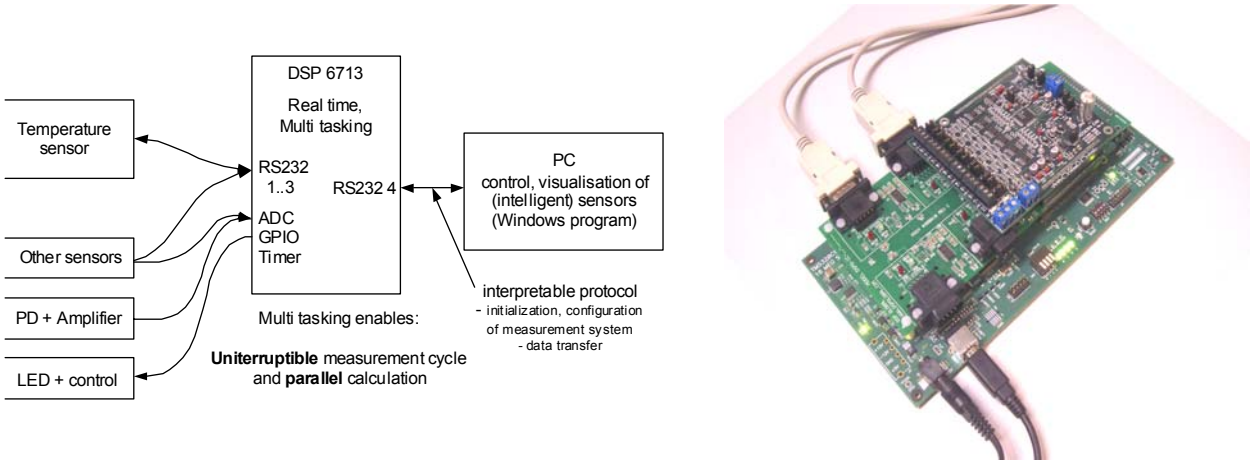


Fig 4.1.1 Screenshots of adopted control and signal analysing software a) LED-spectrum, b) gas cell spectrum



(a) **(b)**

Figure 4.1.2. The Digital Signal Acquisition and Processing Hardware (DSP TI 6713 EVM board)

4.2. Test Results

Several test results were captured using the systems described in Section 4.1 and the sensors of section 3. These are included in this section. They are presented in the following order

- Temperature
- UV Gas Sensors
- Mid IR Gas Sensors

All measurements were recorded on a real engine (The Kubota Diesel Engine of Fig 4.1).

4.2.1. Temperature

The temperature data recorded from the Fibre Bragg Grating (FBG) probe was recorded simultaneously and collocated with a thermocouple. This was recorded over a period of several minutes during which the engine was repeatedly revved and decelerated.

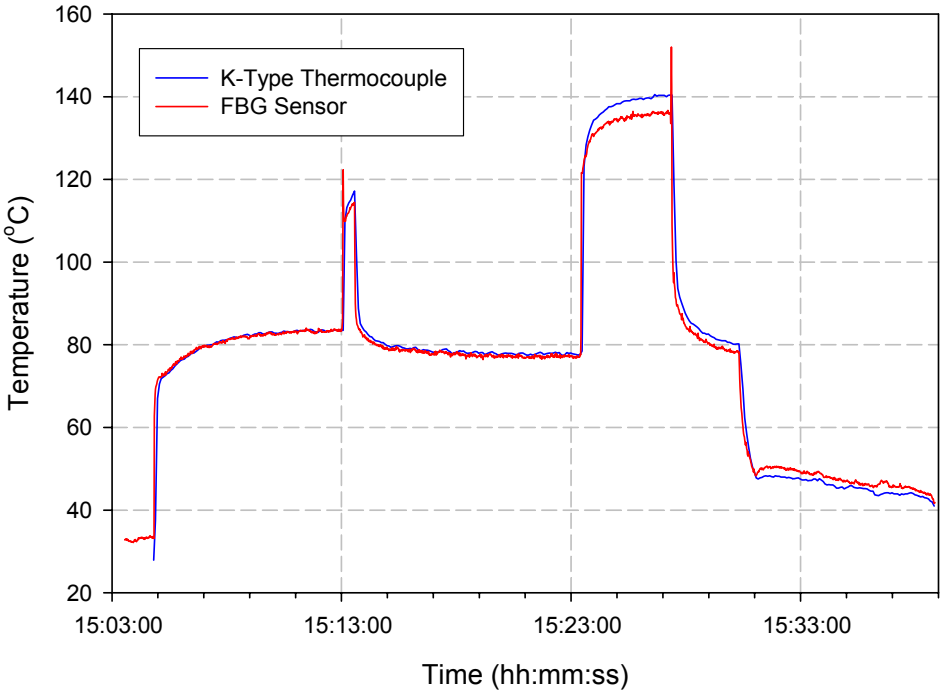


Figure 4.2.1.1. Simultaneous Recording of the Optical Fibre Bragg Grating Temperature Sensor and the K-Type Thermocouple during operation of the Kubota Diesel Engine at the Test Labs in Liverpool

Fig 4.2.1.1 shows that there was excellent agreement between the two sensors with the small differences being accounted for by the small displacement between the location of the two sensors.

4.2.2 UV Gas Sensors

The gas sensors which operate in the UV region and described in Section 3 of this report were used to record levels of NO2, NO and SO2 from the Kubota Diesel Engine. These were recorded simultaneously using a Kane-May Quintox Gas analyser with the relevant plug-in modules.

The results of Fig 4.2.2.1 show a time resolved spectrogram of the gas absorption as the engine starts up and operates for several minutes.

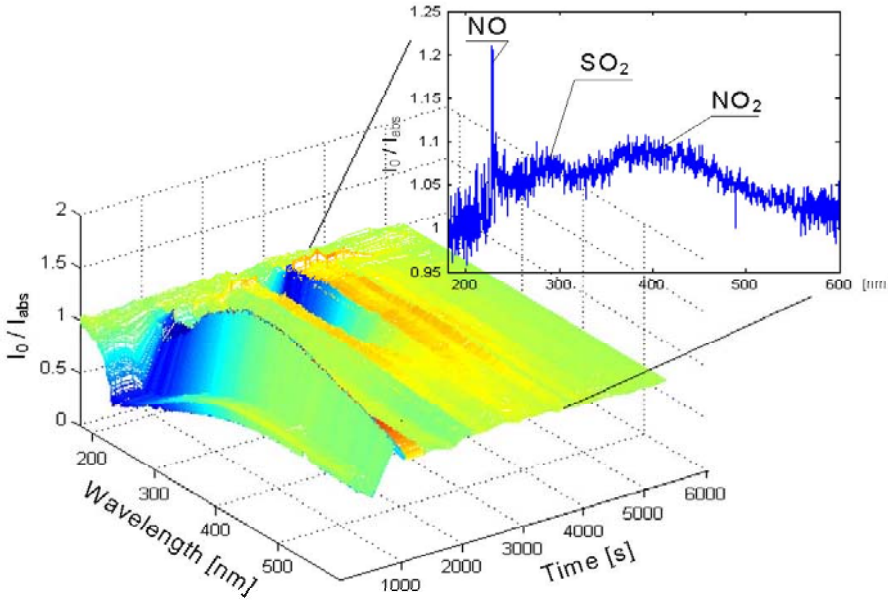


Figure 4.2.1.1. Online Car Exhaust Gas Concentration Measurement, Time Resolved Spectral Data

Following an initial pause during the start up phase of the engine the UV absorption due to all three gases is clearly observable. The inset shows a crossection of the spectral data at a single instant in time. The absorption lines corresponding to the three gases are labelled on this. This record clearly demonstrated the gas sensor's ability to record all three gases simultaneously (in mixture) when discharged from the exhaust of a real engine.

As an alternative to the spectrally resolved detection, a version of this sensor was constructed which relied on illumination by a UV/Blue Light Emitting Diode (LED) and a filtered photodetector. This version allowed simultaneous detection of NO_2 and SO_2 but not NO as the LED to cover that spectral region is not yet commercially available, but the manufacturer (Roithner) states that one is likely to be available in the near future (within 24 months). The results using the UV/Blue LED and a filtered photodetector for detection of NO2 from a controlled supply (not the engine in this case) is shown in Fig 4.2.1.2.

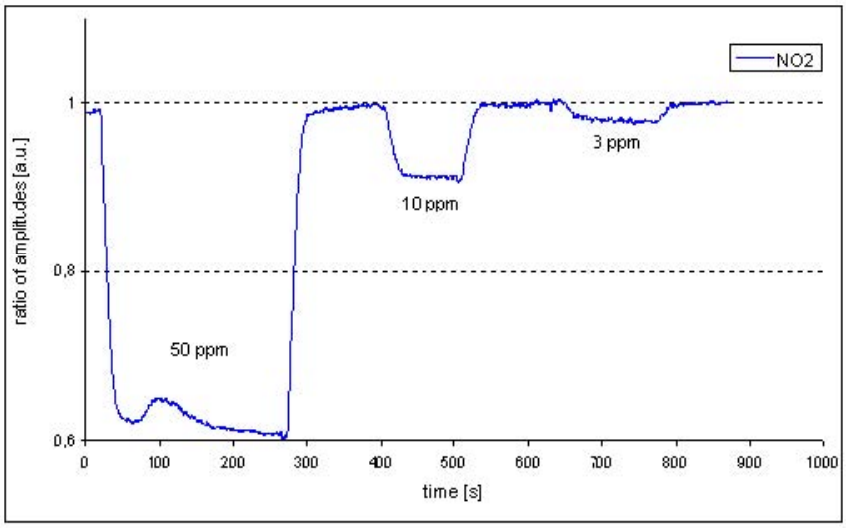


Figure 4.2.1.2. Transmission Of Different NO_2 Concentration Set By a Mixing Device, Recorded Using a Blue/UV LED And Photodiode.

Fig 4.2.1.2. shows that using the LED and photodetector that a minimum level of detection of 3ppm or les can be achieved which is comfortably within the 20 ppm value of the Euro IV standard.

4.2.3 Mid IR Gas Sensors

The data recorded using the mid IR sensor described in Section 3 was performed solely using a broad band filament emitter and a filtered photodetector (pyroelectric detector) for each gas (4.3 μm for CO_2, 4.7 μm for CO and 3.4 μm for HCs) as well as a separate one at a non gas absorbing region (3.9 μm) which acted a s a reference for the active gas sensing channels.

The results of connecting the CO_2 sensor to the exhaust line of the Kubota Engine whilst the engine was running for several minutes at constant speed is shown in Fig 4.2.3.1. The CO_2 concentration was measured simultaneously on the Kane May Quintox gas analyse and was found to be steady at about 2%. Also shown in Fig 4.2.3.1 is the reference channel output. This did not fluctuate throughout the recording period of this test.

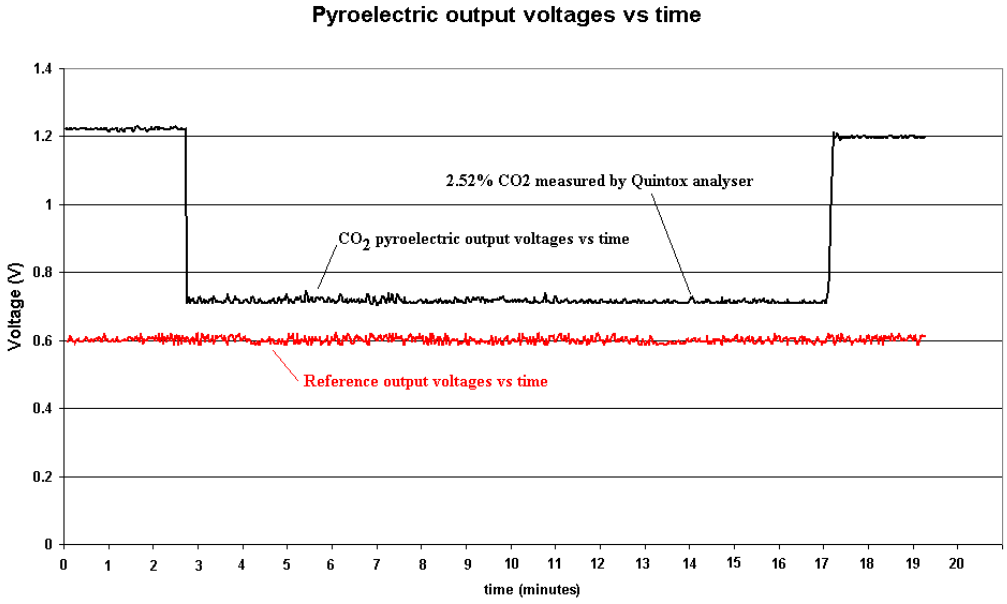


Figure 4.2.3.1. Mid Infra Red Optical Fibre Sensor CO_2 Concentration measured in the exhaust of the Kubota Diesel Engine.

From Fig 4.2.3.1 it is clear that the CO_2 is sensor capable of measuring to at least 2% with a good signal to noise ratio. In order to extend the measuring range to 15% a more compact design was implemented (including a shorter path length) for measurement of the demonstrator vehicle.

The same sensor was used in the laboratories of CRF to demonstrate sensitivity to CO and HC. In the case of the engines with exhausts fitted with a modern catalytic converter these values are very low (lower than single ppm) and are not detectable even very expensive reference instrumentation. The results corresponding to the HC and CO optical fibre concentration measurements are shown in Fig 4.2.3.2 and Fig 4.2.3.3 respectively together with the relevant reference gas analyser instrumentation output which was recorded simultaneously.

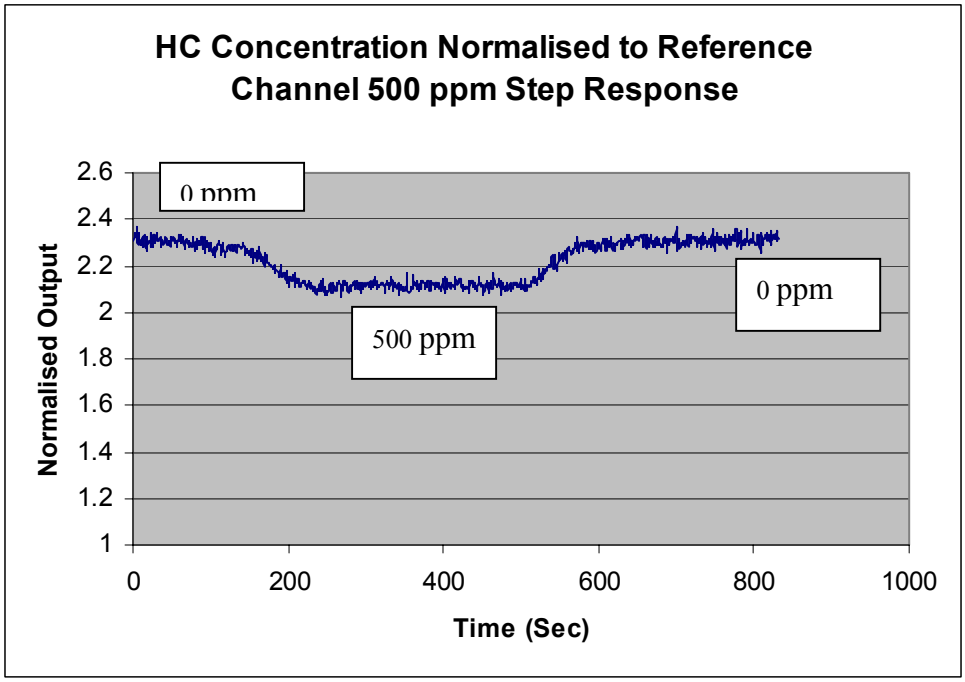


Figure 4.2.3.2. Mid Infra Red Optical Fibre Sensor HC Concentration measured in the Laboratory of CRF when exposed to 500 ppm pulse of HC .

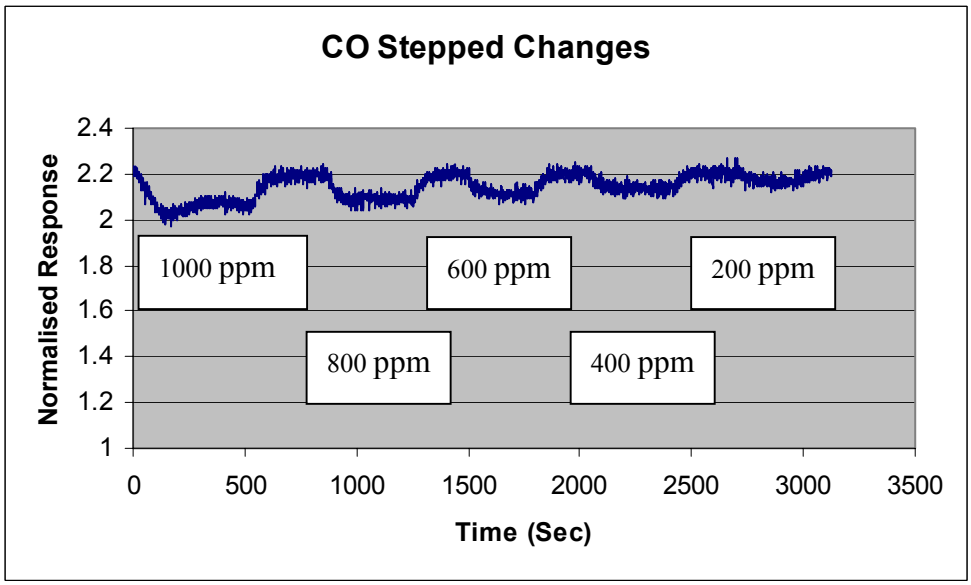


Figure 4.2.3.3. Transmission Of the Mid IR Optical Fibre Sensor when exposed to Different CO Concentration Set By a Mixing Device in the laboratory of CRF,

The results of Fig 4.2.3.2 and Fig 4.2.3.3. show that the limit of detection for HC and CO is currently about 200 ppm. This makes the sensor applicable to On Board Detection (OBD) of exhaust gases where they would detect a threshold limit of the gases in the case of failure of the catalytic converter.

5. Sensor Testing On the Demonstrator Vehicle at CRF

5.1 The Demonstrator Vehicle and Test Facility

The final demonstrator vehicle was selected primarily for being Euro IV compliant but also for being relatively easy to accommodate the projects sensors within the exhaust system. The vehicle selected was a Fiat Croma 1.9 MJT 16v 150 HP as shown in Fig 5.1.1.

The vehicle is Euro IV compliant and equipped with a catalysed Diesel Particulate Filter, necessary to avoid the accumulation of soot onto the downstream positioned optical fiber lens and the consequent signal alteration.

Engine characteristics	
Stroke number	4
Displacement	1.9 dm^3
Max power @ 4000 rpm	150 HP
Max torque @ 2000 rpm	320 Nm

Figure 5.1.1: OPTO EMI SENSE final demonstrator vehicle characteristics.

A portable multi gas analyzer MIR9000 comprisinga multi component non dispersive IR analyzer using Gas Filter Correlation Technique (GFC). GFC is a well established method to reduce the cross sensitivity to gases that cause interference in infrared measurements; therefore, using this analyzer is possible to monitor simultaneously a numbers of different gaseous species with the following detection ranges:

- CO_2 → 0-15%
- CO → 0-5000 ppm
- NO → 0-3000 ppm
- NO_2 → 0-3000 ppm
- THC → 0-2500 ppm
- SO_2 → 0-100 ppm
- O_2 → 0-21%

The above mentioned devices were located in the rear trunk of the car, together with a portable gas bottle of nitrogen, needed for the gas analyzer calibration (Fig 5.1.2); the heated sampling line has been directly connected to the exhaust line just prior the muffler (downstream the aftertreatment devices) in order to monitor the gas composition as close as possible to the optical fibre sensors position.

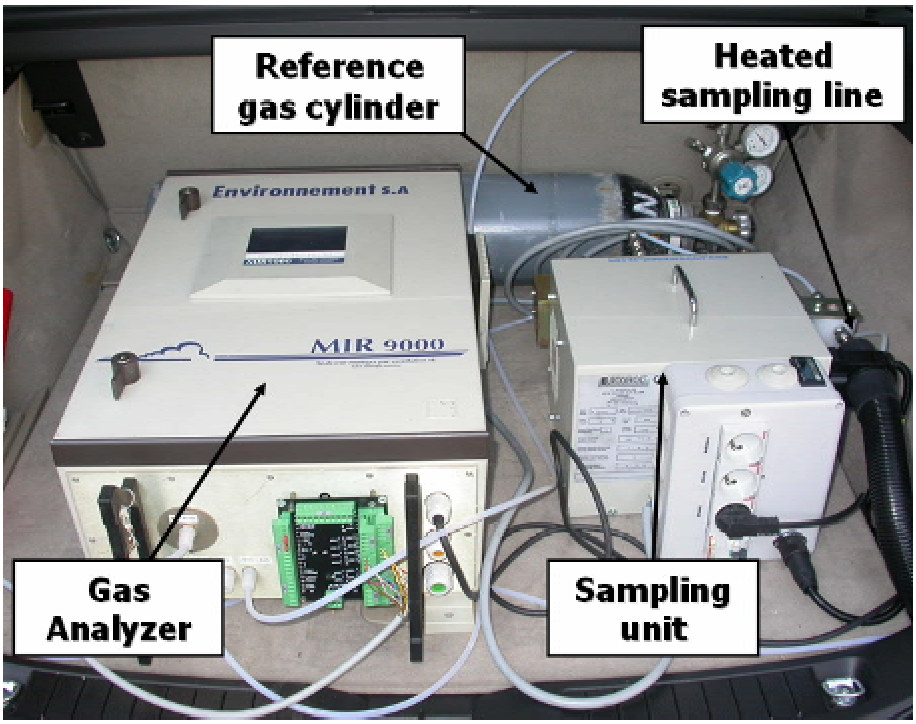


Figure 5.1.2: gas analyser installation layout.

The tests were conducted either driving on the open road (free driving) or on the roller test bench facility (similar to a rolling road) available at CRF. Fig 5.1.3 shows a photograph of the demonstrator vehicle undergoing testing at the roller test bench facility of CRF.

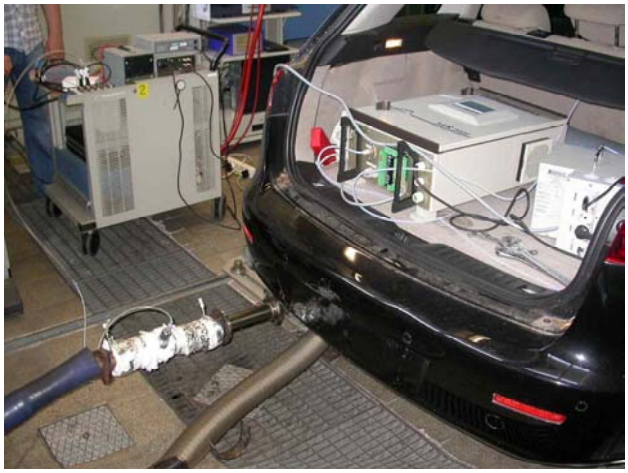


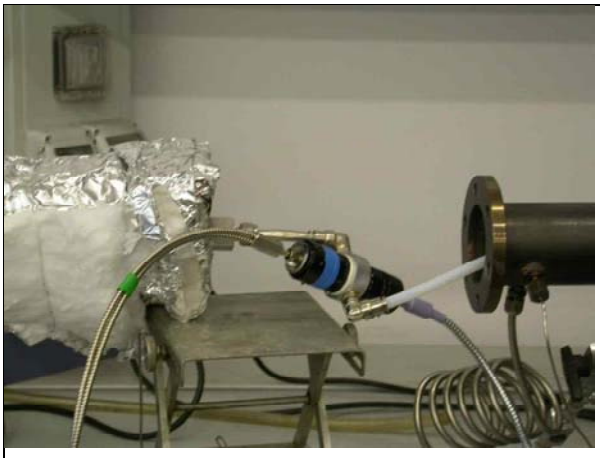
Figure 5.1.3. The Fiat Croma Demonstrator Undergoing Testing at the Roller Test Bench Facility

5.2. Measurements

The optical gas and temperature sensors developed by the optical fibre research groups of the University of Limerick and City University were prepared for mounting underneath the vehicle in the location shown in Figure 5.2.1. A number of sensor configurations were developed for this purpose each of which were successfully tested at the rolling road facility of CRF. A transmission (an in-line tube) and a reflective (a plug like structure) version were fabricated that could be inserted underneath the vehicle. An example of a transmissive gas sensor mounted under the car is shown photographically in Figure 5.2.2

Figure 5.2.1 Photograph of The UV Optical Fibre Gas Sensors Mounted Underneath the Vehicle.

In the case of the temperature sensor, the Fibre Bragg Grating Sensor developed in the second reporting period was commissioned installed on an engine and tested at CRF. The sensor was mounted on a flange which could be inserted either upstream or downstream of the sensor section of Figure 5.2



(a) Close up (in lab)

(b) Mounted on the Demonstrator Car Exhaust

Fig 5.2.2. The Optical Fibre CO2 Sensor for Vehicle Mounting (Transmission Mode)

The optical fibre temperature sensor mounted on the flange of the test system at the laboratory of CRF and co-located with two thermocouples at the CRF test facility is shown photographically in Fig 5.2.3.

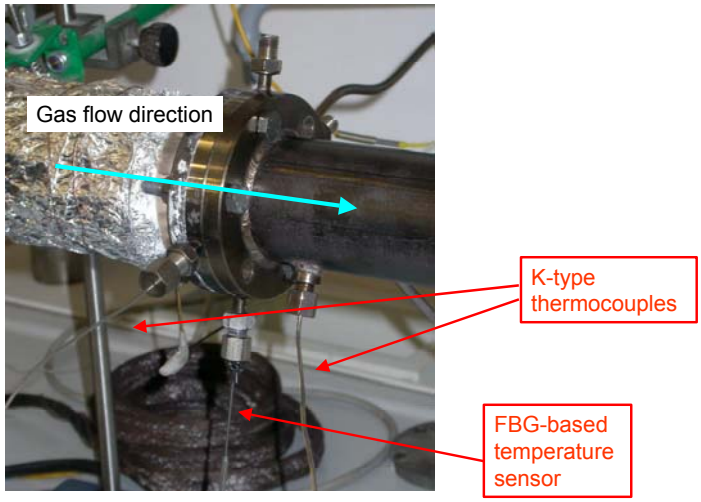


Figure 5.2.3. Photograph Of The Fibre Bragg Temperature Sensor Mounted On The Test Exhaust Line

A comprehensive series of testing of these systems was undertaken during the final 18 month period of this project. These results are detailed later in the report, but the following figures give a summary of the results obtained to date.

1. Gases. Evolution of NO_2 as measured using the UV/VIS optical fibre sensor located underneath the car and for the NEDC cycle test (Fig 5.2.4)
2. Gases. Evolution of CO_2 as measured at Mid IR using the optical fibre sensor located underneath the car and for the NEDC cycle test (Fig 5.2.5)
3. Temperature. Comparison of the FBG probe with thermocouples located on the exhaust system an engine at the laboratory at CRF (Fig 5.2.6)

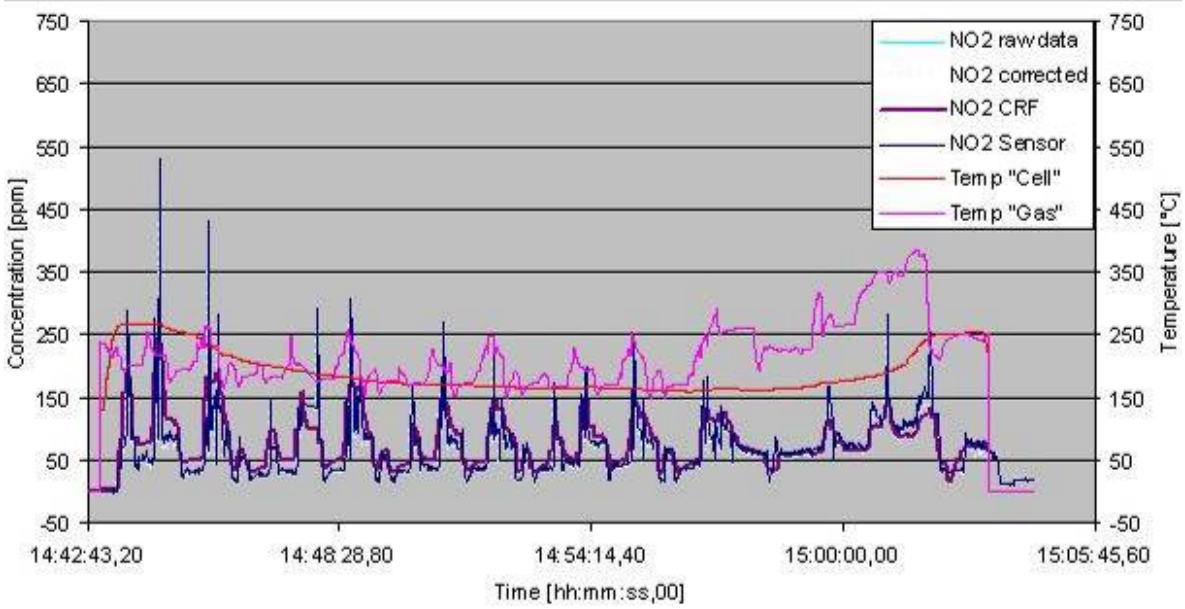


Figure 5.2.4. Evolution of NO_2 versus time as measured using the UV/VIS optical fibre probe under standard engine test conditions for sensor mounted underneath the vehicle

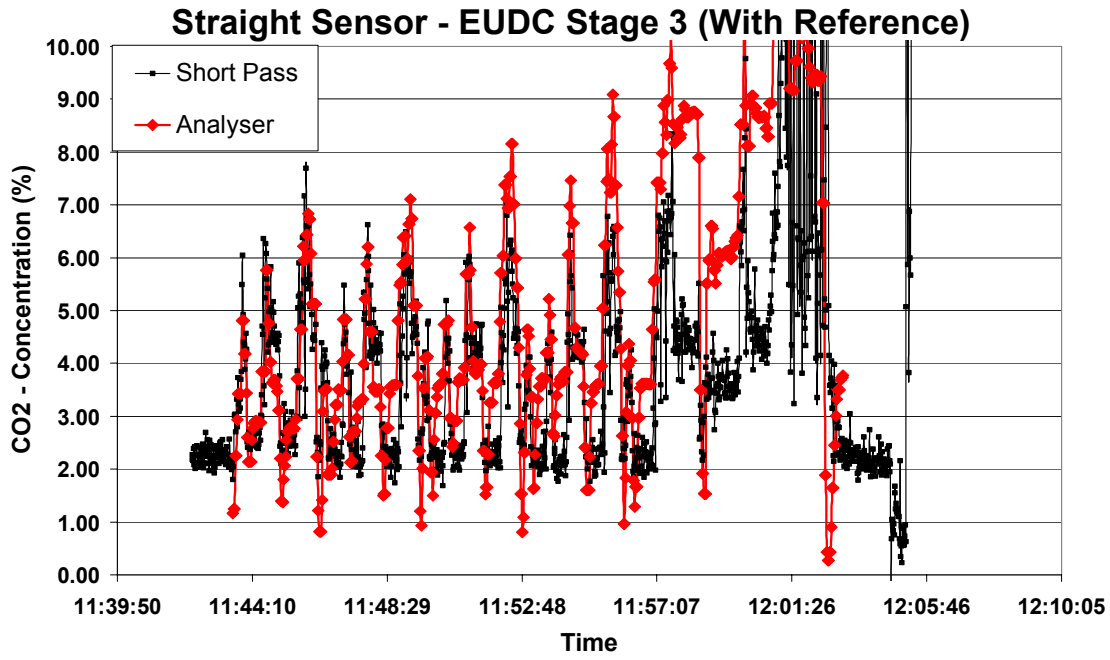


Figure 5.2.5. Evolution of CO_2 versus time as measured using the Mid IR optical fibre probe under standard engine test conditions for sensor mounted underneath the vehicle

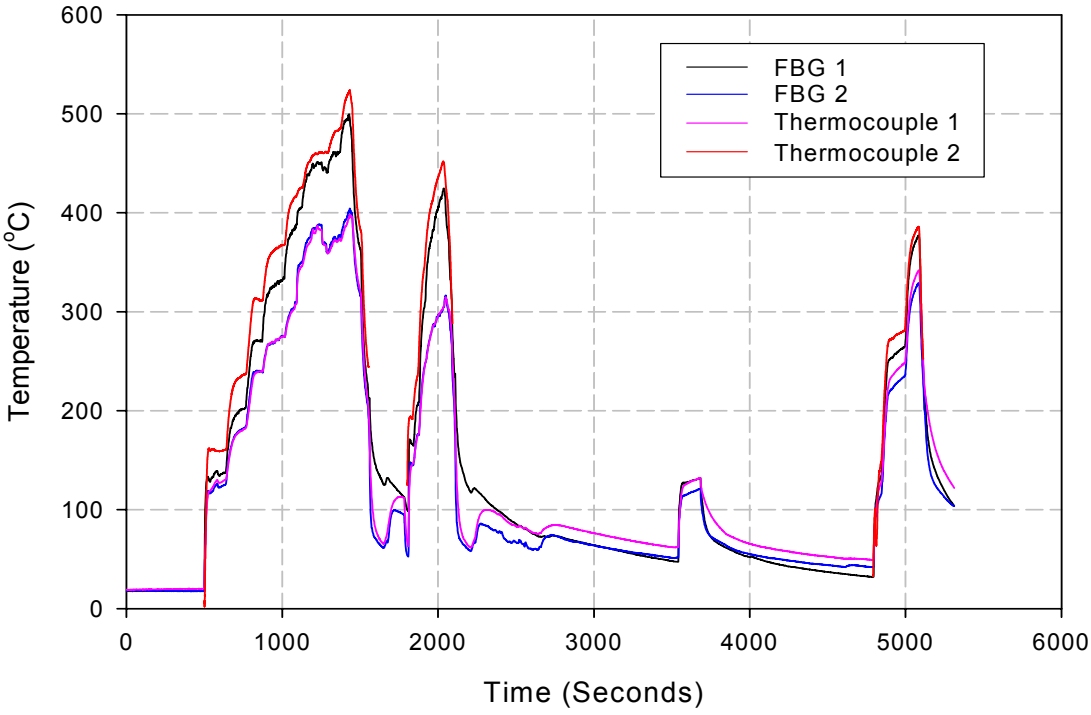


Figure 5.2.6. Comparison of FBG and Thermocouple Probes Under Engine Test Conditions at CRF

The multiple traces of Figure 5.2.4. correspond to simultaneously recorded reference instrumentation (commercial instrumentation) data and temperature. The recorded traces for the concentration recorded by the optical fibre sensor and reference instrumentation correspond very closely and are almost indiscernible on Fig 5.2.4. However, a closer analysis shows that the response time of the optical sensor is shorter than the commercial sensor. Further result and analysis are presented in the main body of this report. The carbon dioxide measurements of Figure 5.2.5 also show excellent agreement between the optical fibre sensor and the commercial sensor. The temperature results of Fig 5.2.6 show good agreement with those of collocated thermocouples for a typical engine cycle test of 10 minutes duration.

Clearly the results of Figures 5.2.4 - 5.2.6 show excellent progress of the project during the final reporting period with temperature and gas concentrations (to EURO IV levels) being successfully measured underneath the car using the optical fibre sensors

6. Dissemination

The results of this project have been extensively disseminated. The form of this dissemination includes presentations at conferences, publication in journals, active participation in exhibitions, publication in a wide range of magazine with many more in various stages of submission and refereeing etc. . To date there have been three PhD completions resulting directly from the research of the OPTO-EMI SENSE project (J. Mulrooney and E.Hawe of (both of Univ. of Limerick) and C Wei (Univ of Liverpool)) with four others nearing completion (M.Degner (ROS), G. Bramman, G. Dooly, K. Gleeson (all UL)). A summary of the publications is given in table 6.1.below

Item →	**Journal Paper (Refereed)**	**Conf Paper - International & Refereed**	**Invited Talks**	**Magazine**	**Patents being Sought**	**Book Contrib. (Submitted)**
Number →	**11**	**42 incl 1 award**	**2**	**4**	**1**	**1**

The journal papers published during the course of this project are detailed below: -

1. O'Keeffe S., Fitzpatrick C. and Lewis E. (2005) *"*Ozone measurement in visible region: an optical fibre sensor system*"* *Electronics Letters*, Vol 41. (No 24) (Nov 2005) pp 1317 –1319

2. Dong H, Zhao W, Sun T, Grattan K T V, Al-Shamma'a A I, Wei C , Mulrooney J, Clifford J, Fitzpatrick C, Lewis E, Degner M, Ewald H, Lochmann S I, Bramann G, Merlone Borla E, Faraldi P and Pidria M (2006) "Vibration-insensitive temperature sensing system based on fluorescence decay and using a digital processing approach" *Meas. Science and Technol.* Vol 17 No 7 (July 2006) pp 2010-2014

3. Degner M., Ewald H., "Fibre optical sensors for automotive application", Landestechnologieanzeiger, (1), 20-21, 2006

4. Dooly, G.; Lewis, E.; Fitzpatrick, C. and Chambers, P., "Low Concentration Monitoring of Exhaust Gases Using a UV based Optical Sensor", *IEEE Sensors* 7(5), (May 2007), pp 685- 691.

5 Mulrooney J., Clifford J., Fitzpatrick C. and Lewis E. "Detection of carbon dioxide emissions from a diesel engine using a mid-infrared optical fibre based sensor" *Sensors and Actuators A: Physical* 136(1), (May 2007), pp 104-110

6 Dooly G., Fitzpatrick C., Chambers P. and Lewis E., (2007) "On-board monitoring of vehicle exhaust emissions using an ultra-violet optical fibre based sensor", *J. Opt. A: Pure Appl. Opt.* 9 (6), (June 2007), pp S24-S31

7. Hawe E., Fitzpatrick C., Chambers P. and Lewis E., "An investigation into the use of an integrating sphere as a gas absorption cell", *J. Opt. A: Pure Appl. Opt.* 9 (6) (June 2007), pp S12-S18

8. Mulrooney J., Clifford J., Fitzpatrick C., Lewis E "Monitoring of carbon dioxide exhaust emissions using mid-infrared spectroscopy" *J. Opt. A: Pure Appl. Opt.* 9 (6) (June 2007), pp S87-S91

9. Hawe, E., G. Dooly, C. Fitzpatrick, E. Lewis, W. Z. Zhao, T. Sun, K. T. V. Grattan, M. Degner, H. Ewald, S. Lochmann, G. Bramman, C. Wei, D Hitchen, A. Al-Shamma'a, E. Merlone-Borla, P. Faraldi and M. Pidria. "Measurement of exhaust gas emissions using absorption spectroscopy", *International journal of systems technologies and applications,* Vol 3, Nos 1-2, (June 2007), pp 33-51.

10. O'Keeffe S., Fitzpatrick C., Lewis E., "An optical fibre based ultra violet and visible absorption spectroscopy system for ozone concentration monitoring", *Sensors and Actuators B: Chemical* Vol 125 (No 2) (August 2007) pp372-378

11. Hawe E., Chambers P., Fitzpatrick C. and Lewis E., "CO_2 monitoring and detection using an integrating sphere as a multipass absorption cell" Measurement Science and Technology, Special issue, in press *Measurement Science and Technology* Vol 18 (No 10) (October 2007) pp 3187-3194

7. Conclusions and Future Work

Optical Fibre Based Sensor Systems for measuring the gas concentration and temperature in the exhaust systems of road vehicles have been developed and fully implemented at the test laboratories of the University of Liverpool and underneath the car at the rolling road test facilities of CRF. Considerable interaction between all partners of the consortium has resulted in a number of packaged sensor probes which has lead to a fully operational demonstrator system mounted underneath a Fiat Croma. Comparison with simultaneously recorded results using commercial instrumentation has showed excellent correspondence with the data recorded using the optical fibre sensors. The next phase of this work will be to develop commercial prototypes of the optical fibre sensors which are suitable for use by the automotive industry and satisfy the EU directives for On Board Measurement (OBM) and On Board Detection (OBD).

Future Cost Estimation

UV-VIS Sensor system:

Based on the work of the project the following would comprise a low cost mass produced cost estimation for LED-based UV-VIS –gas sensor

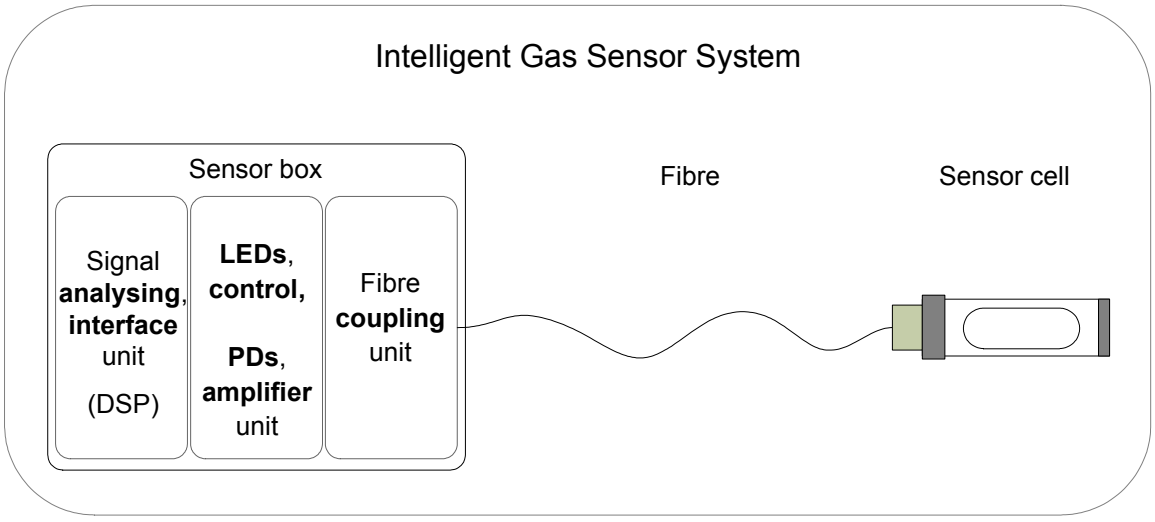


Fig 7.1. Proposed UV Gas Sensor System

System costs:

Actual costs for the low volume (laboratory scale) order are listed. Based on these costs the mass product costs were estimated. A significant price reduction is to be expected in the mass produced electronic and optoelectronic components, since the development costs play a major role here. For instance the UV–LEDs are currently produced in very low quantities (for research grade). However, a large demand with competition would surely decrease the price enormously. In the case of the sensor optical components the production process technology is more important, so the price reduction may be more moderate here.

Components			amount	actual laboratory state costs	estimated mass production costs	NO2 sensor	SO2 sensor	NO2,SO2 sensor	NO, NO2, SO2 sensor
Optics	Lenses		1	70,00 €	10,00 €	x	x	x	x
	Mirror		1	30,00 €	5,00 €	x	x	x	x
	Fibres		2m	* 34,00 €	1,00 €	x	x	x	x
	Coupler		1	-	20,00 €	x	x	x	x
	Connectors		1	4,50 €	0,05 €	x	x	x	x
Optoelectronics	LEDs 405nm	NO2	1	2,00 €	0,02 €	x		x	x
	590nm	Ref	1	1,00 €	0,01 €	x		x	x
	285nm	SO2	1	169,00 €	2,00 €		x	x	x
	255nm	Ref		219,00 €	2,00 €		x	x	x
	219/226 nm	NO	1	?	? 5,00 €				x
		Ref	1	?	? 5,00 €				x
	PDs	Gas	1	10,00 €	0,10 €	x	x	x	x
		Ref	1	10,00 €	0,10 €	x	x	x	x
Electronics	Source control components		4	5,00 €	0,10 €	x	x	x	x
	Amplifier components		2	20,00 €	0,50 €	x	x	x	x
	Digital / Signal analyses e.g. DSP		1	900,00 €	** 10,00 €	x	x	x	x
	Power supply		1	50,00 €	2,00 €	x	x	x	x
Mechanics	cell construction		1	-	5,00 €	x	x	x	x
						55,48 €	59,45 €	59,48 €	69,48 €

* price goes square with fibre diameter, e.g. a smaller diameter (we've also used it before) would take 8,00€ /m – this is depending on the coupler technology
** strong price reduction in electronic components through mass production, development cost are dominating (example with mobile phones)

Mid Infra Red Gas Sensor

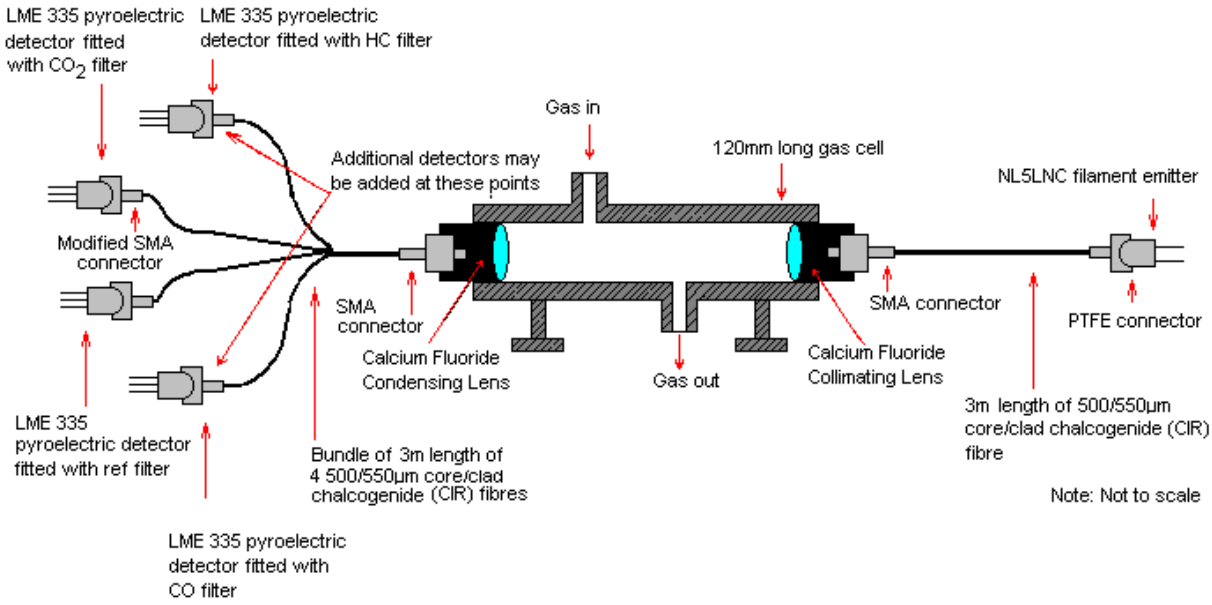


Fig 7.2. Proposed Mid IR Gas Sensor System

System costs:

The cost of assembling the prototype mid-infrared optical fibre is outlined in Table 1. Based on these costs, an estimate is given of the product costs. The most expensive items in the system are the mid-infrared lenses and fibres due to a low market demand at present. It is expected that if the system were to be mass-produced the cost of these components would decrease to values more comparable with telecommunications grade parts. Indicative estimated prices are shown on Table 7.2.

Components		Quantity	Cost per item (€)	Total (€)	Estimated Cost (€)	CO_2	HC or CO	
Optics	Calcium Fluoride Lenses	2	331.55	663.10	20.00		X	
	Chalcogenide fibre 3m length	1	728.34	728.34	20.00	X	X	
	Chalcogenide fibre 3m 1 to 2 bundle	4	1,500.16	1,500.16	40.00	X	X	
	SMA connector	3	25.00	75.00	10.00	X	X	
	Lens holders	2	40.00	80.00	5.00	X	X	
Optoelectronics	Pyroelectric detector							
	with CO2 filter	1	65.80	65.80	5.00	X		
	with Reference filter	1	65.80	65.80	5.00	X	X	
	with HC filter	1	65.80	65.80	5.00		X	
	with CO filter	1	65.80	65.80	5.00			
	Filament emitter	1	62.00	65.80	5.00	X	X	
Electronics	Emitter control electronics	1	50.00	50.00	0.50	X	X	
	Detector amplification/filtering electronics	1	50.00	50.00	0.50	X	X	
	Power supply	1	50.00	50.00	2.00	X	X	
Mechanics	Cell construction	1	200.00	200.00	2.00	X	X	
	Custom fibre coupler fabrication	5	10.00	50.00	1.00	X	X	
			Total:	3310.25	126.00	96.00	96.00	

Table 7.2. Details of the costs associated with the mid-infrared prototype and predicted costs should it be mass produced

Degree to Which Target Specifications have been met

This section is a synopsis of the extent to which the sensors developed within the OPTO-EMI-SENSE project have met the specifications laid out at the beginning of the project and in Section 2 in this report.

Concentration range sensitivity

- CO $\Rightarrow$ 20 – 2000 ppm. Lower Threshold of Detection = 200 ppm (approx.) range up to 2%
- $NO_x \Rightarrow$ 20 – 2000 ppm Lower Threshold of Detection = 2 ppm. Range up to 10,000 ppm
- $SO_x \Rightarrow$ 2 – 200 ppm Lower threshold of Detection = 2 ppm. Range up to 10,000 ppm
- HC $\Rightarrow$ 50 – 5000 ppm Lower Threshold of Detection = 200 ppm (approx.) range up to 2%
- Also Measured CO_2 in the range 350 ppm (atmospheric) to 15%

Sensitivity, accuracy and resolution

- Lower detectable limit: ~ 1 % f.s. Achieved in all cases
- Repeatability: +/- 0.5 % f.s. Comparison with Gas Analyser Data has verified this
- Resolution: ~ 0.5 % f.s. Comparison with Gas Analyser Data has verified this

High selectivity

The independent character of the observed spectra means that all gases can be detected independently and in mixture. No observable effects have been found due to water vapour or other gases e.g. H_2.

Post-production calibration for sensor or control unit

Once calibrated and in the presence of an stable reference channel (not an active gas measurement channel) the amount of optical absorption at a given wavelength is a fundamental property of the gas and thus recalibration is not necessary.

Power-on stabilization time

There are no limitations due to this as there are no warm up times required for the components. There is an effect due to condensation on the windows of the gas cells during start up. However this is temporary and coincides with a similar ‘dead time’ observed when using the reference gas analyzer instrumentation.

Response time

- Exhaust Aftertreatment System Control (2 to 5 Hz). This was achieved in the case of all sensors
- Combustion control (>30 Hz needed for closed loop control). The optical gas detection method is technically instantaneous. However, in the case of an LED/ filtered photodetector type system the response time is limited by the electronic components in the emitter and detector circuits. It is feasible that this may be reduced to the ms range in future developments.

Packaging and low power consumption

Sensors were developed which comprised transmissive gas cells (up to 360 mm length). All of these fitted within the exhaust system the car or as a bypass. Further embodiments of the gas cells were also developed which are reflection mode based and are of plug-like structure and resemble the lambda sensor.

The sensors designed were able to operate from the battery driven dc/ac converter of the car whilst free driving on the road

Output signal independency from gas flow / pressure

The flow rate in the exhaust was always sufficient to allow measurement. No effect due to pressure fluctuations was detected on the optical signals

Insensitiveness to fuel, oil additives and impurities

No effect due to oil additives or any fuel based impurities were observed during any of the measurements undertaken.

Temperature endurance and signal linearity

The sensors maintained measurement throughout the NEDC driving cycle as well as free driving. During one test the DPF regeneration cycle was entered during which the temperature of the gases in the downstream of DPF region exceeded 650 ^{o}C. The sensors survived this cycle and continued operating normally after it had finished.

Permissible vibrations

No effects due to vibration were observed on the optical signals when the sensors were mounted on the exhaust of the vehicle. Stringent vibration tests were also undertaken in the engine test laboratories of the University of Liverpool.

Operating life

This has yet to be evaluated but the sensors have survived since they were first fabricated approximately two years from now..

Target costs

These have been discussed in the previous section.