ON BOARD EXHAUST EMISSION MONITORING OF ROAD VEHICLES - A HIGH TECH SOLUTION TO POLLUTION FROM TRAFFIC?

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Abstract- A significant proportion of the atmospheric pollution that exists particularly in urban areas arises from road vehicles and primarily cars. The European Commission (EC) have introduced a series of regulations, the so called EURO Emission directives from Euro I in 1991 to the present day Euro IV. This legislation and similar ones in other global regions have helped to greatly reduce emission levels from road transport. However, a massive increase in the number of cars on the road have meant that pollution due to a number of gases and particulate species remains to be a problem. This paper describes an approach based on optical fibre sensors which has shown to be an effective means of measuring the gases and particulates in question by using sensing technologies which are both robust and potentially cost effective such that they may be included as part of an on board monitoring system for the car of the future.

Index terms*: mid-infrared gas detection; UV gas detection; optical fibre sensor; vehicle emission detection.*

I. INTRODUCTION

Automotive emissions typically consist of water vapour, carbon dioxide (CO2), carbon monoxide (CO), oxides of nitrogen (NOx), oxides of sulphur (SOx), smoke particles (diameters of 0.05μm to 1μm) and also particulate matter (diameters greater than 1μm). Under perfect combustion conditions the following relationship would hold:

$$\text{Fuel (CxHx)} + \text{Air} \rightarrow \text{CO2} + \text{H2O} \quad (1.1)$$

As carbon dioxide (CO2) and water vapour (H2O) are both present as trace gases in the atmosphere, no pollution would result from this process. However in reality perfect combustion does not occur and the following relationship holds as fuel is burnt in an engine:

$$\text{Fuel (CxHx)} + \text{Air} \rightarrow \text{CO2} + \text{H2O} + \text{CO} + \text{SOx} + \text{NOx} + \text{PM} + \text{CxHx} + \text{smoke} \quad (1.2)$$

Research has shown that each of these species is a threat to either human health or the environment [1]. Carbon monoxide (CO) is known to be poisonous to humans at concentrations above 400 parts-per-million. While CO2 is not strictly considered a pollutant, as it exists naturally as a trace gas in the atmosphere, it is believed that the relatively high levels of CO2 produced by combustion are a prime contributor to global warming [2]. As both CO and CO2 have high absorption in the mid-infrared wavelength range [3], as shown in Figure 1.

Similarly, detection of the other gases namely SO2, NO and NO2 is possible in the UV/Visible part of the spectrum. The theoretical spectra for these gasses are shown in Figure 2.

Optical fibre sensors are particularly well suited to monitoring vehicle exhaust emissions, as they can be made small, lightweight, and as they are made purely from silica glass (doped for high temperature measurement), quartz lenses (for UV) or chalcogenide with Calcium Flouride Lenses for Mid IR they can withstand the high temperature of the gases present in the exhaust system [4,5].

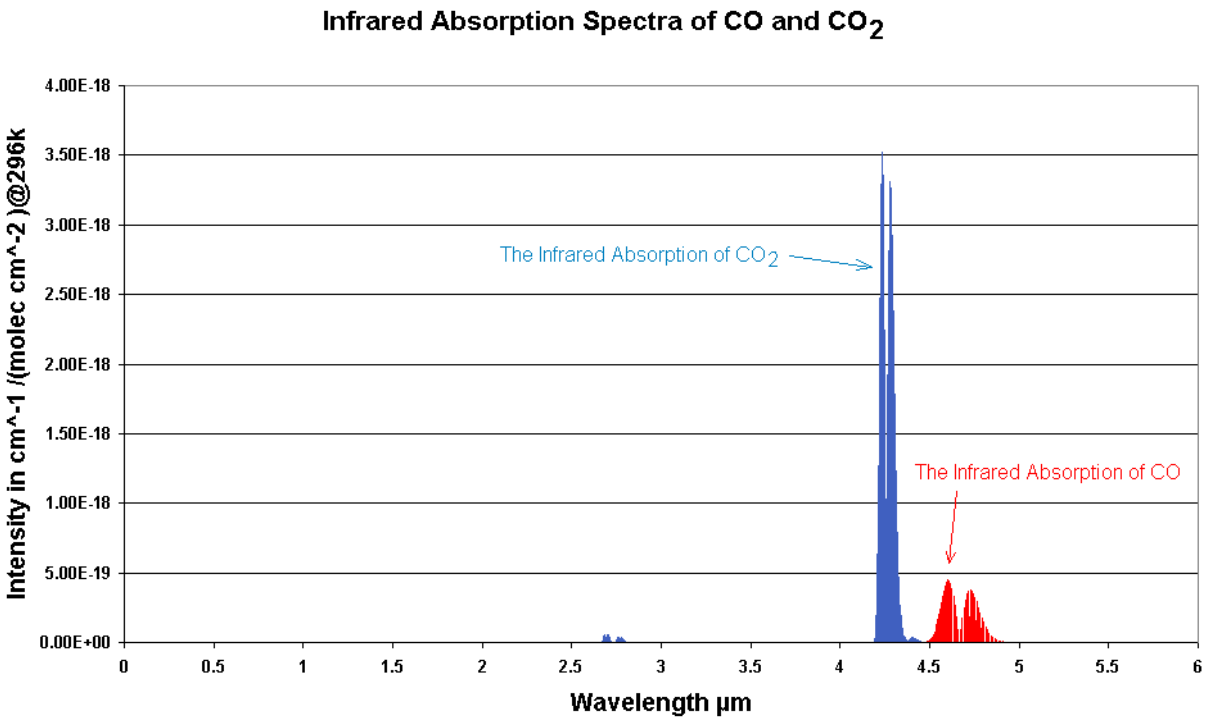

Figure 1 Theoretical Absorption Spectra for CO and CO_2 gases [3]

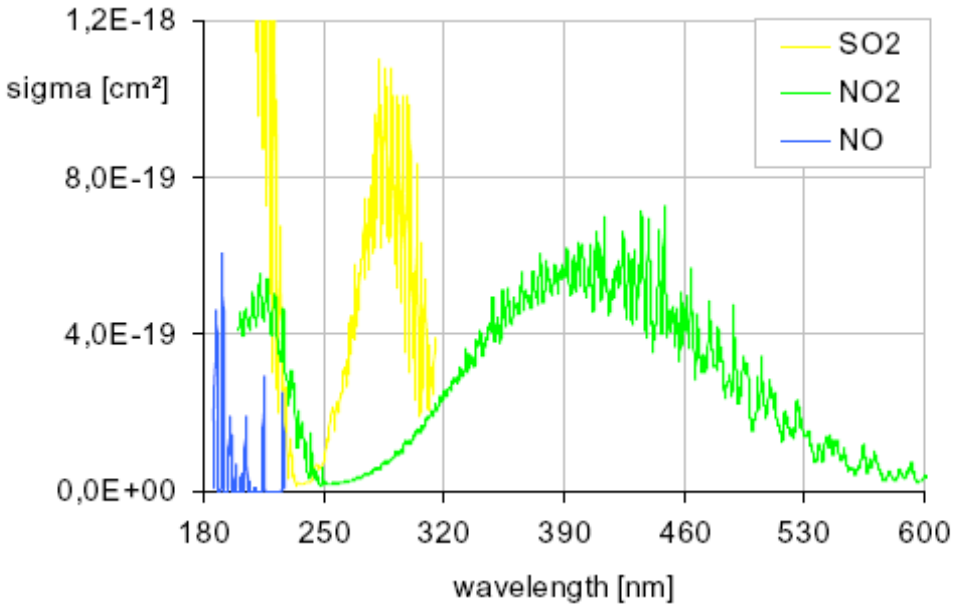

Figure 2 Theoretical Absorption Spectra for CO and CO_2 gases [3]

II. THEORETICAL BACKGROUND

The Beer-Lambert Law is used to calculate how much incident radiation is absorbed by a sample. The sample may be an aqueous solution or a gaseous quantity. If radiation of intensity Io is directed at a sample of path length l, radiation of intensity It leaves the sample. The absorbance A can be defined as:

$$A = \log_{10} \frac{I_o}{I_t} = \varepsilon c l \qquad (3)$$

where ε is called the molar absorption coefficient of the species in question, and c is the concentration of the sample. The ratio It/Io is defined as the transmittance T, by substituting T into equation 3, manipulating the equation gives [6]:

$$T = 10^{-\varepsilon c l} = \frac{I_t}{I_o} \qquad (4)$$

This relationship was used to determine the concentration of the gas based upon experimental results of absorption observed in the mid infra red and UV part of the spectrum in the case of the gas sensor.

The Reference Forward Model (RFM) was developed at Oxford University to simulate the absorption spectra of gases in the HITRAN Database [7] such as CO at different concentrations, pressures, and temperatures. It was possible to use the RFM to vary the path length of the sample, to simulate the experimental results in the wavelength range of interest (i.e. within the pass band of the optical filter fitted to the pyroelectric detector).

Having performing the simulations at the various concentrations (1000ppm, 800ppm, etc) using RFM, the absorption spectra at these concentrations was then interpolated using MATLAB against the filter wavelength data so that it was over the same wavelength scale as the transmission spectrum of the band pass filter fitted to the pyroelectric detector. Having manipulated the data so that it was over the same wavelength range for both data sets (the absorption spectrum of the gas at ambient temperature and pressure over a path length of 360mm, and the filter transmission spectrum), the absorption spectrum was converted to a transmission spectrum and this was multiplied by the filter transmission spectrum. This resulting spectrum corresponds to the transmission by CO at a particular concentration over a path length of 360mm

as measured by the pyroelectric detector. It is shown in Figure 3 for concentrations of 0ppm and 1000ppm of CO over a path length of 360mm, at 23ºC and 1 bar of pressure (i.e. ambient temperature and atmospheric pressure). By calculating the area under the curve at a particular concentration, the theoretical values for I_o and I_t in Eq. 4 can be calculated. The area under the curve at 0ppm corresponds to I_o, while the area under the curve at a particular concentration corresponds to I_t.

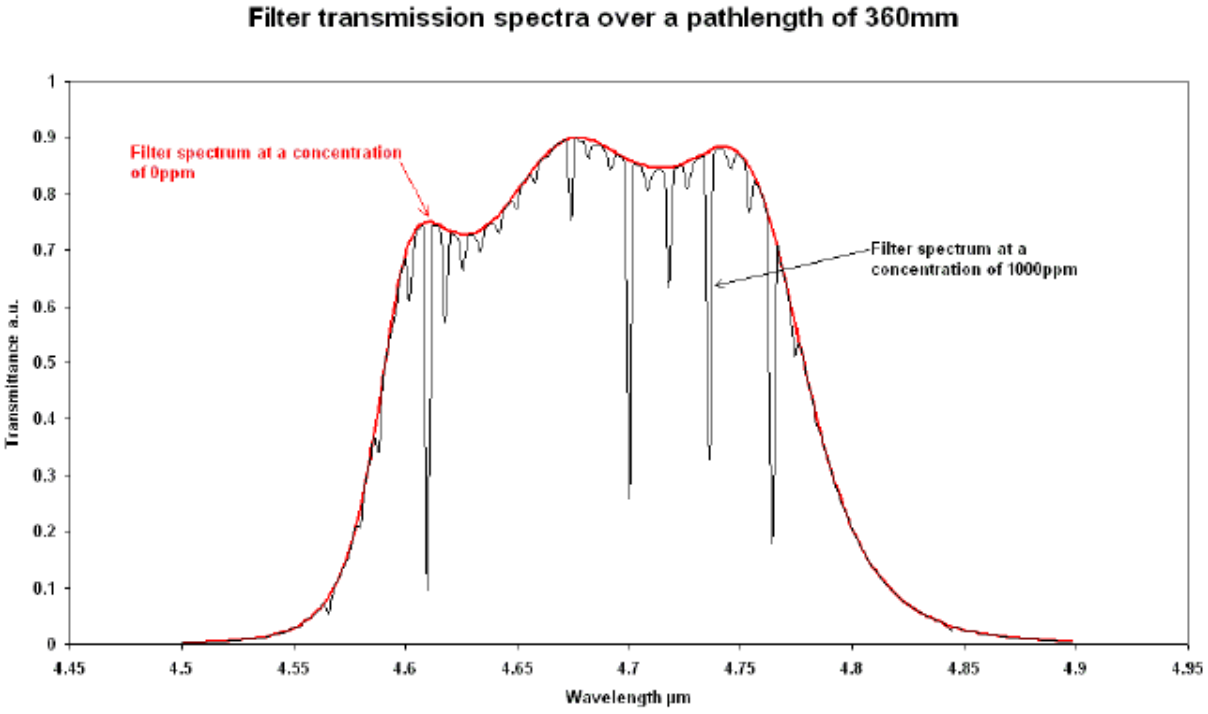

Figure 3 A Comparison Of The Transmission Spectra For CO At 0ppm And 7000ppm Calculated Using RFM

Figure 4 shows the analysis of the 200ppm step test. The transmittance was calculated as the concentration of CO in the cell was increased from 0ppm (when the cell was filled with N_2) to 1000ppm and then decreased in steps of 200ppm.

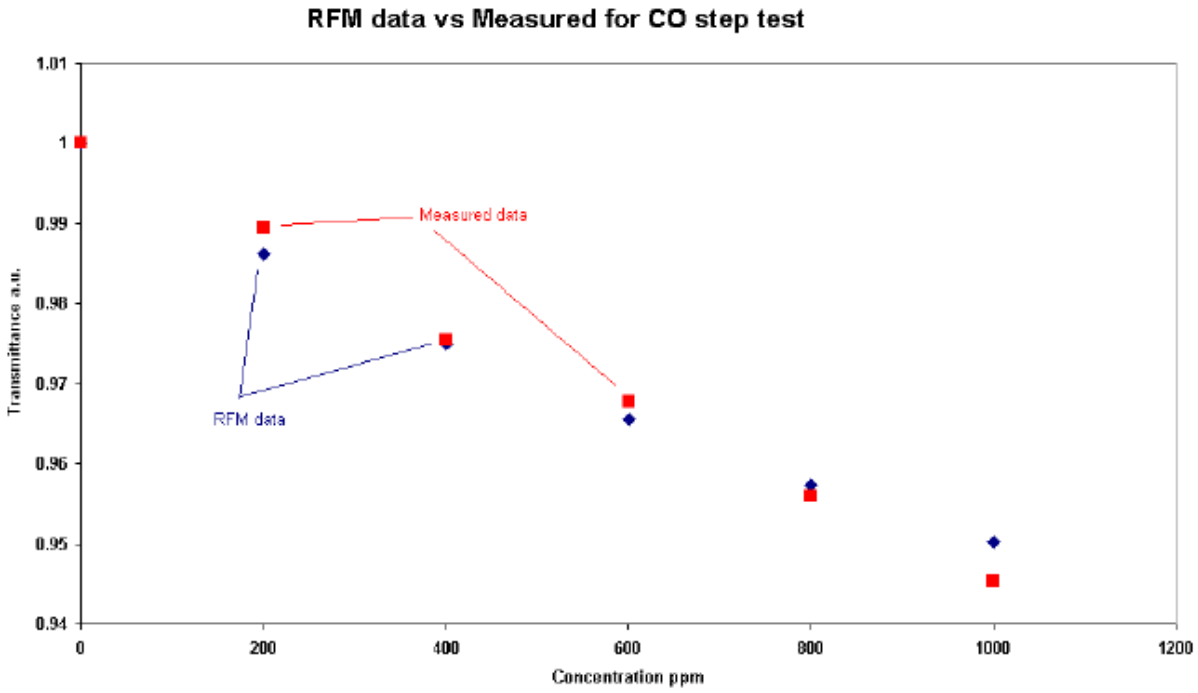

Figure 4 A Comparison Of The Transmittance Values Generated By The RFM Simulation And Those Produced Experimentally For CO

It is clear that the theoretical values (calculated by RFM, using the Beer-Lambert Law model) are in close agreement with the measured values. The largest deviation (1%) is at a concentration of 1000ppm. The difference between the measured and theoretical results can be attributed to experimental uncertainty e.g. electrical noise on the outputs of the pyroelectric detectors. This could be reduced in future by improved the coupling of the emitter and detector to fibre which would increase the amount of radiant flux arriving at the detector which would increase the signal to noise ratio.

EXPERIMENTAL RESULTS

IIIa. GAS MEASUREMENT IN THE MID INFRA RED RANGE

The experimental rig for measuring CO, HC and CO_2 in the mid infra red region in the exhaust is shown in Fig 5. The response of the sensor to 200ppm step changes of CO was carried out using the gas mixing facility at Centro Ricerche Fiat. The NL5LNC filament emitter was pulsed at 2Hz with a 50% duty cycle. The radiant flux from the infrared emitter was guided to the 380mm long test cell (effective pathlength of 360mm) using a 710/820µm core/clad chalcogenide fibre. The infrared radiation from the fibre was guided across the cell using a 25.4mm CaF_2 collimating lens. A second CaF_2 lens was used to guide the collimated beam into a 500/550µm fibre bundle, which guided the infrared beam to a pyroelectric detector fitted with a narrow band CO filter (centred at 4.66µm with a 180nm bandwidth) and a reference detector pyroelectric detector (centred at 3.95µm with a 90nm bandwidth). A Dell Latitude D610 notebook with a National Instruments PCIMCIA 6024E data acquisition card was used to acquire the output voltages of the pyroelectric detector and a Lab View Virtual Instrument was used to store these voltages to a file. Figure 1shows the experimental set-up.

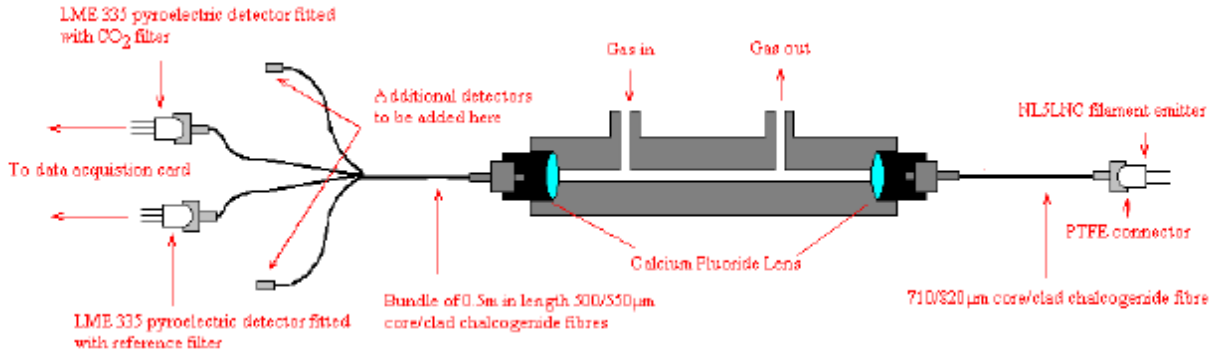

Figure 5 The Gas Sensor for measuring in the Mid Infra Red

The gas cell was initially purged with nitrogen (N_2) supplied from a cylinder using a mass flow controller (MFC). The gas cell was then filled with 1000ppm of CO for several minutes before the cell was purged with N_2. Following this the cell was filled with 800ppm of CO before again being purged with N_2. This process was repeated in steps of 200ppm of CO. The concentration of CO in the test cell was measured using a conventional ABB gas analyser. Figure 6 shows the

results of the experiment. The ratio of the voltage on the CO pyroelectric detector to the reference pyroelectric detector was calculated and is given as the response of the sensor (to eliminate any drift in the output of the filament emitter). The concentration of CO measured by the ABB gas analyser during the experiment is also shown.

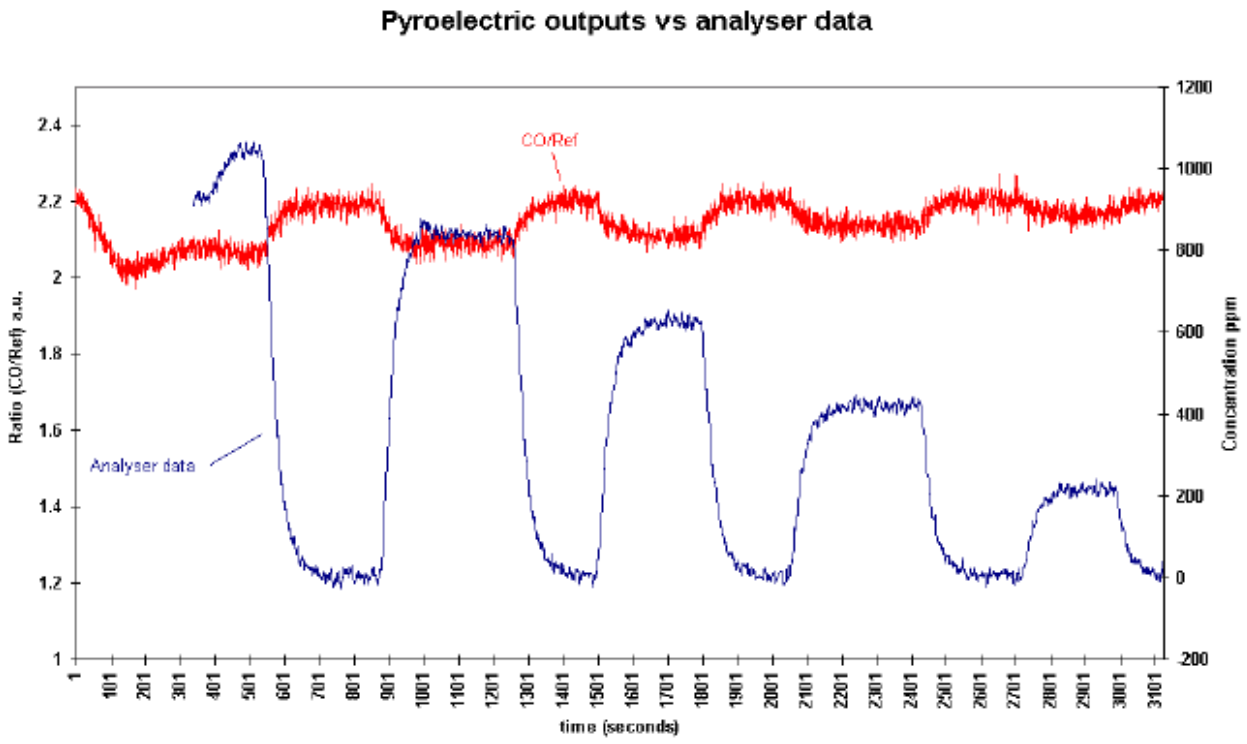

Figure 6 Results Of CO Recorded In 200ppm Steps Compared With A Reference Commercial Instruments

IIIb. GAS MEASUREMENT IN THE ULTRA VIOLET RANGE

The system for measuring the gases NO, NO_2 and SO_2 in the UV range is shown schematically in figure 7

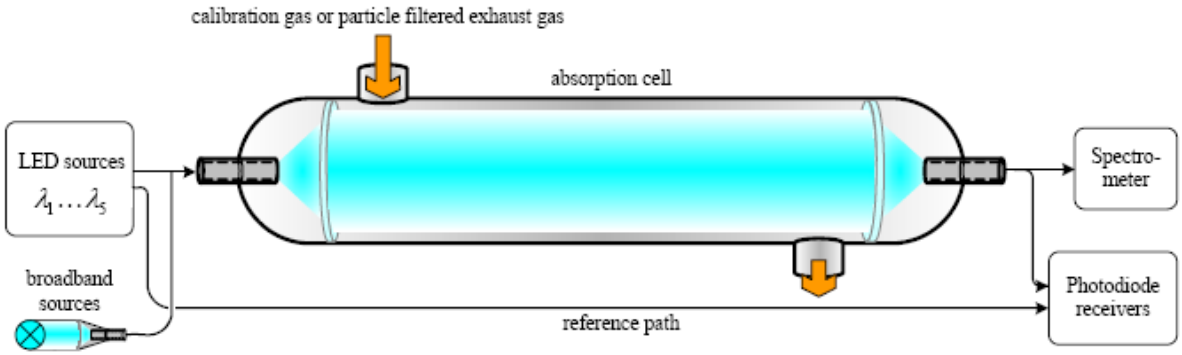

Figure 7 The Gas Sensor for Measuring in Ultra Violet Range

The cell shown in figure 7 was enclosed in a steel flanged section which was inserted in line in the exhaust system under the car. This is shown photographically in Fig 8.

Figure 8 The UV Gas Sensor Mounted Underneath the Car

The cell was used to record the levels of NO, NO_2 and SO_2 for a full cycle of the standard acceleration/ deceleration test with the car mounted on a rolling road at the test facility of

CRF in Turin. The results of these tests corresponding to NO_2 are shown in Figure 9.

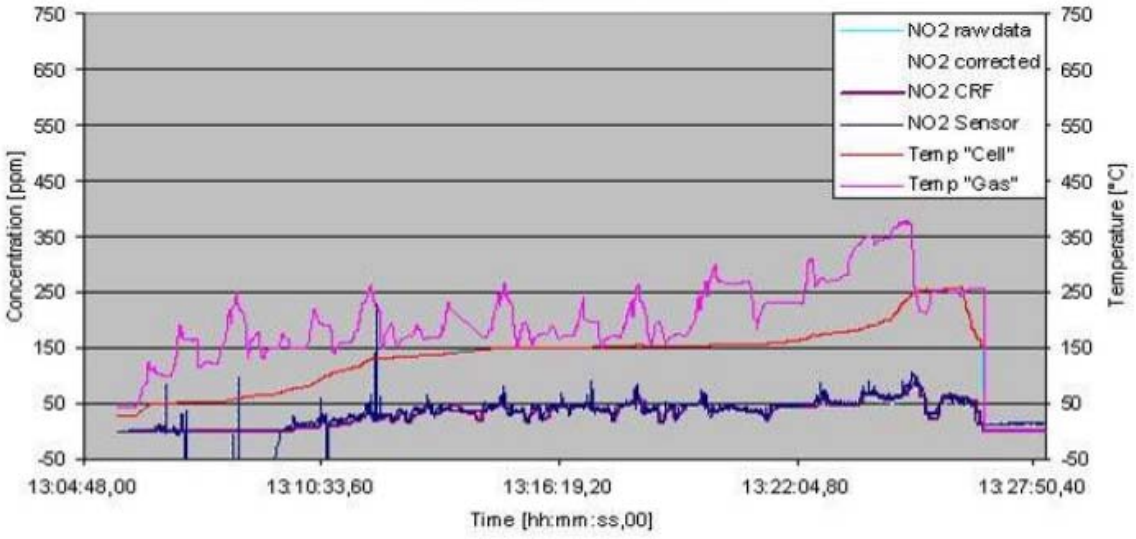

Figure 9. NO_2 Test Results Under the Car With Simultaneous Reference Instruments Recording

It is clear from Fig 9 that the value of NO2 recorded on the optical sensor faithfully reproduces the values measured on the reference (lab based) instrumentation. The optical fibre sensor has therefore been proved to be capable of measurement within the exhaust of the vehicle.

III. CONCLUSIONS

Optical fibre sensor suitable for the detection of exhaust gas emissions and temperature has been described in this paper. The development of the sensors are novel as they uses a low cost and compact components coupled to optical fibre, to provide a practical solution for the measurement in the harsh environment of the car exhaust system.

This sensors have proved to be capable of detecting onboard gas concentrations as low as single ppm values for NO, NO_2 and SO_2, 200 ppm of CO (and $C0_2$) and Hydrocarbons (Non Methane HCs). An analysis of these results using the Reference Forward Model (RFM) and MATLAB indicated that the measured and theoretical values are in close agreement.

IV. ACKNOWLEDGMENTS

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