Multi-criteria / Multi-sensor early Fire Detection in the Engine Compartment of Road Vehicles: Gas sensors' Performance in a Test Vehicle

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Abstract

An inexpensive and practical laboratory setup ("fire simulator") for the evaluation of gas sensors for early fire detection in bus engine compartments was previously presented. Here, the improved and extended setup is presented. The gas sensors have been further evaluated in the lab [1] and in the engine compartment of a van. This paper presents the results of long-term road tests. Additionally, combustion experiments with the fire simulator during which the sensors were installed in a vehicle are presented and compared with available literature values.

Keywords: Gas sensor array, automotive, ambient temperature, VOC

Introduction and initial situation

The measurement and heating electronics from the fire simulator [2] were modified for operation in the engine compartment of a vehicle. A suitable enclosure was developed using computational fluid dynamics [3] and 3D printed from Polycarbonate. The material was pretested in the fire simulator to ensure that it does not emit detectable gas at a temperature of 160 °C, which is significantly higher than would be expected in the engine compartment during regular vehicle operation. The enclosure should protect the electronics from mechanical damage, dust and spray liquids, but allow for an unobstructed passive airflow around the gas sensors. A connector for a regulated fan is available for later use. The airflow in the sensor chamber was simulated at ambient airflow speeds of 1 m/s, 2 m/s, 5 m/s, and 10 m/s. This range is reasonable as faster airflows outside the driving vehicle will not reach the sensor chamber inside the engine compartment without turbulence. Two boxes containing the electronics and sensors for temperature, humidity and gas were installed on the left and right side of the engine compartment in a Diesel-powered van (Mercedes-Benz Viano 2.2 CDI).

The boxes were connected to a specifically developed power supply and multiplexer unit, which was installed under the driver seat using shielded and heat resistant wires. The gas sensors were Figaro TGS2600 for CO and volatile organic compounds (VOC, or hydrocarbons/HC in automotive terminology), AS-MLC for CO/NO_2, and UST GGS5430T for NO_x or diesel exhaust gas. The conductance of all these sensors' increases in reducing atmospheres (CO/VOC), and decreases in oxidizing conditions (NO_2). Figaro's electrochemical CO_2 sensor TGS4161 was tested, too, but was found to be destroyed quickly by the environmental conditions in the engine compartment, and could thus only be considered in the laboratory. A telematics unit of type Sitec S4 with GPS and mobile internet access served as a controller and transmitted the collected data to a server for later evaluation.

The data included the measured values of both arrays (gas, temperature and relative humidity sensors), the ambient conditions in the passenger compartment (air pressure, temperature and relative humidity), as well as the GPS position, velocity and climb, and status/error messages. The clock was set according to the GPS time signal. A GPS signal was not available e.g. in tunnels; the gas sensors' values from such situations are interesting nonetheless, as the restricted ventilation may lead to higher concentrations of exhaust gas, VOCs, or particulate matter.

Expected background values in traffic

The German Federal Environment Agency publishes annual reports on CO concentration alongside roads [4]. Peak values are not available, but annual averages (consistently lower than 0.5 ppm) and the information that no days with an eight-hour-average value above approx. 10 ppm occurred. NO_2 values are also published [5]. They are below 35 ppb. It is important that the values were measured in spots accessible to pedestrians. The concentration e.g. in tunnels can be up to 1000 times higher [6], which might exceed the sensors' dynamic range; such high values, however, were not identified in the presented measurements. Ambient concentrations of some VOCs, like Toluene and Xylene, can be 8 times higher when the ambient temperature increases from 11 to only 25 °C [7]. This result was confirmed for the general VOC concentration for higher temperatures in the engine compartment as well.

Exhaust gas measurement for comparison

The exhaust gas of various types of vehicles with gasoline (Opel Insignia B 2.0 SIDI) and diesel engines (MB Viano 2.2 CDI, VW Passat B7 2.0 TDI, Peugeot Expert 2.0l BlueHDI) was lead through an aluminum hose from the vehicle's exhaust pipe to the furnace of the laboratory setup, and from there to the sensors. In each case, the engine was idling for about an hour and then the revolution speed was increased to 2500 or 3500/min for three minutes.

A CO_2 concentration of about 4000 ppm at lower revolution speed and about 12000 ppm at higher revolution speed was measured for diesel engines. A lower concentration, under 1000 ppm, was detected for the gasoline engine. These results indicate that as a similar CO_2 concentration, around 4000 ppm, was measured during combustion experiments, that it is not suitable alone as an indicator for fire. NO_2 was detected in rare instances in the diesel exhaust gas. Particulate matter load (added to the ambient one) was lower than 8 µg/m³ in all cases - much lower than in any case of sample fire, where it was often up to 200 mg/m³. CO concentration could not precisely be determined, as the sensors have cross sensitivities to VOCs and general air contaminants, which are present around the furnace from earlier combustion experiments. Based on the sensors' responses and the published sensitivity curves, a CO concentration in the exhaust gas between 1 and 100 ppm, depending on revolution speed, can be estimated.

The considered engines had about 2 l of swept volume; they ran at about 3000/min, resulting in an air throughput of 6 m³/min. Assuming a driving speed of 1 km/min, and 1 ppm = 1.15 mg/m³ in case of CO [8], a CO output of less than 690 mg/km can be estimated. This is within the allowed range, between 500 mg/km and 740 mg/km, for diesel engines in the considered vehicles classes [9]. These values may of course vary greatly, and the threshold values for an output per distance are difficult to apply to a parked vehicle. The above values, however, assume a relatively high engine load, which is not continuously maintained during regular vehicle operations, supporting the assumption that the average CO concentration in exhaust gas is lower than calculated.

Combustion experiments with fire simulator and vehicle

Experiments combining the fire simulator with the gas sensors installed in a vehicle's engine compartment were done to identify if it is possible to discriminate gases emitted by the combustion of a vehicle part from the background. The van with the mounted sensors was parked so that its engine compartment was placed above the furnace's exhaust pipe. Various vehicle parts were then set on fire in the laboratory setup's furnace. Corrugated hose made of polyamide-6 or polypropylene was chosen as a standard test material, as it is common in engine compartments, easily available for testing, and shows a more reproducible combustion behavior than many other materials. Both the sensors in the laboratory and in the vehicle were simultaneously measured during the combustion experiments (and the vehicle remained undamaged). Discrimination of exhaust gases from different sources (fire and engine) is generally possible (Fig. 1), but requires a mass of combusted material of about 10 g, which equals about 50 cm in case of corrugated hose. A flashover of the sample, as in the first case at 50 minutes, can lead to the emission of NO_2, which, as an oxidizing gas, causes the sensors' conductance to decrease.

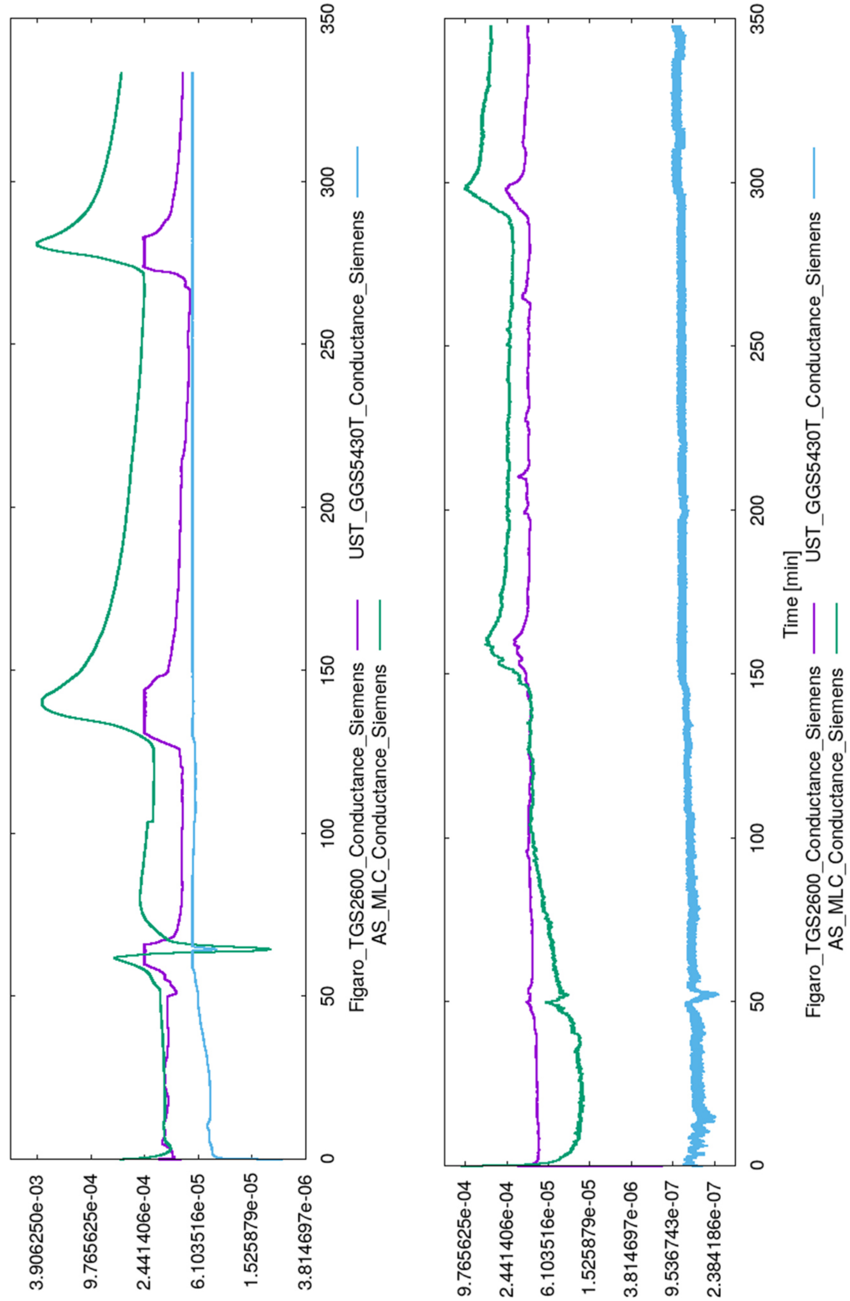

Fig. 1. Gas sensors' response to combustion of corrugated hose at 50/130/275 min. (top) small chamber in laboratory, (bottom) vehicle.

Such events were ignored for the tables, as they are not relevant for the early combustion stage. As can be seen from the tables, an obvious sensor signal was less probable in case of a smaller sample mass of 3 g, or if no flashover occurred (smoldering fire). The latter case is acceptable, as the intended use of the sensor array is to achieve an early warning of flashovers. Windy situations also reduced detection, which may be explained by the fact that the smoke from the furnace is not released inside the engine compartment, but right below it. The influence of the vehicle's cooling fan is discussed below.

The VOC sensor TGS2600 shows no cross-sensitivity towards NO_x diesel exhaust gas at the given concentrations, but does not have sufficient dynamic range in a situation with a stronger CO/VOC background, i.e. heavy traffic. GGS5430T was most prone to aging among the selected sensors, and showed an unstable baseline and reduced sensitivity. This could be attributed to the fact that the manufacturer does not pre-age it. AS-MLC reproducibly showed a stronger response to combustion events than TGS2600, but, as will be shown below, was also more sensitive to non-fire events in regular traffic.

In contrast to TGS2600, the concentration of reducing gas species in the air around the test stand during a series of combustion experiments could increase the baseline conductance of AS-MLC by a factor of 2 or even 4 in some cases (Fig. 1). As the test stand is located outside in a well-ventilated region next to a forest, an accumulation of CO, with a density lower than that of air, is highly unlikely. This finding is thus indicative that the sensor is sensitive to other reducing gases. Additionally, a smell was perceived by the experimenter near the test stand. The increased conductance served as a new baseline G_0 in Table 2. It is therefore necessary to discriminate between a reducing background atmosphere and CO, the early indicator of combustion. In the future, this may become possible in temperature-cycled operation of the sensor [10].

Road tests with vehicle

The sensors were installed in the vehicle for over a year. Relative humidity and air pressure do not show any effect on either of the sensors. Ambient temperatures of up to 85°C were observed in the test vehicle's engine compartment. The car traveled across longer distances from the southwest of Germany to Croatia and the North Sea in summer pulling a caravan with a weight of more than two tons, causing a considerable engine load. Other routes of varying length in the southwest of Germany were driven repeatedly at different times of the year. The engine is water cooled, and the fan in the engine compartment starts once the temperature of the cooling water exceeds 90°C.

This happened several times in the ride shown in Fig. 2 when driving uphill (indicated by decreasing air pressure) between minute 90 and 180 and led to a reduced ambient temperature in the engine compartment by the exchange of air.

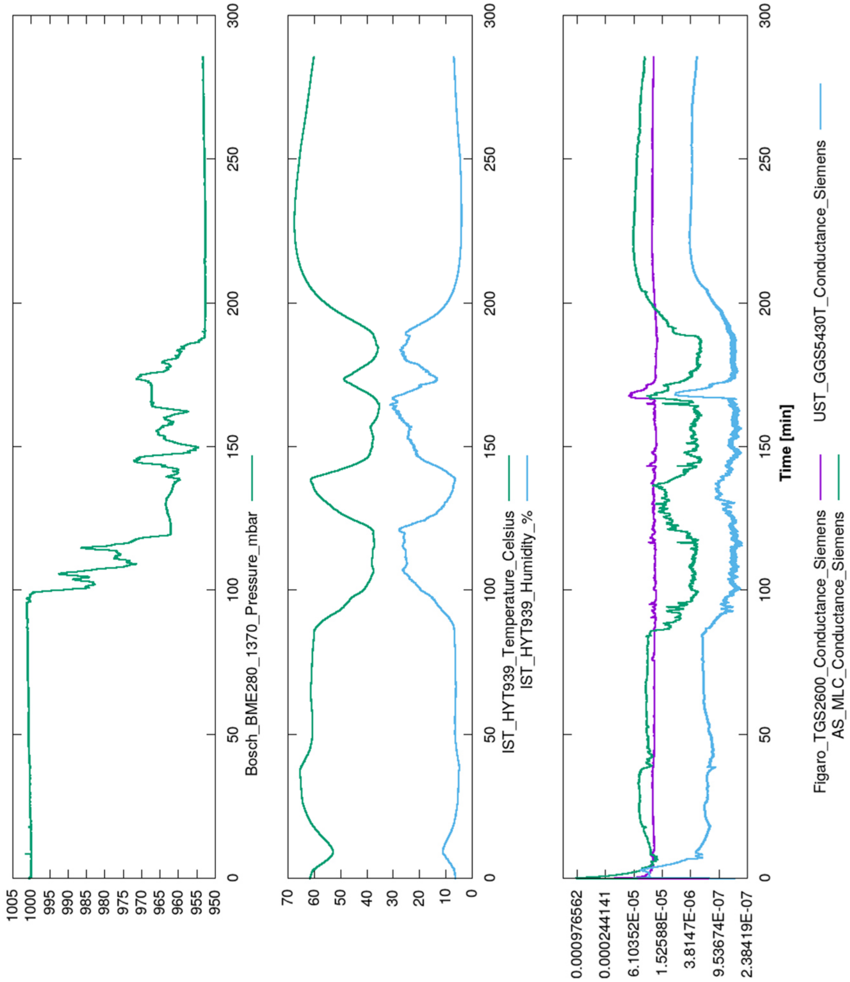

Fig. 2. Measured values in the test vehicle's engine compartment driving from the coast of the North Sea towards the Black Forest.

AS-MLC and GGS5430T responded by reducing their conductance, indicating a lower concentration of reducing gas species. In contrast to previous lab experiments [1], they immediately respond to a changing ambient temperature and seem to maintain their sensitivity. Thus, it can be concluded that they have not been harmed by the higher temperature, but that the VOC concentration is actually increased to an almost steady level in the engine compartment when the fan is off.

This is logical as soot and lubricants are abundant there. This conclusion is further supported by the fact that especially AS-MLC was not saturated in the given example: its conductance reached higher levels in the combustion experiments. Conductance spikes could be observed occasionally everywhere in road traffic, even during rural passages, but more frequently in heavy traffic, in tunnels, and when stopped e.g. at crossings or traffic lights. This finding is expected and in agreement with literature [6] [7]. The events during rural passages correlate with a reduced driving speed. This could indicate that the test car drove behind an agricultural vehicle with a higher output of soot in such cases. AS-MLC remains more sensitive than TGS2600, but also more volatile, probably due to its stronger cross sensitivity towards NO_2, which is a component of diesel exhaust gas; GGS5430T lost sensitivity over time.

Conclusion and outlook

An electrochemical CO_2 sensor is not suitable as a fire detector, as the CO_2 concentration in exhaust gas can be higher than during combustion and the sensor is unstable in the harsh conditions. The SMOX gas sensors showed acceptable stability against the harsh environmental conditions in the engine compartment. In the future the stability could be further improved by using sensors with an integrated filter, or a more protective ventilated enclosure. The best overall detection performance was shown by AS-MLC (which is no longer available); this is not surprising, as the manufacturer specified it for ambient temperatures of up to 120 °C, and equipped it with a PTFE filter. TGS2600 showed by far the best stability and lowest cross sensitivity, but also had a poor detection performance compared to AS-MLC. The sensors' performance for fire detection in a controlled situation without heavy traffic looks promising, but in some cases, no signal during combustion is obvious. It is assumed to vanish in the increased VOC background; in order to make combustion-related CO events discriminable from possible false alarms caused by VOCs or soot also in heavy traffic, temperature-cycled operation will be tested.

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Overview of combustion experiments (laboratory: large chamber [1])

Event	Smoldering				Flashover			
Mass	3 g		10 g		3 g		10 g	
Setup	lab	car	lab	car	lab	car	lab	car
Min	1.96	1.09	1.58	1.12	1.31	1.10	1.26	1.08
Avg	2.31	1.20	1.96	1.6	1.73	1.34	1.69	1.39
Max	2.93	1.51	2.2	2.26	2.12	1.7	1.94	1.70

Table 1. TGS2600's response ($G_{max}/G_0 = R_0/R_{min}$).

Event	Smoldering				Flashover			
Mass	3 g		10 g		3 g		10 g	
Setup	lab	car	lab	car	lab	car	lab	car
Min	1.14	1.53	1.29	1.33	1.09	1.79	1.05	1.38
Avg	1.19	2.81	1.34	3.34	1.10	2.73	1.23	2.19
Max	1.32	6.61	1.39	5.0	1.13	4.27	1.43	2.81

Table 2. AS-MLC's response ($G_{max}/G_0 = R_0/R_{min}$).

Event	Smoldering				Flashover			
Mass	3 g		10 g		3 g		10 g	
Setup	lab	car	lab	car	lab	car	lab	car
Min	1.15	1.43	1.06	1.11	1.13	1.29	1.02	1.24
Avg	1.25	2.39	1.20	1.97	1.15	1.52	1.08	1.47
Max	1.41	5.25	1.35	4.88	1.16	2.1	1.47	2.1

Table 3. GGS5430T's response ($G_{max}/G_0 = R_0/R_{min}$).

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