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## ABSTRACT

Low oxygen, high carbon monoxide and carbon dioxide concentrations can typically exist within a vehicle cabin. Such poor air quality may cause drowsiness, fatigue, impairment of judgement, and poor coordination to vehicle occupants. Also, many deaths are caused by motor vehicle exhaust gas suicides from carbon monoxide poisoning. The introduction of an air quality monitor within the vehicle cabin can alarm occupants preventing any adverse health effects. A vehicle cabin air quality monitor was designed and developed. The monitor was tested under various driving conditions and simulated suicide attempts. Alarms are triggered when poor air quality exists within the vehicle cabin.

## INTRODUCTION

The quality of air inside enclosed spaces has become a matter of growing concern. A confined space that has received little attention is the vehicle cabin environment. Commonly, vehicle occupants choose to operate the vehicle ventilation system in the "recycle" mode to prevent outdoor-polluted air entering the vehicle cabin. However, it too prevents fresh air from entering the cabin, resulting in a decrease of oxygen ($O_2$) and an increase in carbon dioxide ($CO_2$) gases. Such poor air quality may cause headaches, drowsiness, fatigue, impairment of judgement, and poor coordination to vehicle occupants [1,2].

Furthermore, thousands of fatal unintentional carbon monoxide (CO) poisoning's occur annually, in and around motor vehicles. In the US in 1996 there were 1508 suicides and 219 accidental deaths caused by CO poisoning from motor vehicle exhaust gas [3]. Although the level of CO in exhaust gas from catalyst equipped cars is extremely low, it is still sufficient to cause death. Before the introduction of catalytic converters, the exhaust of new automobiles frequently contained 7-12% CO during engine idling [4]. Newer cars with emission control devices tend to emit CO levels at idle operation considerably below legal limits, typically less than 0.1%, however may still contain 2-4% of CO [4].

By continuously monitoring the cabin air environment, adverse human health effects resulting from poor cabin air quality can be reduced. Alarms may be set if poor air quality is detected. Visual and audible alarms may provoke the occupants to lower the windows or allow fresh air to enter the cabin via the ventilation system. If such warnings are ignored, the system may automatically switch the ventilation system to "fresh air" mode, until adequate fresh air has entered the cabin. By analysing the carbon monoxide and oxygen concentration profiles a suicide attempt can be detected. In such a case, the engine could be shut down and the electric windows lowered if the vehicle is stationary.

A vehicle cabin air quality monitor has been developed. The monitor alerts vehicle occupants when poor air quality exists. The specific aims of this study have been the following:

- To develop a vehicle cabin air quality monitor.
- To gain an understanding of vehicle cabin gas behaviour in various driving conditions and suicide attempts.
- To clearly identify driving conditions which may produce poor cabin air quality.
- To determine adequate alarm thresholds and sensing algorithms for the air quality monitor.

## BACKGROUND

Gas may enter the vehicle cabin through the inlet ventilation system, door and window seals, outlet ventilation slots located at the rear of most cars, and panel holes that may exist. However, the transportation mechanism of the gas into the cabin is affected and influenced by several factors. Phenomena like the diffusion rate, molecular weight, turbulence effects, velocities and temperature gradients of gas effect the gas mixing properties, and ultimately the instantaneous concentration of a gas within an enclosed environment like a vehicle cabin. Furthermore, turbulence is generated at high flow rates and macroscopic mixing of gas takes place, particularly where a gas flows past rough or irregular surfaces, like the edges of a vehicle door panel [5].

OXYGEN ($O_2$) – The atmosphere contains 20.9% of oxygen. Unless there is adequate ventilation the level is reduced surprisingly quickly by breathing and combustion as in a vehicle cabin. People suffering from low oxygen levels considered to be below 19.5%, have no idea they are clumsy and thinking slowly. In fact they behave much like someone who is intoxicated with alcohol showing a measurable impairment of judgement [6]. Oxygen can be sensed by using solid state and electrochemical sensing mechanisms.

CARBON MONOXIDE (CO) – Carbon monoxide is an odourless and toxic gas produced by the incomplete combustion of carbonaceous materials. When inhaled, CO binds to blood haemoglobin, which reduces the oxygen-carrying capacity of the blood. The affinity of CO to haemoglobin is 200 to 250 times higher than oxygen [2,7]. Symptoms like headaches, nausea and dizziness are experienced. CO can be sensed using electrochemical, semiconductor and optical sensors.

CARBON DIOXIDE ($CO_2$) – Carbon dioxide is present in the atmosphere at about 400 ppm (0.04%). It is a colourless, odourless, noncombustible gas [2]. When exhaling, carbon dioxide and water vapour are emitted. Furthermore, carbon dioxide is produced during combustion and in brewing and other fermentation processes. The lowest level at which $CO_2$ effects has been observed in both humans and animal studies is about 1000 ppm. At concentrations above 1500 ppm respiration is effected and breathing becomes faster and more difficult. Concentrations above 3000 ppm can cause headaches, dizziness and nausea [2]. Non-dispersive infra red (NDIR) is the usual sensing technique for $CO_2$ measurement.

GAS EXPOSURE LIMITS – Acceptable workplace limits for air pollutants are published by numerous regulatory and quasi-regulatory bodies both in the U.S. and abroad. These include the Occupational Safety and Health Administration (OSHA), National Institute for Occupational Safety and Health (NIOSH), and the World Health Organisation (WHO) [1]. The NIOSH recommended exposure limits and OSHA permissible exposure limits are listed in Table 1.

Table 1. Common gas safety limits.

| Gas | WHO | OSHA [8] | NIOSH [8] |
|---|---|---|---|
| $O_2$ | - | 19.5% | 19.5% |
| CO | 9 ppm [4] | 50 ppm | 35 ppm |
| $CO_2$ | 1000 ppm | 5000 ppm | 5000 ppm |

## VEHICLE CABIN AIR QUALITY MONITOR

HARDWARE – The monitor developed continuously analyses the oxygen and carbon monoxide concentration of the vehicle cabin. The vehicle cabin air quality monitor consists of the following primary components:

- Oxygen Sensor (Resolution: 0.1%; Accuracy: 1%)
- Carbon Monoxide Sensor (Resolution: 1 ppm; Accuracy: 10%)
- Temperature Sensor
- Signal Processing Circuitry
- Analog to Digital Converter
- Microprocessor
- RS-232 Interface

All components are integrated onto a PCB (Printed Circuit Board). A PC was connected to the monitor via the RS-232 interface used for datalogging. The microprocessor performs the analogue to digital conversion and the control and processing functions of the monitor. The oxygen sensors have been calibrated with certified oxygen bottles and the carbon monoxide sensor with a commercially available CO monitor.

SOFTWARE – The monitor samples the sensors every second. Warning signals are activated when gas concentrations are exceeded. The signals can be used to trigger audible and visual devices or can be used as input into the engine and body management systems for advanced control functionality. Table 2 illustrates the alarm thresholds used as recommended [4,9].

Table 2. Monitor alarm thresholds.

| Gas | First Warning | Second Warning | Final Warning |
|---|---|---|---|
| $O_2$ | 19.5% | 17% | 16% |
| CO | 25 ppm | 50 ppm | 100 ppm |
| $CO_2$ | 1000 ppm | - | 5000 ppm |

## EXPERIMENTAL

The purpose of the experiments is to determine vehicle cabin gas behaviour and concentrations in various driving conditions and in suicide attempts. Three main experiments were conducted. First, the monitor was tested with four popular Australian sedan automobiles:

1. Ford Falcon (1996, 4.0 litre)
2. Holden Commodore (1995, 3.8 litre)
3. Mitsubishi Magna (1995, 3.0 litre)
4. Toyota Camry (1997, 2.2 litre)

Each vehicle was tested under 4 typical driving scenarios:

1. City driving with “recycle”
2. City driving with “fresh air”
3. Motorway driving with “recycle”
4. Motorway driving with “fresh air”

The monitor was placed in the middle of the instrumentation panel. The concentration versus time profile was measured in each test for a 20-minute duration. There were two vehicle occupants. The purpose of this test was to deduce the CO and $O_2$ levels within each driving scenario. By understanding typical concentrations that exist within a vehicle cabin, appropriate alarm thresholds can be developed for fatigue warning.

Second, the maximum CO concentration that would typically exist in a vehicle cabin must be known, so that suitable alarm thresholds are set to prevent a false suicide alarm. The Mitsubishi Magna was used to monitor CO concentrations whilst driving in city traffic with both front windows lowered. CO profiles were also obtained in undercover carpark areas and whilst occupants were smoking in the vehicle cabin.

Third, the Ford Falcon was used for simulated suicide testing. The vehicle was started and left running until the coolant temperature had stabilised. A hose of 30mm diameter was connected to the exhaust outlet of the vehicle and then directed into the vehicle cabin. A back door window was lowered 4 inches to make this possible. The speed of $O_2$ depletion and CO increase must be known to devise an algorithm that would identify a suicide attempt.

## RESULTS

OXYGEN AND CARBON MONOXIDE AUTOMOBILE TESTING – Table 3 shows the minimum cabin $O_2$ concentrations detected.

Table 3. Minimum $O_2$ concentrations detected.

| | City | Motorway | City | Motorway |
|---|---|---|---|---|
| | Recycle | | Fresh Air | |
| Ford Falcon | 20.5% | 20.7% | 20.5% | - |
| Holden Commodore | 20.2% | 20.4% | 20.4% | 20.5% |
| Mitsubishi Magna | 19.2% | 20.3% | 20.0% | 20.6% |
| Toyota Camry | 19.1% | 19.4% | 20.2% | 20.4% |

It was found when driving in the “city with recycle” the lowest average $O_2$ of 19.75% was detected with a minimum $O_2$ depletion of 19.1% occurring. The best case driving scenario was “motorway driving with fresh air”; recording an average of 20.5% $O_2$. Studies have shown [10] that carbon dioxide and water vapour from respiration displaces the oxygen. Hence, the depletion of oxygen and the increase in carbon dioxide is a complimentary effect. Figure 1 illustrates typical oxygen depletion due to vehicle occupant respiration.

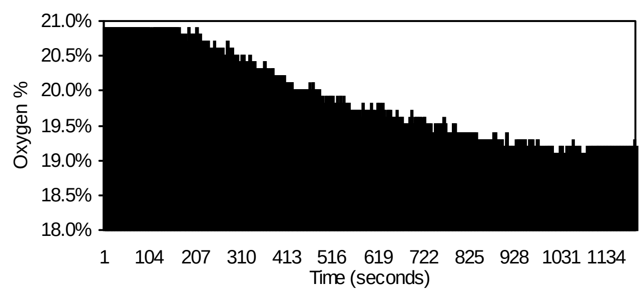


Figure 1. Typical vehicle cabin oxygen depletion.

The rate of fresh air entering the vehicle cabin is largely determined by the average speed of the vehicle. Other variables that influence the air quality within the vehicle are the number of occupants, cabin volume, ventilation system throughput, exit ventilation throughput, and the door and window seal efficiency. Table 4 shows the maximum CO detected. The maximum CO concentration reached was 16 ppm.

Table 4. Maximum CO concentrations detected.

| | City | Motorway | City | Motorway |
|---|---|---|---|---|
| | Recycle | | Fresh Air | |
| Ford Falcon | 13 ppm | 9 ppm | 7 ppm | - |
| Holden Commodore | 7 ppm | <1 ppm | 7 ppm | 11 ppm |
| Mitsubishi Magna | 8 ppm | <1 ppm | 16 ppm | 9 ppm |
| Toyota Camry | <1 ppm | <1 ppm | <1 ppm | 8 ppm |

MAXIMUM CARBON MONOXIDE DETECTION – To prevent false suicide alarm triggering, and for a comprehensive understanding of ambient CO concentrations, the monitor was tested whilst both front windows were lowered in peak traffic conditions. A maximum of 30 ppm CO was detected. Congested expressway tunnels and parking garages may at times reach CO concentrations of 50-100 ppm [4]. Figure 2 represents a CO profile whilst driving in peak traffic conditions with both front windows lowered. The CO concentration peaks occurred when the vehicle was stationary. In such a case, the polluted air enters the vehicle cabin, and whilst increasing in speed is diluted by the incoming fresh air. The results obtained heavily depend on traffic and weather conditions. Other variables such as wind amplitude and wind direction effected CO concentrations. Furthermore, the CO concentration exponentially peaked to 15 ppm whilst two vehicle occupants one male and the other female were cigarette smoking within the vehicle cabin.

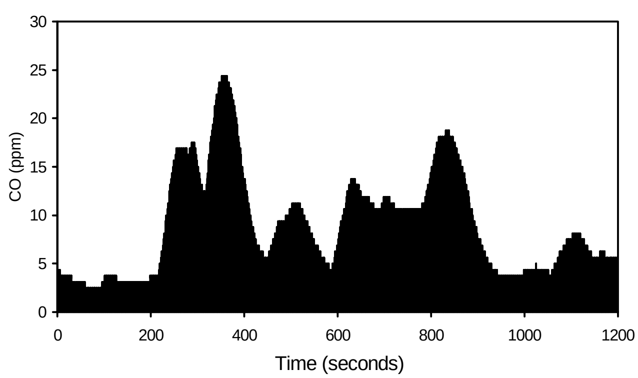


Figure 2. CO profile at peak traffic conditions.

SIMULATED SUICIDE TESTING – Whilst redirecting the exhaust back into the vehicle cabin to simulate a suicide taking place, the oxygen level depleted down to 7%, displaced by the vehicle exhaust gases. Figure 3 shows the oxygen concentration depleting to 7% after 30 minutes.

The carbon monoxide level reached a level undetectable by the monitor. Measurements exceeded 600 ppm.

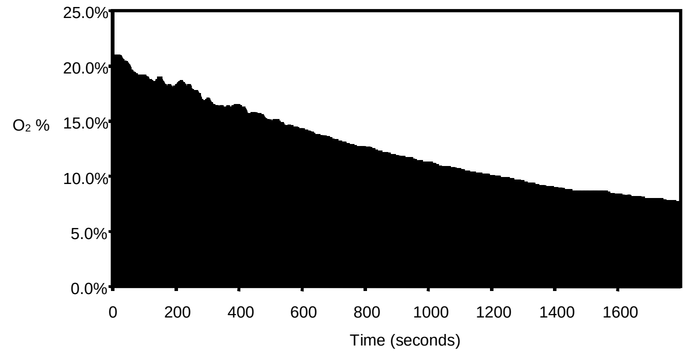


Figure 3. $O_2$ depletion during a suicide attempt.

## CONCLUSIONS

By continuously monitoring oxygen and carbon monoxide within a vehicle cabin, warning devices can be activated when a poor quality cabin gas mixture is present. This enables the vehicle occupants to take charge by allowing fresh air to enter the cabin by various means, or can automatically switch the ventilation system to fresh air mode. It has been found that driving with recycle both at low and high speeds, oxygen depletion to 19.1% can occur within a 20-minute period. This is below the 19.5% limit set by both OSHA and NIOSH [8]. Such depletion in oxygen displaced by carbon dioxide can have an adverse health effect on the vehicle occupants.

Carbon monoxide has been found to reach up to 30 ppm within a vehicle cabin while driving in heavy traffic. It would be desirable that passengers be made aware and to take precaution by switching the ventilation system to “fresh air” mode or lower the windows to allow fresh air to enter the vehicle cabin. This would prevent common headaches experienced when driving in heavy traffic.

During a suicide attempt, it has been found $O_2$ rapidly decreases while CO increases. A gas behaviour signature of this kind with appropriate thresholds could be used to identify a suicide attempt. Thereafter, an action could be taken, such as lowering the windows or engine shutdown. In such a case, false alarms are of prime concern. The experimental results indicate that setting the upper threshold at >100 ppm would reduce the likelihood of false alarms occurring.

Future work will investigate sensing of carcinogens within the vehicle cabin. Also, investigating the effect of various numbers of vehicle occupants on cabin gas behaviour. However for device feasibility, further research into sensor packaging, sensors placement, sensor tampering prevention design, sensor calibration drift [11] and alarm triggering algorithms is required. Short and long term testing in a fleet of vehicles will provide a quantitative analysis.

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