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Automotive carbon monoxide sensors: sensing technologies, in-cabin monitoring, electronic integration, and safety challenges

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ABSTRACT

Carbon monoxide (CO) is a colorless, odorless, and toxic gas that may enter a vehicle cabin through exhaust leakage, poor ventilation, or exposure to surrounding traffic emissions. Because occupants cannot recognize its presence, continuous monitoring can provide an additional layer of vehicle safety. This review examines CO sensing technologies relevant to automobiles, emphasizing in-cabin detection while also considering the distinct requirements of exhaust-gas monitoring. Literature published up to 2018 is synthesized to compare metal-oxide semiconductor (MOS), electrochemical, and optical or colorimetric sensing approaches. The review considers sensing mechanisms, sensitivity, selectivity, response and recovery behavior, temperature and humidity effects, calibration, power consumption, and electronic integration. Metal-oxide sensors offer low cost and compact construction, but their heater requirements and cross-sensitivity can complicate reliable cabin measurements. Electrochemical and colorimetric approaches offer alternative routes to selective detection, although packaging, lifetime, and calibration remain important engineering concerns. Vehicle studies further indicate that ventilation settings and driving conditions influence cabin CO exposure, supporting the need for representative placement and validated alarm logic. The review proposes a practical architecture combining calibrated sensing, signal conditioning, diagnostics, and occupant alerts, and identifies priorities for robust automotive deployment.

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1. INTRODUCTION

Carbon monoxide (CO) is a hazardous combustion product that can accumulate in enclosed or poorly ventilated environments. In vehicles, possible sources include exhaust-system leakage, defective engine components, inadequate sealing between the engine compartment and cabin, and polluted outdoor air entering through the ventilation system. The risk is particularly important because CO has no distinctive smell or color that can warn occupants of increasing exposure. Its interaction with hemoglobin reduces the blood's oxygen-carrying capacity, while additional cellular effects can contribute to neurological and cardiovascular injury [1]–[4].

Vehicle cabins are dynamic environments in which pollutant concentrations depend on traffic conditions, vehicle design, ventilation settings, and the condition of the exhaust system. Xu *et al.* [5] reviewed research on vehicle-cabin air quality and identified exhaust-related pollutants among the important sources of occupant exposure. Dirks *et al.* [6] specifically investigated in-cabin CO concentrations under different ventilation settings, demonstrating why cabin air exchange should be considered when evaluating exposure. These findings establish a practical need for reliable CO monitoring rather than assuming that a closed vehicle cabin is automatically protected from external or internal emissions.

This review examines the technologies and engineering considerations involved in automotive CO detection. It distinguishes in-cabin safety monitoring from exhaust-gas measurement because the two applications have different concentration ranges, operating temperatures, response requirements, and installation conditions. The discussion covers sensor principles, performance limitations, electronic integration, and system-level safety functions. The central argument is that a useful automotive CO detector must combine an appropriate sensing element with reliable calibration, environmental compensation, fault diagnosis, and a clearly defined occupant-warning strategy.

2. AUTOMOTIVE CO DETECTION REQUIREMENTS

The first design decision is to define where the sensor will operate and what hazard it is intended to detect. An in-cabin sensor is designed to identify CO concentrations that may threaten occupants, whereas an exhaust sensor operates in a chemically complex stream with high temperature, variable flow, and potentially corrosive contaminants. These applications should not be treated as interchangeable because a sensor optimized for exhaust analysis may be unnecessarily expensive or unsuitable for continuous cabin monitoring. Automotive exhaust research also highlights the difficulties caused by changing flow conditions, high temperatures, and sensor exposure to contaminants [7].

A cabin-monitoring system must respond quickly enough to warn occupants while avoiding frequent false alarms. It should operate reliably across changes in cabin temperature, humidity, air-conditioning mode, and electrical supply voltage. Sensor placement is also important because local airflow can create concentration differences between the dashboard, footwell, and rear passenger area. Therefore, validation should include realistic vehicle operating conditions rather than relying exclusively on controlled laboratory gas exposure.

3. CO GAS-SENSING TECHNOLOGIES

3.1. Metal-oxide semiconductor sensors

Metal-oxide semiconductor (MOS) sensors are widely investigated because they can be manufactured in compact forms and are generally compatible with relatively simple electronic circuits. Materials such as tin oxide (SnO_2), zinc oxide (ZnO), and other semiconducting oxides change their electrical resistance when gas molecules interact with their surfaces. In the presence of CO, surface reactions alter the concentration of charge carriers and produce a measurable resistance change. The magnitude and direction of the response depend on the sensing material, operating temperature, surface structure, and gas concentration [8]–[10].

SnO_2-based sensors are particularly relevant to CO detection because their sensing characteristics can be modified through catalytic additives and structural engineering. Kim *et al.* [11] demonstrated a low-temperature Pd/SnO_2 sensor for CO detection, showing how palladium modification and electrode design can improve sensing performance. Kutukov *et al.* [12] investigated platinum- and palladium-containing clusters on SnO_2 and demonstrated the influence of catalytic surface modification on CO response. These studies illustrate that material composition and surface chemistry are central to improving sensitivity and selectivity.

Despite their advantages, MOS sensors present several challenges for vehicle applications. Many devices require an integrated heater to maintain the temperature needed for effective gas-surface reactions, which increases power consumption and thermal-management requirements. Their responses may also be influenced by other reducing gases, humidity, and changes in ambient temperature. Reviews of semiconductor gas sensors emphasize that sensitivity, selectivity, stability, and operating conditions must be evaluated together rather than treating a high response value as sufficient evidence of practical suitability [8], [10], [13].

3.2. Electrochemical sensors

Electrochemical CO sensors detect gas through an electrochemical reaction at an electrode, producing an electrical signal related to the gas concentration. These sensors are attractive for cabin monitoring because they can offer relatively low power consumption and useful sensitivity at ordinary ambient temperatures. Their operation does not generally depend on the same high-temperature surface-reaction conditions required by many MOS devices. However, electrode chemistry, electrolyte stability, sensor lifetime, and environmental compensation influence long-term performance.

Electrochemical devices also require careful calibration and evaluation of cross-sensitivity. Other gases present in vehicle environments may contribute to the measured current or affect the sensor's response characteristics. Temperature and humidity can influence electrolyte behavior and the stability of the electrochemical reaction. Consequently, an automotive design should use a sensor with documented performance under the expected environmental conditions rather than relying only on its nominal detection range.

3.3. Optical and colorimetric sensors

Optical approaches provide an alternative to conventional resistance- or current-based sensing. In a colorimetric CO sensor, a chemical sensing layer changes its optical properties after exposure to the target gas, and the change can be measured using a light source and photodetector. Lin *et al.* [14] reported a colorimetric CO sensing platform with a detection limit of 1 ppm and a reported dynamic range extending to 500 ppm. Their work demonstrates the potential of optical sensing for compact exposure-monitoring devices, although the study was not specifically a validation of an automotive cabin product.

Optical methods can offer useful selectivity when the sensing chemistry is designed for a particular target gas. However, their practical implementation requires stable optical alignment, protection against contamination, and compensation for changes in ambient light or sensor-layer aging. Packaging must also prevent dust, condensation, and vibration from degrading the optical measurement. For automotive use, these requirements should be considered alongside the cost and complexity of the complete detector.

4. SENSOR PERFORMANCE AND ENVIRONMENTAL CHALLENGES

Sensor performance should be evaluated using several complementary characteristics rather than sensitivity alone. Detection limit indicates the lowest concentration that can be distinguished from background noise, while response and recovery times describe how quickly the sensor reacts to exposure and returns toward its baseline. Selectivity determines whether the device can distinguish CO from other gases, and long-term stability indicates whether calibration remains valid during extended operation. These characteristics are particularly important in vehicles because a delayed or misleading warning can undermine the purpose of the safety system [8], [13], [14].

Temperature and humidity are among the most important environmental influences on gas-sensor behavior. MOS sensors can show substantial changes in baseline resistance when ambient temperature varies, while humidity can alter surface adsorption and the interaction between the sensing layer and target gas. Electrochemical sensors may also experience changes in reaction rate and electrolyte behavior under different environmental conditions. A robust detector should therefore include temperature and humidity measurement or validated compensation methods, supported by testing across the expected vehicle operating range [8], [9], [13].

Calibration is another essential requirement for trustworthy CO measurement. A sensor's raw electrical output cannot automatically be interpreted as an accurate concentration because manufacturing variation, aging, contamination, and environmental conditions can change its response. Calibration should use certified reference gas mixtures and cover the concentration range relevant to the intended safety application. Periodic self-diagnostics and fault reporting can help identify sensor disconnection, abnormal baseline drift, or a sensing element that no longer responds adequately.

5. ELECTRONIC ARCHITECTURE AND VEHICLE INTEGRATION

An automotive CO monitoring system requires more than a sensing element to produce useful safety information. A practical architecture includes a CO sensor, signal-conditioning circuit, analog-to-digital conversion, microcontroller, display or warning interface, and regulated power supply. The microcontroller processes the sensor signal, applies calibration data and compensation, and evaluates whether the measured concentration meets the selected warning criteria. The system should also monitor sensor faults so that a failed detector is not mistakenly interpreted as a safe cabin condition.

The warning strategy should communicate risk clearly without creating unnecessary distraction for the driver. Visual indicators can provide continuous status information, while audible alerts can attract attention when a validated alarm condition occurs. A system may also recommend switching to fresh-air ventilation, stopping the vehicle safely, and checking for possible exhaust leakage. Automatic actions, such as controlling windows or ventilation, should only be implemented after careful safety analysis because they may interact with other vehicle systems and operating conditions.

Integration with the vehicle electrical system introduces additional engineering requirements. The detector should tolerate supply-voltage variation, electromagnetic interference, vibration, and the temperature range expected inside the cabin. Wiring, connectors, enclosure materials, and sensor mounting should be selected to withstand long-term vehicle use. If the system communicates with the vehicle network, its data interface should be designed so that monitoring functions do not interfere with essential vehicle control functions.

6. SAFETY, APPLICATIONS, AND RESEARCH GAPS

In-cabin CO monitoring is best regarded as an additional protective layer rather than a substitute for vehicle maintenance or proper ventilation. The sensor can alert occupants to a developing hazard, but it cannot repair a leaking exhaust system or guarantee that every exposure source has been eliminated. Studies

of CO toxicity show that exposure can have serious consequences, supporting the importance of early detection and effective risk communication [1]–[4], [15]. Vehicle-cabin measurements further indicate that ventilation settings can influence exposure, reinforcing the need to assess sensor behavior under realistic air-exchange conditions [5], [6].

Several research gaps remain before low-cost CO detectors can be considered fully reliable automotive safety devices. More studies are needed to compare sensor technologies under identical test conditions, including humidity changes, temperature cycling, vibration, and interference from other vehicle-related gases. Long-term field trials should assess baseline drift, calibration intervals, false alarms, and sensor lifetime in vehicles with different cabin designs. Research should also distinguish clearly between cabin safety sensors and exhaust-analysis sensors, since their measurement environments and engineering requirements are fundamentally different [16], [17].

7. CONCLUSION

Automotive CO sensors can provide an important additional safeguard against exposure to a toxic gas that occupants cannot detect through their senses. MOS, electrochemical, and optical or colorimetric technologies each offer potential advantages, but their suitability depends on the intended measurement environment and required performance. MOS sensors are attractive because of their compactness and cost, although heater power and cross-sensitivity remain important limitations. Electrochemical and optical approaches provide alternatives, but calibration, environmental stability, packaging, and service life must be addressed before reliable vehicle deployment. A practical automotive CO detector should integrate a validated sensing element with signal conditioning, environmental compensation, fault diagnostics, and clear occupant alerts. Its performance must be demonstrated under realistic vehicle conditions rather than inferred from laboratory sensitivity alone. Future development should prioritize long-term reliability, low power consumption, selectivity, and systematic field validation. Ultimately, the value of an automotive CO sensor lies not simply in detecting gas, but in delivering timely and dependable information that helps protect vehicle occupants.

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