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Optimizing Air Quality in Military Vehicles: A Sensor Fusion and Machine Learning Approach Focusing on Low-Ventilation Scenarios

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ABSTRACT

Urban military vehicles frequently operate in environments with limited ventilation, a condition that can lead to the dangerous accumulation of airborne contaminants such as particulate matter (PM) and volatile organic compounds (VOCs). This ongoing study highlights the critical need for continuous air quality monitoring to safeguard the health and operational readiness of military personnel. Preliminary observations suggest that low-ventilation scenarios may significantly increase exposure to harmful substances, potentially resulting in adverse health effects ranging from respiratory irritation to long-term cardiovascular issues. Although final results are not yet available, our work emphasizes the urgency of developing robust monitoring strategies and raising awareness among military decision-makers and vehicle designers about the risks posed by inadequate air circulation.

Keywords: Air quality monitoring, Data-driven decision making, Sensor fusion, IoT, Environmental sensing

INTRODUCTION

Ensuring adequate air quality in military vehicles is crucial for maintaining the health, safety, and operational readiness of personnel involved in critical missions. Armored vehicles designed for naval forces, in particular, play essential roles in combat support scenarios, including providing fire support and protection during ship-to-shore operations, facilitating tactical and logistical transport of troops and materials, and navigating challenging terrains such as rough landscapes, urban environments, and bodies of water with moderate currents. Vehicles commonly employed in these operations—such as the Amphibious Assault Vehicle, the Mowag Piranha IIIC, the Joint Light Tactical Vehicle, and the M113 Armored Personnel Carrier—are typically powered by robust diesel engines. These engines, selected for their reliability and durability under strenuous military conditions, are often characterized by mechanical fuel injection systems and can vary from two-stroke diesel engines, as found in older models, to modern four-stroke configurations.

However, reliance on diesel engines poses significant environmental and health risks due to the emission of harmful combustion byproducts, including particulate matter (PM) and volatile organic compounds (VOCs). These substances are known to cause respiratory irritation, cardiovascular issues, and long-term health complications. Two-stroke diesel engines, especially older or poorly maintained units, often exhibit incomplete combustion processes, resulting in higher concentrations of toxic airborne contaminants. The situation is exacerbated in scenarios involving prolonged operational periods within confined or semi-enclosed spaces.

In addition to diesel combustion byproducts, operators of military vehicles with limited ventilation are routinely exposed to a range of other harmful airborne pollutants, particularly particulate matter (PM) and volatile organic compounds (VOCs) originating from sources beyond engine emissions. Particulate matter can include dust and soil particles raised during off-road maneuvers, fragments from brake and tire wear, and even metallic residues resulting from operational use and vehicle maintenance activities. Similarly, VOC exposure is not limited solely to combustion processes; operators may inhale compounds emitted from interior vehicle components, including plastics, adhesives, lubricants, solvents, paints, and protective coatings, especially under conditions of elevated temperature and limited airflow. The cumulative effect of exposure to these diverse pollutants, coupled with restricted ventilation, significantly elevates potential health risks for personnel, underscoring the necessity of comprehensive air quality monitoring and effective mitigation strategies within military operational environments.

Previous research into air quality has extensively focused on fully sealed environments, such as submarines, aircraft cabins, spacecraft, and other completely enclosed compartments. While valuable, these studies have left a notable gap regarding scenarios involving limited — but not negligible — ventilation, conditions commonly found within military ground vehicles and amphibious transports. Unlike fully sealed compartments, these low-ventilation spaces allow minimal air exchange, leading to potentially hazardous accumulations of pollutants due to inadequate airflow. Such environments have not received sufficient attention in existing literature, despite their frequent occurrence in military operations.

This research aims to address this critical gap by highlighting the importance of continuous air quality monitoring in low-ventilation scenarios. Leveraging state-of-the-art technologies such as the Internet of Things (IoT), sensor fusion techniques, and data-driven decision-making processes, this study seeks to understand, characterize, and mitigate the risks posed by PM and VOCs. Continuous monitoring of airborne contaminants within these vehicles is not only a proactive measure but a necessary strategy to protect military personnel from acute and chronic health impacts. By enhancing awareness among military decision-makers, vehicle designers, and health and safety professionals, this research emphasizes the urgent need for effective air quality solutions tailored specifically to low-ventilation military operational environments.

LITERATURE REVIEW

Optimizing air quality in confined environments, such as military vehicles and submarines, is crucial for maintaining crew health and performance. This review highlights key studies related to air quality monitoring and the effects of carbon dioxide exposure in such environments.

Air Quality Monitoring Technologies

The application of advanced air monitoring technologies has been explored in various closed environments. For instance, Shi et al. (2007) discussed the development and application of mass spectrometry technologies in nuclear submarines, emphasizing their role in monitoring air quality. This includes the use of magnetic mass spectrometers, quadrupole mass spectrometers, GC-MS, and ion mobility mass spectrometry, which provide comprehensive analysis of air components. Similarly, Limero et al. (2016) detailed the use of the NASA Air Quality Monitor (AQM) in U.S. Navy submarines, which utilizes gas chromatography and differential mobility spectrometry to detect volatile organic compounds. The AQM's ability to operate at atmospheric pressure and use air as a carrier gas makes it a reliable and compact instrument for continuous monitoring. These technologies are essential for maintaining air quality in confined spaces, where the buildup of harmful substances can occur rapidly.

Effects of Carbon Dioxide Exposure

Carbon dioxide levels are a significant concern in submarines due to their impact on crew health. One research (Margel et al., 2003) investigated how intermittent exposure to high CO_2 levels affects submariners' sleep patterns, finding that respiratory disturbances increase as CO_2 levels fluctuate during ventilation cycles. This study highlighted the importance of managing CO_2 levels to prevent sleep disorders among crew members. Howard et al. (2019) focused on the prenatal developmental effects of CO_2 exposure, recommending exposure limits to protect crew health, particularly for pregnant personnel. The study established a No Observed Adverse Effect Level (NOAEL) of 2.5% CO_2 and a Lowest Observed Adverse Effect Level (LOAEL) of 3.0%, leading to a recommended continuous exposure limit of 0.8% CO_2. Rodeheffer et al. (2018) examined the impact of CO_2 on submariners' decision-making abilities, finding no significant impairments despite elevated CO_2 levels. This contrasts with studies in other populations, suggesting that submariners may adapt to higher CO_2 levels over time.

Integration With Sensor Fusion and Machine Learning

The integration of sensor fusion and machine learning techniques can enhance air quality monitoring by providing real-time data analysis and predictive modeling. This approach can help optimize ventilation systems and mitigate the adverse effects of CO_2 exposure in low-ventilation scenarios. By leveraging advanced monitoring technologies and understanding the physiological impacts of CO_2, military vehicles can ensure a safer and healthier environment for their crews. Sensor fusion can combine data from multiple sensors to provide a comprehensive view of air quality, while machine learning algorithms can predict when CO_2 levels are likely to exceed safe thresholds, allowing for proactive adjustments to ventilation systems. This proactive management can reduce the risk of respiratory disturbances and cognitive impairments associated with high CO_2 levels.

Future Directions

Ongoing research and future work focus on integrating sensor fusion and machine learning with existing air quality monitoring technologies to create adaptive systems that respond to changing environmental conditions. This could involve developing predictive models that account for factors such as crew size, activity levels, and ventilation system efficiency. Additionally, studies on the long-term effects of CO_2 exposure in military personnel could provide valuable insights into setting optimal exposure limits and designing more effective ventilation strategies.

IoT Device

We developed an IoT device to continuously monitor air quality inside military vehicle crew compartments. By tracking pollutants such as particulate matter (PM), volatile organic compounds (VOCs), carbon monoxide (CO), and carbon dioxide (CO_2), the system provides essential data to enable historical tracking and diagnostic analysis of air quality conditions. The device collects sensor readings at 10-second intervals during operations and once per minute during idle periods, as a way to balance the level of detail required with storage efficiency.

The device employs a set of specialized gas sensors from the MQ series —including MQ-2, MQ-3, MQ-4, MQ-5, MQ-6, MQ-7, MQ-8, and MQ-135. These sensors detect gases such as alcohol, smoke, methane, LPG, hydrogen, ammonia (NH_3), benzene, and propane through electrodes coated with sensitive materials that respond to gas exposure by changing electrical resistance. Specifically, the device identifies combustible gases like methane and propane—which can build up dangerously in enclosed diesel-powered compartments—as well as toxic gases such as carbon monoxide, ammonia, and hydrogen sulphide, typically originating from engine exhaust or vehicle components. Additionally, the system detects VOCs emitted by internal materials such as adhesives, paints, and cleaning substances, known to cause short-term discomfort and long-term respiratory or neurological effects. The sensors also monitor carbon dioxide (CO_2) concentrations, as elevated levels can induce fatigue, impair alertness, and negatively affect decision-making.

The prototype uses a Raspberry Pi 5 to control and collect data from the eight sensors. Since the sensors produce analog signals, analog-to-digital converters (ADCs) were used to convert these signals for processing by the Raspberry Pi. Communication between components occurs via the efficient and simple I2C protocol. We prioritized security and reliability over ease of use by storing data locally on the Raspberry Pi's microSD card, avoiding external network or cloud transmission to prevent exposure of sensitive military information. All wireless modules are disabled to eliminate unauthorized access risks. Data retrieval occurs exclusively through physical access to the microSD card, complying with strict military security protocols. Sensor readings and summaries are stored in widely compatible CSV and JSON formats, facilitating future integration and analysis using common tools such as Excel and Python's data analysis modules.

DATA ANALYSIS PLAN

The analysis of air quality data collected from the eight MQ-series gas sensors will follow a structured approach to evaluate the necessity and effectiveness of personal protective equipment (PPE) for military vehicle operators. Before conducting the experiments, all sensors will undergo rigorous calibration procedures to ensure accurate and reliable gas concentration measurements. Calibration data, stored in JSON format, will enable the precise conversion of raw sensor readings into meaningful pollutant concentration values.

After data collection, raw sensor readings stored in CSV files will first undergo preprocessing using Python-based tools, particularly Pandas and NumPy, to organize the dataset and identify any missing or inconsistent data points. Exploratory data analysis (EDA) will then be performed using visualization libraries such as Matplotlib and Seaborn to generate detailed plots, including time-series analyses and pollutant concentration distributions. This stage aims to visually identify patterns and highlight scenarios with elevated pollutant levels.

Following this initial assessment, statistical and machine learning techniques—including correlation analysis, regression modeling, and clustering algorithms—will be employed to analyze pollutant exposure within each of the four Brazilian Navy vehicles targeted in this research: the Amphibious Assault Vehicle, the Mowag Piranha IIIC 8×8, the Joint Light Tactical Vehicle, and the M113 Armored Personnel Carrier. This targeted analysis will help determine the specific conditions within each vehicle model that lead to higher concentrations of particulate matter (PM), VOCs, and other harmful gases.

Ultimately, the primary goal of this detailed analysis is to inform decision-making regarding the use of personal protective equipment. By identifying scenarios that either require additional protective measures—such as respirators or filtration devices—or scenarios in which existing vehicle ventilation systems are adequate, the study will provide practical guidance to ensure personnel safety. The findings will directly support recommendations about PPE usage, vehicle modifications, and potential air quality improvements, thereby safeguarding the health and operational readiness of military personnel across diverse operational contexts.

CONCLUSION AND FUTURE WORK

This research has presented the design, development, and initial evaluation of a cost-effective, real-time air quality monitoring IoT device specifically tailored for military vehicles operating in low-ventilation environments. Utilizing an array of MQ gas sensors and a robust data acquisition architecture built upon the Raspberry Pi 5, the device addresses the critical need for reliable assessment of airborne pollutants within crew compartments. Preliminary laboratory testing has demonstrated the system's effectiveness and accuracy, setting the stage for ongoing field deployments in collaboration with the Brazilian Navy across four specific vehicle models: the Amphibious Assault Vehicle, the Mowag Piranha IIIC 8×8, the Joint Light Tactical Vehicle, and the M113 Armored Personnel Carrier.

Moving forward, a comprehensive data analysis plan is in place to interpret sensor data collected during operational scenarios. This analysis aims primarily to determine whether personal protective equipment (PPE) is necessary for vehicle operators, and if so, to identify which types of PPE would be most effective in mitigating exposure risks. In situations where PPE usage may be impractical, the findings will inform recommendations for modifications to vehicle ventilation systems or interior designs to improve operator safety and health.

Overall, this study establishes a foundational platform for continued investigation into air quality within military vehicles. Future advancements in sensor technologies, analytical methods, and integration approaches promise to extend the system's applicability across a broader spectrum of military vehicles and diverse operational contexts, directly benefiting the health, safety, and mission readiness of military personnel.

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