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A Survey on IoT-Based Systems for Vehicular Emission Monitoring and Air Quality Management

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Abstract: *With the continuous rise in the number of vehicles worldwide, vehicular emissions have become one of the major contributors to urban air pollution, posing severe environmental and health hazards. Traditional pollution monitoring methods are often limited by their fixed locations, high costs, and inability to provide real-time data. In recent years, the Internet of Things (IoT) has emerged as a promising solution for real-time vehicle emission monitoring, enabling continuous data collection, remote monitoring, and timely alerts. This review paper presents a comprehensive analysis of existing IoT-based vehicle pollution monitoring systems, including their architectures, sensor technologies, communication protocols, cloud platforms, and data visualization methods. The paper also discusses the challenges, limitations, and future research directions to enhance the efficiency, scalability, and accuracy of these systems for effective air quality management and smart city implementation.*

Keywords: IoT, Vehicle Emission Monitoring, Air Pollution, Real-Time Monitoring, Smart City

I. INTRODUCTION

1.1 Overview

The rapid growth of industrialization and urbanization has led to a sharp increase in the number of vehicles on roads globally. This growth, while facilitating economic development and improving mobility, has also resulted in significant environmental challenges, particularly air pollution. Vehicular emissions contribute substantially to air quality degradation by releasing harmful gases such as carbon monoxide (CO), nitrogen oxides (NOx), hydrocarbons (HC), and particulate matter (PM) into the atmosphere. These pollutants not only deteriorate air quality but also pose severe health risks, contributing to respiratory problems, cardiovascular diseases, and even premature death in extreme cases.

Conventional vehicle emission monitoring techniques largely rely on stationary air quality monitoring stations and periodic vehicle inspections. While these methods provide valuable data, they suffer from several critical limitations. Fixed monitoring stations cover only limited geographic areas, failing to capture localized pollution variations caused by traffic congestion, vehicle types, or road conditions. Periodic vehicle inspections, though useful, are infrequent and cannot track real-time emissions, allowing poorly maintained or tampered vehicles to emit pollutants unchecked between inspections.

The Internet of Things (IoT) offers an innovative and efficient alternative to address these shortcomings. IoT refers to a network of interconnected devices equipped with sensors, actuators, and communication modules that enable real-time data collection, transmission, and processing. By integrating IoT with vehicle emission monitoring systems, it becomes possible to track and manage pollution levels continuously and more accurately. This approach allows authorities to identify high-emission vehicles instantly and take timely corrective measures, contributing significantly to pollution control and environmental sustainability.

IoT-based vehicle emission monitoring systems typically consist of gas sensors mounted either on vehicles or roadside units, microcontrollers for data acquisition and processing, and wireless communication modules for

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data transmission. These systems transmit emission data to centralized cloud platforms, where it can be stored, analyzed, and visualized in real-time through web dashboards or mobile applications. Moreover, threshold-based alert mechanisms can notify vehicle owners and authorities when emission levels exceed permissible limits, enabling immediate interventions to minimize environmental harm.

Several research studies have been conducted to explore and develop various IoT-enabled solutions for vehicle pollution monitoring. These studies have demonstrated the feasibility and effectiveness of using sensors such as MQ-7 for carbon monoxide, MQ-135 for general air quality, and MQ-136 for nitrogen oxides, along with microcontrollers like Arduino and ESP32 for data processing and transmission. Cloud platforms such as ThingSpeak, Firebase, and AWS IoT have been widely employed for data storage and visualization, while communication technologies like Wi-Fi, GSM, and LoRa ensure seamless data transfer across different environments.

Despite the promising capabilities of IoT-based systems, there are still multiple challenges that need to be addressed. Sensor calibration and accuracy, data security and privacy, power consumption, cost-effectiveness, and scalability are among the key issues that researchers and developers must consider to enhance system performance and usability. Furthermore, the integration of such systems into smart city infrastructures requires the collaboration of multiple stakeholders, including government agencies, vehicle manufacturers, environmental organizations, and the public.

This review paper aims to provide a comprehensive analysis of the existing IoT-based vehicle emission monitoring technologies. It examines the various hardware and software components used in these systems, discusses their strengths and limitations, and identifies research gaps and future opportunities. By consolidating current knowledge in this field, the paper seeks to contribute valuable insights for researchers, policymakers, and industry professionals working towards developing more efficient, scalable, and sustainable solutions for vehicle pollution control.

1.2 Problem Definition

The alarming rise in vehicular emissions has become a significant contributor to global air pollution, particularly in rapidly urbanizing regions. Traditional emission monitoring systems, such as periodic vehicle inspections and stationary air quality monitoring stations, are often inefficient, costly, and limited in both scope and real-time applicability. These conventional methods fail to provide continuous, real-time data on vehicular emissions, making it difficult for regulatory bodies to identify and take timely action against vehicles that exceed permissible pollution levels. Moreover, manual inspections are labor-intensive and cannot easily scale with the growing number of vehicles on the road. There is a pressing need for an intelligent, automated, and real-time emission monitoring system that can effectively track, analyze, and report vehicle pollution levels while enabling timely interventions. This review paper addresses these challenges by evaluating various IoT-based solutions that leverage modern sensor technologies, wireless communication, and cloud computing to provide scalable, real-time vehicle emission monitoring systems capable of contributing to environmental sustainability and smart city initiatives.

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II. LITERATURE REVIEW

Several research studies have been conducted to address the problem of vehicular pollution monitoring using advanced technologies like IoT, wireless communication, and cloud computing. This section reviews recent work relevant to the development of a real-time vehicle emission monitoring system.

In [1], Sharma et al. proposed an IoT-based vehicle emission monitoring system using MQ series sensors for detecting Carbon Monoxide (CO) and Nitrogen Oxides (NOx). The system utilized an Arduino microcontroller and GSM module for data transmission to a central server. Real-time monitoring allowed authorities to track vehicles emitting excessive pollutants, but the system lacked integration with cloud platforms for advanced data analytics.

In [2], Patel and Desai developed a prototype that integrated the ESP8266 microcontroller with multiple gas sensors to detect CO, CO_2, and hydrocarbons. The collected data was transmitted to the ThingSpeak cloud platform, allowing for real-time visualization and historical data analysis. Their work demonstrated the feasibility of cloud integration for pollution monitoring but focused primarily on stationary sources rather than mobile vehicles.

In [3], Kumar et al. presented a wireless sensor network-based approach for monitoring vehicular emissions. The system utilized LoRa communication for long-range, low-power data transmission from multiple vehicles to a centralized server. While effective in rural and semi-urban areas with limited network infrastructure, the study emphasized the need for robust power management for continuous vehicle-based deployment.

In [4], Singh et al. introduced a GPS-enabled IoT system that not only monitored emission levels but also tracked vehicle locations in real time. The system combined GPS, GSM, and pollution sensors to generate a comprehensive database for authorities, allowing targeted enforcement of emission norms. However, the system required constant network availability, which may limit its effectiveness in areas with poor cellular coverage.

In [5], Ali et al. proposed a smart city application for vehicular pollution monitoring, integrating data from multiple vehicles into a centralized urban environmental monitoring platform. The system used edge computing techniques to preprocess data before sending it to the cloud, reducing network load and improving real-time response. This work highlighted the scalability of IoT-based pollution monitoring for smart city integration but required higher computational resources at the vehicle level.

From the reviewed literature, it is evident that while several solutions exist for monitoring vehicular emissions, most face challenges related to real-time data availability, network dependency, system scalability, and cost. This motivates the present work to design and implement a cost-effective, real-time, cloud-integrated, and scalable IoT-based Vehicle Pollution Monitoring System suitable for both individual vehicles and large-scale smart city applications.

III. EXISITING SYSTEM

Currently, vehicle emission monitoring is predominantly carried out using traditional and semi-automated systems that have several inherent limitations. The most common method is the use of stationary air quality monitoring stations installed in select urban locations. These stations continuously measure pollutant levels in the atmosphere but do not provide information about specific pollution sources or individual vehicles. While they help to assess the overall air quality of an area, they cannot identify highly polluting vehicles in real-time, limiting their ability to support targeted enforcement.

Another widely adopted method is periodic vehicle emission testing during mandatory vehicle inspections. In many countries, vehicles are required to undergo emissions testing at authorized centers on a scheduled basis. During these inspections, sensors and analyzers measure the emission levels of CO, NOx, HC, and particulate matter emitted from the vehicle's exhaust. While effective to some extent, these inspections are infrequent, allowing vehicles to emit pollutants unchecked for long periods between inspections. Additionally, some vehicle owners may temporarily modify their vehicles to pass inspections, further reducing the reliability of this approach.

Some advanced cities have introduced remote sensing technologies (RST), where specialized equipment is installed along roadways to monitor passing vehicles. These systems use infrared and ultraviolet beams to detect emission levels as vehicles drive by. Although RST offers non-intrusive real-time data, the installation and maintenance costs are high, and the technology requires precise alignment and calibration to function accurately, limiting widespread adoption.

Moreover, on-board diagnostics (OBD) systems installed in newer vehicles can monitor some emission parameters internally. However, OBD systems mainly focus on engine performance and do not always provide detailed data on all types of harmful pollutants. Additionally, OBD data is often not accessible to regulatory authorities in real-time, limiting its usefulness for large-scale monitoring.

Overall, while these existing systems contribute to pollution monitoring efforts, they share common drawbacks: limited geographic coverage, lack of continuous real-time data, high cost, low scalability, and minimal direct enforcement capabilities. These challenges highlight the need for a more efficient, real-time, and scalable solution—

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such as IoT-based vehicle emission monitoring systems—that can provide continuous tracking, immediate alerts, and seamless integration with smart city infrastructure to more effectively combat vehicular pollution.

IV. SYSTEM DESIGN

4.1 System Architecture

The below figure specified the system architecture of our project.

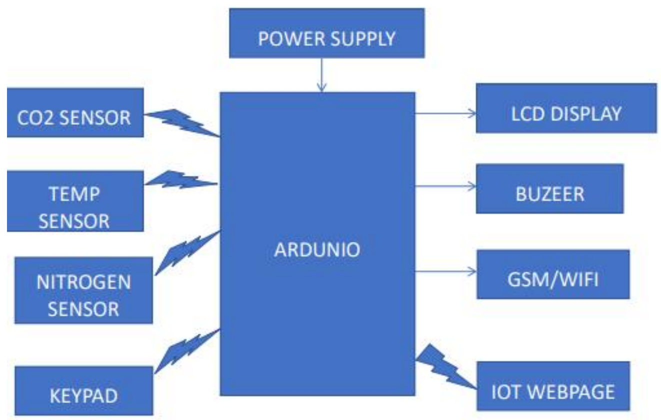

Fig. 1 System Architecture

4.2 Working of the Proposed System

The proposed system leverages Internet of Things (IoT) technology to monitor vehicle emissions in real time, addressing the limitations of existing monitoring systems. It consists of multiple integrated modules that work collaboratively to detect, process, transmit, store, and visualize vehicle emission data.

First, the gas sensing module is installed close to the vehicle's exhaust pipe. Sensors such as MQ-7, MQ-135, and MQ-136 continuously detect concentrations of harmful gases like Carbon Monoxide (CO), Nitrogen Oxides (NOx), and Hydrocarbons (HC). These sensors generate analog signals proportional to the gas concentrations detected.

The processing module, primarily built on a microcontroller (such as ESP32 or Arduino UNO), receives these analog signals and converts them into digital form using its onboard Analog-to-Digital Converter (ADC). The microcontroller filters and averages the data to reduce noise and ensure accuracy. Threshold values are pre-programmed into the microcontroller's memory to identify whether the detected pollutant levels exceed safe limits.

After processing, the communication module transmits the emission data to a cloud server using Wi-Fi, GSM, or LoRa technology, depending on network availability and geographical location. For urban areas, Wi-Fi or GSM is typically used, while LoRa may be employed for long-range, low-power communication in rural or remote locations.

On the cloud server, platforms like ThingSpeak, Firebase, or AWS IoT receive, store, and analyze the incoming data. The server continuously monitors the data for threshold violations. When pollution levels surpass permissible limits, the cloud system triggers automated alerts.

These alerts are then pushed to authorized personnel and vehicle owners through a mobile or web application. The application provides a real-time dashboard displaying live emission levels, historical data, and notifications. Authorities can use this data to enforce pollution control regulations, while vehicle owners receive timely alerts to service or repair their vehicles.

Additionally, an optional GPS module may be integrated to track the vehicle's location, allowing authorities to pinpoint high-pollution zones and identify frequent offenders.

The system is powered by either the vehicle's existing 12V battery, regulated to the required voltage levels, or by an independent rechargeable battery system for development or demonstration purposes.

This fully automated, real-time system ensures continuous monitoring of vehicle emissions, allows immediate response to violations, reduces manual intervention, and provides reliable, scalable, and cost-effective pollution monitoring that can be seamlessly integrated into smart city frameworks.

4.3 Advantages & Disadvantages

Advantages:

1. **Real-time Monitoring:** The system provides continuous, real-time data on vehicle emissions, allowing for immediate detection of pollution level violations.
2. **Remote Accessibility:** Data can be accessed remotely by authorities and vehicle owners through mobile apps or web dashboards, improving convenience and responsiveness.
3. **Scalability:** IoT-based architecture allows easy scaling to monitor a large number of vehicles across multiple geographic locations without the need for extensive physical infrastructure.
4. **Cost-Effective:** Compared to large stationary monitoring stations or manual inspection processes, the proposed system is relatively inexpensive to deploy and maintain.
5. **Data-Driven Decision Making:** Historical data storage enables analysis of long-term emission trends, helping policymakers and researchers develop better air quality control strategies.
6. **Integration with Smart City Systems:** The system can seamlessly integrate with other smart city components like traffic management and urban planning systems.
7. **Automated Alerts:** Immediate alerts notify vehicle owners and authorities about emission violations, allowing prompt corrective actions to reduce pollution.

Disadvantages:

1. **Sensor Calibration Issues:** Gas sensors may require periodic calibration to maintain accuracy, increasing maintenance efforts.
2. **Environmental Factors:** Extreme weather conditions, humidity, or temperature fluctuations may affect sensor readings and system reliability.
3. **Power Dependency:** Continuous operation requires a stable power supply; any disruption may halt the monitoring process.
4. **Initial Installation Cost:** Although cost-effective long-term, the initial installation for large-scale deployment might be significant.
5. **Data Security and Privacy:** Transmission and storage of vehicle data over networks may raise security and privacy concerns that need to be addressed through secure protocols.
6. **Limited for Older Vehicles:** Some older vehicle models may not support integration with newer IoT-based technologies without significant modification.

V. CONCLUSION

In this review paper, various IoT-based vehicle pollution monitoring systems have been explored to address the growing environmental and health challenges posed by vehicular emissions. The proposed system offers a real-time, automated, and scalable solution that integrates gas sensors, microcontrollers, wireless communication, and cloud platforms to continuously monitor and report emission levels. Unlike traditional monitoring methods, this approach allows for immediate detection of pollution violations, timely alerts to both authorities and vehicle owners, and comprehensive data analysis for informed policymaking. While there are challenges such as sensor calibration and data security, the advantages in terms of real-time tracking, scalability, and integration with smart city initiatives make IoT-based vehicle pollution monitoring a promising tool in the global effort to combat air pollution and promote sustainable urban living.

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