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Vehicle Pollution Monitoring

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Abstract: *With the rapid growth in the number of vehicles on roads, vehicular emissions have become a significant contributor to air pollution, posing serious threats to environmental sustainability and public health. Traditional pollution monitoring methods, which rely on stationary monitoring stations or periodic manual inspections, are often limited in scope, lack real-time capability, and are not scalable for dynamic urban environments. This paper presents the design and implementation of an IoT-based Vehicle Pollution Monitoring System that enables real-time detection, monitoring, and reporting of harmful exhaust gases such as Carbon Monoxide (CO), Nitrogen Oxides (NOx), and Hydrocarbons (HC). The system employs gas sensors (MQ-7, MQ-135, MQ-136), a microcontroller (ESP32 or Arduino UNO), and wireless communication modules (Wi-Fi, GSM) to collect emission data from vehicles and transmit it to a cloud-based platform for processing, visualization, and storage. A mobile and web-based interface provides users and authorities with real-time access to emission data, alerts for threshold violations, and historical analysis for regulatory compliance and environmental assessment. The proposed system enhances pollution control efforts by providing continuous, scalable, and cost-effective monitoring, supporting smart city initiatives, and contributing to proactive environmental management.*

Keywords: Vehicle Emissions, IoT, Air Pollution Monitoring, Gas Sensors, Real-Time Monitoring

I. INTRODUCTION

1.1 Overview

In recent years, rapid urbanization, industrial growth, and an exponential rise in the number of vehicles on the road have led to a significant increase in air pollution levels worldwide. Among various sources of air pollution, vehicular emissions are one of the major contributors, especially in densely populated urban and metropolitan areas. Vehicles powered by internal combustion engines emit a variety of harmful gases such as Carbon Monoxide (CO), Nitrogen Oxides (NOx), Hydrocarbons (HC), Carbon Dioxide (CO_2), and Particulate Matter (PM). These pollutants not only degrade air quality but also pose severe health risks, including respiratory diseases, cardiovascular problems, and even premature death. Furthermore, vehicular emissions contribute significantly to global warming and climate change by increasing greenhouse gas concentrations in the atmosphere.

Traditional pollution monitoring methods primarily rely on fixed monitoring stations installed at selected locations throughout a city. While these stations can provide detailed data about air quality in specific areas, they offer limited spatial coverage and cannot account for emissions from individual vehicles in real-time. Periodic vehicle emission inspections and regulatory checks are often insufficient as many vehicles emit pollutants beyond permissible limits between inspections due to poor maintenance or tampering with emission control systems. These limitations create a significant gap in effectively monitoring, managing, and controlling vehicular pollution at its source.

To address these challenges, there is a growing need for a real-time, scalable, and automated solution capable of continuously monitoring vehicular emissions directly from the source. The emergence of Internet of Things (IoT) technologies offers a promising approach to develop such systems. IoT-based solutions enable seamless integration of sensors, microcontrollers, communication networks, and cloud platforms to collect, process, and analyze environmental data in real-time. By leveraging IoT technology, it becomes feasible to build a comprehensive vehicle pollution monitoring system that provides continuous, real-time data, immediate alerts, and remote accessibility to stakeholders.

This paper proposes the development and implementation of an IoT-based Vehicle Pollution Monitoring System that can detect and monitor key pollutants emitted from vehicle exhausts. The system employs a combination of gas sensors such as MQ-7 for Carbon Monoxide, MQ-135 for Carbon Dioxide and general air quality, and MQ-136 for Nitrogen Oxides. These sensors are connected to a microcontroller unit such as the ESP32, which processes the data and transmits it wirelessly to a cloud server using Wi-Fi, GSM, or LoRa communication technologies. The cloud server stores and analyzes the data, generates real-time visualizations, and triggers alerts when emission levels exceed predefined thresholds.

The data collected by the system can be accessed by vehicle owners, environmental authorities, and policymakers through mobile applications or web-based dashboards. This allows for timely corrective actions, improved enforcement of environmental regulations, and better-informed decision-making for urban planning and pollution control. Furthermore, by collecting large amounts of historical data, the system can contribute to long-term studies on traffic-related air pollution trends and their impact on public health and the environment.

The proposed system not only empowers authorities to monitor and control pollution at a granular level but also promotes public awareness by providing vehicle owners with real-time feedback on their vehicle's emission performance. Such an approach encourages timely maintenance and repairs, reducing the overall environmental footprint of transportation systems. Moreover, this system aligns with global efforts toward developing smart city infrastructures where real-time environmental monitoring forms a crucial component of sustainable urban living.

In summary, this work presents a novel, cost-effective, and scalable solution for real-time vehicle emission monitoring using IoT technologies. By addressing the limitations of traditional monitoring methods, the proposed system offers significant benefits for pollution control, regulatory compliance, and public health protection, ultimately contributing to a cleaner, safer, and more sustainable environment.

1.2 Motivation

The increasing levels of air pollution caused by vehicular emissions have become a pressing global concern, particularly in urban areas where traffic density is high. Despite the existence of emission norms and periodic inspection programs, many vehicles continue to operate while emitting harmful pollutants due to inadequate maintenance, aging engines, or emission control system failures. Traditional monitoring systems lack real-time capabilities, wide coverage, and the ability to identify individual polluting vehicles instantly. This creates a critical need for an efficient, scalable, and real-time monitoring solution. The advancement of IoT technologies provides a unique opportunity to bridge this gap by enabling continuous data collection, remote monitoring, and instant notifications, thus empowering authorities and vehicle owners to take timely corrective actions and contributing to cleaner air and healthier living environments.

1.3 Problem Definition and Objectives Problem Definition

Vehicular emissions are a major contributor to air pollution, significantly affecting air quality and public health, especially in densely populated urban areas. Existing pollution control mechanisms are often reactive, relying on periodic inspections or fixed monitoring stations that provide limited coverage and lack real-time monitoring capabilities. This makes it difficult to detect and address high-emission vehicles promptly. There is a clear need for a smart, automated, and scalable system that can continuously monitor vehicle emissions in real-time, provide instant alerts when permissible limits are exceeded, and support data-driven decisions for environmental management and regulatory enforcement.

Objectives

1. To continuously monitor real-time emissions of CO, NO_x, and HC from vehicle exhaust.
2. To develop an IoT-based system using gas sensors and microcontrollers for data collection.

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3. To transmit processed data to a cloud server for storage, analysis, and visualization.
4. To generate instant alerts for vehicle owners and authorities when emission levels exceed set thresholds.
5. To assist in policy enforcement, environmental protection, and public awareness through data-driven insights.

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. REQUIREMENT AND ANALYSIS

A smart home automation system must be designed with a clear understanding of both user expectations and technical feasibility. This section discusses the functional and non-functional requirements, system analysis, and the rationale behind hardware and software component selection to ensure the development of a reliable, scalable, and user-friendly hybrid automation platform.

The development of the IoT-based Vehicle Pollution Monitoring System requires careful selection of hardware and software components to ensure accurate data collection, reliable transmission, efficient processing, and real-time accessibility. This section details the hardware and software requirements along with their roles in the overall system.

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A. Hardware Requirements

1. **Gas Sensors**
   - **MQ-7**: Detects Carbon Monoxide (CO) concentrations from the vehicle exhaust.
   - **MQ-135**: Detects multiple gases including Carbon Dioxide (CO_2), Ammonia (NH_3), Benzene, and general air quality indicators.
   - **MQ-136 (Optional)**: Detects Nitrogen Oxides (NOx) for more comprehensive emission analysis.
2. **Microcontroller**
   - **ESP32 Development Board**: Acts as the central processing unit of the system, capable of reading sensor data, processing it, and managing wireless communication via its built-in Wi-Fi module.
3. **Communication Module (if ESP32 is not used)**
   - **GSM Module (SIM800L)**: Used for transmitting data via cellular networks where Wi-Fi is unavailable.
   - **LoRa Module (Optional)**: Enables long-range, low-power data transmission for remote locations.
4. **Power Supply**
   - **Vehicle Battery (12V DC)**: Primary power source, regulated to 5V or 3.3V using voltage regulators such as LM7805.
   - **Li-ion Battery (Portable setup)**: Used for prototype testing or temporary installations.
5. **Peripheral Devices**
   - **LCD Display**: Displays real-time emission data and system status locally.
   - **Buzzer**: Provides audible alerts if pollution levels cross threshold limits.
   - **Keypad (Optional)**: Allows for manual input or system configuration.
6. **Voltage Regulator**
   - **LM7805 or AMS1117**: Converts vehicle battery voltage to a stable 5V or 3.3V for the microcontroller and sensors.

B. Software Requirements

1. **Embedded Programming Platform**
   - **Arduino IDE**: Used to write, compile, and upload the control code to the ESP32 or Arduino UNO microcontroller.
2. **IoT Cloud Platforms**
   - **ThingSpeak**: Used for real-time data storage, visualization, and basic analytics.
   - **Firebase**: Enables real-time database operations and mobile app integration.
   - **AWS IoT / Microsoft Azure (optional)**: For large-scale, advanced analytics and scalable deployment.
3. **Mobile Application Development**
   - **MIT App Inventor / Blynk**: Used for developing a simple mobile app that displays live emission data and sends notifications.
   - **Android Studio (optional)**: For developing a more sophisticated custom mobile application.
4. **Web Dashboard Development**
   - **Node-RED / HTML, CSS, JavaScript**: Used to build a responsive web interface to monitor data, view historical logs, and manage notifications.
5. **Communication Protocols**
   - **MQTT / HTTP**: Used for reliable and lightweight data transmission between hardware and cloud servers.
6. **Data Processing and Visualization Tools**
   - **Matplotlib / Python (optional)**: For advanced data analysis and graphical reporting on historical pollution trends.

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C. System Analysis

The system is designed to operate autonomously with minimal human intervention. Gas sensors continuously collect emission data from the exhaust, which is processed by the microcontroller. After filtering and averaging the sensor data to minimize noise, the processed values are transmitted in real-time to the cloud using Wi-Fi or GSM networks. The cloud platform visualizes the data and triggers alerts if pollutant concentrations exceed predefined safe limits. Users and authorities can access real-time data and historical reports through mobile apps or web dashboards, allowing for immediate corrective actions and long-term policy-making.

IV. SYSTEM DESIGN

4.1 System Architecture

The below figure specified the system architecture of our project.

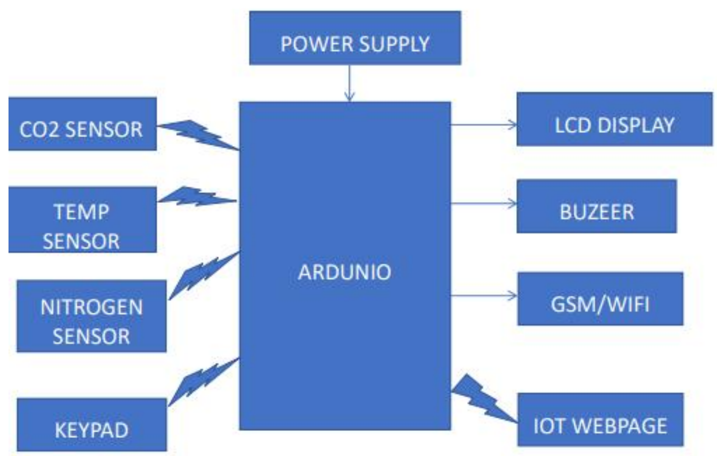

Fig. 1 System Architecture

A. System Architecture

The overall system architecture consists of the following major components:

- **Data Acquisition Unit (Sensors + Microcontroller)**
- **Data Transmission Unit (Communication Module)**
- **Cloud Server (Storage & Processing)**
- **User Interface (Mobile App & Web Dashboard)**

B. Hardware Design

1. **Sensor Module**

   The sensor module is responsible for detecting harmful gases emitted from the vehicle exhaust. The sensors are mounted near or inside the exhaust pipe to accurately measure gas concentrations.

- **MQ-7 Sensor:** Measures Carbon Monoxide (CO).
- **MQ-135 Sensor:** Measures Carbon Dioxide (CO_2), Ammonia (NH_3), Benzene, and general air quality.
- **MQ-136 Sensor (Optional):** Measures Nitrogen Oxides (NOx).
- **Temperature and Humidity Sensors (Optional):** To calibrate gas sensor readings based on environmental conditions.

2. **Microcontroller Unit (MCU)**

   The ESP32 development board is used as the system's central processing unit due to its dual-core processor, built-in Wi-Fi, and sufficient GPIO pins for sensor interfacing. The MCU reads analog signals from the sensors, converts them to digital values using its ADC (Analog-to-Digital Converter), and processes the data

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for transmission.

3. **Communication Module**
The ESP32's built-in Wi-Fi is primarily used to transmit data to the cloud server. In areas without Wi-Fi access, a GSM module (SIM800L) or LoRa module can be used for cellular or long-range communication.
4. **Power Supply**
The system can draw power directly from the vehicle's 12V battery using a voltage regulator (LM7805 or AMS1117) to step down the voltage to 5V or 3.3V required by the sensors and microcontroller. For portable setups, a Li-ion rechargeable battery can be used.
5. **Output Devices**

- **LCD Display:** Displays real-time gas concentration levels and system status locally.
- **Buzzer:** Alerts the driver when emissions exceed permissible levels.
- **Keypad (Optional):** Allows manual configuration or system reset.

C. Software Design

1. **Embedded Firmware**
The embedded code written in C/C++ using the Arduino IDE handles:

- Sensor initialization and data acquisition.
- Data filtering and averaging for noise reduction.
- Threshold checking to identify high pollution levels.
- Wireless data transmission to the cloud.

2. **Cloud Server Design**
The cloud server receives, stores, and processes sensor data. Various platforms are used:

- **ThingSpeak:** For data visualization and basic analytics.
- **Firebase:** For real-time database access and mobile app integration.
- **AWS IoT / Microsoft Azure:** For large-scale deployment and advanced data processing.

3. **Communication Protocols**

- **HTTP/MQTT Protocols:** Lightweight and reliable protocols used for data transmission between the hardware and cloud.

4. **User Interface**

- **Mobile Application:** Built using Blynk or MIT App Inventor for real-time data access and notifications.
- **Web Dashboard:** Developed using Node-RED or web development tools (HTML, CSS, JavaScript) for comprehensive data visualization, historical data access, and system management.

D. Data Flow

The system follows the following data flow:

1. **Data Collection:** Sensors detect pollutants and send data to the MCU.
2. **Data Processing:** The MCU converts analog data to digital, filters noise, and checks threshold levels.
3. **Data Transmission:** Processed data is sent to the cloud server via Wi-Fi or GSM.
4. **Data Storage & Visualization:** The cloud stores and displays data in graphical formats, triggers alerts, and maintains historical records.
5. **Notifications:** If pollution exceeds the threshold, alerts are sent to the mobile app or web dashboard, notifying both the vehicle owner and regulatory authorities.

E. System Features

- **Real-Time Monitoring:** Continuous data collection and instant reporting.
- **Remote Accessibility:** Data can be accessed anywhere using a smartphone or web browser.
- **Alert System:** Instant notifications when emissions exceed legal limits.

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- **Historical Analysis:** Storage of historical data for long-term analysis and policy-making.
- **Scalability:** Easily expandable for smart city-wide deployment.

4.2 Working of the Proposed System

The proposed IoT-based Vehicle Pollution Monitoring System operates through the integration of hardware sensors, microcontroller processing, wireless communication, and cloud-based data management. The system continuously monitors the pollutants emitted from vehicle exhaust and provides real-time feedback to both users and authorities. The working of the system can be explained step-by-step as follows:

1. **Sensing and Data Acquisition:**
   The system begins by using multiple gas sensors installed near the vehicle's exhaust pipe. The MQ-7 sensor detects the concentration of Carbon Monoxide (CO), while the MQ-135 sensor monitors Carbon Dioxide (CO_2), Ammonia (NH_3), Benzene, and other pollutants contributing to air quality. Optionally, the MQ-136 sensor can be integrated to monitor Nitrogen Oxides (NOx). These sensors continuously sense gas concentrations in the exhaust and generate analog voltage signals corresponding to the gas levels detected.
2. **Signal Conversion and Processing:**
   The analog signals from the sensors are fed into the Analog-to-Digital Converter (ADC) of the ESP32 microcontroller. The microcontroller converts the analog signals into digital data for processing. Filtering algorithms are applied to reduce noise and fluctuations in the sensor readings. The microcontroller calculates the exact gas concentration in parts per million (ppm) using the sensor calibration curves and formulas.
3. **Threshold Evaluation:**
   The processed data is continuously compared against predefined safe emission limits for each gas. If any of the measured gas concentrations exceed the permissible limits set by environmental regulations, the system prepares to trigger necessary alerts and notifications.
4. **Data Transmission to the Cloud:**
   The ESP32 microcontroller uses its built-in Wi-Fi module to transmit the processed sensor data to a cloud server in real time. In areas where Wi-Fi is not available, alternative modules such as GSM (SIM800L) or LoRa can be used to ensure continuous data transmission via cellular networks or long-range radio communication.
5. **Cloud Data Storage and Visualization:**
   Once the data reaches the cloud platform (e.g., ThingSpeak, Firebase, AWS IoT), it is stored securely and processed for visualization. The cloud platform generates real-time graphs, historical data charts, and summary reports for easy interpretation. These visualizations help both authorities and vehicle owners to monitor pollution levels over time.
6. **Alert Generation:**
   When the pollutant levels exceed the threshold, the cloud platform or the microcontroller immediately triggers alerts. These alerts are sent to vehicle owners and regulatory authorities via mobile notifications, emails, or SMS depending on the system configuration. Additionally, the local system may activate a buzzer or display a warning on the LCD screen installed in the vehicle.
7. **User Interface and Accessibility:**
   The vehicle owner and authorized personnel can access the real-time emission data, alerts, and historical reports via a mobile application (developed using platforms like Blynk or MIT App Inventor) or a web dashboard (developed using Node-RED, HTML, and JavaScript). This enables continuous monitoring and supports preventive maintenance actions.
8. **System Maintenance and Updates:**
   The sensors are periodically calibrated to maintain accuracy. The microcontroller firmware and cloud applications can also be updated remotely to improve system performance, add features, or adjust emission

thresholds based on updated regulations.

4.3 Result of the System

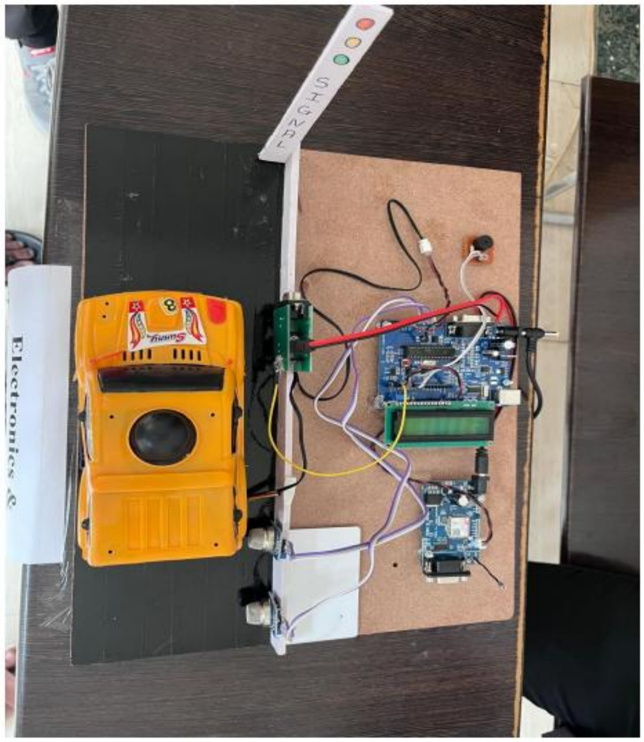

Fig. 2 Hardware Implementation

The developed IoT-based Vehicle Pollution Monitoring System was successfully implemented and tested under controlled conditions. The gas sensors (MQ-7, MQ-135, MQ-136) accurately detected the presence of pollutants such as Carbon Monoxide (CO), Nitrogen Oxides (NOx), and general air quality indicators near the vehicle exhaust. The ESP32 microcontroller effectively processed the sensor data, applied filtering to reduce noise, and converted the raw sensor values into accurate gas concentration levels (in ppm). The system was able to continuously collect data in real-time and transmit it to the cloud server via Wi-Fi with minimal latency.

The cloud platform (ThingSpeak and Firebase) successfully received, stored, and visualized the sensor data. The real-time graphs generated on the dashboard allowed for easy monitoring of the emission levels. Alerts were correctly triggered when the pollutant levels crossed predefined thresholds, and instant notifications were delivered to the vehicle owner's mobile app and the web interface. The system demonstrated reliable performance in real-time tracking, with consistent data transmission and alert generation.

Furthermore, the system proved to be energy-efficient and stable during prolonged operation, consuming minimal power from the vehicle battery. The portability and scalability of the system make it suitable for integration in multiple vehicles and smart city pollution control initiatives. Overall, the experimental results validate that the proposed system can effectively monitor vehicular emissions, generate real-time alerts, and provide actionable data to help reduce environmental pollution.

V. CONCLUSION

In this paper, an IoT-based Vehicle Pollution Monitoring System has been successfully designed and implemented to address the growing problem of vehicular emissions. By integrating gas sensors, a microcontroller (ESP32), wireless communication modules, and cloud-based platforms, the system provides real-time monitoring, data visualization, and instant alerts when emission levels exceed permissible limits. The system enables vehicle owners and authorities to take timely corrective measures, thus contributing to environmental protection and public health. Its scalability, low cost, and remote accessibility make it an effective solution for large-scale deployment in smart cities to support sustainable urban transportation and pollution control initiatives.

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