IoT-Based Vehicle Emission Monitoring System for Real Time Visualization

Jesvinth S
B.Sc. Information Technology
Department of Information technology
Sri Krishna Adithya College of Arts and Science
Jesvinth7613@gmail.com

Dr. Sreejith Vignesh B P., Ph.D.,
Associate Professor & Head
Department of Information Technology
Sri Krishna Adithya College of Arts and Science
sreejithvigneshbp@skacas.ac.in

Abstract
With the rapid growth of urbanization and the increasing number of vehicles on the roads, air pollution has emerged as a major environmental concern. This project proposes an IoT-based Vehicle Emission Monitoring System that enables real-time detection and analysis of vehicular emissions. The system uses sensor modules to continuously measure concentrations of harmful gases such as CO, CO_2, and NOx, transmitting the collected data to a centralized server for processing and evaluation.
To enhance accountability and regulatory enforcement, the system integrates Automatic Number Plate Recognition (ANPR), allowing authorities to identify vehicles exceeding emission limits and notify owners automatically. Alerts are generated when pollution levels surpass permissible thresholds, and information is displayed on an LCD panel as well as transmitted via connected networks.
By providing immediate feedback and actionable data, this intelligent system supports sustainable urban management, promotes environmental awareness, and assists government agencies in implementing stricter emission control measures. The framework ensures proactive monitoring, contributing to cleaner air and improved public health.

Keywords: IoT, Vehicle Emission Monitoring, Air Pollution Detection, Automatic Number Plate Recognition (ANPR), Real-Time Data Analysis, Environmental Monitoring, Smart Cities, Sensor Networks, CO/CO_2/NOx Detection, Pollution Control System

I. INTRODUCTION

Vehicle emissions are one of the major contributors to air pollution, environmental degradation, and public health issues. Harmful exhaust gases such as **carbon monoxide (CO), carbon dioxide (CO_2), nitrogen oxides (NOx), and hydrocarbons (HC)** are directly linked to problems such as smog, respiratory diseases, and climate change. The increasing concentration of these pollutants emphasizes the urgent need for practical solutions capable of **real-time monitoring and control of vehicular emissions**.

This project proposes an **IoT-based Vehicle Emission Monitoring System** designed to continuously detect and analyze harmful pollutants. The system uses gas sensors interfaced with an **ESP32 microcontroller** to measure emission levels and automatically send alerts whenever readings exceed predefined safety thresholds.

A key innovation of this system is the integration of **Automatic Number Plate Recognition (ANPR)** technology using a webcam. Unlike traditional emission monitoring systems that only detect pollutant levels, this system can **identify high-emission vehicles by capturing and processing their license plates**. This allows authorities to monitor non-compliant vehicles effectively and take targeted actions, such as sending notifications to owners, imposing fines, or recommending vehicle maintenance.

The system is suitable for deployment at **toll booths, urban areas, pollution control zones, and highway checkpoints**, due to its cost-effectiveness, portability, and ease of operation. With features such as **wireless connectivity, real-time notifications, and automated vehicle identification**, the proposed framework supports air quality management and regulatory compliance. By combining intelligent vehicle identification with real-time emission monitoring, the system promotes **sustainable urban development, environmental**

protection, and reduced health risks associated with vehicular pollution.

II. LITERATURE REVIEW

Research on vehicle emission monitoring has gained considerable attention due to its potential to reduce urban air pollution and support regulatory enforcement. Numerous studies have explored sensor-based, automated, and data-driven approaches for real-time detection and management of vehicular emissions.

Sricharan et al. (2013) proposed an intelligent automated emission monitoring system for traffic signals. Their approach used sensor arrays combined with lane-based vehicle detection to measure pollution levels in real time. When pollutant concentrations exceeded permissible limits, the system captured images of the vehicle license plate and sent SMS alerts to both the vehicle owner and relevant authorities. This design demonstrated the feasibility of automated, cost-effective pollution monitoring in urban environments.

Tiwari et al. developed a system that continuously monitored emissions of gases such as CO and NOx using sensors. When thresholds were exceeded, the system intervened in real time by recording the vehicle's GPS location, sending SMS notifications via GSM, and even implementing engine shutdown in certain scenarios. Although practical challenges remained—such as user acceptance and safety concerns—the system highlighted the potential for proactive pollution reduction through integrated detection and control mechanisms.

He et al. (2020) addressed the challenges of monitoring emissions when vehicle fuel type or registration data were unknown, such as for new or non-local vehicles. Their study employed machine learning algorithms including decision trees, random forests, AdaBoost, and XGBoost to analyze remote sensing data. A cascaded classification approach allowed the system to estimate vehicle features and emissions accurately, demonstrating the value of advanced analytics when direct vehicle information is unavailable.

Xia et al. (2022) further advanced emission monitoring by combining on-road remote sensing (ORRS) data with vehicle inspection and maintenance records. Using a dataset of 103,831 light-duty gasoline vehicles, they applied an ensemble model integrating neural networks and XGBoost to predict CO, HC, and NOx emissions under typical driving conditions. This method achieved high accuracy in identifying both high and low emitters, illustrating the effectiveness of integrating machine learning with large-scale, real-time monitoring for continuous emission control.

Overall, these studies reflect a clear progression from localized, sensor-based monitoring to sophisticated, data-driven systems capable of large-scale, real-time vehicle emissions assessment. They underscore the importance of combining automated sensing, machine learning, and real-time control to develop scalable solutions for urban air quality management and regulatory compliance.

II. WORKING OF THE PROPOSED SYSTEM

The proposed IoT-based Vehicle Emission Monitoring System is designed to continuously track, analyze, and manage vehicular emissions in real time. The block diagram of the system is shown in Figure 1, illustrating the integration of sensors, microcontroller processing, alert mechanisms, and image recognition modules.

At the core of the system is the ESP32-S microcontroller, which acts as the central control unit. The system uses the MQ-7 gas sensor to detect carbon monoxide (CO), while the MQ-135 sensor monitors nitrogen oxides (NOx) and carbon dioxide (CO_2). These sensors continuously collect emission data, which is processed by the microcontroller and displayed on LCD and OLED screens for real-time visualization.

When emission levels exceed predefined thresholds, the system triggers multiple responses:

1. An instant audio alert is generated through a buzzer to warn nearby personnel.
2. A webcam captures an image of the vehicle's license plate, activated via a Wi-Fi signal from the ESP32.
3. The captured image is processed using the EasyOCR model for Automatic Number Plate Recognition (ANPR), allowing authorities to identify non-compliant vehicles.

Using the extracted license plate information, authorities can take corrective actions, such as notifying vehicle owners, issuing fines, or

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recommending repairs. In addition to detection and enforcement, the system stores emission data for regulatory compliance and analysis.

The architecture supports wireless data transfer to cloud platforms, enabling remote monitoring and long-term data storage. The system is designed to be portable, scalable, and cost-effective, making it suitable for deployment at toll booths, urban pollution zones, smart cities, and highway checkpoints. This approach provides a practical solution for enhancing air quality, enforcing environmental regulations, and promoting sustainable urban management.

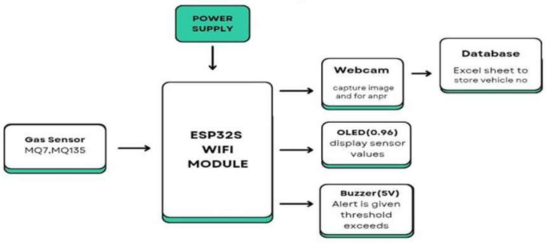


Figure 1 illustrates the block diagram of the proposed system.

Initialization and Workflow of the Proposed System

The operation of the **IoT-based Vehicle Emission Monitoring System** is divided into a sequence of phases to ensure real-time detection, alerting, and documentation of high-emission vehicles.

1. **Initialization Phase:** When the **ESP32-S microcontroller** is powered on, it activates the connected **MQ-7 and MQ-135 gas sensors** to begin monitoring emission levels. This phase prepares the sensors and the microcontroller for continuous data acquisition.
2. **Sensor Data Processing:** The ESP32 reads real-time levels of **CO, CO_2, and NOx** from the sensors. These readings are displayed on the **OLED screen**, providing immediate feedback about the air quality near the vehicle.
3. **Alert and Response Mechanism:** If any of the measured emission levels exceed predefined thresholds, the system triggers an **alert sequence**. A **5V buzzer** sounds an audible alarm, and the ESP32 sends a **Wi-Fi signal** to activate the connected webcam.
4. **Automatic Number Plate Recognition (ANPR):** The webcam captures an image of the vehicle's license plate, which is then sent to a **Python-based ANPR server** for processing. The system extracts the license plate number from the image automatically.
5. **Documentation:** For record-keeping and regulatory purposes, the detected license plate number is stored in an **Excel file**, ensuring proper documentation of non-compliant vehicles.
6. **End Process:** After completing the monitoring, alert, and documentation steps, the system returns to the monitoring state, ready for the next vehicle. This cycle enables **continuous, real-time surveillance** of vehicle emissions.

This structured workflow ensures that the system not only monitors air quality in real time but also provides **immediate alerts, automatic identification, and accurate record-keeping**, making it a practical solution for urban pollution control and regulatory enforcement.

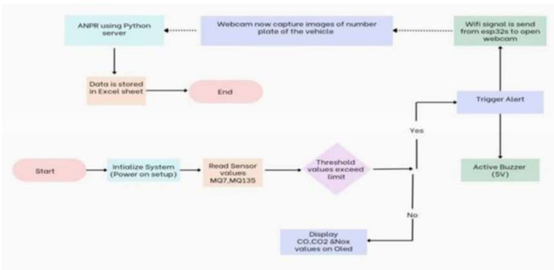


Figure 2 shows the flowchart of the proposed system

IV. RESULTS AND DISCUSSION

The experimental setup of the proposed Vehicle Emission Monitoring System (VEMS) is illustrated in Figure 3. The system integrates both hardware and software components to detect, display, and respond to elevated pollution levels in real time.

At the core of the system is the ESP32-S (NodeMCU), a high-performance microcontroller featuring Wi-Fi and Bluetooth connectivity, a dual-core 32-bit processor, multiple GPIO ports, and low power consumption—making it suitable for real-time IoT applications.

Air quality is measured using the MQ-7 gas sensor for carbon monoxide (CO) and the MQ-135 gas sensor for multiple gases, including CO_2, NOx, NH_3, and benzene. Both sensors provide analog outputs and require preheating to deliver accurate and stable readings.

A 0.96-inch OLED display with an I2C interface is used to visualize sensor readings and system status in real time, providing immediate feedback on pollution levels. When emissions exceed predefined safety thresholds, a webcam captures images of vehicle license plates for automatic identification. The images are processed using Python, OpenCV, and Tesseract OCR, and the recognized license plate numbers are stored in an Excel file for record-keeping and regulatory purposes.

For alerting, a 5V active buzzer sounds when gas concentrations surpass safe limits, providing a clear audible warning. The system software combines Arduino IDE programming for the ESP32 with Python for ANPR operations, ensuring smooth integration of all hardware and software components for real-time monitoring, data processing, and enforcement of emission regulations.

The experimental results demonstrate that the system can reliably detect pollutants, trigger alerts, and identify high-emission vehicles automatically, making it an effective solution for urban air quality monitoring, regulatory compliance, and proactive environmental management.

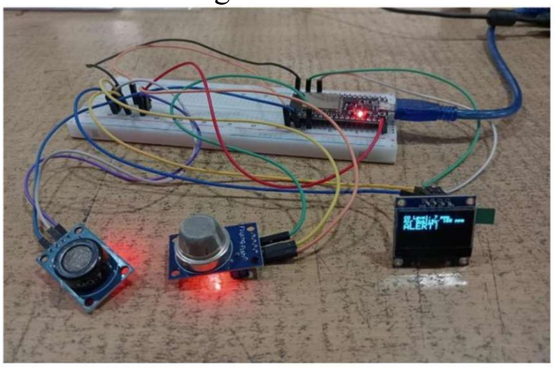
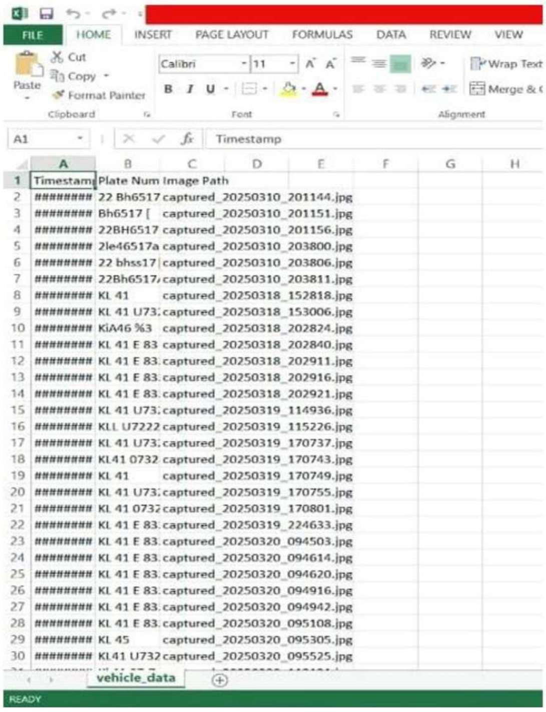


Figure 3 shows the setup the proposed system

Following successful detection of vehicle license plates, the extracted plate numbers are **automatically recorded in an Excel spreadsheet** for future reference. This allows regulatory authorities to access the data as needed for monitoring, compliance, and enforcement purposes. A **screenshot of the stored database** is presented in Figure 4, illustrating the structured storage and easy retrieval of detected vehicle information.



	A	B	C
1	Timestamp	Plate Num	Image Path
2	#########	22 Bh6517	captured_20250310_201144.jpg
3	#########	Bh6517 [	captured_20250310_201151.jpg
4	#########	22BH6517	captured_20250310_201156.jpg
5	#########	2le46517a	captured_20250310_203800.jpg
6	#########	22 bhss17		captured_20250310_203806.jpg
7	#########	22Bh6517	captured_20250310_203811.jpg
8	#########	KL 41	captured_20250318_152818.jpg
9	#########	KL 41 U73	captured_20250318_153006.jpg
10	#########	KiA46 %3	captured_20250318_202824.jpg
11	#########	KL 41 E 83	captured_20250318_202840.jpg
12	#########	KL 41 E 83	captured_20250318_202911.jpg
13	#########	KL 41 E 83	captured_20250318_202916.jpg
14	#########	KL 41 E 83	captured_20250318_202921.jpg
15	#########	KL 41 U73	captured_20250319_114936.jpg
16	#########	KLL U7222	captured_20250319_115226.jpg
17	#########	KL 41 U73	captured_20250319_170737.jpg
18	#########	KL41 0732	captured_20250319_170743.jpg
19	#########	KL 41	captured_20250319_170749.jpg
20	#########	KL 41 U73	captured_20250319_170755.jpg
21	#########	KL 41 0732	captured_20250319_170801.jpg
22	#########	KL 41 E 83	captured_20250319_224633.jpg
23	#########	KL 41 E 83	captured_20250320_094503.jpg
24	#########	KL 41 E 83	captured_20250320_094614.jpg
25	#########	KL 41 E 83	captured_20250320_094620.jpg
26	#########	KL 41 E 83	captured_20250320_094916.jpg
27	#########	KL 41 E 83	captured_20250320_094942.jpg
28	#########	KL 41 E 83	captured_20250320_095108.jpg
29	#########	KL 45	captured_20250320_095305.jpg
30	#########	KL41 U732	captured_20250320_095525.jpg

Figure 4 Displays the vehicle plate number output stored in a CSV file.

V. MODULES

The proposed system is divided into several **interconnected modules**, each performing a specific function to enable real-time emission monitoring, vehicle identification, and regulatory compliance.

1. Sensor Module

This module includes the **MQ-7 and MQ-135 gas sensors**, which continuously detect harmful gases such as CO, CO_2, and NOx. The sensors provide analog signals that are read by the **ESP32-S microcontroller**, ensuring accurate monitoring of vehicle emissions. Preheating of the sensors ensures reliable and stable readings.

2. Microcontroller Module

The **ESP32-S microcontroller** acts as the system's brain, receiving data from the sensors, processing it, and managing alerts. It is equipped with **Wi-Fi and Bluetooth connectivity**, a dual-core 32-bit processor, and multiple GPIO ports, making it suitable for **real-time IoT applications**. The microcontroller handles data visualization, threshold checks, and communication with the ANPR module.

3. Display Module
A **0.96-inch OLED display** shows real-time emission readings, system status, and alerts. This module provides immediate visual feedback, allowing on-site operators to monitor air quality at a glance.

4. Alert and Response Module
When gas concentrations exceed permissible limits, this module triggers:

- **Audible alerts** via a 5V buzzer
- **Activation of the connected webcam** for license plate capture
  This ensures that high-emission vehicles are detected and the appropriate response is initiated immediately.

5. Automatic Number Plate Recognition (ANPR) Module
The **webcam captures images** of the vehicle license plate, which are then processed using **Python, OpenCV, and Tesseract OCR**. This module extracts the license plate number for storage and regulatory action.

6. Data Storage and Documentation Module
The recognized license plate numbers and associated emission data are **automatically saved in an Excel sheet**. This provides an organized record for authorities, enabling follow-up actions, compliance tracking, and analysis of pollution trends.

7. Cloud and Remote Monitoring (Optional Enhancement)
Future iterations can integrate cloud platforms for **real-time remote monitoring, analytics, and reporting**, allowing authorities to access multiple sites simultaneously and generate long-term emission reports.

VI. FUTURE ENHANCEMENTS

The Vehicle Emission Monitoring System (VEMS) has significant potential for further development to improve its functionality, efficiency, and user experience. Future enhancements may include:

1. **Cloud Integration and Remote Monitoring:**
   Connecting the system to cloud platforms would allow real-time data storage, analysis, and remote access. Regulatory authorities could monitor multiple locations simultaneously, generate automated reports, and track emission trends over time.
2. **Mobile Application Interface:**
   Developing a dedicated mobile application could provide instant notifications and alerts to authorities and vehicle owners, making the system more interactive and user-friendly.
3. **Automatic Bank/Fine Integration:**
   Integration with government databases could enable automated penalty issuance for non-compliant vehicles, streamlining enforcement processes.
4. **Advanced Sensor Expansion:**
   Adding sensors for particulate matter (PM2.5 and PM10), sulfur oxides (SOx), and volatile organic compounds (VOCs) could improve air quality monitoring and provide a more comprehensive assessment of vehicular pollution.
5. **Machine Learning for Emission Prediction:**
   Incorporating machine learning algorithms could predict high-emission vehicles, classify emission patterns, and optimize traffic management to reduce overall pollution levels.
6. **Solar-Powered or Low-Power Designs:**
   Implementing energy-efficient or solar-powered components could make the system more sustainable and suitable for remote or off-grid locations.
7. **Expanded ANPR Capabilities:**
   Enhancing the Automatic Number Plate Recognition system to support multiple vehicle types, international plate formats, and high-speed vehicles would broaden the system's applicability in urban and highway environments.

These enhancements would increase the **accuracy, scalability, and intelligence** of the system, enabling authorities to manage urban air quality more effectively and promoting a cleaner, healthier, and sustainable environment.

VII. CONCLUSION

The **Vehicle Emission Monitoring System (VEMS)** offers an innovative **IoT-based solution** for real-time monitoring and analysis of vehicular

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emissions. With increasing concerns about urban air quality, there is a critical need for automated pollution detection systems that incorporate **Automatic Number Plate Recognition (ANPR)** to identify high-emission vehicles and notify relevant authorities.

VEMS effectively detects vehicles exceeding emission limits and captures their license plate information, which is stored in a database for regulatory monitoring and enforcement. By integrating **gas sensors, automated alerts, and license plate recognition**, the system provides real-time data that supports timely corrective action.

The system's **accuracy, scalability, and reliability** make it a practical tool for government agencies, environmental organizations, and traffic management authorities. By enabling proactive monitoring and enforcement of emission standards, VEMS contributes to **better air quality, smarter urban management, and a healthier environment**, supporting sustainable urban development and long-term public health improvements.

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