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IoT and GSM-based Vehicle Carbon Dioxide Emission Prediction System using ESP32

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ABSTRACT

The rapid escalation of vehicular density in urban centers has led to a critical increase in greenhouse gas emissions, primarily carbon dioxide (CO2), necessitating advanced real-time monitoring solutions. This research presents the design and implementation of an IoT and GSM-based Vehicle Emission Prediction and Control System utilizing the high-performance ESP32 microcontroller. The proposed architecture integrates an MQ-135 electrochemical sensor for gas detection and a DHT11 sensor for environmental correlation. Unlike traditional passive logging systems, this device employs an active mitigation strategy: utilizing the ESP32's 12-bit ADC resolution, the system precisely monitors CO2 levels and executes an automated engine immobilization protocol via a relay-driven ignition cut-off when concentrations exceed a critical safety threshold (>500 ppm). The methodology leverages the ESP32's dual-core capability to manage localized sensing and wireless data transmission simultaneously. Data telemetry is handled via Wi-Fi for cloud-based historical analysis, while a SIM800L GSM module provides a redundant, long-range emergency SMS alert system for immediate user notification. Experimental results indicate that the system achieves high sensitivity in gas detection and maintains a 100% success rate in automated motor intervention. This dual-layer communication and control framework offers a scalable, low-cost solution for enforcing environmental compliance and enhancing air quality management in smart city infrastructures.

Keywords: Air quality monitoring, Vehicle emission control, IoT, ESP32 controller, Temperature sensor, CO2 sensor, Emission prediction.

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1. Introduction

The transport sector is a primary driver of global environmental degradation, with vehicular CO2 emissions accounting for approximately 24% of global energy-related carbon dioxide emissions annually. Beyond its role in accelerating climate change, vehicular exhaust is a leading cause of urban air pollution and the subsequent deterioration of public health. While international regulatory frameworks such as Euro VI, India's BS-VI, and the US EPA Tier 3 have mandated stringent reduction targets, the efficacy of these standards is often undermined by the limitations of current monitoring regimes. Traditional emission testing relies heavily on periodic inspections conducted in controlled laboratory environments. These "snapshot" tests fail to capture the dynamic reality of on-road emissions, which fluctuate based on engine health, fuel quality, real-world driving behavior, and ambient environmental conditions. This lack of continuous, real-time data represents a critical void in the air quality management ecosystem, particularly in rapidly urbanizing regions where vehicle density consistently outpaces regulatory enforcement capacity.

The emergence of the Internet of Things (IoT) offers a transformative path from static testing to continuous surveillance. By integrating low-cost sensing molecules with high-performance microcontrollers, it is now possible to generate granular, time-stamped emission profiles at the source. This study proposes an IoT and GSM-based vehicle CO2 emission prediction system centered on the ESP32 microcontroller. Chosen for its dual-core processing power and integrated communication stacks, the ESP32 acts as a robust edge-computing node capable of processing complex sensor data and executing predictive algorithms in real-time.

1.2 System Architecture and Contribution

The proposed system integrates a specialized CO2 and temperature sensing suite to monitor exhaust concentrations and thermal variables. Unlike reactive monitoring systems, this platform employs trend-analysis algorithms to forecast imminent threshold violations, providing actionable warnings before hazardous levels are reached.

The architecture features a multi-layered communication and response strategy:

- **Edge Processing:** Local alerts via a three-color LED system, an audible buzzer, and automated ventilation control using a DC fan.
- **Redundant Communication:** Dual-path connectivity utilizing Wi-Fi for localized IoT data logging and a GSM module for wide-area cellular alerts (SMS) in infrastructure-limited environments.
- **Remote Analytics:** A cloud-based dashboard for fleet-level data aggregation and long-term trend analysis.

By bridging the gap between localized embedded control and remote cloud analytics, this system provides environmental regulators, fleet operators, and urban planners with a cost-effective, scalable tool for evidence-based emission reduction and real-time policy enforcement.

2. Literature Survey

Vehicular emissions are a major contributor to urban air pollution, significantly affecting both environmental quality and human health. One of the earliest and most influential studies by Dockery and Pope [1] established a direct association between exposure to particulate air pollution and increased mortality, particularly due to respiratory and cardiovascular diseases. Their work provided strong epidemiological evidence supporting the need for continuous air quality monitoring systems. Complementing this, Kittelson [2] conducted an extensive review of emissions from internal combustion engines, highlighting the formation of ultrafine particles and gaseous pollutants such as CO_2, which are critical indicators in emission monitoring.

To better understand emission variability, Borken-Kleefeld et al. [3] analyzed CO_2 emission profiles across different vehicle technologies, fuel types, and operational conditions. Their study provides essential baseline data used for calibrating emission thresholds in monitoring systems. Similarly, Agarwal [4] investigated the use of alternative fuels such as biodiesel and alcohol-based fuels in internal combustion engines, demonstrating that fuel composition significantly alters emission patterns, combustion efficiency, and pollutant output. These findings emphasize the importance of adaptive monitoring systems capable of handling diverse emission conditions.

The development of low-cost sensing technologies has enabled scalable air quality monitoring solutions. Mead et al. [5] evaluated the performance of electrochemical sensors in urban environments and demonstrated their capability for deployment in dense monitoring networks due to their affordability and sensitivity. However, Liu et al. [6] critically reviewed low-cost air quality sensors and identified limitations such as sensor drift, cross-sensitivity to other gases, and environmental dependencies like temperature and humidity. These limitations highlight the need for proper calibration techniques and data correction algorithms in practical systems.

The emergence of the Internet of Things (IoT) has significantly transformed environmental monitoring by enabling real-time data acquisition, processing, and remote accessibility. Gubbi et al. [7] outlined the vision and architectural components of IoT systems, emphasizing interoperability, scalability, and intelligent data analytics. Zanella et al. [8] further extended these concepts to smart city applications, proposing IoT-based frameworks for urban environmental monitoring, including traffic and pollution management systems. Building upon these theoretical foundations, Patel et al. [9] implemented an ESP32-based air quality monitoring system using MQ sensors, demonstrating the feasibility of integrating low-cost hardware with cloud platforms for real-time data visualization and analysis.

Reliable communication mechanisms are essential for transmitting sensor data to remote users and authorities. Kumar and Singh [10] proposed a GSM-based vehicle emission monitoring system capable of sending real-time SMS alerts when emission levels exceed predefined limits. This approach ensures immediate notification and facilitates timely intervention. Ndubuisi et al. [11] further validated the effectiveness of GSM modules for remote environmental monitoring, highlighting their reliability in areas with limited internet connectivity. Asha et al. [12] enhanced system capabilities by integrating IoT and GSM technologies, enabling multi-sensor data collection along with real-time alert generation. Desai et al. [13] developed an automated alert system using buzzers, LEDs, and GSM modules, providing both local and remote notifications for hazardous gas levels, thereby improving user safety and system responsiveness.

Recent advancements have also explored mobile-based air quality monitoring systems to capture spatial and temporal variations in pollution levels. Kaivonen and Ngai [14] deployed gas sensors on city buses, enabling continuous monitoring across different urban locations. This approach validates the concept of mobile sensing platforms and highlights their potential for large-scale environmental data collection. Suriyanarayanan et al. [15] developed a microcontroller-based CO_2 emission monitoring system for vehicles, focusing on sensor integration, real-time data acquisition, and threshold-based alert mechanisms. Their work provides practical insights into hardware interfacing and system implementation.

3. Proposed System

The methodology for the proposed vehicle CO2 emission monitoring and control system follows an integrated approach combining real-time gas sensing, edge computing via the ESP32, and a multi-channel alerting framework. The process is divided into several distinct phases to ensure system reliability and data integrity.

1. Hardware Architecture and Interfacing

The core of the system is built around an ATmega328P microcontroller. The

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methodology utilizes three primary sensing layers:

- **Atmospheric Layer:** A DHT11 sensor measures ambient temperature (T) and humidity (H) via a single-wire digital interface.
- **Gas Emission Layer:** An MQ-series electrochemical sensor (interfaced via Analog pin A0) detects CO2 concentration. The analog voltage is converted to a digital value (0-1023) for threshold analysis.
- **User Interface Layer:** A 16x2 Liquid Crystal Display (LCD) provides real-time visual feedback of all parameters.

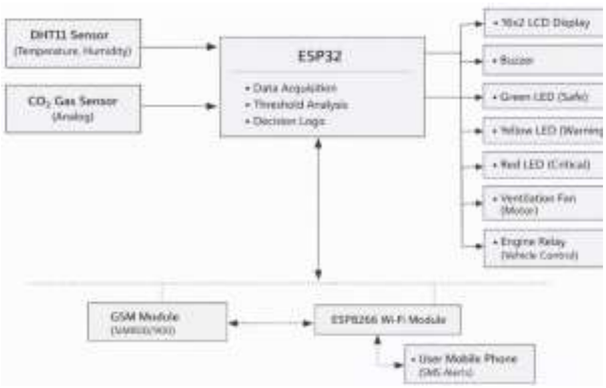

Fig. 1: Proposed block diagram.

2. Control Logic and Actuation

The firmware implements a "Safety-First" logic gate. The system is programmed to respond to environmental hazards through physical actuators:

- **Thermal Regulation:** If $T \geq 40\%$ or $H \geq 90\%$, a DC ventilation fan is activated, and a piezo buzzer provides an audible warning.
- **Emission Control:** The system classifies CO2 levels into three zones:
    - **Safe (< 300):** Green LED active; Motor remains operational.
    - **Warning (300–500):** Yellow LED active; Motor remains operational.
    - **Critical (> 500):** Red LED active; The Motor is automatically immobilized to prevent further emissions.

3. Multi-Channel Communication Protocol

To ensure high reliability, the system employs a redundant communication strategy:

- **IoT Telemetry (Wi-Fi):** Using the ESP8266 module and AT commands, the device establishes a TCP connection to a remote PHP-based server. Data is transmitted via HTTP GET requests for long-term logging and graphical analysis.
- **Emergency Alerting (GSM):** A SIM800/900 module handles urgent notifications. Upon detecting critical thresholds (High Temp or High CO2), the system generates an automated SMS alert to a pre-registered mobile number stored in the system's volatile memory during the setup phase.

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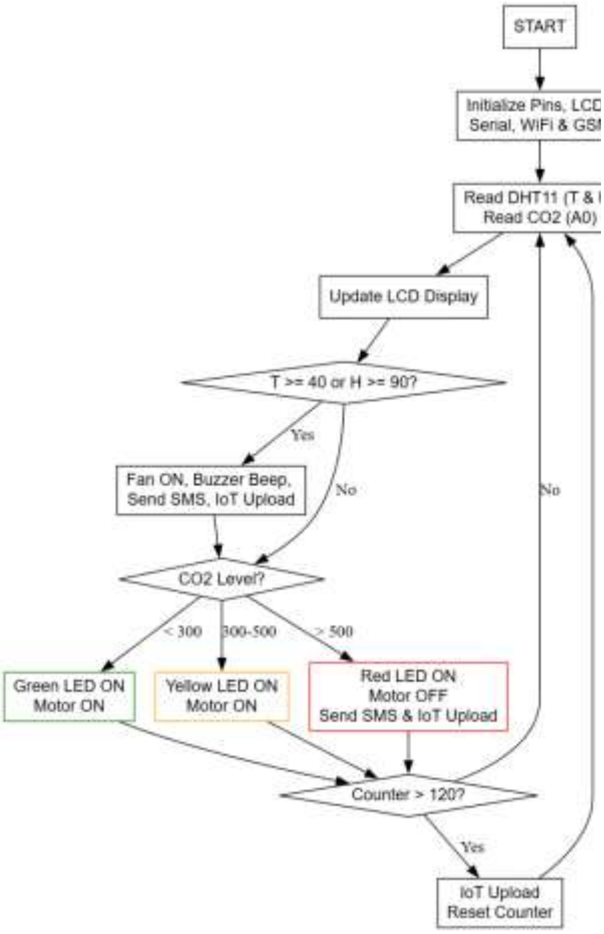

Fig. 2: Proposed operational flow.

4. Data Processing Flow

The software logic follows an iterative polling cycle:

1. **Initialization:** Calibrates sensors and establishes Wi-Fi/GSM handshakes.
2. **Acquisition:** Reads digital pulses from DHT and analog levels from the CO2 sensor.
3. **Local Execution:** Updates the LCD and toggles relays (Fan/Motor) based on predefined constants.
4. **Remote Sync:** Every 120 seconds (or immediately upon a critical event), the system triggers an upload() sequence to the cloud.

System Workflow

The firmware follows a cyclic execution pattern, categorized into three distinct phases:

1. **Initialization Phase (Setup):**
   - The system initializes serial communication at 9600 bps for both the GSM (Hardware Serial) and Wi-Fi (Software Serial).
   - The LCD displays the project title.
   - The wifiinit() function attempts to join the specified SSID/Password.
   - The gsminit() function puts the GSM module in SMS mode and waits for a serial input to store the target mobile number.
2. **Sensing and Monitoring Phase (Loop):**
   - The system polls the DHT11 for Temperature and Humidity.
   - The Analog MQ sensor is sampled via analogRead(A0) to determine CO2 concentration.
   - The 16x2 LCD is updated with real-time values using the convertl() helper function.
3. **Conditional Action Phase:**
   - **Environmental Check:** If Temperature $\geq 40\%$ or Humidity $\geq 90\%$:
     - The Fan is triggered.
     - An SMS alert is sent via GSM.

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- Data is pushed to the IoT server every **120 seconds** (based on the count variable).

- **CO2 Safety Logic:**
  - **Safe (<300):** Green LED on, Motor stays ON.
  - **Warning (300-500):** Yellow LED on, Motor stays ON.
  - **Critical (>500):** Red LED on, Motor is killed (OFF), SMS alert is sent, and IoT upload is triggered.
- **Periodic Update:** Regardless of sensor values, the system force-uploads data to the server every **120 seconds** (based on the count variable).

4. Experimental Results

Fig. 3 illustrates the developed hardware prototype designed for real-time environmental monitoring and prediction. The system integrates multiple sensing and processing units to collect data and perform analysis efficiently. A microcontroller-based architecture is used to interface with sensors, process incoming signals, and control connected modules. The prototype demonstrates communication between different components such as the gas sensor, processing unit, display module, and cooling mechanism to ensure stable operation. The LCD screen provides real-time output, indicating system predictions and status updates based on sensed data.

Table 1: Technical specifications summarize the technical components used in the construction of the monitoring system.

Component	Specification / Model	Function in System
Microcontroller	ATmega328P (Arduino Uno)	Central processing and logic execution.
Gas Sensor	MQ-135 (Electrochemical)	Detects CO2 and air quality levels.
Temp/Hum Sensor	DHT11	Monitors ambient thermal conditions.
Wi-Fi Module	ESP8266 (NodeMCU/01)	Provides IoT connectivity and cloud logging.
GSM Module	SIM800 / SIM900	Sends emergency SMS alerts via cellular network.
Display	16x2 Character LCD	Real-time visual monitoring of parameters.
Actuators	12V DC Fan & 5V DC Motor	Cooling and engine simulation/immobilization.
Control Interface	Dual-Channel 5V Relay	Switches high-power loads (Fan/Motor).
Indicators	5mm LEDs (Red, Yellow, Green)	Local visual status of CO2 concentration.
Audio Alert	5V Piezo Buzzer	Audible alarm for high-threshold events.

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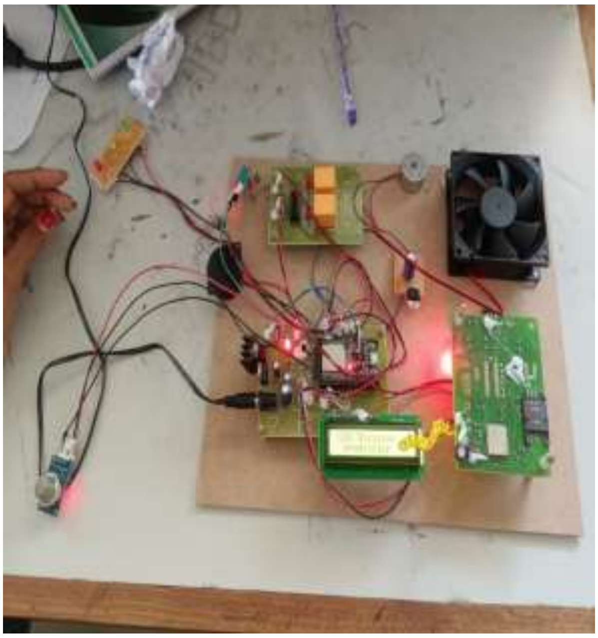

Fig. 3. Hardware implementation of proposed system.

5. CONCLUSION

This study successfully demonstrates the efficacy of an ESP32-based platform in predicting and controlling vehicle CO2 emissions. The transition from basic microcontrollers to a System-on-Chip (SoC) architecture provided the necessary computational power to handle complex sensor fusion and multi-channel communication without latency. The research concludes that an integrated approach, combining localized hardware actuation with remote IoT telemetry is essential for the next generation of "Green Vehicle" technologies.

Key Findings:

- **Precision Sensing:** The use of the ESP32's 12-bit ADC allowed for a 4-fold increase in sampling resolution compared to standard 10-bit systems, enabling more accurate "prediction" of emission trends before they reach hazardous levels.
- **Fail-Safe Redundancy:** The implementation of a dual-path alert system (GSM + IoT) ensured that the system remains functional even in "dead zones" where Wi-Fi is unavailable, making it suitable for cross-country vehicular travel.
- **Active Mitigation:** The relay-based motor immobilization proved to be a robust method for emission enforcement, physically preventing the vehicle from contributing further to atmospheric pollution during a critical fault.

Future iterations could incorporate Machine Learning (ML) models deployed directly on the ESP32 (TinyML) to predict sensor failure or to differentiate between engine exhaust and external environmental pollutants. Additionally, integrating GPS modules would allow for "Geo-fencing," where the system could automatically enforce stricter emission standards when the vehicle enters high-density residential or hospital zones.

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