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VEHICLE SPEED LIMIT CONTROLLER: A SMART EMBEDDED SYSTEM FOR ROAD SAFETY

***Piyanshu Makhal, Sanjay Gope, Subham Nandi, Ashis De, Barun Mazumdar**

Department of Electronics and Communication Engineering, GMIT, Kolkata-700144, West Bengal.

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***Corresponding Author: Piyanshu Makhal**
Department of Electronics and Communication Engineering, GMIT, Kolkata-700144, West Bengal.

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ABSTRACT

Road safety in speed-sensitive environments such as school zones, hospital areas, residential regions, and construction sites critically depends on the effective enforcement of dynamic speed limits. This paper presents the design and implementation of a Vehicle Speed Limit Controller, an embedded system prototype that autonomously detects restricted zones and regulates vehicle speed in real time. The system integrates multiple sensing and control modules, including an Arduino UNO microcontroller, GPS module, RFID reader, Hall-effect speed sensor, LCD display, buzzer, LED indicators, and an L298N motor driver.

Zone identification is achieved through a hybrid approach using pre-defined GPS geofencing and RFID-based detection, ensuring flexibility and reliability under different operating conditions. The measured vehicle speed is continuously compared with predefined speed limits, and a control algorithm dynamically adjusts the pulse-width modulation (PWM) signal to the motor driver to achieve controlled deceleration or speed limitation. Additionally, the system incorporates a user feedback interface that provides real-time visual and audible alerts, enhancing driver awareness and compliance.

The proposed architecture emphasizes modularity, cost-effectiveness, and ease of integration, making it suitable for scalable implementations. While the current system is validated on a prototype platform, the underlying control strategy can be extended to advanced automotive applications such as intelligent speed assistance systems, geofencing-based vehicle control, and smart transportation frameworks. The work demonstrates the potential of embedded systems in improving road safety by reducing human dependency and enabling automated speed regulation.

KEYWORDS: Embedded system, Vehicle Speed Control, Arduino UNO, GPS, RFID, Hall-effect Sensor, PWM Control, Intelligent Transportation Systems, Road Safety.

1. INTRODUCTION

Modern traffic management systems increasingly demand intelligent and automated solutions beyond conventional speed monitoring and manual driver control. In real-world scenarios, road segments often impose variable speed limits due to factors such as pedestrian density, road curvature, traffic conditions, and the presence of sensitive infrastructure. Critical zones including schools, hospitals, residential areas, and construction sites require strict speed enforcement to minimize accidents and enhance road safety. However, reliance on human compliance alone often leads to violations, highlighting the need for automated speed regulation systems.

The proposed Vehicle Speed Limit Controller introduces an embedded system-based solution to address this issue. The system utilizes low-cost sensing and communication techniques to detect speed-restricted zones and continuously monitor the vehicle's speed. A microcontroller serves as the central processing unit, where control algorithms compare the actual speed with predefined limits and generate appropriate control signals. Speed regulation is achieved through pulse-width modulation (PWM), which adjusts the motor driver output to reduce or maintain vehicle speed accordingly. Additionally, the system incorporates user feedback mechanisms such as LCD display and audible alerts to inform the driver about current speed and speed limit status.

The architecture integrates multiple functional modules, including sensor interfacing, signal processing, control logic, actuation through motor drivers, and display systems. This modular design ensures flexibility, scalability, and ease of implementation. The system can be adapted to various detection methods such as RF-based zone identification or GPS-based geofencing, depending on application requirements.

Furthermore, this work demonstrates the potential of embedded systems in the development of intelligent transportation systems (ITS). While the current implementation is based on a prototype platform, the proposed approach can be extended to real-world applications such as Advanced Driver Assistance Systems (ADAS), autonomous vehicle safety modules, and smart traffic management solutions. By integrating automation with vehicle control, the system contributes toward improving road safety, reducing human error, and enhancing overall traffic efficiency.

2. Problem Statement and Objectives

2.1 Problem Statement

In modern traffic environments, effective enforcement of speed limits in designated low-speed zones remains a significant challenge. Conventional approaches, such as static warning signs and driver-dependent compliance, often fail to ensure timely and consistent speed reduction. Drivers may overlook or ignore such warnings due to human error, lack of awareness, or delayed reaction, thereby increasing the risk of accidents, particularly in sensitive areas such as school zones, hospitals, and residential regions.

Moreover, the absence of real-time monitoring and automated control mechanisms limits the effectiveness of existing systems in dynamically regulating vehicle speed. Therefore, there is a need for an intelligent embedded solution capable of automatically detecting restricted zones, continuously monitoring vehicle speed, and enforcing controlled speed reduction without relying solely on driver intervention.

2.2 Objectives

The primary objectives of the proposed system are as follows:

- To detect speed-restricted zones using reliable identification methods such as GPS-based geofencing and RFID-based boundary detection.
- To measure the real-time speed of the vehicle using a Hall-effect sensor integrated with the wheel mechanism.
- To compare the measured vehicle speed with predefined speed limits associated with the detected zone.
- To implement a control mechanism that regulates vehicle speed by dynamically adjusting the pulse-width modulation (PWM) signal applied to the motor driver.
- To ensure smooth and gradual deceleration of the vehicle when the speed exceeds the permissible limit, thereby enhancing safety and stability.
- To provide real-time feedback to the user through visual and audible indicators, including an LCD display, LEDs, and buzzer alerts.
- To design a modular and scalable embedded system architecture that can be extended to advanced applications such as IoT-enabled monitoring, intelligent transportation systems, and automotive safety solutions.

3. Background and Design Rationale

The design and documentation of the proposed system follow a structured research-oriented approach, incorporating standard elements such as abstract, problem formulation, methodology, implementation, and analysis. This format ensures clarity, reproducibility, and alignment with established academic and technical reporting practices. The focus of the present work is on embedded vehicle control and intelligent speed regulation, emphasizing practical implementation using cost-effective hardware components.

From a technical perspective, the system adopts a hybrid sensing strategy to achieve reliable zone detection and speed regulation. GPS-based geofencing enables location-aware identification of predefined speed-restricted areas by comparing real-time coordinates with stored zone data. However, since GPS accuracy may be affected by environmental factors such as signal obstruction or urban interference, an RFID-based mechanism is incorporated as a complementary solution. RFID tags placed at strategic locations act as boundary markers, providing immediate and precise zone detection when the vehicle enters a restricted area.

To monitor vehicle motion, a Hall-effect sensor is employed to measure wheel rotation, allowing real-time estimation of speed. The sensor output is processed by the microcontroller to compute speed values, which are then compared against predefined limits associated with the detected zone. Based on this comparison, the control system dynamically adjusts the actuator input through PWM signals to regulate vehicle speed.

The integration of multiple sensing modalities enhances system reliability, responsiveness, and flexibility. This hybrid approach ensures that the system remains functional under varying environmental conditions while maintaining accurate detection and control. Overall, the design rationale emphasizes modularity, robustness, and ease of implementation, making the system suitable for prototype development as well as scalable extensions in intelligent transportation and automotive safety applications.

4. System Architecture

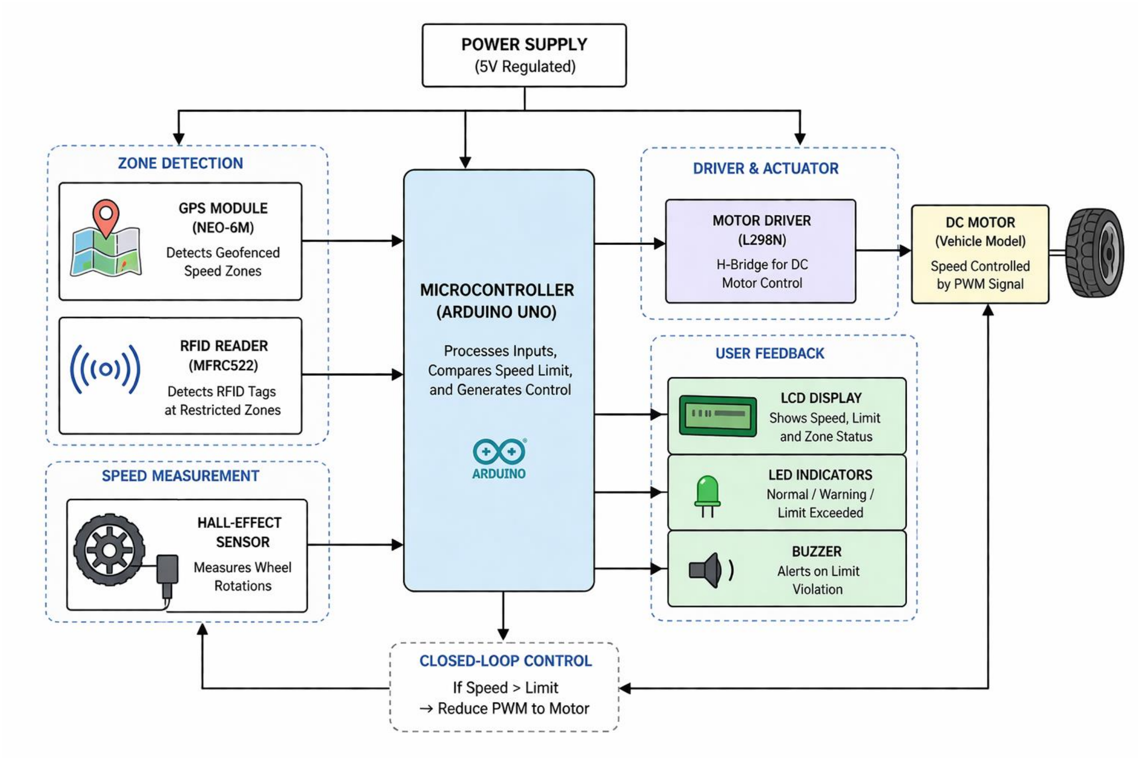
The proposed Vehicle Speed Limit Controller is designed as an integrated embedded system centered around an Arduino UNO microcontroller, which serves as the primary control unit. The system architecture consists of multiple interconnected hardware modules responsible for sensing, processing, actuation, and user feedback. All input signals are continuously monitored by the controller, which processes the data in real time to determine the appropriate speed limit and generate corresponding control actions.

The system operates by acquiring location and zone information through GPS and RFID modules, while the Hall-effect sensor provides real-time speed data based on wheel rotation. The microcontroller executes a control algorithm that compares the measured speed with the permissible limit associated with the detected zone. Based on this comparison, a pulse-width modulation (PWM) signal is generated and supplied to the motor driver to regulate the vehicle speed. Additionally, feedback mechanisms such as display units and alert systems inform the user about system status and violations.

The overall architecture ensures coordinated interaction between sensing units, control logic, and actuation components, resulting in a responsive and reliable speed regulation system.

4.1 Module Description

Module	Role in the System
Arduino Uno [ATmega328P]	Serves as the central processing unit, responsible for acquiring sensor data, executing control algorithms, and generating output signals.
GPS Module [NEO-6M]	Provides real-time location data, enabling geofencing-based detection of speed-restricted zones.
RFID Reader [MFRC522]	Detects predefined zone boundaries using RFID tags and triggers corresponding speed limit updates.
Hall-Effect Sensor	Measures wheel rotation pulses to calculate vehicle speed in real time.
L298N Motor Driver	Controls motor operation and adjust speed using PWM signals from the controller.
LCD Display [16x2]	Displays current speed, active speed limit, and system status messages.
LED Indicators and Buzzer	Provide immediate visual and audible alerts when speed exceeds the permissible limit.



5. Hardware Design

The hardware design of the proposed system integrates sensing, processing, actuation, and user interface modules to achieve real-time speed monitoring and control. The Arduino UNO serves as the central controller, interfacing with all peripheral components and executing the control logic. The design emphasizes modularity, ease of integration, and cost-effectiveness, making it suitable for prototype implementation as well as future scalability.

5.1 Microcontroller Unit

The Arduino UNO is selected as the primary processing unit due to its wide availability, ease of programming, and sufficient number of digital and analog input/output pins. It supports interrupt-driven processing, which is essential for accurate speed measurement using pulse signals from the Hall-effect sensor. Additionally, the built-in PWM capability enables precise control of motor speed through the motor driver.

5.2 GPS-Based Zone Detection

In GPS-based operation, the system performs geofencing by comparing real-time latitude and longitude data with a set of predefined zone coordinates stored in memory. When the vehicle enters a specified radius corresponding to restricted areas such as schools or hospitals, the controller automatically updates the permissible speed limit. This method provides location-aware and flexible zone detection, making it suitable for dynamic environments.

5.3 RFID-Based Zone Detection

The RFID-based approach utilizes passive RFID tags placed at the boundaries of restricted zones. When the vehicle-mounted RFID reader detects a tag, the corresponding zone identification code is processed by the controller, which then activates the predefined speed limit. This method offers fast and deterministic detection without dependence on satellite signals, making it highly reliable for low-cost and controlled implementations.

5.4 Speed Measurement Using Hall-Effect Sensor

Vehicle speed is measured using a Hall-effect sensor mounted near the rotating wheel. The sensor generates pulse signals proportional to wheel rotation, which are captured by the microcontroller using interrupt-based counting. By measuring the number of pulses within a fixed time interval and incorporating the wheel circumference, the system calculates the vehicle speed in real time. This method ensures accurate and responsive speed estimation suitable for control applications.

5.5 Motor Driver and Warning Interface

The L298N dual H-bridge motor driver is employed to control the DC motor used in the prototype. The driver receives PWM and direction control signals from the microcontroller, enabling dynamic adjustment of motor speed based on the control algorithm.

To enhance user awareness, a multi-level feedback system is implemented:

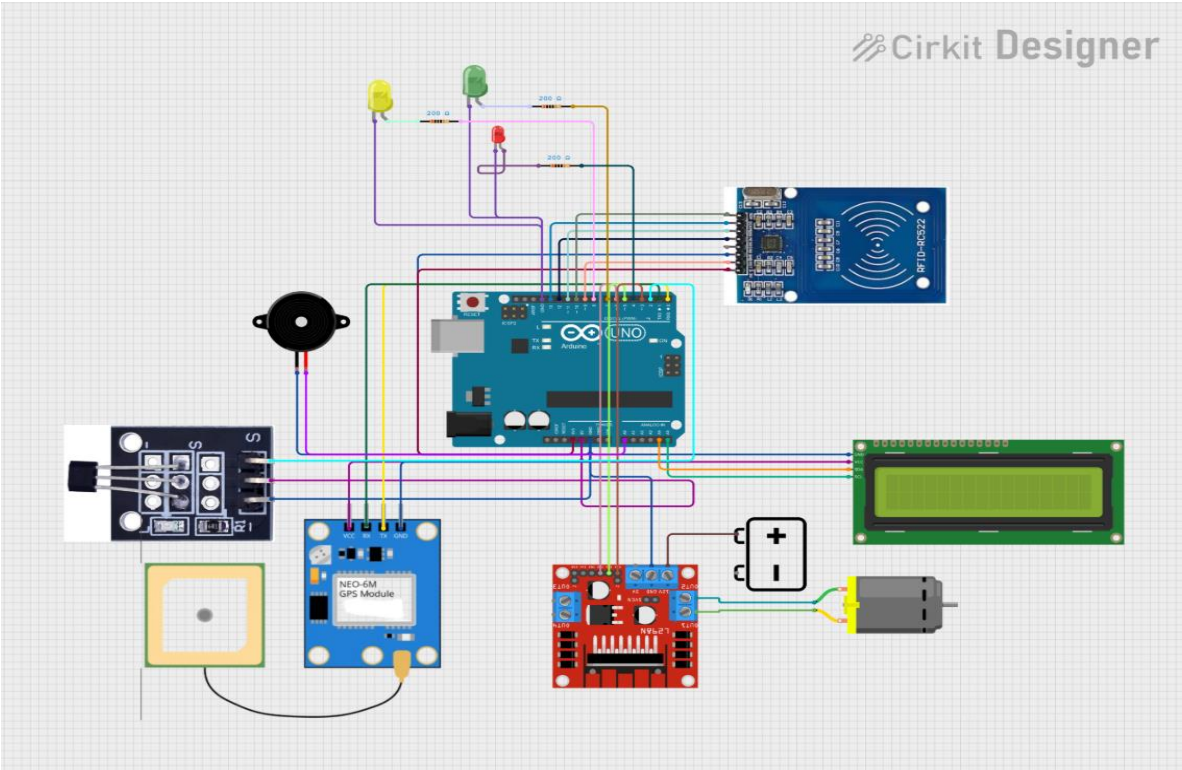
- A **green LED** indicates normal operation within the speed limit
- A **yellow LED** signals a warning when approaching the limit
- A **red LED** indicates overspeed conditions
- A **buzzer** provides an audible alert if the vehicle continues to exceed the permissible speed

Additionally, an LCD display presents real-time information such as current speed, active speed limit, and system status messages.

5.6 Subsystem Connections

Subsystem	**Key Connection/Notes**
GPS Module[Neo-6M]	VCC to 5V, GND to GND, TX/RX connected via hardware serial or SoftwareSerial interface
RFID [MFRC522]	VCC to 3.3V, GND to GND, RST to D9, SDA/SS to D10, SPI lines to D11 (MOSI), D12 (MISO), D13 (SCK)
Hall-Effect Sensor	Output connected to interrupt pin D2 for pulse counting
L298N Motor	ENA to PWM pin D3, IN1 to D5, IN2 to D6, motor connected to output

Driver	terminals, powered via external 12V supply
Indicator and Buzzer	Green LED to D7, Yellow LED to D8, Red LED to D4, buzzer to A0
LCD [I2C 16x2]	SDA to A4, SCL to A5



6. Software Design and Control Logic

The software architecture of the proposed system is designed as a real-time control loop that continuously monitors sensor inputs, processes zone information, and updates the control output accordingly. The program is implemented on the Arduino UNO platform and follows a structured sequence of operations, including data acquisition, decision-making, and actuation.

The system operates through a cyclic execution model consisting of five primary tasks: acquisition of location data, identification of the active speed-restricted zone, real-time speed estimation, comparison with the predefined speed limit, and updating of control outputs along with user feedback. To ensure accurate and responsive speed measurement, an interrupt-driven mechanism is employed for counting pulses from the Hall-effect sensor. This approach allows the system to maintain precise speed estimation even while performing other operations such as display updates and communication handling.

6.1 Control Sequence

The operational flow of the system can be described as follows:

- Initialization of all input/output pins, communication interfaces, display modules, RFID reader, and interrupt service routines.
- Acquisition of zone information using either GPS-based geofencing or RFID-based detection, depending on system configuration.
- Measurement of wheel rotation pulses over a fixed time interval to estimate the current vehicle speed.
- Comparison of the measured speed with the permissible speed limit corresponding to the detected zone.
- If the vehicle speed is within the safe limit, the system maintains normal PWM output and indicates a **safe state** using a green LED.
- If the speed approaches the threshold, a **warning state** is triggered, activating the yellow LED and buzzer to alert the user.
- If the speed exceeds the permissible limit, the controller reduces the PWM duty cycle to enforce speed regulation and activates a **critical state** indicated by a red LED and continuous alert signals.
- The entire process is executed continuously in a loop to ensure real-time responsiveness.

6.2 Speed Calculation

The vehicle speed is estimated based on the number of pulses generated by the Hall-effect sensor during a fixed sampling interval. The relationship between speed and sensor output can be expressed as:

$$v = \frac{N \times C}{T}$$

where:

- v= vehicle speed
- N= number of pulses counted
- C= wheel circumference
- T= time interval

In practical implementation, calibration factors are applied to account for sensor resolution, wheel dimensions, and system delays, ensuring that the computed speed closely matches real-world values.

6.3 Pseudocode

Algorithm 1: Vehicle Speed Limit Controller

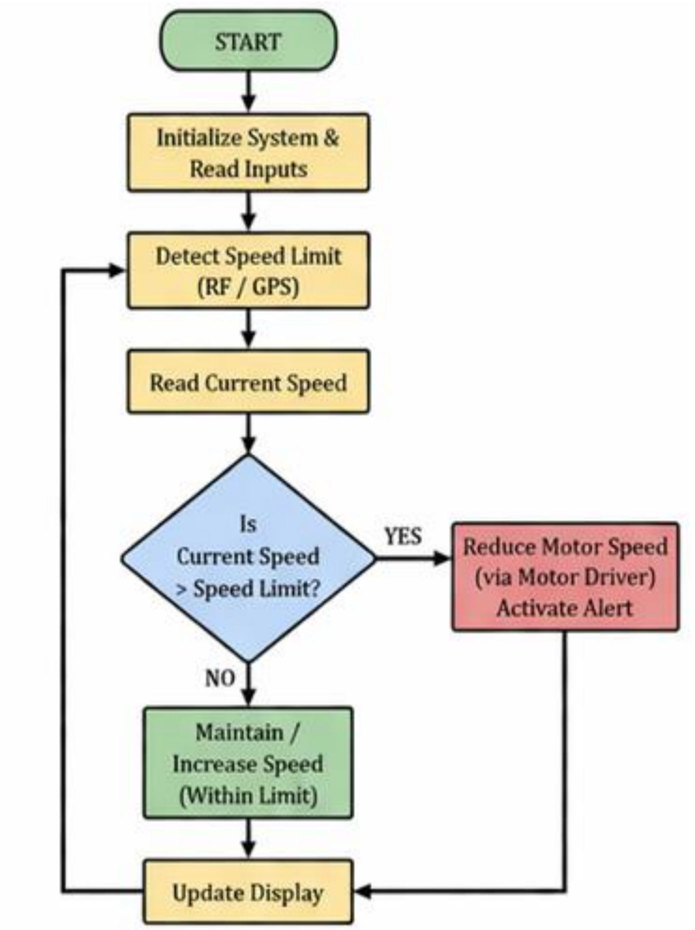
1. Initialize system components, including sensors, display, RFID module, and interrupt routines.
2. Detect the active zone using GPS coordinates or RFID tag identification.
3. Measure wheel pulses and calculate the current speed.
4. Compare the measured speed with the predefined limit for the detected zone.
5. If the current speed exceeds the limit:

- Reduce PWM duty cycle
- Activate warning indicators (LEDs and buzzer)

6. Else:

- Maintain normal motor operation
- Indicate safe status

7. Repeat the process continuously for real-time control.



7. Prototype Implementation

The proposed system is implemented as a hardware prototype built around an Arduino UNO microcontroller, integrated with modules such as GPS, RFID reader, Hall-effect sensor, L298N motor driver, display unit, LEDs, and buzzer. The circuit is designed for controlled demonstration, where a DC motor is used to simulate the vehicle drive system. This approach enables safe testing and validation of the speed control logic within a laboratory environment.

The implementation supports two zone-identification modes. In the RFID-based mode, the system detects predefined tags placed at zone boundaries and updates the corresponding speed limit upon detection. In the GPS-based mode, the controller performs geofencing by comparing real-time location data with stored coordinates, activating the appropriate speed restriction when the vehicle enters a defined zone. Both detection methods are integrated into a common control framework, ensuring modularity and ease of extension.

7.1 User Interface

The system includes an LCD interface that provides real-time information such as the current vehicle speed, active speed limit, and system status. This immediate feedback allows users to observe system behaviour and evaluate the effectiveness of the control algorithm during operation.

7.2 Safety Logic

Safety mechanisms are incorporated to ensure reliable system operation. An emergency control feature is implemented to immediately disable motor output under critical conditions. In such cases, the PWM signal is cut off, the buzzer is activated, and the red LED indicator is triggered to alert the user.

For practical deployment, additional features such as manual override and fail-safe protection mechanisms can be incorporated to enhance system safety and user control.

8. Testing and Validation

The performance evaluation of the proposed system is conducted through a structured testing approach consisting of multiple stages, including sensor-level verification, subsystem integration, and overall system validation. This staged methodology ensures that individual components function correctly before being integrated into the complete system, thereby improving reliability and ease of debugging.

At the initial stage, each sensor module—such as the Hall-effect sensor, RFID reader, and GPS unit—is tested independently to verify proper operation and signal accuracy. This is followed by integration testing, where communication between modules and the microcontroller is validated. Finally, full-system testing is performed to evaluate the real-time response of the control algorithm under varying operating conditions.

The system performance is evaluated against predefined design targets, which serve as reference benchmarks for validating functionality and responsiveness.

8.1 Experimental Results / Testing Table

Parameter	Design Target	Measured Value	Remarks
Speed Measurement Accuracy	±2 km/h	±1.5 km/h	Achieved after proper wheel calibration
RFID Detection Range	5–10 cm	6 cm	Stable detection within close proximity
GPS Zone Detection Delay	< 3 seconds	2.5 seconds	Depends on signal availability
Speed Control Response Time	< 2 seconds	1.8 seconds	Smooth PWM adjustment observed
Speed Overshoot	< 3 km/h	2 km/h	Controlled deceleration achieved
System Response to RFID	Immediate	< 1 second	Fast zone switching
Buzzer/Alert Response	Immediate	Immediate	Works reliably

8.2 Validation Approach

For comprehensive validation, the system should be tested under controlled conditions by varying input parameters such as speed, zone transitions, and load conditions. Key performance metrics include accuracy of speed measurement, responsiveness of PWM-based control, reliability of zone detection, and overall system stability.

In a complete implementation, these predefined targets should be replaced with experimentally measured values obtained from the working prototype. Relevant measurements include calibrated speed readings, RFID detection distance, control response time, and power consumption under different operating conditions. Such quantitative evaluation enhances the credibility and reproducibility of the system, making it suitable for academic and practical applications.

9. RESULTS AND DISCUSSION

The experimental results demonstrate that the proposed Vehicle Speed Limit Controller performs effectively within the defined design constraints. The system achieves satisfactory speed measurement accuracy with minimal deviation, indicating proper calibration of the Hall-effect sensor.

The response time of the control system is observed to be within acceptable limits, ensuring smooth and gradual speed reduction without abrupt changes. The integration of RFID and GPS-based zone detection provides reliable identification of restricted areas, with RFID offering faster response and GPS enabling location-based flexibility.

The PWM-based control mechanism successfully regulates motor speed, minimizing overshoot and maintaining system stability. The user interface, including LEDs, buzzer, and display, provides clear and immediate feedback, enhancing usability and system transparency.

Overall, the results validate the effectiveness of the proposed design in achieving automated speed regulation, while maintaining simplicity, reliability, and cost efficiency.

10. Limitations and Challenges

1. The system is only a prototype and cannot be directly used in real vehicles.
2. GPS may not work accurately in cities or areas with weak signal.
3. RFID detection depends on proper tag placement and has limited range.
4. Low-cost components may reduce accuracy and reliability.
5. Speed measurement may have small errors if the sensor is not properly calibrated.
6. Environmental factors like noise, vibration, or temperature can affect performance.
7. The system does not include advanced safety features like backup or fail-safe mechanisms.
8. Real-world use would require strict testing and approval, which is not included in this project.

11. Future Enhancements

1. **IoT Integration:** Add a Wi-Fi module to enable cloud data logging and remote monitoring of vehicle speed and system status.
2. **Machine Learning:** Implement predictive speed control based on road conditions and driving patterns.
3. **Emergency Services Integration:** Connect the system with local authorities to send alerts in case of speed violations.
4. **Vehicle Communication (V2V):** Enable communication between vehicles using technologies like LoRa or NRF24 for improved coordination and safety.
5. **Advanced Sensors:** Integrate sensors such as LiDAR or cameras for obstacle detection and autonomous braking.

6. **Mobile Application:** Develop an Android/iOS application to provide a driver dashboard, alerts, and route planning features.
7. **Real-Time Traffic Integration:** Connect with map APIs to dynamically update speed limits based on live traffic conditions.
8. **Driver Behaviour Monitoring:** Detect harsh acceleration, sudden braking, and unsafe driving patterns to improve safety.

12. CONCLUSION

This paper presented the design and implementation of a Vehicle Speed Limit Controller based on an embedded systems approach. The proposed system integrates GPS and RFID technologies for reliable detection of speed-restricted zones, along with a Hall-effect sensor for real-time vehicle speed estimation. A PWM-based control mechanism is employed to regulate motor speed when the detected speed exceeds the permissible limit.

The system also incorporates a user feedback interface consisting of a display unit, LED indicators, and a buzzer, providing clear and immediate information to the user. The prototype demonstrates effective coordination between sensing, processing, and control modules, making it suitable for controlled testing and demonstration of automated speed regulation.

The design emphasizes low cost, modularity, and ease of implementation, which makes it adaptable for further development. With additional calibration, enhanced sensing techniques, and rigorous testing, the proposed system can be extended to support advanced applications in intelligent transportation systems and driver assistance technologies.

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