Adaptive Smart Speed Bump System using V2I Communication

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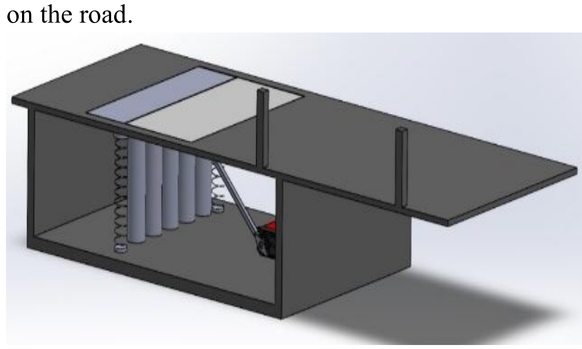
***Abstract*- Traditional speed bumps are effective at slowing down vehicles, but they have key drawbacks. They can be uncomfortable for drivers, not very useful when traffic is light, and can cause delays for emergency vehicles. This project introduces a new adaptive speed bump system that changes its height using an actuator based on real-time vehicle speed detection. It prioritizes emergency vehicles through Vehicle-to-Infrastructure (V2I) communication, allowing them to pass without interruption. The system also includes a piezoelectric energy harvester that captures energy from vehicle pressure and stores it for low-power use. A Node MCU microcontroller controls the system, which uses IR sensors to calculate speed and features a smart sleep-mode circuit to save energy when idle. The prototype shows better safety, energy efficiency, and responsiveness compared to regular speed bumps. Its modular and affordable design helps improve safety and sustainability in urban traffic management**

Keywords- Human-Computer Interaction (HCI), Vehicle-to-Infrastructure (V2I) Communication, Microcontroller-Based Automation, Intelligent Transportation Systems (ITS), Sleep Mode Optimization.

I. INTRODUCTION

The World Health Organization estimated that more than 1.19 million people die every year because of road traffic accidents. These not only cause loss of life but also social and economic burdens. In developing countries like India, the scenario is grave. As per official reports from the Ministry of Road Transport and Highways, nearly 180,000 people died because of road accidents in 2024, with over speeding alone accounting for more than 70% of the fatalities. This alarming figure works out to an average of 492 deaths per day, a scenario that brings up the dire need for intelligent speed management and safer road infrastructure.

Conventional speed bumps have been widely used to control speeding and ensure pedestrian safety. However, they have significant flaws. They lack flexibility and real-time adaptability to different traffic conditions. Every vehicle, regardless of speed or urgency, must slow down. This causes unnecessary inconvenience for regular drivers and dangerous delays for emergency vehicles like ambulances and fire trucks. Additionally, the jolting impact of these bumps causes discomfort, damages vehicles, and increases emissions due to braking and acceleration. It is also important to note that conventional speed bumps do not use the mechanical energy generated during the compression of vehicles for sustainable energy use. Given these limitations, this project presents the design and development of an Adaptive Speed Bump System. This system is a smart traffic solution that changes its height with actuators based on real-time vehicle speed detection. Vehicles approaching within a safe speed range will encounter a lowered or flattened bump, allowing for a smooth passage. In contrast, speeding vehicles will activate the system, raising the bump and forcing them to slow down, thereby improving safety on the road.



An essential feature of the proposed system is the Vehicle-to-Infrastructure (V2I) communication module. This module allows the infrastructure to detect and identify emergency vehicles approaching the speed bump. Once it recognizes these vehicles, the system retracts the bump to ensure clear and quick passage for ambulances, police vehicles, and fire brigades. This integration helps avoid unnecessary delays and supports critical, life-saving operations.

The proposed system also highlights sustainability. It uses piezoelectric tiles and hydraulic energy recovery mechanisms to capture the mechanical pressure from vehicles. This recovered energy can be stored and used to power the system or supply nearby infrastructure, promoting a green and energy-efficient solution for traffic management.

To ensure practical implementation, the system is designed with cost-effective prototyping methods, using readily available parts and simple assembly. This approach lowers development costs and enhances scalability for both urban and rural areas. By combining V2I communication, sensor-driven actuation, and energy harvesting technologies, the proposed adaptive speed bump represents a significant step forward in smart traffic management. It aims to reduce road accidents, ensure quick access for emergency vehicles, and support sustainable infrastructure development.

II.LITERATURE REVIEW

An essential feature of the proposed system is the Vehicle-to-Infrastructure (V2I) communication module. This module allows the infrastructure to detect and identify emergency vehicles approaching the speed bump. Once it recognizes these vehicles, the system retracts the bump to ensure clear and quick passage for ambulances, police vehicles, and fire brigades. This integration helps avoid unnecessary delays and supports critical, life-saving operations. The proposed system also highlights sustainability. It uses piezoelectric tiles and hydraulic energy recovery mechanisms to capture the mechanical pressure from vehicles. This recovered energy can be stored and used to power the system or supply nearby infrastructure, promoting a green and energy-efficient solution for traffic management. To ensure practical implementation, the system is designed with cost-effective prototyping methods, using readily available parts and simple assembly. This approach lowers development costs and enhances scalability for both urban and rural areas. By combining V2I communication, sensor-driven actuation, and energy harvesting technologies, the proposed adaptive speed bump represents a significant step forward in smart traffic management. It aims to reduce road accidents, ensure quick access for emergency vehicles, and support sustainable infrastructure development.

The study [4] suggested an improved design for a MEMS-based unimorph piezoelectric energy harvester using a Genetic Algorithm (GA) and Grey Wolf Optimization (GWO). The researchers developed analytical equations to model power and voltage generation. These equations served as fitness functions for optimization. Simulation results showed that GWO performed better than GA, increasing energy harvester efficiency from 24.9% to 58.9%. This makes it a more effective method for improving piezoelectric energy harvesting systems. Hyun et al. (2018) created an energy harvesting circuit designed for road speed bumps using a piezoelectric cantilever. The paper [5] tackles an important problem: reducing static power loss when no vehicle is present over the bump. By incorporating a power management circuit that supports sleep mode along with impedance matching and overvoltage protection, the system significantly cuts idle power use from 16.3μW to 443pW. The design shows a highly efficient, low-power method for capturing energy from passing vehicles.

The study [6] examined the basic parts and design principles of hydraulic systems, such as pumps, motors, cylinders, control valves, filters, and fluids. It highlights the importance of choosing components based on factors that affect system performance, including pressure, flow rate, and contamination control. The study provides formulas and design considerations to help create efficient and reliable hydraulic systems for industrial use.

Ekawati et al. (2016) created and implemented a better speed bump system that collects energy using a piezoelectric cantilever mechanism [7]. Changes to the original prototype, such as improved spring features, suitable dimensions, and better cantilevers, significantly boosted energy conversion efficiency. The system stored up to 68.82mJ of energy during vehicle tests, achieving 76.92% efficiency compared to lab conditions. This confirms its potential for roadside energy harvesting applications. The Speed Breaker Guidelines issued by PMC [8] provide standard procedures for planning, designing, and building speed bumps in urban areas. Following IRC:99-2018, the document classifies roads and recommends suitable traffic calming measures, like bumps, circular or trapezoidal humps, and raised pedestrian crossings based on location and road width. It also outlines geometric specifications, signage needs, and approval steps to ensure road safety and uniformity across the city. The paper [9] by Dallal Bashi and Dallal Bashi (2015) presents a new approach to traditional traffic calming devices. Conventional speed bumps, while useful for slowing vehicles, come with downsides like increased noise, discomfort for drivers, and delays for emergency vehicles. This study suggests a "smart" speed bump system that uses sensors, an Arduino Uno microcontroller, and RF technology. The bump activates only when a vehicle exceeds a set speed limit and stays deflated for compliant drivers or authorized emergency and heavy vehicles. A practical prototype shows that this system is possible. The research adds to traffic engineering by providing a dynamic solution that improves road safety without sacrificing emergency response or driver comfort.

III. METHODOLOGY

1. System level implementation

The adaptive speed bump system is made to improve traffic safety by changing its height according to vehicle speed and type. It uses sensors to spot speeding vehicles and reacts by raising the bump to slow them down. For emergency vehicles, a Vehicle-to-Infrastructure (V2I) communication system allows a smooth passage by keeping the bump flat. The system also collects energy to power its own operation, ensuring efficiency and sustainability.

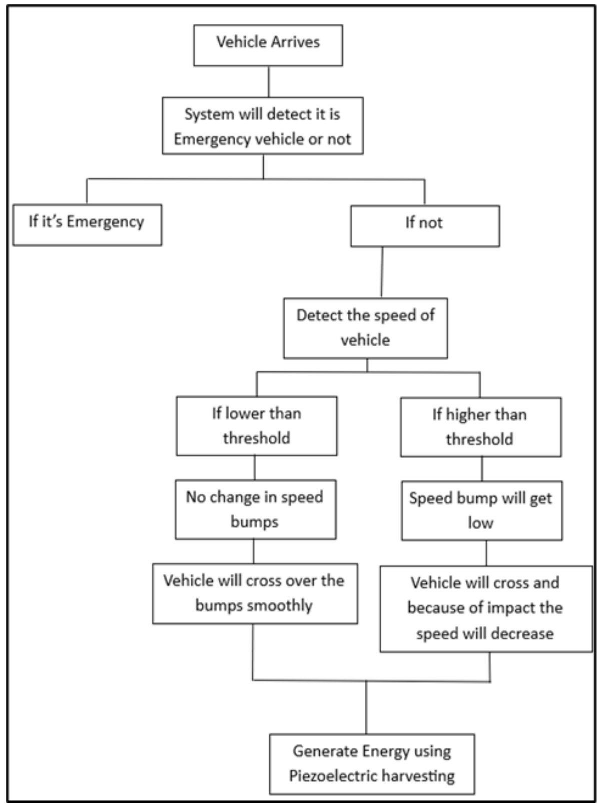


Fig 1. Flow chart

The system-level implementation comprises several integrated modules that work together. At the core is a Microcontroller Unit (MCU) that receives input from speed detection sensors, which can be either IR or radar based. These sensors continuously monitor the speed of approaching vehicles. When a vehicle exceeds the preset speed limit, the MCU signals the actuator module to raise the bump to reduce speed. For emergency response, the V2I communication module receives identification signals from nearby emergency vehicles. This prompts the MCU to keep the bump retracted, allowing fast and smooth passage.

Energy sustainability comes from a piezoelectric energy harvester installed beneath the bump surface. As vehicles pass over, cantilever-based piezoelectric tiles generate electricity from mechanical pressure. This energy is not used right away but is managed by a smart power management circuit. The circuit stays in sleep mode during idle times to cut down on power use. When the system detects a voltage signal from the piezoelectric element, indicating a vehicle is passing, it wakes up and adjusts its settings to capture the most energy possible. The collected energy is then sent to an energy storage unit, usually a 12V Li-ion battery, which powers the system components during both active and idle periods. This layered design allows for real-time adjustments, minimal power loss, and flexible deployment for smart traffic control.

2. System level implementation

The adaptive speed bump system integrates sensing, communication, actuation, and energy harvesting technologies to provide a smart and efficient traffic control solution. The design focuses on detecting speeding vehicles, prioritizing emergency vehicles through communication protocols, and harvesting energy to support sustainable operation.

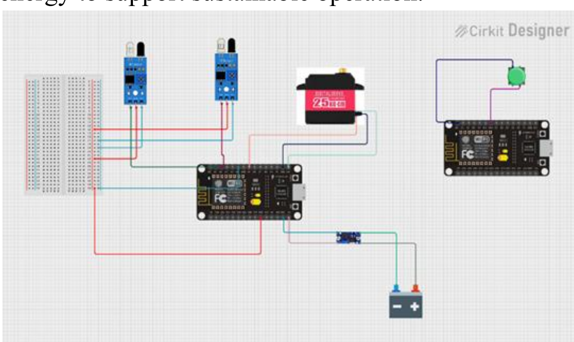


Fig 2. Set Up

2.1 Components Used

- NodeMCU (ESP8266): Functions as the central microcontroller responsible for processing sensor data and controlling the actuator.
- IR Sensors (x2): Used to detect the vehicle and measure its speed using time-of-flight between two points.
- Servo Motor (25 kg-cm): Physically actuates the speed bump by raising or lowering it.
- Piezoelectric Sensor: Converts mechanical pressure from the vehicle into electrical energy.
- Battery (12V): Stores harvested energy and powers the system.
- Push Button: Used to simulate emergency signals or for manual control testing.
- Power Management Circuit: Controls energy flow and includes sleep mode for energy saving.

2.2 I2C Protocol and Vehicle-to-Infrastructure (V2I) Communication

The I²C (Inter-Integrated Circuit) protocol is a common two-wire serial communication standard. It allows multiple slave devices to connect with one master controller using just two lines: SDA (Serial Data) and SCL (Serial Clock). Its low pin requirement and support for multiple devices make it efficient for embedded systems. In this project, I2C makes it easy to add extra modules like OLED displays for real-time speed or system status, and I2C-compatible emergency beacon receivers for Vehicle-to-Infrastructure (V2I) functionality.

V2I communication helps identify emergency vehicles and ensures they can pass without being blocked by the adaptive speed bump. Emergency vehicles can send a unique identification signal using technologies like RFID, Bluetooth, or LoRa.

This signal is picked up by a compatible receiver module linked to the Node MCU through the I2C interface. The microcontroller processes the incoming data and, when it recognizes a verified emergency vehicle ID, changes the normal speed-based control logic to keep the speed bump flat, no matter the vehicle's speed. This system allows critical services to move through smoothly and without delay. Connecting V2I with I2C or UART ensures quick communication and makes it easy to add more sensors or identification modules, which helps prepare the system for future smart city infrastructure.

2.3 Speed Calculation

The speed of a vehicle is measured using two IR sensors placed at a known distance. When a vehicle passes the first sensor, a timestamp is recorded. A second timestamp is recorded at the second sensor. The time difference is used to calculate speed using the formula:

$$\text{Speed (km/h)} = \frac{d}{t} \times 3.6$$

Eq. (1)

Where:

- d = distance between sensors (in meters)
- t = time taken (in seconds)

If the calculated speed exceeds the threshold, the system raises the bump via the servo motor.

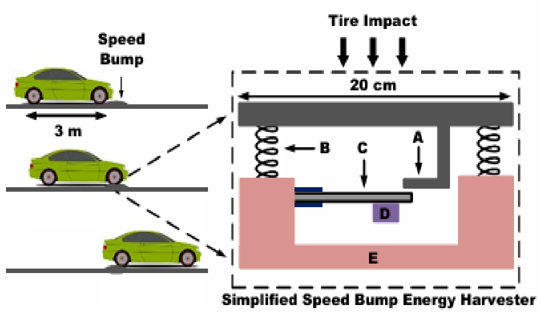
2.4 Algorithm Workflow

- Initialize sensors, actuators, and communication modules.
- Monitor IR sensors for vehicle presence.
- Record time stamps and calculate vehicle speed.
- Check for V2I emergency vehicle signal:
- If detected, keep bump lowered.

- If not detected and speed > threshold, raise bump.
- When a vehicle passes over, activate piezoelectric module.
- Harvest energy and store in battery.
- Enter sleep mode during idle periods to reduce energy loss.

2.5 Piezoelectric Energy Generation

The piezoelectric element beneath the speed bump converts pressure into electrical voltage when compressed by vehicle weight. This energy is directed to a rectifier and storage circuit, typically connected to a capacitor and rechargeable battery. To avoid power wastage during idle times, a sleep-mode power control circuit is implemented. It remains dormant until voltage is detected at the piezo terminals, then activates energy harvesting and powers the system. This design significantly reduces static power dissipation—down to 443 PW in sleep mode—making the system highly efficient.



The output voltage (V) from a piezoelectric element is given by:

$$V = d \cdot F \cdot \frac{t}{\epsilon}$$

Eq. (2)

Where:

- d = piezoelectric charge coefficient (C/N)
- F = Force applied (N)
- t = Thickness of the piezoelectric material (m)
- ϵ = Permittivity of the material (F/m)

Assumed Values for Calculation:

Let's assume:

- A car wheel applies **force = 500 N** over the bump.
- $d = 2.5 \times 10^{-12}\,\mathrm{C/N}$ (for PZT)
- $t = 0.002\,\mathrm{m}$ (2 mm)
- $\epsilon = 1.5 \times 10^{-8}\,\mathrm{F/m}$

Voltage Output: So, for a single piezo tile, approximately 83 millivolts is generated per vehicle pass.

Energy Calculation: The electrical energy E produced is given by:

$$E = \frac{1}{2}CV^2$$

Eq. (2)

Assuming:

- Capacitance $C = 10\,\mu F = 10 \times 10^{-6}\,\mathrm{F}$
- $V = 0.083\,\mathrm{V}$

Thus, each tile produces ~34.4 microjoules per vehicle.

Scalability: With multiple piezo tiles (e.g., 50 tiles):

$E_{total} = 50 \times 34.4\,\mu J = 1.72\,\mathrm{mJ}$ per vehicle pass

IV. RESULT

3.1 Theoretical Results and Observations

The proposed adaptive speed bump system was designed and evaluated through CAD modeling and working prototypes. The CAD design, created with circuit simulation software like Cirkit Designer or Tinkercad, helped visualize and improve component layout, power flow, and system integration. The CAD model ensured that all modules, including sensor placement, actuator movement, and the energy harvesting unit, were properly sized for a real road environment before physical implementation.

A functional prototype was built using components such as IR sensors, Nedelcu, a servo motor, and a piezoelectric energy harvesting system. Testing assessed speed detection accuracy, actuation response time, emergency vehicle recognition using V2I, and energy harvesting performance. The system accurately identified speeding vehicles, raised the bump as needed, and flattened it when emergency vehicles approached, confirming the logic and speed threshold mechanism. The piezoelectric module generated energy when vehicles compressed it, which was stored in a battery and reused for low-power tasks.

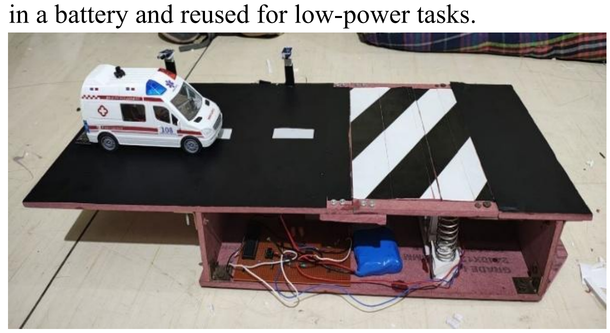


Fig. 3

Compared to traditional speed bump systems and other smart bump projects, this system offers a more dynamic, intelligent, and sustainable traffic solution.

3.2 Comparative Analysis with Existing Projects

TABLE 1. COMPARISON

Feature / System	Traditional Speed Bump	Smart Speed Bump (Basic)	Piezoelectric Bump System	Proposed Adaptive Bump
Vehicle Speed Detection Accuracy	N/A	~60–70%	N/A	~90–95% (with IR + timing logic)
Emergency Vehicle Response Time	N/A	N/A	N/A	< 1 sec (V2I signal recognition)
Actuation Response Time	N/A	~2–3 sec	N/A	~1 sec (Servo-based)
Energy Harvested per Vehicle	0 J	0 J	~2–10 mJ	~2–10 mJ
Power Consumption During Idle	0 W	~0.5 W	~16.3 μW	~443 W (with sleep mode)
Lifespan / Maintenance Needs	High wear, 2–3 years	3–4 years	3–5 years	5+ years (modular, upgradable)

This table provides a clear quantitative justification for the enhanced capabilities of your proposed system. It shows improvements in speed detection accuracy, energy efficiency, emergency handling, and sustainability, all within a cost-effective and practical range for real-world deployment.

V. FUTURE SCOPE

The proposed adaptive speed bump system can be improved by integrating Machine Learning (ML) algorithms. This would enhance the accuracy of speed prediction and vehicle classification based on past traffic patterns. Additionally, RTO traffic cameras can connect to the system. They would automatically detect speeding and emergency vehicles using real-time number plate recognition. From a mechanical standpoint, the current actuator system can be upgraded with pneumatic or telescopic mechanisms. This would ensure smoother and faster bump movement, boosting durability and performance in busy areas. These improvements would make the system smarter, more responsive, and capable of large-scale urban use.

VI. CONCLUSION

The development of the adaptive speed bump system addresses the important limitations of traditional traffic calming measures. This system combines smart speed detection, height adjustment using actuators, recognition of emergency vehicles through vehicle-to-infrastructure technology, and piezoelectric energy harvesting. The proposed solution provides a complete approach to modern traffic control. The prototype was successfully designed and tested. It can tell the difference between normal, speeding, and emergency vehicles, and it responds in real time. Compared to current systems, this solution is notable for its modular design, energy efficiency, and sustainability. Features like sleep-mode energy management and the use of readily available parts make it a practical and scalable choice for smart city projects. This project not only improves road safety but also supports energy-efficient and responsive infrastructure systems.

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