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Dynamic Speed Management Enhancing Traffic Safety with Adaptive Speed Breaker

Mr B Ramakrishna[1], Ch Phani Satwik kmar[2], P Omsai[3], R Anudeep singh[4] S Arjun[5]
[1]Assisstant professor, Dept. of MECH Mahatma Gandhi Institute of technology, Hyderabad, Telangana, India.
[2,3,4,5]UG Student, Dept. of Mechanical Engineering Mahatma Gandhi Institute of technology, Hyderabad, Telangana, India.
Emails: *bramakrishna_mct@mgit.ac.in[1], phanikumarthe@gmail.com[2], oommssaii@gmail.com[3], rajputhanudeep1125@gmail.com[4], Arjunk.ak44@gmail.com[5]*

Abstract
Dynamic Speed Management (DSM) with adaptive speed breakers offers an innovative traffic solution. Unlike static bumps, these breakers use real-time data from advanced sensors (like IR for velocity) to respond dynamically. They remain retracted for vehicles within speed limits, ensuring smooth travel, but activate only for speeding vehicles to enforce safer driving. Machine learning models, such as YOLOv8, identify emergency vehicles, deactivating the breakers for their unobstructed passage. This selective system significantly enhances road safety by reducing accidents caused by abrupt braking. It optimizes traffic flow, minimizes disruptions, and consequently lowers fuel consumption, emissions, road wear, and vehicle maintenance costs. DSM also fosters a culture of safer driving. Integrating smart technologies like IoT and advanced controls, DSM's future includes smart city ecosystem integration, predictive analytics, and energy-harvesting capabilities, potentially making breakers self-sustaining. Its scalability suits diverse environments, from urban intersections to highways. DSM represents an intelligent, sustainable, and environmentally conscious approach to modern traffic management, pivotal for evolving smarter transportation systems.

Keywords: *AI system for Emergency Vehicle Detection, Dynamic Speed Management (DSM), Adaptive Speed, Breakers, Real-Time Monitoring*

1. Introduction

Dynamic Speed Management (DSM) with Adaptive Speed Breakers represents an advanced and intelligent approach to modern traffic control, designed to enhance road safety, optimize traffic flow, and reduce congestion by directly addressing the inherent limitations of traditional, static speed breakers. [1-2] Unlike conventional measures that remain unchanged regardless of traffic volume or environmental conditions and uniformly impede all vehicles, DSM leverages real-time data, sophisticated smart technologies, and responsive road structures that adapt dynamically to individual vehicle behavior. This innovative system not only promises improved safety for all road users but also contributes to a more efficient, controlled, and environmentally considerate road environment. At the core of the DSM concept is the adaptive speed breaker, an innovative device embedded within the roadway. This smart infrastructure component can adjust its physical characteristics—such as height, firmness, or even visibility—in real-time, based on incoming data related to vehicle speeds, traffic flow, and prevailing environmental conditions. These speed breakers are meticulously programmed to stay retracted or

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maintain a low profile for vehicles traveling within legally prescribed speed limits, thereby allowing compliant drivers to pass smoothly and without interruption. However, should an approaching vehicle be detected by the system's array of sensors—such as IR sensors for velocity monitoring—as exceeding the safe speed limit, the control system triggers the adaptive speed breaker to activate. This activation typically involves the breaker rising or increasing its firmness, creating a physical impediment that compels the driver to reduce speed. A crucial aspect of this technology is its selective engagement. The system can incorporate advanced machine learning models, like YOLOv8, to identify specific vehicle types, such as emergency vehicles (e.g., ambulances, fire trucks), ensuring the breaker deactivates to allow their unobstructed and rapid passage. This selective functionality ensures that only vehicles posing a risk by speeding are targeted, thereby promoting safer driving habits without unnecessarily penalizing responsible drivers or hindering critical services. This intelligent differentiation minimizes unnecessary braking, reduces traffic disruptions, and prioritizes critical vehicle movement, making DSM significantly more efficient and nuanced than static traffic control measures. The system, therefore, fosters a culture of safer driving behavior by directly addressing non-compliance. [3]

2. Methodology

First, real-time speed detection is established using sensors (e.g., IR sensors) to continuously monitor approaching vehicles. The system then employs selective activation: the breaker only engages for vehicles exceeding a preset speed limit. A critical feature is the identification of emergency vehicles, like ambulances, using a YOLOv8 machine learning model. If an emergency vehicle is detected, the breaker remains deactivated, ensuring unobstructed passage. The physical breaker utilizes adjustable mechanisms, such as servo motors, to change its height or firmness. An Arduino Uno microcontroller serves as the central processing unit. It receives speed data from IR sensors and emergency vehicle alerts from a Python program (interfacing with the YOLOv8 model) via serial communication. Based on this input, the Arduino, programmed in C, actuates the servo motor to raise or lower the breaker and controls LED indicators to notify drivers. This integrated approach, combining sensor data, machine learning, and microcontroller logic, allows for a dynamic and responsive traffic safety solution. (Figure 1,2,3,4)

2.1. Figures

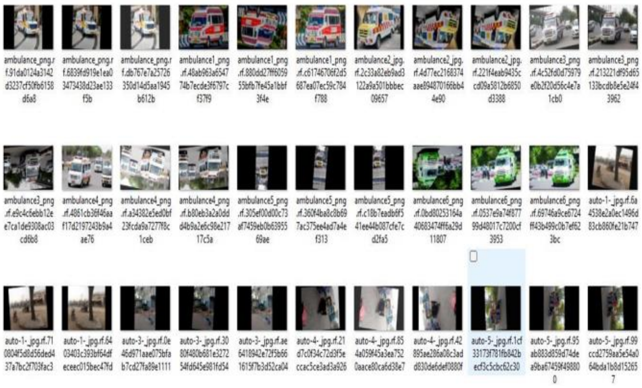

Figure 1 Image Collection for Model Training

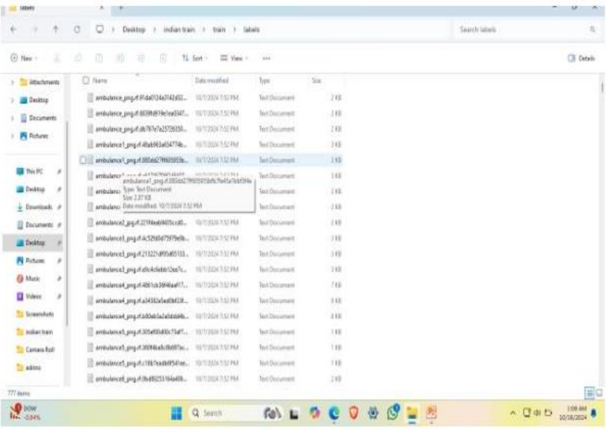

Figure 2 Trained Model After Labelling

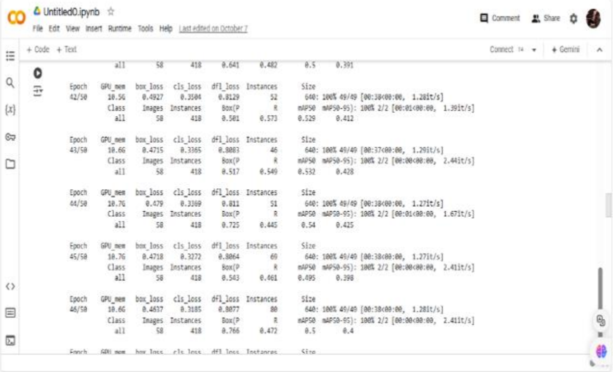

Figure 3 Model Training in Google Collab

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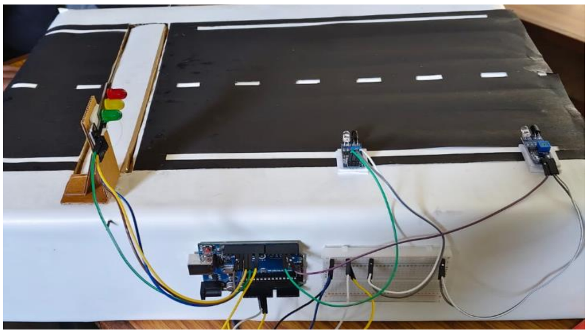

Figure 4 **Model Training in Google Collab**

3. Results and Discussion

3.1.Results

Successful Emergency Vehicle Identification: The implemented YOLOv8 machine learning model demonstrated the capability to accurately detect and classify emergency vehicles (e.g., ambulances) from a real-time camera feed. [4]

Effective Emergency Vehicle Prioritization: Upon detection of an emergency vehicle by the YOLOv8 model, the system successfully communicated this status to the Arduino, ensuring the adaptive speed breaker remained deactivated for unobstructed passage. [5]

Accurate Real-Time Speed Detection: The dual IR sensor array reliably detected approaching vehicles and enabled the calculation of their speed based on the time interval between sensor triggers.

Selective Breaker Activation for Speeding Vehicles: The system effectively triggered the adaptive speed breaker (via servo motor actuation) only when a non-emergency vehicle's detected speed exceeded the pre-set speed limit. [6]

Uninterrupted Passage for Compliant Vehicles: For non-emergency vehicles traveling at or below the speed limit, the adaptive speed breaker remained in its retracted state, allowing for smooth and unimpeded travel.

Reliable Actuator Mechanism Performance: The DC servo motor demonstrated consistent and responsive movement, effectively raising and lowering the model speed breaker mechanism as commanded by the control system.

Functional Microcontroller-Based Control Logic: The Arduino Uno successfully processed inputs from the IR sensors and serial communication (for emergency vehicle alerts), executing the programmed logic to control the speed breaker and LED indicators.

Established Inter-System Communication: Successful serial communication was established between the Python environment (running YOLOv8 and managing camera input) and the Arduino microcontroller for transmitting critical data like emergency vehicle alerts.

Clear Driver Notification System: The integrated LED traffic light system provided distinct visual feedback to simulate driver alerts: green for compliant speed/no activation, yellow for emergency vehicle detection (breaker deactivation), and red for over-speeding (breaker activation).

Integrated Prototype Functionality: The complete prototype, encompassing sensors, camera, processing units (computer for YOLOv8, Arduino), and the actuator, successfully demonstrated the core operational principles of the Dynamic Speed Management system.

Demonstrated Feasibility of Targeted Speed Enforcement: The system showcased the practical feasibility of a speed management solution that selectively targets only non-compliant vehicles, unlike traditional, indiscriminate speed bumps.

3.2.Discussion

Paradigm Shift in Speed Management: The successful prototype signifies a move away from passive, static speed control towards active, intelligent, and context-aware traffic management, addressing key limitations of traditional speed bumps. [7]

Enhanced Road Safety with Reduced Collateral Impact: The system's ability to target only speeders while ensuring smooth passage for others (especially emergency vehicles) suggests a significant potential to reduce speed-related accidents without negatively impacting overall traffic efficiency or critical services.

Significant Implications for Emergency Response: The demonstrated prioritization of emergency vehicles could translate into tangible reductions in response times in real-world scenarios, potentially saving lives and improving emergency service effectiveness.

Contribution to Smoother Traffic Flow and Reduced Congestion: By eliminating unnecessary stops for compliant drivers, the DSM system is poised to alleviate localized congestion points often created by traditional speed breakers, especially in urban areas. [8]

Environmental Benefits through Optimized Driving Patterns: The reduction in forced braking and acceleration for the majority of traffic (compliant vehicles) implies lower fuel consumption and reduced vehicle emissions, contributing to greener urban environments. [9]

Fostering a Culture of Compliance: The immediate and targeted consequence for speeding, coupled with unimpeded travel for compliant drivers, is likely to positively reinforce adherence to speed limits more effectively than static measures.

Scalability and Adaptability Potential: The modular design (sensors, ML, actuators) suggests that the system can be adapted for various road types and integrated with broader smart city initiatives, although specific environmental challenges (weather, lighting for YOLOv8) need addressing for robust deployment.

Economic Advantages Beyond Safety: The potential reduction in vehicle wear (tires, brakes) for compliant drivers and less strain on road surfaces (due to selective engagement) could lead to long-term economic benefits for both individuals and infrastructure authorities. [10]

The Role of AI in Evolving Traffic Infrastructure: The successful use of YOLOv8 underscores the transformative potential of AI and machine learning in creating more nuanced, responsive, and efficient transportation infrastructures.

Addressing Vulnerable Road User Safety: While not explicitly tested for cyclists/motorcyclists in the PDF's methodology, the principle of a retracted breaker for compliant speeds inherently benefits these users who are often disproportionately affected by abrupt static bumps. [11]

Challenges for Real-World Implementation: Despite prototype success, considerations for large-scale deployment include installation costs, maintenance of mechanical and electronic parts, power supply, data security, and public acceptance, which require further investigation.

A Stepping Stone to Fully Integrated ITS: This DSM system serves as a tangible example of an Intelligent Transportation System component that can be further developed and integrated with connected vehicle technologies and centralized traffic management platforms for even greater efficacy.

Conclusion

Successful Prototype Development: This research successfully designed, developed, and demonstrated a functional prototype of a Dynamic Speed Management (DSM) system featuring adaptive speed breakers.

Real-Time Responsiveness Achieved: The system effectively responds in real-time to vehicle speed, utilizing IR sensors for detection and an Arduino-controlled mechanism for breaker actuation.

Intelligent Emergency Vehicle Prioritization: The integration of the YOLOv8 machine learning model successfully enables the identification and prioritization of emergency vehicles, ensuring their unimpeded passage.

Selective Enforcement Validated: The core principle of selective activation—engaging the breaker only for speeding vehicles while allowing compliant and emergency vehicles to pass smoothly—was effectively implemented.

Enhanced Road Safety Potential: The DSM system demonstrates a significant potential to enhance road safety by directly addressing speeding, a primary cause of accidents, without the indiscriminate impact of traditional speed bumps.

Optimized Traffic Flow Capability: By minimizing disruptions for compliant drivers, the system promises to improve traffic flow efficiency and reduce unnecessary congestion.

Environmental Benefits Indicated: The reduction in unnecessary braking and acceleration for the majority of vehicles suggests a positive environmental impact through lower fuel consumption and emissions.

Technological Integration Feasibility: The project confirms the feasibility of integrating diverse technologies—sensors, machine learning, microcontrollers, and mechanical actuators—into a cohesive and effective traffic management solution.

Addressing Limitations of Static Measures: The adaptive nature of the system directly overcomes key limitations of traditional static speed breakers, such as their negative impact on emergency services and complaints about drivers.

Foundation for Smarter Infrastructure: This DSM system serves as a tangible step towards more intelligent, responsive, and data-driven transportation infrastructure, aligning with smart city concepts.

Contribution to Safer Driving Culture: The system's targeted approach is likely to encourage better adherence to speed regulations, fostering a safer driving culture. [12]

Significant Advancement in Traffic Control: Overall, the Dynamically Adjusting Speed Breaker project represents a significant and innovative advancement in traffic control, offering a more efficient, safe, and sustainable approach to managing vehicle speeds on modern roadways.

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