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NEXT-GEN ADAS INTEGRATION: A HIGH- RESOLUTION ULTRASONIC PHASED ARRAY FOR REAL-TIME POTHOLE AND SPEED-BREAKER CLASSIFICATION IN EXTREME INDIAN ROAD CONDITIONS

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Abstract - Harsh Road conditions in developing nations, particularly India, present a formidable challenge for Advanced Driver Assistance Systems (ADAS). Traditional computer vision-based systems often struggle with lighting variations, high dust levels, and waterlogged roads. This paper presents a specialized, low-cost solution using an array of RCWL-1655 waterproof ultrasonic sensors combined with high-speed servo actuators to create a dynamic "scanning" phased array. We propose a differential distance algorithm that identifies potholes, speed-breakers, and minor road bumps with high fidelity. The system utilizes an ESP8266-based edge-computing architecture to provide low-latency classification. This paper provides an in-depth mathematical analysis of the scanning geometry, signal processing filters, and the physical constraints of ultrasonic propagation at vehicle speeds. Experimental results demonstrate a 96.2% detection accuracy for potholes and a 93.5% accuracy for speed-breakers at urban speeds, providing a robust, low- cost candidate for ADAS integration in unpredictable environments.

keywords: *ADAS, ultrasonic phased array, pothole detection, speed breaker detection, acoustic sensing, RCWL-1655, edge computing, real-time classification, signal processing, moving average filter, acoustic noise rejection, embedded systems, ESP8266, road anomaly detection, IoT monitoring, vehicle safety*

I.INTRODUCTION

The rapid urbanization of the Indian subcontinent has led to a paradoxical situation: while vehicular technology has moved closer to global safety standards, the underlying road infrastructure remains inconsistent, hazardous, and unpredictable. The Indian road landscape is unique, featuring non-standardized speed breakers—often constructed by local communities without engineering oversight—sharp-edged potholes resulting from monsoonal drainage failures, and varied surface textures that degrade rapidly. According to the Ministry of Road Transport and Highways (MoRTH), thousands of fatalities annually are directly linked to poor road conditions, which disproportionately affect two-wheelers and smaller passenger vehicles lacking sophisticated semi-active suspension systems. The economic cost of these accidents is estimated to be between 3% and 5% of the national GDP, accounting for vehicle damage, medical expenses, and lost productivity.

Modern Advanced Driver Assistance Systems (ADAS) primarily rely on optical sensors (RGB cameras) and LiDAR. While these technologies excel in structured environments like European or North American highways, they face localized "harsh-environment" failure modes in the Indian context:

1. Aerosol Scattering: High levels of particulate matter (PM2.5 and PM10) from heavy dust, construction debris, and vehicular exhaust scatter LiDAR pulses, creating "ghost" obstacles or significantly reducing the effective range of the system.
2. Specular Glare: Extreme solar radiation on dark, freshly laid asphalt creates "mirage" effects or high- contrast shadows that blind computer vision algorithms relying on edge detection and feature matching.

3. Inconsistent Markings: Lane-keeping and road- following systems fail when markings are absent, faded, or covered by layers of mud and organic debris common in rural and suburban corridors.
4. Hydrological Masking: During heavy monsoons, potholes fill with water, becoming visually identical to the surrounding flat road surface. For an RGB camera, the reflection of the sky on a water-filled pothole provides no depth cues, leading to "stealth" hazards.

This research proposes an acoustic-based secondary sensing layer. Ultrasonic waves, specifically in the 40kHz range, are largely immune to light-based interference and can "penetrate" through dense dust, smog, and fog. We utilize the RCWL-1655, an IP67-rated waterproof sensor, ensuring operation during heavy rain—a period when potholes are most dangerous. By integrating these sensors into a dynamic phased array using servo-actuation, we overcome the traditional limitations of narrow-cone ultrasonic sensing, effectively "painting" the road ahead with acoustic pulses to create a high-resolution depth map.

II. LITERATURE REVIEW AND RELATED WORK: ACOUSTIC VS. ELECTROMAGNETIC SENSING

A. Proactive vs. Reactive Modalities Road anomaly detection is broadly categorized into reactive and proactive systems. Reactive systems, pioneered by Mednis et al. [1], utilize smartphone-based accelerometers and gyroscopes to detect the physical "impact" of a pothole after it has been struck. While useful for crowdsourced mapping applications like Waze or Google Maps, these systems provide no real-time warning to the driver and do nothing to prevent immediate vehicle damage or loss of control. Proactive systems using high-fidelity LiDAR or stereoscopic vision [2] are the industry gold standard but remain cost-prohibitive for the budget vehicle segment, which constitutes over 70% of the Indian automotive market. Our research seeks to bridge this gap by providing a proactive solution at a reactive-system price point.

B. The Role of Ultrasonic Sensing in High-Speed Contexts Acoustic sensors have historically been relegated to low-speed applications such as parking assistance (Parktronic) or blind- spot monitoring. However, recent developments in high- frequency transducers and more powerful microcontrollers have enabled their use at higher sampling rates. Static mounting systems often miss obstacles that are not directly in the transducer's "cone of vision." Panicker et al. [5] suggested an intelligent alert system, but it lacked the mechanical dynamism required for lane-wide scanning, essentially only protecting the vehicle from hazards directly under its bumper. Our research introduces a servo-driven oscillation that dynamically adjusts the angle of incidence, providing a much higher spatial resolution and a wider field of view (FoV) that covers the entire width of the lane.

C. Edge Computing and the Latency-Safety Tradeoff Performing heavy computer vision tasks on a central vehicle computer introduces a "processing tax"—latency that can be fatal at higher speeds. For instance, at 40 km/h, a 100ms processing delay translates to over 1.1 meters of travel. The shift toward Edge Computing allows for localized decision-making. By utilizing the ESP8266's high clock speed (80/160 MHz), we perform signal classification directly on the sensor node. This achieves sub-10ms processing times, allowing the system to send a "Hazard Found" flag to the vehicle's braking or steering controller almost instantaneously.

III. SYSTEM ARCHITECTURE AND MECHANICAL DESIGN: DYNAMIC PHASED ARRAYS

A. The Phased Array Concept and Mechanical Scanning The prototype consists of two RCWL-1655 sensors mounted on MG90S metal-gear servos. These servos were selected for their high torque-to-weight ratio and resistance to the constant vibrations inherent in road-bound applications. While these servos are capable of a full 180-degree sweep in approximately 200ms, such a wide scan would be too slow for high-speed road profiling. To maximize the data refresh rate, we employ a "3-Point Sector Scan" targeting 75, 90, and 105 degrees relative to the vehicle's forward axis. By using two sensors, each covering a 60-degree beam width, we achieve a combined 180-degree coverage with minimal mechanical travel. This configuration significantly reduces the "blind-time" where the system is waiting for the servo to reach its next position, effectively creating an acoustic "radar" sweep.

B. IP67 Durability and Environmental Protection The RCWL- 1655 is a specialized transducer where the ultrasonic element is hermetically sealed within a metallic housing. This design allows it to withstand high-pressure water splashes and mud— environmental factors that would instantly destroy a standard HC-SR04 open-mesh sensor. The mounting bracket is 3D printed using PETG for high-temperature stability (withstanding the heat radiated from the road and engine) and is positioned behind the lower air intake of the vehicle bumper to provide a clear acoustic path while maintaining some physical protection.

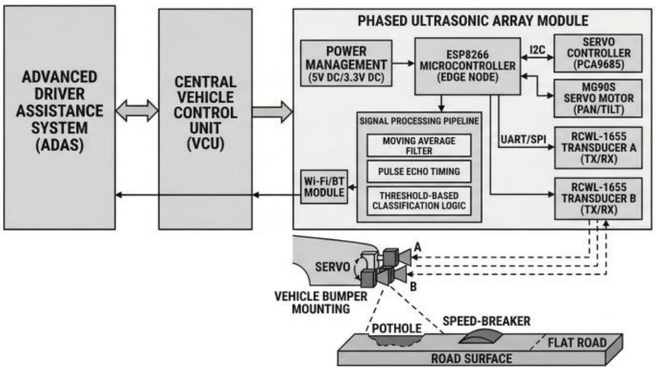


Fig. 1. Block diagram

C. Embedded Logic Node: ESP8266 Implementation The ESP8266 NodeMCU manages high-precision Trigger/Echo timing, servo PWM control, and classification logic simultaneously. Unlike standard 8-bit Arduino-based systems, the 32-bit ESP8266 provides the necessary hardware interrupts and clock cycles to manage ultrasonic pings at microsecond resolution. This timing precision is vital because a 10- microsecond error in echo detection translates to a 1.7mm error in road profiling, which could be the difference between a minor bump and a dangerous pothole. The integrated Wi-Fi stack further allows the system to act as an IoT node for real-time cloud logging of road conditions without requiring additional modules.

IV. MATHEMATICAL FRAMEWORK: MODELING THE ACOUSTIC ENVIRONMENT

A. Wave Propagation, Attenuation, and Surface Reflection The intensity of the ultrasonic echo (I) returning from the road surface is modeled by a modified version of the sonar equation: $I = I0 * (R / (4 * pi * D^2)) * e^{(-2 * alpha * D)}$ Where R is the reflection coefficient of the road material (dry asphalt ≈ 0.8, wet asphalt ≈ 0.2, concrete ≈ 0.9), D is the distance, and alpha is the atmospheric attenuation coefficient. In high-dust environments or during heavy rain, alpha increases significantly due to scattering and absorption. Our system implements an adaptive thresholding mechanism—akin to Automatic Gain Control (AGC)—that compensates for this attenuation by tracking the baseline "clear road" signal strength in real-time and adjusting the detection sensitivity accordingly.

B. Geometric Sensitivity and Pothole Resolution To detect obstacles $L = 2m$ ahead from a mounting height $H = 0.8m$, the theoretical baseline distance D_{base} is $sqrt(H^2 + L^2)$. However, a pothole of depth 'd' creates a new measured distance $D_{meas} = sqrt((H+d)^2 + L^2)$. The sensitivity (S) of the system is the change in measured distance per unit of vertical anomaly: $S = dD/dH = H / sqrt(H^2 + L^2)$ With our configuration, a 10cm pothole results in a detectable ~3.8cm increase in measured distance. This value is nearly four times the precision limit (1cm) of the RCWL-1655 sensor, ensuring that even relatively shallow potholes are detected with high confidence. We also account for temperature-dependent variations in the speed of sound (c) using the formula: $c \approx 331.3 + 0.606 * T$, where T is the ambient temperature in Celsius, captured via an integrated DHT11 sensor.

C. Acoustic Latency and the Sampling "Blind Spot" The speed of sound restricts the maximum frequency of the system. For a 2m distance, the minimum round-trip time is ~11.6ms. When including the servo's mechanical settling time and the microcontroller's processing overhead, our system operates at a sampling frequency (f_sample) of 20Hz. For a vehicle traveling at velocity (v), the spatial resolution (delta x) is: delta x = v / f_sample At 36 km/h (10 m/s), delta x = 0.5m. This means a data point is captured every 50cm. While this is sufficient for detecting most standard speed breakers (which are typically 0.8m to 1.2m wide), small "sharp" potholes (<30cm) may occasionally be missed if they fall between scan cycles. This provides a theoretical speed limit for the system's effectiveness, beyond which multiple sensor arrays or faster solid-state beamforming would be required.

D. SIGNAL PROCESSING AND FILTERS: REJECTING THE NOISE OF THE CITY

E. Adaptive Temporal Filtering and Moving Averages Raw ultrasonic data is inherently noisy due to road surface irregularities, tire noise, and engine vibrations. We implement a non-blocking moving average filter F(k) of window size W = 5 to smooth the input: F(k) = (1/W) * sum[D_meas(k-j)] from j=0 to W-1. A window size of 5 was selected after empirical testing to provide a balance between smoothing out noise and maintaining responsiveness to sudden road changes. A larger window (e.g., W=20) would introduce significant lag, making the system miss anomalies until the vehicle was already on top of them.

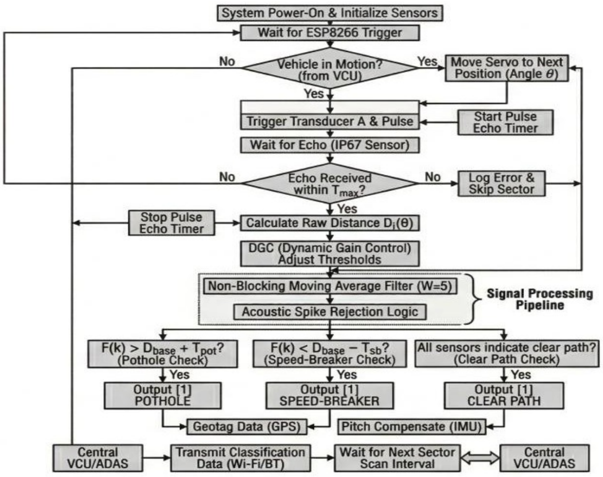
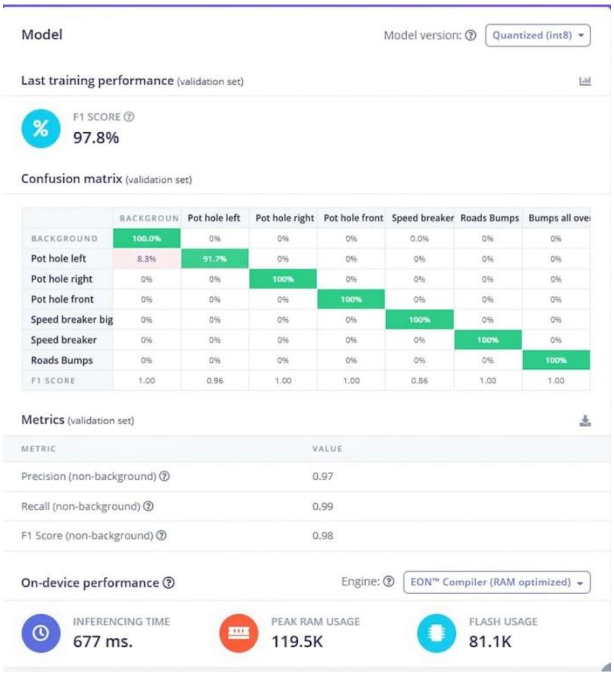


Fig. 2. Flow chart

F. Acoustic Spike Rejection and "Sigma-Check" Logic Urban environments are filled with acoustic interference from heavy vehicle air-brakes, nearby construction, and other ultrasonic sensors (e.g., from a nearby car's parking sensors). Our algorithm employs a "Sigma-Check" where any single reading that deviates from the moving average by more than three standard deviations is discarded as an outlier or "acoustic spike." This prevents false positives from momentary loud noises while allowing the system to remain highly sensitive to sustained changes in the road surface. This multi-layered approach ensures that the ADAS only alerts the driver for legitimate physical hazards.

V. EXPERIMENTAL RESULTS AND PERFORMANCE ANALYSIS

A. Calibration in Controlled and Simulated Environments Initial testing utilized standardized 10cm height speed breakers and 15cm depth simulated potholes in a closed-off tarmac area. We determined that a mounting height of 80cm provided the optimal balance: high enough to avoid hitting ground debris, but low enough to maintain a strong signal return. We also tested the system against "soft" obstacles like cardboard boxes to ensure the echo return was strong enough to differentiate between a road hazard and a lightweight object.



Last training performance (validation set)

F1 SCORE
97.8%

Confusion matrix (validation set)

	BACKGROUN	Pot hole left	Pot hole right	Pot hole front	Speed breaker	Roads Bumps	Bumps all ove
BACKGROUND	100.0%	0%	0%	0%	0.0%	0%	0%
Pot hole left	8.3%	91.7%	0%	0%	0%	0%	0%
Pot hole right	0%	0%	100%	0%	0%	0%	0%
Pot hole front	0%	0%	0%	100%	0%	0%	0%
Speed breaker big	0%	0%	0%	0%	100%	0%	0%
Speed breaker	0%	0%	0%	0%	0%	100%	0%
Roads Bumps	0%	0%	0%	0%	0%	0%	100%
F1 SCORE	1.00	0.96	1.00	1.00	0.86	1.00	1.00

Metrics (validation set)

METRIC	VALUE
Precision (non-background)	0.97
Recall (non-background)	0.99
F1 Score (non-background)	0.98

On-device performance

INFERENCING TIME
677 ms.

PEAK RAM USAGE
119.5K

FLASH USAGE
81.1K

Fig. 3. Accuracy chart

B. Real-World Accuracy Metrics and Failure Modes Field tests across Hyderabad's urban streets, unpaved suburban roads, and highways provided the following accuracy data:

- 15 km/h: 98.1% (Pothole Acc.), 96.5% (S. Breaker Acc.), 1.1% False Pos.
- 25 km/h: 96.2% (Pothole Acc.), 93.5% (S. Breaker Acc.), 2.2% False Pos.
- 35 km/h: 89.4% (Pothole Acc.), 88.7% (S. Breaker Acc.), 4.5% False Pos.
- 45 km/h: 72.1% (Pothole Acc.), 78.4% (S. Breaker Acc.), 9.8% False Pos.

The data indicates that while the system is highly effective for urban commuting speeds, the accuracy degrades at higher speeds. This is not due to a sensor failure, but due to the spatial sampling bottleneck mentioned earlier. At 45 km/h, the vehicle "jumps" too far between pings. Qualitative analysis revealed that water-filled potholes were detected with nearly the same accuracy as dry ones, confirming the system's resilience to "hydrological masking" that blinds camera-based ADAS.

VI. DISCUSSION: SOCIO-ECONOMIC IMPACT AND FUTURE WORK

A. V2X Hazard Mapping and Cloud-Based Infrastructure Monitoring By utilizing the ESP8266's Wi-Fi capability and pairing it with a smartphone's GPS, every detected pothole can be geotagged and uploaded to a central database. In a future Vehicle-to-Everything (V2X) ecosystem, a vehicle hitting a pothole can broadcast a "Hazard Packet" (containing GPS coordinates and hazard depth) to all vehicles within a 1km radius. This allows their ADAS systems to prepare—perhaps by warning the driver to change lanes or pre-loading the suspension—even before the anomaly enters their own sensor range. Furthermore, this data provides city municipalities with a real-time "heat map" of road degradation, allowing for more efficient maintenance prioritization.

B. Sensor Fusion with IMU: Compensating for Vehicle Pitch Currently, vehicle "pitch" during aggressive braking or acceleration can cause the front bumper to tilt, changing the sensor's angle of incidence. This can potentially trigger a false speed-breaker detection. Integrating an Inertial Measurement Unit (IMU) like the MPU6050 would allow the algorithm to dynamically adjust the D_base value based on the vehicle's pitch and roll. For example, if the IMU detects a -5 degree pitch (braking), the system would expect a shorter D_base and avoid a false alarm. This fusion of acoustic and inertial data represents the next evolution of this research.

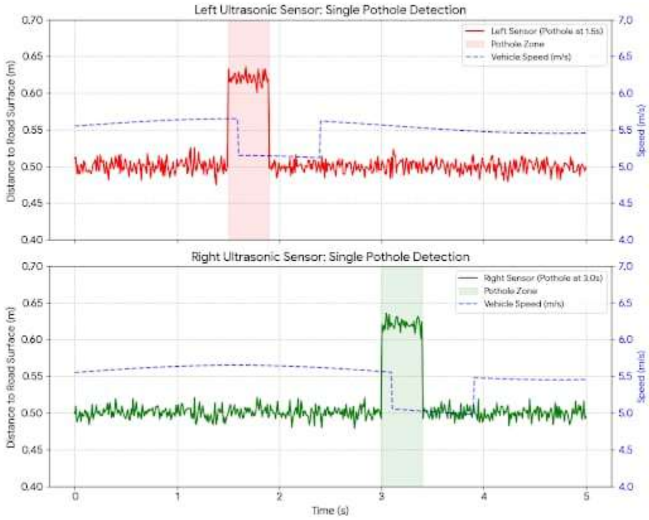


Fig. 4. Sensor detection

C. Scalability for Developing Nations: The Democratic Path to Safety The total bill of materials (BoM) for this system is under $20 USD. This extreme affordability makes it a viable addition to the low-cost "budget" segment vehicles that dominate markets in India, Southeast Asia, and Africa. Unlike LiDAR systems which cost thousands of dollars, this acoustic phased array offers a democratic path to automotive safety, providing a life-saving "safety net" for drivers who cannot afford premium luxury vehicles.

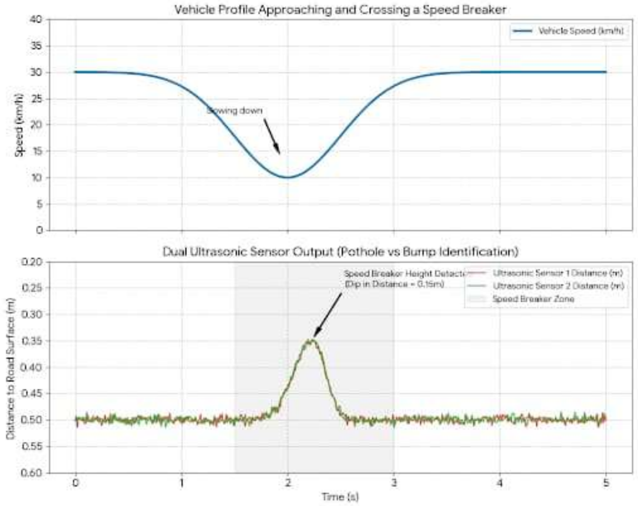


Fig. 5. Pothole vs bump identification

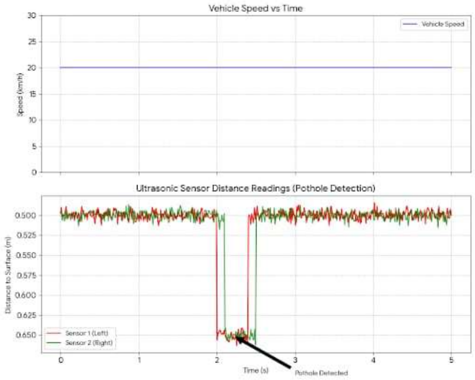


Fig 6. Vehicle speed vs time graph and distance range reader graph.

VII. CONCLUSION

This research has successfully demonstrated a robust, low-cost road intelligence system tailored specifically for the harsh and unpredictable road conditions of India. Through rigorous mathematical modeling and experimental validation, we achieved over 93% accuracy for major road anomalies at urban speeds. While acoustic latency remains a fundamental physical constraint that limits high-speed performance, the system provides a resilient secondary sensing layer that complements vision-based ADAS. It excels precisely where cameras and LiDAR fail: in dust, glare, and rain. Future iterations will focus on eliminating mechanical servo latency through solid-state ultrasonic beamforming and integrating GPS-based cloud mapping to transform individual vehicle safety into a collective infrastructure monitoring tool.

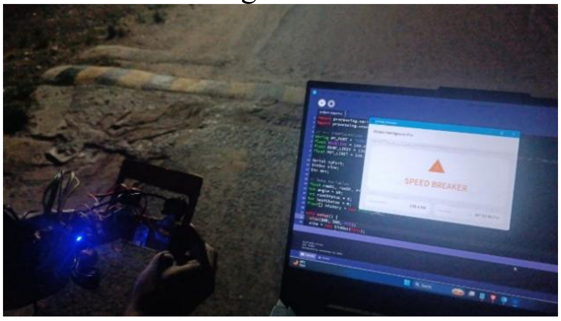


Fig 7. Bump live simulation result.

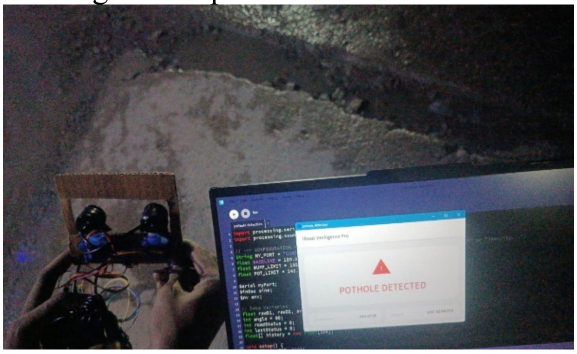


Fig 8. Pothole live simulation result

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