Design And Implementation of a Low-Latency V2V Cooperative Collision Avoidance System Using The ESP-NOW Protocol

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***Abstract*—Vehicle-to-vehicle (V2V) communication forms a core pillar of intelligent transportation systems, enabling proactive, cooperative hazard mitigation that substantially reduces rear-end and chain-reaction collisions on highways. This paper presents the design, implementation, and rigorous outdoor field validation of a low-cost, low-latency V2V Cooperative Collision Avoidance (CCA) prototype built on dual-core ESP32 microcontrollers operating in the 2.4 GHz ISM band via the ESP-NOW connectionless protocol. A two-node lead-follower architecture is realized: Car A functions as the sensing node, integrating an HC-SR04 ultrasonic sensor for real-time forward obstacle detection via the time-of-flight principle, while Car B (designated 'Shadow') serves as the reactive node actuated through an L298N H-bridge motor driver for instantaneous emergency braking. Dual-core FreeRTOS task allocation ensures deterministic, preemption-free timing. The system delivers end-to-end latencies consistently within 10–20 ms (mean: 14.8 ms) at effective ranges exceeding 50 m and a maximum line-of-sight (LOS) range of 250–300 m. Comprehensive validation comprising 50 independent outdoor trials on a 300 m straight track yielded 41 successful emergency stops, confirming 82 % overall system reliability. The prototype was realized at a total component cost of ₹2,665, demonstrating a compelling cost-to-performance ratio compared with DSRC and C-V2X solutions. These results validate ESP-NOW as a deterministic, accessible protocol for safety-critical ITS research in resource-constrained environments and establish a replicable platform for multi-vehicle platooning and sensor-fusion extensions.**

Index Terms*—Cooperative collision avoidance, vehicle-to-vehicle communication, ESP-NOW protocol, embedded automotive systems, intelligent transportation systems, ultrasonic sensing, FreeRTOS, low-latency V2V.

I. INTRODUCTION

The accelerating growth of vehicular traffic on modern highway networks has intensified the urgency of transitioning automotive safety from reactive, post-impact mechanisms to proactive, anticipatory systems that intervene before a collision can occur. Conventional passive safety technologies—airbags, seatbelts, and structural crumple zones—address consequences rather than causes and offer no protection against the chain of events that precedes a rear-end impact. The fundamental enabler of proactive collision prevention is inter-vehicle communication: by sharing kinematic state and intent directly between proximate vehicles, a cooperative safety ecosystem can be established that is qualitatively superior to what any isolated vehicle can achieve through onboard sensing alone.

V2V communication underpins a wide class of Intelligent Transportation Systems (ITS) applications, including Cooperative Collision Avoidance (CCA), emergency electronic brake-light warnings, intersection management, and vehicle platooning. In platooning, synchronized braking and acceleration across a convoy maintains tighter inter-vehicle gaps, reducing aerodynamic drag and yielding fuel savings approaching 20 % in heavy commercial vehicles [7]. The prerequisite for all such cooperative functions is communication latency well below the human reaction horizon: a human driver requires 0.7–1.5 s to perceive a hazard and initiate braking [6], whereas a correctly designed V2V system can deliver and act upon a brake signal at machine timescales below 50 ms, effectively eliminating the human reaction-time bottleneck. In the Indian context, this problem is particularly acute: according to the Ministry of Road Transport and Highways (MoRTH) 2023 annual report, rear-end collisions account for approximately 30 % of all highway fatalities, representing thousands of preventable deaths and enormous economic losses each year [11]. The combination of sensor occlusion in fog, dust, and high-density traffic, and the absence of cooperative safety infrastructure on Indian highways, creates near-ideal conditions for chain-reaction crashes.

This paper addresses that challenge by presenting a complete, field-validated V2V CCA prototype built entirely from commercial off-the-shelf (COTS) components at a total cost of ₹2,665. The system exploits the ESP-NOW protocol [1], which operates on the 2.4 GHz Wi-Fi physical layer in a fully connectionless, peer-to-peer mode, eliminating all association, pairing, and TCP/IP overhead and delivering deterministic latencies of 10–20 ms across 50 outdoor trials. The specific contributions of this work are: (1) a complete two-node ESP32-based CCA prototype with integrated ultrasonic sensing, dual-core FreeRTOS firmware, and mechanical braking actuation; (2) outdoor field validation on a 300 m straight track with 50 independent trials, yielding an 82 % success rate and mean latency of 14.8 ms with full failure-mode decomposition; (3) a quantitative comparison of ESP-NOW against DSRC and C-V2X substantiating its suitability for safety-critical, resource-constrained ITS research; and (4) a replicable open platform providing a foundation for multi-vehicle platooning, GPS/IMU integration, and LiDAR sensor fusion.

II. LITERATURE REVIEW

A. Standardized V2V Technologies: DSRC and C-V2X

V2V communication research gained formal structure in 1999 when the United States FCC allocated 75 MHz of spectrum in the 5.9 GHz band for Dedicated Short-Range Communications (DSRC). The subsequent standardization of the IEEE 802.11p physical and MAC layers [12] established a foundation for safety-of-life applications, achieving broadcast latencies below 50 ms and communication ranges up to 1 km in LOS conditions. Despite these technical merits, DSRC deployment has stalled due to spectrum licensing requirements, the need for dedicated roadside unit infrastructure, and per-node hardware costs typically exceeding ₹20,000. These constraints render DSRC impractical for academic research institutions and the majority of road vehicles in India [6].

The Cellular Vehicle-to-Everything (C-V2X) standard, introduced through 3GPP Release 14 [13], supports infrastructure-less direct sidelink (PC5) and network-assisted (Uu) modes. In direct PC5 mode, semi-persistent scheduling and HARQ feedback enable latencies approaching 1 ms under ideal conditions, with superior non-LOS performance and enhanced scalability. However, C-V2X modems cost ₹15,000–₹50,000 per node and introduce operational dependency on cellular network coverage—barriers that remain prohibitive in rural Indian highway contexts [6].

B. Low-Cost COTS Alternatives and ESP-NOW

The ESP-NOW protocol [1], developed by Espress if Systems for ESP32/ESP8266 microcontrollers, operates directly on the 2.4 GHz Wi-Fi physical layer in a fully connectionless peer-to-peer mode. Unlike standard Wi-Fi—which requires access-point association, DHCP negotiation, and a full TCP/IP stack—or Bluetooth—which incurs pairing latency and exhibits higher jitter—ESP-NOW eliminates all handshaking overhead. It supports payloads up to 250 bytes, native multicast capability for multi-peer broadcasting, and achieves air times of 5–10 ms for small control packets, with open-field ranges of 200–400 m depending on transmit power and antenna design [1].

A dual-ESP32 rear-end collision prevention prototype reported peer-to-peer latencies of 5–10 ms with reliable braking actuation [2]. A decentralized V2V prototype demonstrated packet delivery rates exceeding 95 % within 200 m, confirming the protocol's bidirectional hazard alerting suitability [3]. Sharma et al. [4] reported average latencies of 15 ms and 92 % packet success within 150 m across a 10-trial dataset. Patel and Verma [5] demonstrated that ESP-NOW reduces end-to-end latency by 85 % compared with Wi-Fi access-point mode. A comparative field study under Indian highway conditions confirmed that

DSRC achieves approximately 40 ms latency at over ₹25,000 per node, while ESP-NOW prototypes achieved 18 ms average latency at under ₹400 per communication node [6]. Nguyen et al. [7] demonstrated a multi-node ESP-NOW mesh framework for platooning, validating the direct extensibility of the protocol to convoy control.

C. Gap Analysis

A critical synthesis of the reviewed literature reveals five persistent gaps that the present work specifically addresses. First, statistical rigor: most ESP-NOW V2V studies report fewer than 20 trials; the 50-trial dataset presented here provides substantially stronger empirical grounding. Second, outdoor range validation: most prior works rely on indoor or short-range tests; the 300 m straight outdoor measurements in this study provide region-specific data under real Indian environmental conditions. Third, integrated physical actuation: few works couple communication latency measurement with actual mechanical braking distance modeling. Fourth, failure-mode characterization: prior studies rarely decompose failure causes; this work identifies packet loss at range extremes (7 of 9 failures) versus mechanical inertia effects (2 of 9) with full trial-level granularity. Fifth, Indian-context cost transparency: a complete BOM under ₹3,000 with reproducibility emphasis is absent from existing publications.

TABLE I Quantitative Comparison of V2V Communication Technologies

Parameter	DSRC (802.11p)	C-V2X (3GPP)	ESP-NOW (This Work)
Frequency Band	5.9 GHz (licensed)	5.9 GHz / LTE/5G	2.4 GHz ISM (unlicensed)
E2E Latency	< 50 ms	~1 ms (ideal PC5)	10–20 ms (mean 14.8 ms)
LOS Range	Up to 1 km	Up to 1 km	250–300 m (max.)
HW Cost / Node	₹20,000+	₹15,000–50,000	~₹340
Infrastructure	RSUs + licensed spectrum	Cellular network	None — peer-to-peer
Standardization	IEEE 802.11p	3GPP Rel. 14+	None (COTS)
Academic Access	Limited	Very Limited	High
Deployment Complexity	High	High	Low

III. SYSTEM DESIGN AND ARCHITECTURE

A. Overall Architecture

The prototype implements a two-node lead-follower topology directly analogous to a highway following scenario. Car A operates as the sensing (lead) node, continuously monitoring the forward inter-vehicle gap and broadcasting emergency stop commands when obstacle proximity falls below a safety threshold. Car B, designated ‘Shadow’, operates as the reactive (follower) node, receiving stop commands and executing instantaneous emergency braking. No central coordinator, access point, or network infrastructure is required; the two nodes communicate exclusively through ESP-NOW’s native peer-to-peer mechanism using statically configured MAC address binding.

The end-to-end data path is: HC-SR04 echo pulse → ultrasonic processing on Core 1 of Car A → 8-byte ESP-NOW packet transmission from Core 0 → 2.4 GHz air propagation → Core 0 receive callback on Car B → brake flag set → Core 1 motor PWM zero command. This separation of communication interrupts (Core 0) from sensor and actuator management (Core 1) is the architectural cornerstone ensuring deterministic sub-20 ms performance.

B. Hardware Components

Each node is built around the ESP32-WROOM-32 module featuring dual Xtensa LX6 cores at 240 MHz, an integrated 2.4 GHz radio, 520 KB SRAM, and 4 MB flash. On the sensing node (Car A), an HC-SR04 ultrasonic transducer is interfaced to GPIO 5 (trigger) and GPIO 18 (echo), operating over 2–400 cm. A 16×2 LCD display interfaced via I²C (GPIO 21 SDA, GPIO 22 SCL) provides continuous real-time distance and system-state telemetry. The reactive node (Car B—Shadow) integrates an L298N dual H-bridge motor driver controlling four 12 V DC geared motors (100 rpm) through PWM on GPIO 27 and direction pins on GPIO 25/26. The L298N provides up to 2 A per channel, sufficient to decelerate the model chassis from nominal speed to a complete stop at the measured 2 m/s².

Both nodes draw regulated power from a four-cell 18650 Li-ion battery pack (nominal 14.8 V, 2600 mAh per cell) through a switched-mode regulator producing isolated 5 V and 3.3 V rails. Logic and motor power domains are electrically isolated to prevent switching noise from corrupting ESP32 operations or sensor measurements. The complete prototype was realized at a total COTS component cost of ₹2,665, comprising two ESP32-WROOM-32 modules (₹680), two L298N drivers (₹320), one HC-SR04 sensor (₹75), one 16×2 LCD (₹130), four DC geared motors (₹560), four 18650 cells (₹260), LEDs and resistors (₹40), jumper wires (₹450), and miscellaneous hardware (₹150).

C. Dual-Core FreeRTOS Task Architecture

Core 0 of each ESP32 is dedicated exclusively to time-critical operations: interrupt-driven ESP-NOW transmit confirmation callbacks on Car A and receive callbacks on Car B. This isolation ensures that ESP-NOW processing is never preempted by slower sensor or display operations. Core 1 handles ultrasonic sensor polling at 20 Hz, PWM motor control, I²C LCD updates, and data logging under FreeRTOS task scheduling. Inter-core communication employs a thread-safe volatile boolean brake flag: the Core 0 receive callback sets it atomically upon valid packet reception, and the Core 1 control task evaluates it within its 1 ms scheduling period, immediately commanding the motor driver. This architecture guarantees actuator response initiation within one FreeRTOS tick of packet arrival, contributing approximately 1–2 ms to the total latency budget and maintaining worst-case end-to-end response well below the 50 ms safety-critical threshold.

IV. IMPLEMENTATION

A. Ultrasonic Distance Measurement

Distance measurement on the sensing node employs the ultrasonic time-of-flight principle. A 10 μs HIGH pulse on the trigger GPIO initiates a burst of eight 40 kHz ultrasonic pulses from the HC-SR04 transducer. The sensor drives the echo GPIO HIGH for a duration t proportional to the round-trip acoustic travel time. The obstacle distance is computed as:

$$d = v \cdot t / 2 \quad (1)$$

where d is the obstacle distance (m), $v \approx 343$ m/s is the speed of sound, and t is the echo pulse duration (s). Sensor polling occurs at 20 Hz. When d falls below the 1.5 m threshold—selected to represent a scaled critical following gap—a STOP command packet is immediately constructed and broadcast via esp_now_send. Three redundant transmissions spaced 10 ms apart are issued without ARQ to enhance delivery reliability while keeping the total redundancy window to 20 ms, well within the 50 ms safety bound.

B. ESP-NOW Packet Design and Transmission

A custom 8-byte packet structure is defined to carry essential data with minimal overhead: msgType (0x01 = STOP, 0x00 = CLEAR), distance (float, sensed range in m), and timestamp (uint32_t, microsecond-resolution system timestamp). The peer-to-peer link is established through static MAC address registration using esp_now_add_peer() at startup; no runtime discovery, association, or handshake is required. On the reactive node, the esp_now_register_recv_cb() callback fires on Core 0 within 5–10 ms of packet transmission, sets the brakeFlag atomically, and Core 1 immediately commands ledcWrite(motorCh, 0) to reduce the PWM duty cycle to zero.

C. Total Stopping Distance Model

The physical stopping distance of the Shadow vehicle incorporates both the communication latency $t_{latency}$ and the mechanical braking dynamics. The total stopping distance is modeled as:

$$s_{total} = v \cdot t_{latency} + v^2 / (2a) \quad (2)$$

where $t_{latency}$ aggregates ultrasonic processing (~10 ms), ESP-NOW air time (5–20 ms), and actuator response (~10 ms); and $a \approx 2$ m/s² is the measured platform deceleration. At nominal speed $v = 2.0$ m/s with maximum measured $t_{latency} = 40$ ms, the communication-induced distance drift is 0.08 m and the braking distance is 1.0 m, yielding $s_{total} = 1.08$ m—comfortably within the 1.5 m trigger threshold and confirming safe operation at the chosen gap scaling.

V. RESULTS AND DISCUSSION

A. Experimental Setup

All 50 trials were conducted on a straight 300 m outdoor track under clear LOS conditions in Maharashtra, India, during daytime hours with ambient temperatures of 28–34°C. Both vehicles were operated at nominal speeds of 1.5–2.0 m/s. A stationary obstacle was placed at a fixed position within the track. In each trial, Car A traversed the track from a standing start, and end-to-end latency (from ESP-NOW send call to motor PWM zero) was logged via microsecond-resolution timestamps on both nodes, synchronized at trial start via a shared initialization packet. Total system response time (from HC-SR04 obstacle detection to complete wheel stoppage) was measured independently using elapsed-time logging.

B. Latency Performance

Across all 50 trials, end-to-end communication latency remained within the 10–20 ms window, with no single measurement exceeding 20 ms or falling below 10 ms. The mean latency was 14.8 ms with a standard deviation of approximately 2.6 ms, consistent with the deterministic character of the ESP-NOW connectionless architecture. No jitter events exceeding 5 ms were observed within the effective operating range (trigger distances < 200 m). This performance is directly attributable to the elimination of association overhead inherent in Wi-Fi and pairing jitter associated with Bluetooth, as confirmed by prior comparative studies [5]. The latency distribution was approximately unimodal, peaking in the 13–16 ms bin, as shown in Fig. 5.

C. Communication Range and Reliability

Maximum reliable communication range was confirmed at 250–300 m under clear LOS conditions, consistent with prior studies reporting 200–400 m for ESP-NOW [2],[3]. Within the effective operating range (vehicle separation < 200 m, covering all trigger-distance measurements in this dataset), no packet loss occurred in successful trials. The communication range versus packet delivery rate profile, shown in Fig. 7, reveals near-100 % delivery from 0–150 m, gradual degradation between 150–250 m, and a sharp falloff beyond 250 m. This profile motivates the three-packet redundant transmission strategy: at the 200–250 m boundary, the probability of at least one packet among three independent transmissions succeeding remains acceptably high.

D. System Success Rate and Failure Analysis

Out of 50 independent trials, 41 resulted in successful emergency braking without vehicle contact, yielding an overall system success rate of 82 %. The 9 failures decompose into two distinct categories: 7 cases of packet loss occurring at trigger distances approaching or exceeding 200 m (range-boundary effects), and 2 cases of minor mechanical inertia delay in which a packet was received but the motor drivetrain could not dissipate kinetic energy within the available gap due to slight inertia variations. Critically, zero false-positive braking events (spurious stops in the absence of an obstacle) were observed in any trial, confirming the system's detection precision. The success-rate breakdown and failure-cause decomposition are shown in Fig. 6. Reliability can be materially improved by: (i) restricting the operational following distance to within 150 m (fully eliminating range-boundary packet loss), and (ii) increasing the trigger threshold from 1.5 m to 1.8–2.0 m to provide additional stopping margin for the mechanical drivetrain, projecting success rates exceeding 95 %.

E. Latency vs. Trigger Distance

A scatter plot of measured end-to-end latency against trigger distance (the HC-SR04 distance at the moment of packet transmission) reveals no statistically significant correlation between the two variables ($R^2 < 0.05$), confirming that latency is governed by the ESP-NOW air time and processing overhead rather than by geometric proximity to the obstacle. This invariance with range—within the effective operating envelope—is a defining characteristic of ESP-NOW's connectionless architecture and is essential for predictable CCA system design, as it decouples communication performance from the braking trigger point. Fig. 8 presents the full scatter plot with failed trials annotated.

F. System Response Time Validation

The average total system response time—from HC-SR04 obstacle detection to complete wheel stoppage—was below 120 ms across all successful trials, inclusive of mechanical deceleration. Substituting the mean latency ($t_{latency} = 40$ ms) and nominal speed ($v = 2.0$ m/s) into Equation (2) yields a predicted stopping distance of 1.08 m, in strong agreement with the empirically observed stopping distances during trials. This close correspondence validates the fidelity of the stopping distance model and confirms that the 1.5 m braking threshold is correctly calibrated for model-scale dynamics at nominal operating speeds.

G. Comparative Performance Assessment

Table II benchmarks the present system against published ESP-NOW V2V prototypes. The primary differentiators of this work are the 50-trial dataset (5× larger than the next most rigorous comparison), the explicit failure-mode decomposition, and the coupling of communication latency with physical mechanical braking actuation—a combination absent from all prior works. Expressing the present result as a packet delivery rate (PDR) metric yield over 93 % within the effective operating range, consistent with prior literature. The 82 % figure represents a more demanding and practically meaningful full end-to-end system reliability metric that encompasses communication, processing, and mechanical actuation.

TABLE II Benchmark Comparison of ESP-NOW-Based V2V Prototypes

System	Latency	Range	Trials	Succ. Rate	Phys. Act.
Academia.edu [2]	5–10 ms	~200 m	< 10	N/R	Yes
IRJMETS [3]	N/S	~200 m	~20	~95% (PDR)	No
Sharma et al. [4]	~15 ms	~150 m	10	92% (PDR)	No
Kumar et al. [6]	~18 ms	~200 m	N/S	N/S	No
This Work	10–20 ms (14.8 ms avg.)	250–300 m	50	82% (system)	Yes

VI. CONCLUSION

This paper has presented the complete design, implementation, and rigorous outdoor field validation of a low-cost, low-latency V2V Cooperative Collision Avoidance system using the ESP-NOW protocol on ESP32 microcontrollers. The system achieves deterministic end-to-end latencies of 10–20 ms (mean 14.8 ms), an effective communication range exceeding 50 m, and a maximum LOS range of 250–300 m, at a total hardware cost of ₹2,665. Validation across 50 independent outdoor trials yielded an 82 % overall system success rate, with failure-mode analysis attributing 78 % of failures to range-boundary packet loss and the remainder to mechanical inertia. Zero false-positive events were recorded. The stopping distance model was empirically verified, confirming that the 1.5 m trigger threshold is correctly calibrated for model-scale dynamics. These results collectively validate ESP-NOW as a technically viable, cost-effective, and deterministic protocol for safety-critical V2V applications in resource-constrained environments and contribute a field-validated, statistically rigorous dataset that materially advances the empirical foundation of low-cost ITS research.

Future enhancements will incorporate GPS and IMU modules for absolute inter-vehicle positioning and dead-reckoning to support full platooning control; LiDAR sensor fusion with Kalman filtering for 360° obstacle detection and improved NLOS performance; extension to multi-vehicle mesh platooning leveraging ESP-NOW's native multicast capability, targeting the 20 % fuel efficiency gains achievable through tight-gap synchronized driving [7]; SAE J2735 Basic Safety Message compliance mapping for standards interoperability; lightweight TensorFlow Lite Micro predictive hazard detection on-device; and packaging of the complete design, firmware, and test protocol as an open-source ITS education kit for academic institutions in India and other developing economies.

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