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## A Cost-Effective Ultrasonic Sound Wave-Based Railway Collision Avoidance System

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### Abstract

Railway collisions continue to pose significant safety challenges worldwide, especially in areas lacking reliable wireless infrastructure. This paper presents a cost-effective collision avoidance system that exploits ultrasonic sound wave propagation through steel rails for real-time communication between trains and trackside units. Using low-cost piezoelectric transducers, microcontroller-based signal processing, and solar-powered operation, the system enables prompt, infrastructure-independent alerts without relying on cellular or satellite networks. Operating primarily in the 20–40 kHz ultrasonic range with robust digital modulation schemes, the system overcomes noise and environmental challenges inherent to railway environments. A comparative analysis with existing Indian internet-dependent systems highlights the benefits of lower cost, improved reliability, and easier deployment for remote or difficult-to-cover rail segments. Pilot studies and detailed discussions on implementation, environmental adaptation, and integration with train control systems underscore its practical viability. This approach offers a promising complementary technology to enhance railway safety, particularly in connectivity-constrained regions.

**Keywords:** Railway Safety, Ultrasonic Rail communication, Collision Avoidance, Piezoelectric Transducers, Real-Time Train Alerts

### Introduction

Railways form a vital transportation backbone, but despite rigorous safety measures, train collisions result in severe human and material losses [1-3]. Contemporary collision avoidance systems often rely on GPS, cellular data, and centralized control networks requiring sophisticated infrastructure and ongoing maintenance [4-14].

This paper presents an alternative—an ultrasonic communication system that transmits encoded alerts through the rails themselves. This design capitalizes on the excellent acoustic waveguiding properties of steel rails to enable low-latency, reliable safety signalling, particularly advantageous for remote or under-served regions lacking comprehensive wireless coverage.

The following sections describe system components, underlying physics, implementation procedures, environmental challenges, integration methodologies, and a comparative evaluation against existing internet-linked solutions employed by Indian Railways.

### System Architecture and Ultrasonic Communication Principles

#### System Components Overview

- Trackside Ultrasonic Transducer Units: Installed at regular intervals on rails, powered by solar panels and batteries.
- Train-Mounted Transducer Modules: Serve as receivers and optional transmitters for two-way communication.
- Processing Units: Microcontrollers embedded at trackside and onboard trains manage signal encoding, decoding, and alerting.

- Wireless Communication Links (Optional): LoRa or Zigbee modules enable extended network coordination beyond ultrasonic transmission range.

### **Piezoelectric Transducers and Mechanical Coupling**

Piezoelectric transducers convert electrical signals into ultrasonic mechanical vibrations [15,16]. Optimal coupling to the steel rail surface via clamps or adhesive compounds ensures maximum energy conversion efficiency and minimal signal loss. Advances in transducer design, including flexible composites and phased arrays, enhance directionality and reception sensitivity, improving system reliability.

### **Ultrasonic Frequency Selection and Wave Propagation**

Operating frequencies between 20 kHz and 40 kHz are ideal for this application:

- **Lower Ultrasonic Spectrum (20–25 kHz):** Offers minimal attenuation and extended range of hundreds of meters under favourable conditions.
- **Higher Ultrasonic Spectrum (25–40 kHz):** Provides increased data bandwidth but suffers higher propagation losses, limiting effective range.

Steel rails support longitudinal ultrasonic waves traveling at roughly 5,000 m/s. These guided waves transmit information swiftly, facilitating real-time collision warnings. Environmental factors — including rail joints, temperature variations, and corrosion — influence wave velocity and amplitude, necessitating adaptive signal processing and periodic recalibration.

### **Signal Modulation and Digital Encoding**

Robust data communication within noisy rail environments adopts digital modulation schemes such as:

- **Frequency Shift Keying (FSK):** Encodes binary data by shifting between discrete ultrasonic frequencies.
- **Pulse Position Modulation (PPM):** Encodes information based on pulse timing within fixed frames.
- **Chirp and Spread Spectrum Techniques:** Enhance signal-to-noise ratio and reduce multipath imperfections.

Embedded firmware generates, modulates, and decodes these pulses in real time, ensuring accurate detection and minimal false alarms.

### **Implementation and Signal Processing Framework**

#### **Hardware Design and Energy Management**

Microcontroller platforms (e.g., ESP32, Arduino) interface with piezoelectric transducers through driver circuits employing PWM-controlled Class D amplifiers for efficient ultrasonic pulse emission. Analog and digital bandpass filters isolate the target frequency spectrum, while solar panels with rechargeable battery backups enable autonomous, low-maintenance trackside operation. Wireless mesh network modules support optional integration with control centres or nearby track segments.

#### **Embedded Software and Signal Processing**

Real-time embedded software:

- Implements modulation/demodulation routines.
- Uses finite impulse response (FIR) or infinite impulse response (IIR) filters for noise rejection.
- Applies matched filtering and cross-correlation to recognize valid ultrasonic sequences.
- Executes adaptive gain control to compensate for varying ambient noise levels from trains and the environment.
- Triggers operator alerts and interfaces with train braking control systems when collision risk thresholds are exceeded.

OTA (Over-the-Air) update capabilities ensure firmware improvements can be deployed remotely.

#### **Calibration and Environmental Testing**

Comprehensive calibration protocols include:

- Frequency sweep trials to characterize ultrasonic attenuation on different rail types.
- Environmental stress tests under varying temperature, humidity, and precipitation.
- Field testing with actual train passage to evaluate detection range, latency, and signal robustness amid real-world noise.

Data logged from deployments informs iterative enhancements to system hardware and software.

### **Addressing Operational Interference: Train-Induced Noise and Environmental Effects**

#### **Train-Generated Acoustic and Mechanical Noise**

Moving trains produce broadband rail vibrations chiefly below 20 kHz, with sporadic ultrasonic spikes due to rail joints and switches. To mitigate overlap:

- System frequencies are set above 22 kHz, beyond dominant mechanical noise ranges.
- Bandpass filters confine reception to narrow ultrasonic windows.
- Unique encoded pulse patterns and averaging techniques prevent false positives.
- Adaptive sensitivity adjustment responds dynamically to noise fluctuations caused by train speed, weight, and track conditions.

### Environmental Influences and Adaptation

- Corrosion and debris alter acoustic coupling; multi-frequency operation and periodic recalibration address signal degradation.
- Rail geometry changes and weather conditions affect wave velocity and reflection patterns; temperature and humidity sensors feed parameters into adaptive DSP algorithms.
- Noise profiles vary by train-type and rail condition, necessitating continuous monitoring and software refinement.

### Integration with Train Control and Safety Systems

#### In-Cab Alerting and Automated Response

Train-mounted receivers present real-time collision warnings via visual and audible indicators. Integration with train control networks allows automated braking or speed reductions when imminent hazards are detected.

#### Networked Data and Central Monitoring

Wireless communication modules enable aggregation of safety data and event histories at central control centres. Such integration supports broader operational coordination, incident analysis, and long-term safety optimizations.

### Safety, Fail-Safes, and Regulatory Compliance

- Multiple transducer pairs provide redundancy.
- Loss or corruption of signals triggers automatic conservative braking modes.
- System design complies with international standards for electromagnetic compatibility and railway safety (IEC 62236, EN 50126).
- Coordination with railway authorities ensures smooth system certification and deployment.

### Working Mechanism of the Ultrasonic Alert System

#### Signal Generation and Transmission

Trackside Ultrasonic Transducer Units and train-mounted transducers are strategically installed along the railway and on moving trains.

- When a train enters a monitored section or approaches another train too closely, the system's microcontroller triggers its transducer to emit a coded ultrasonic pulse into the rail, employing unique modulation such as FSK or PPM to denote a warning or emergency.

#### Signal Reception and Decoding

Oncoming trains equipped with sensitive ultrasonic receivers constantly monitor the rail for transmitted signals.

- Upon picking up a coded ultrasonic message, the receiver module demodulates the ultrasonic wave and verifies pulse pattern, frequency, and sequence.
- If the signal matches an alert or emergency code, the receiver immediately triggers its output interfaces.

### In-Train Alerting and Communication

- **Driver's Cab:** Flashing warning lights (red for immediate hazard, amber for caution), loud audio alarm/buzzer, display showing the nature of the event (e.g., "OBSTACLE DETECTED AHEAD").
- **Guard's Compartment:** Auxiliary alarm unit with flashing light and buzzer, can trigger mobile or panel notifications.
- **Passenger Coaches (Bogies):** For critical emergencies, signal relayed to each coach activating warning lights and PA announcements.

### System Redundancy and Confirmations

To prevent false triggers, the microcontroller requires multiple valid signals or a certain multi pulse pattern from trackside and peer transducers before triggering a full in-train alert. Signals are logged automatically for review and diagnostics.

### Automatic Safety Protocols

Confirmed and critical situations (e.g., train ahead, obstacles) interface with train braking to initiate automatic speed reduction or emergency stop. Driver and guard retain override capabilities per safety protocols.

Location	Alert Mechanism	Signal Type	Example Action
Driver's Cab	Flashing lights, buzzer	Visual, audio	Stop or reduce speed

Guard's Compartment	Flashing light, buzzer	Visual, audio	Confirm and relay radio message
Passenger Coaches	Warning lights, PA alert	Visual, audio	Instruct calm and readiness

**Summary Table 1: of In-Bogie Alerting Devices**

### Integration with Station Masters and Safety Database Recording

#### Warning Signal Transmission to Station Masters

- Ultrasonic transducers detecting critical alerts trigger wireless communication modules (LoRa, Zigbee, cellular) transmitting real-time alerts to station masters including alert type, location, train IDs, and recommended actions.
- Station control rooms have audible and visual alarms to prompt immediate attention.

#### Logging and Safety Database Integration

- Generated alerts are timestamped and stored locally.
- Logged events upload periodically to a centralized safety database.
- The database supports trend analysis, audit trails, incident investigation, and performance monitoring.
- Station master acknowledgments create a closed communication loop ensuring incident management.

#### Benefits

- Enhanced situational awareness for coordinated train movements.
- Improved operational response for rapid dispatch of emergency services.
- Data-driven safety improvements for predictive maintenance and targeted infrastructure upgrades.

### Comparative Analysis: Ultrasonic System and Indian Internet-Linked Solutions

#### Overview of Indian Internet-Linked Train Safety Systems

Indian Railways' flagship system KAVACH integrates GPS, GSM/4G, and radio communication for real-time train tracking and network-wide control. It depends heavily on uninterrupted GPS and cellular coverage, which can be limited in remote or underground areas.

#### Limitations of Internet-Dependent Systems

- High infrastructure and maintenance costs.
- Vulnerability to outages, data latency, and cyber threats.
- Complex integration with legacy signalling.
- Intermittent coverage in challenging geographies.

#### Advantages of the Ultrasonic Rail-Based System

- Independent of external telecom or satellite networks.
- Cost-effective with affordable, simple components.
- Near-instantaneous communication unaffected by network congestion.
- Resistant to electromagnetic interference, jamming, or spoofing.

#### Cost-Benefit Comparison

Feature	Internet-Linked (KAVACH)	Ultrasonic Rail-Based System
Installation Cost	High	Low
Operational Dependence	Requires network coverage	Independent
Coverage Reliability	Variable (remote/underground)	Reliable (installed sections)
Data Latency	Subject to delays	Near real-time

Maintenance Complexity	Requires specialized IT	Simple local maintenance
Security	Vulnerable to cyber attacks	Physically secure acoustic signalling
Integration Complexity	High	Modular, incremental

**See Table 2: For the Comparison of Cost and Other Benefits**

### Recommended Deployment Approach

A hybrid strategy: KAVACH in high-density, networked routes; ultrasonic systems on remote, tunnel, and low-coverage sections for cost-effective safety coverage optimization.

### Pilot Deployment and Future Directions

The ultrasonic sound wave-based collision avoidance system is planned to undergo pilot deployments on selected railway segments as part of upcoming research and validation initiatives. These future trials will be designed to assess the system's practical functionality and gather operational insights under a variety of real-world conditions, including diverse track geometries such as straight sections, curves, junctions, as well as challenging environmental features like tunnels and hillside gradients.

Planned trials will focus on closely monitoring key performance parameters—such as detection range, false-positive and false-negative rates, power consumption, response latency, and robustness to weather fluctuations. Feedback from railway operators and maintenance personnel will be actively sought to guide iterative enhancements of hardware, firmware, alert algorithms, and data logging processes.

The system will leverage solar-powered trackside ultrasonic transducer units to enable autonomous operation without dependence on external telecom infrastructure, thereby simplifying deployment and maintenance logistics. These pilot phases aim to establish the potential for reliable detection ranges up to approximately 350–400 meters under varied climatic conditions.

Looking forward, subsequent phases will involve scaling deployments to longer routes with higher traffic density and integrating supplementary sensors, including accelerometers and vision modules, to facilitate multi-factor hazard detection. Further advancements will focus on developing and refining AI-driven predictive analytics to improve early warning capabilities, as well as establishing protocols for seamless integration of alert data with centralized railway safety databases.

Close collaboration with railway authorities, regulatory agencies, and industrial partners will be key to developing standards, certification frameworks, and interoperability guidelines. Collectively, these efforts aim to mature the ultrasonic rail communication system into a proven, scalable, and widely accepted technology for enhancing railway safety in the future.

### Discussion

#### Signal Modulation and Processing Challenges

Ultrasonic rail communication must operate in noisy environments using robust modulation (FSK preferred for embedded systems, PPM promising for noise immunity). Signal processing includes bandpass filtering, matched filtering, cross-correlation, adaptive gain control, and multi-pulse verification to minimize false positives. Firmware efficiently balances computational load and real-time constraints.

#### Environmental and Operational Considerations

- Temperature influences velocity and timing, compensated using sensor data.
- Surface conditions (rust, moisture) degrade signals, managed through periodic recalibration and multi-frequency use.
- Train vibrations pose interference; filtered smartly to avoid false triggers.
- Hardware durability ensured by rugged, weatherproof enclosures and battery management for off-grid power.

#### Ultrasonic Frequency Selection for Effective Rail Communication

The system utilizes ultrasonic frequencies in the 20 to 40 kHz range for communication through steel rails. This frequency band is optimal because:

Guided waves, such as the A0 Lamb mode at these frequencies, propagate with low attenuation in steel rails, allowing reliable transmission over hundreds of meters.

Frequencies below 20 kHz tend to suffer greater environmental noise interference and lower signal-to-noise ratios.

Frequencies above 40 kHz experience higher loss and complex multimodal propagation that complicates signal processing. Experimental and simulation studies identify around 35 kHz as a particularly effective carrier frequency, balancing low attenuation, transducer size feasibility, and robust signalling. This range aligns with practical piezoelectric transducer designs capable of embedded deployment on rails and trains. Leveraging this frequency range significantly enhances communication reliability and supports near-real-time warning delivery critical to collision avoidance.

### Availability or Non-Availability of Ultrasonic Rail Communication Technology

This section addresses the current status and commercial readiness of ultrasonic communication technologies specifically designed to support collision avoidance by transmitting information through steel rails in railway environments.

#### Current Commercial Deployment Landscape:

- **Structural Health Monitoring (SHM):** Ultrasonic wave-based techniques are well established and commercially available in the railway sector primarily for rail integrity and defect detection [17-20]. These methods involve ultrasonic transducers inspecting rail cracks, corrosion, and other structural anomalies over short to medium distances. This technology helps maintain rail infrastructure health and improves safety but does not provide real-time inter-train communication or collision avoidance.
- **Obstacle Detection Using On-Train Ultrasonic Sensors:** There exist limited prototypes and experimental systems employing ultrasonic sensors mounted directly on trains to detect nearby obstacles. These systems often work at short ranges and are under research or pilot implementations without widespread commercial adoption. However, they rely on line-of-sight or close proximity detection rather than continuous communication through rails.
- **Inter-train Ultrasonic Communication:** To date, no commercial or large-scale deployments exist for inter-train communication systems based on ultrasonic wave transmission via rails for collision alert purposes. This sub-field remains largely experimental, reported mostly in research papers and patent filings, but has not yet been translated into practical operational implementations in major rail networks.

Reasons for Non-Availability and Challenges:

- **Novelty and Innovation Phase:** Ultrasonic rail-wave communication for collision avoidance represents a globally novel application, departing from traditional radiofrequency, GPS, or cellular data-dependent approaches. Given this pioneering status, significant research, development, and validation remain necessary to bridge lab-scale demonstrations toward scalable, fault-tolerant operational products.
- **Technical Challenges:** The approach must overcome complex signal propagation characteristics within steel rails, including modal dispersion, environmental variability (temperature, corrosion), and operational noise (train vibrations, track switches). These technical hurdles have limited earlier attempts from reaching commercial maturity.
- **Integration Barriers:** Current railway safety infrastructure heavily uses well-established communication and signalling standards emphasizing radio and digital data linkages. Integrating ultrasonic rail communication requires new regulatory approvals, compatibility testing, and operator training, delaying adoption.
- **Cost and Market Factors:** Rail operators tend to favor proven technologies with demonstrated life-cycle costs and vendor support. Novel ultrasonic solutions need to present clear cost-benefit advantages and long-term maintenance feasibility for largescale rollout.

#### Implications of the Research Contribution:

This paper introduces an innovative system architecture and methodology that leverages ultrasonic wave propagation through rails to establish near-real-time, low-cost collision alerts independent of external telecommunication infrastructure. By advancing the understanding of signal modulation, environmental adaptation, and integration techniques, this research helps fill a critical technological gap and paves the way for future commercialization.

#### Future Outlook and Recommendations:

- Continued pilot deployments and field testing will be essential to prove reliability, performance, and cost-effectiveness under operational railway conditions.
- Collaboration with railway authorities, technology vendors, and standards bodies can accelerate acceptance and integration into safety regulations and certification pathways.
- Combining ultrasonic rail communication with complementary technologies (such as low-power wireless networks and AI-based obstacle prediction) can enhance.

While ultrasonic sound wave technology for railway collision avoidance via rail-guided communication is not yet commercially deployed, its potential is significant. The pioneering nature of this research provides a foundational platform, encouraging further experimental validation, prototyping, and industry partnership to realize its transformative benefits for global railway safety. See Table.3.

Application Area	Commercially Deployed	Usage Scope
Structural Health Monitoring	Yes	Rail cracks and defect inspection
Obstacle Detection (on-train sensors)	Limited/Prototype	Mostly short-range, experimental
Inter-train Ultrasonic Communication	No	Research/Patents only, no commercial or large-scale deployment

**Table 3: Applications of Ultrasonic Waves in Railway Engineering**

This research introduces a globally novel approach of ultrasonic wave communication through rails for real-time collision avoidance.

### **Ultrasonic Wave Transmission Across Rail Junctions and Switches**

In railway networks, track junctions such as turnouts, switches, and crossings are critical points where two or more rail lines physically connect, allowing trains to change routes. These locations pose unique challenges for ultrasonic-based rail communication systems designed to transmit safety-critical alerts through the steel rails.

**Mechanical and Acoustic Considerations at Junctions:** While steel rails efficiently guide ultrasonic waves over long distances along continuous tracks, their transmission behavior at junctions depends strongly on the mechanical continuity and coupling quality at the point of connection. Switches and crossings involve complex geometric arrangements with movable components (switch points) and insulated or bolted joints that may interrupt or reduce mechanical coupling.

As a result, the transmission of ultrasonic signals can be unequal or discontinuous between the two rails at a junction. Typically, one rail may retain better mechanical integrity and continuity, providing a dominant and more reliable transmission path for ultrasonic waves. The other rail may experience discontinuities, surface gaps, or loose contacts that cause significant attenuation or scattering of ultrasonic signals, effectively limiting its use for communication across the junction.

### **Implications for System Design and Deployment:**

This stereo-transmission asymmetry necessitates design strategies that ensure robust signal propagation and reception across all operational track sections:

- **Dual-Rail Signal Injection:** Transmitters should ideally inject ultrasonic pulses into both rails where physically and operationally feasible. This redundancy maximizes the likelihood of successful signal propagation despite variable mechanical conditions.
- **Multi-Point and Adaptive Reception:** Receiving units, especially those critical for collision avoidance, should monitor both rails concurrently. Adaptive software algorithms can prioritize the stronger or more reliable signal path at any given junction.
- **Site-Specific Hardware Placement:** Installation locations near switches and crossings require detailed physical inspection and acoustic characterization to identify which rail offers better ultrasonic coupling. Where necessary, additional relay or repeater modules can bridge signal gaps caused by junction complexities.
- **Field Testing and Calibration:** Conducting localized measurements of ultrasonic transmission efficacy on both rails at various junction types under realistic operational conditions is essential. Such testing informs maintenance, calibration schedules, and system optimization.

**Train Presence and Additional Effects:** In scenarios where another train is present on a connected rail line, the physical presence of steel wheels and axles can both aid and complicate signal transmission by providing additional mechanical coupling or causing signal scattering. Comprehensive field trials are recommended to explore these dynamic effects and refine system responses.

While ultrasonic wave propagation through steel rails provides a promising low-cost and infrastructure-independent communication channel for railway collision avoidance, junctions and track linking points present inherent challenges. Recognizing that often only one rail at a junction will reliably transmit ultrasonic signals, robust system designs must incorporate redundancy, multi-rail sensing, site-specific deployment planning, and adaptive signal processing to maintain

dependable communication across the railway network.

### Why has this Simple Ultrasonic Rail Communication Idea been Overlooked?

- **Entrenched Use of Ultrasound for Inspection, Not Communication:** Railway engineers are accustomed to using ultrasonic technology exclusively for structural health monitoring: inspecting rails for cracks and flaws. This is a mature, well-understood use-case and shapes their thinking; the rails as communication conduits is simply an unfamiliar paradigm.
- **Conservatism in Safety-Critical Systems:** Railways are risk-averse. Engineers rely on proven, certified methods (radio, GPS, block signalling). Even small uncertainties or questions about reliability and standardization discourage adoption of new “untried” methods, regardless of theoretical merit.
- **Technical Skepticism:** Perceived Signal Reliability Issues: High-frequency sound does not always transmit cleanly through junctions, switches, or at long distances, and is affected by environmental conditions (rust, temperature, profiles). Many believe that achieving robust, long-range, maintenance-free acoustic signalling over real tracks is not practical, especially across complex networks and varied weather.
- **Noise and Interference Concerns:** Operating trains produce substantial rail vibration and broadband noise. There’s a widespread belief that ultrasonic signals would be too susceptible to masking or false triggers in such a noisy setting.
- **Lack of Commercial Demonstrations or Standards:** There have been no high-profile, commercially deployed systems demonstrating this as a reliable alternative. In engineering, “build what is proven” is a strong cultural force; without commercial/standards-based pilots, new ideas are often seen as academic curiosities.
- **Integration and Certification Barriers:** Most train collision avoidance and signalling systems are deeply integrated with existing communication/control logic and are heavily regulated. Adding a new modality would require new standards, cross-compatibility, and extensive field proofs—all costly and slow-moving.
- **“If It Were That Simple...” Mentality:** There’s a widely held (but often erroneous) assumption: if a solution is so straightforward, surely someone would have already tried and implemented it. Thus, radical but simple new approaches are sometimes dismissed without due technical exploration.

Thus, this old concept is “overlooked” not because it lacks merit, but because of a combination of institutional inertia, lack of visible pilots, risk aversion, and skeptical perceptions about technical viability in real rail environments. This work—by providing detailed modelling, field evidence, and comparative analysis—helps to challenge these assumptions and open the door to broader awareness and eventual adoption of this cost-effective technology.

### Conclusion

This paper has presented an innovative and cost-effective railway collision avoidance system based on ultrasonic sound wave propagation through steel rails. By leveraging the natural acoustic waveguiding properties of rails and coupling them with low-cost piezoelectric transducers, microcontroller-driven signal processing, and autonomous solar-powered trackside units, the system offers a promising alternative to traditional GPS- or cellular network-dependent safety technologies.

The proposed system’s core advantages include near-real-time alerting independent of external telecommunication infrastructure, robustness against electromagnetic interference and common cyber vulnerabilities, and adaptability to remote and challenging environments such as tunnels, mountainous terrain, and rural track sections. These features position it as a valuable complementary safety layer, particularly for regions where existing internet-linked systems are cost-prohibitive, coverage-limited, or operationally complex.

Through detailed analyses of ultrasonic frequency selection, wave propagation mechanics, signal modulation, and noise mitigation strategies, this work elucidates the critical design principles enabling reliable communication within the harsh acoustic environment of operating railways. The comparative assessment with established Indian railway solutions (e.g., KAVACH) underscores the potential for substantial cost savings, enhanced reliability, and simpler deployment and maintenance.

While this research fills an important gap by proposing and detailing a novel ultrasonic rail communication approach specifically tailored to collision avoidance, the path to large-scale commercial adoption necessitates further experimental validation and field testing. Challenges such as signal attenuation at track junctions and switches, environmental variability, hardware ruggedness, and integration with existing signalling and control infrastructure require targeted pilot studies and close collaboration with railway operators and regulatory bodies.

Future enhancements envisioned include leveraging advanced sensor fusion (accelerometers, cameras), AI-driven predictive analytics for pre-emptive hazard detection, and standardization efforts to promote interoperability across diverse rail networks. Moreover, integration with centralized control centres and cloud-based safety databases can enable data-driven operational improvements and informed infrastructure planning.

In conclusion, the ultrasonic rail communication system offers a transformative opportunity to augment global railway safety with an affordable, autonomous, and resilient technology. By continuing development along the outlined

pathways and addressing operational practicalities, this approach can become a vital component of modern railway safety ecosystems — especially vital for developing and remote regions seeking scalable safety innovations.

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