Ultrasound and Material Properties of Railway Tracks:

1. Ultrasonic Wave Properties

Wavelength Calculation:

$$\lambda \text{ (lambda)} = v / f$$

Where:

λ = Wavelength (m)

v = Velocity of sound in material (m/s)

f = Frequency of ultrasonic wave (Hz)

For longitudinal wave:

$v = 5900$ m/s,

$f = 5$ MHz $= 5 \times 106$ Hz

$\lambda = 5900 / 5 \times 106 = 1.18$ mm

2. Railway Track Material Properties

Property	Pearlitic Carbon Steel	Medium Carbon Steel
Type	High Carbon Steel with Pearlitic Microstructure	Plain Medium Carbon Steel
Common Grades	R260, R350HT (UIC); 1080, 1320 (AREMA)	AISI 1040, 1045, 1050
Carbon Content	0.6 – 0.8%	0.3 – 0.6%
Manganese Content	0.7 – 1.3%	0.6 – 1.0%
Silicon Content	0.1 – 0.6%	Up to 0.4%
Sulfur & Phosphorus	Very low (improved ductility and fatigue resistance)	Typically controlled to low levels

Microstructure	Fine pearlite (alternating ferrite & cementite layers)	Ferrite and pearlite, with coarser structure than rail-grade steel
Tensile Strength	High (≈ 880–1200 MPa depending on grade)	Moderate (≈ 600–800 MPa)
Hardness	High (used for wear resistance)	Medium
Applications	Railway tracks, heavy load wear surfaces	Shafts, gears, axles, general engineering
Longitudinal Wave Speed	~5900 m/s	~5850 m/s
Shear Wave Speed	~3250 m/s	~3200 m/s

3. Railway Track Weld Material Properties:

Property	**Aluminothermic Weld Metal**	**Flash Butt Weld (FBW) Metal**	**Gas Pressure Weld Metal**
Type	Thermite-based steel weld	Fusion weld (electrical resistance)	Pressure + heat-based solid-state weld
Common Applications	Field welding of rails (on-site)	Factory/pre-assembled rail joints	Some field applications (less common today)
Base Metal Compatibility	R260, R350HT, 1080, 1320	R260, R350HT, 1080, 1320	Mild to medium carbon steels
Composition	- Carbon: ~0.6–0.75% - Mn: 1.0–1.3% - Si: 0.2–0.5%	Matches parent steel closely Controlled for ductility	Slight carbon variation Lower Mn/Si levels
Microstructure	Cast pearlite (slightly coarser than parent rail)	Fine pearlite + HAZ zone (heat affected)	Fine-grained ferrite–pearlite
Tensile Strength	~800–1000 MPa	~950–1200 MPa	~700–900 MPa
Hardness (HV)	~270–320 HV	~280–340 HV	~220–280 HV

Ductility	Moderate	High	Moderate
Common Defects (UT focus)	Porosity, shrinkage cracks, lack of fusion	Inclusions, internal cracking, misalignment	Brittle zone, incomplete bonding
Longitudinal Wave Speed	~5850–5900 m/s	~5900 m/s	~5800 m/s
Shear Wave Speed	~3200–3250 m/s	~3250 m/s	~3150 m/s

4. Ultrasound Wave Calculation for Optimal Distance Between Two Consecutive Sensors:

a. System Parameters:

Parameter	**Value**
Frequency	**5 MHz**
Wavelength in steel (λ)	1.18mm
Sensor height above track	20 cm (air-coupled or guided)
Sensor spacing	5 cm
Train speed	15–120 km/h (4.17–33.33 m/s)
Wave speed (longitudinal steel)	5900 m/s
Sampling rate	Typically, ≥ 100 MS/s for 5 MHz

The wavelength of 1.18mm indicates that system can resolve gaps as small as 0.6mm

b. Time-of-Flight for Echo Return

$$t = \frac{2d}{v}$$

In air (20 cm height):

$$t_{air} = \frac{2 \times 0.2}{343} = 1.17ms$$

In steel (for 10 mm defect depth):

$$t_{steel} = \frac{2 \times 0.01}{5900} \approx 3.39\mu s$$

Echoes from defects at 1 cm depth **return in ~3.4 microseconds** — very easy to detect at 5 MHz

c. **Sensor Spacing Vs Train Speed:**

$$t = \frac{distance\ between\ sensors}{train\ speed}$$

Train Speed (km/h)	Speed (m/s)	Time between sensors (5 cm apart)
15	4.17	0.012 sec = 12 ms
30	8.33	6 ms
60	16.67	3 ms
120	33.33	1.5 ms

5 MHz system can sample every 0.2 µs, so in 1.5 ms (at 120 km/h), system gets,

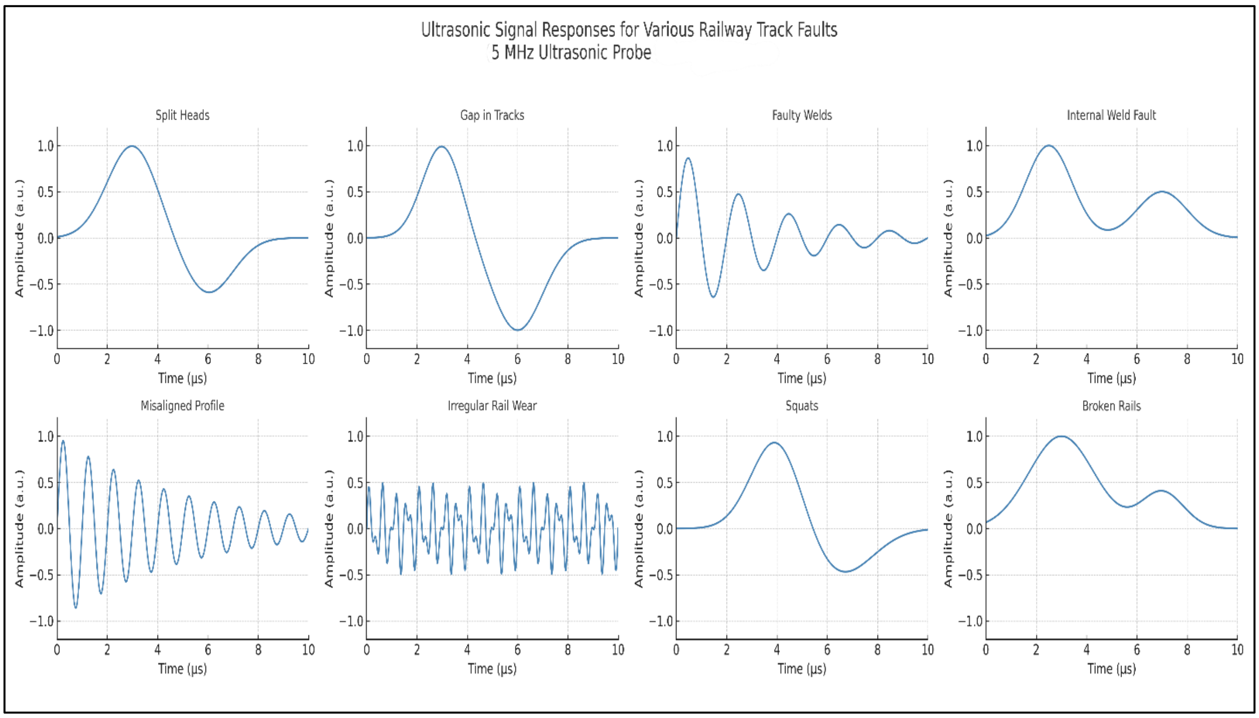
$$\frac{1.5ms}{0.2\mu s} = 7500\ samples$$

Which is enough to for formation of detailed waveform and defect validation.

According to calculations 5cm spacing between two sensors is optimal in individual sensor grid. It provides with high spatial resolution at all speeds. Echo correlation between sensors. If sensors were placed too close (less than 5cm) there would be redundant data at high speeds because of less delay between signals. If sensors were placed too far (more than 5cm) at 120km/h there would be risk of missing short and fine defects between sensors. The 5 cm distance is optimal for timed fault detection, Angle Compensation and Echo triangulation.

Factor	**Result**
Faults as small as	~0.6 mm (due to 1.18 mm wavelength)
Max measurable defect depth	> 25 mm easily (based on echo time and signal strength)
Echo return time (10 mm steel)	~3.4 µs (well within response window of 5 MHz system)
Sampling per pass (at 120 km/h)	~7500 samples per sensor spacing
Echo filtering logic	1.17 ms air return filtered, defect echoes measured accurately
Optimal spacing	5 cm (ideal delay at all operating speeds)

5. Different Ultrasonic Waveforms Obtained:



1. Split Heads

- **Graph Description**: Two distinct peaks, one large and one smaller, slightly delayed.
- **Explanation**: The ultrasonic wave reflects from the upper crack in the rail head (first peak), and a smaller delayed reflection from deeper in the head (second peak). This suggests material separation or crack branching.

- **Typical Signature**: Asymmetric double peak due to partial wave trapping.

2. Gap in Tracks

- **Graph Description**: Strong reflection at early time, followed by another inverted echo.
- **Explanation**: The wave hits the air gap between two rails. Air causes a strong reflection with phase inversion, seen as a negative peak. The second reflection is from the rear edge.
- **Typical Signature**: Strong reflection + polarity reversal = physical gap.

3. Faulty Welds

- **Graph Description**: Oscillatory, noisy waveform dampened over time.
- **Explanation**: Uneven weld material and gas pores scatter the wave. This causes multiple internal reflections and high-frequency attenuation.
- **Typical Signature**: Irregular, decaying sine wave — sign of porous or cracked welds.

4. Internal Weld Fault

- **Graph Description**: Two significant peaks at different positions.
- **Explanation**: One echo from weld boundary, another from an internal defect like a void or inclusion. Delays in reflections indicate depth.
- **Typical Signature**: Time-separated strong reflections indicate trapped wave in internal discontinuity.

5. Misaligned Profile

- **Graph Description**: Continuous sinusoidal pattern fading over time.
- **Explanation**: Misalignment leads to unstable angle of incidence → mode conversions → complex surface wave behavior. Shows up as phase-shifted oscillation.
- **Typical Signature**: Continuous high-frequency sine-like decay.

6. Irregular Rail Wear

- **Graph Description**: Composite wave with rapid oscillations.
- **Explanation**: Uneven surface wear scatters sound unevenly. Ultrasonic probe receives mixed mode echoes from multiple irregularities.
- **Typical Signature**: Superimposed multiple sine waves — short wavelength disruptions.

7. Squats

- **Graph Description**: Single broad peak followed by a smaller dip.
- **Explanation**: Squats are shallow surface defects causing a strong, single echo with a weaker trailing reflection.
- **Typical Signature**: Bell-shaped peak followed by ripple — indicates depression on the top rail surface.

8. Broken Rails

- **Graph Description**: Two strong peaks, well-separated.
- **Explanation**: Wave hits the break edge, bounces back strongly. Then it reflects from the second edge of the break.
- **Typical Signature**: High-amplitude twin peaks with gap = fracture region.

General Notes:

- **X-axis**: Time in microseconds (μs) — indicates time taken for wave to reflect and return.
- **Y-axis**: Amplitude in arbitrary units (a.u.) — relative signal strength.
- **Amplitude Behavior**:
  - High amplitude = clear reflection (dense or abrupt change).
  - Low amplitude = scatter, absorption, or mode conversion.
  - Echo delay = depth or distance of fault from probe.