PRINCIPLES COURSE

JUNE 10-12, 2025

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WRI2025HH

PRINCIPLES COURSE - JUNE 10, 2025

TRACK STRUCTURES AND COMPONENTS

J. RILEY EDWARDS

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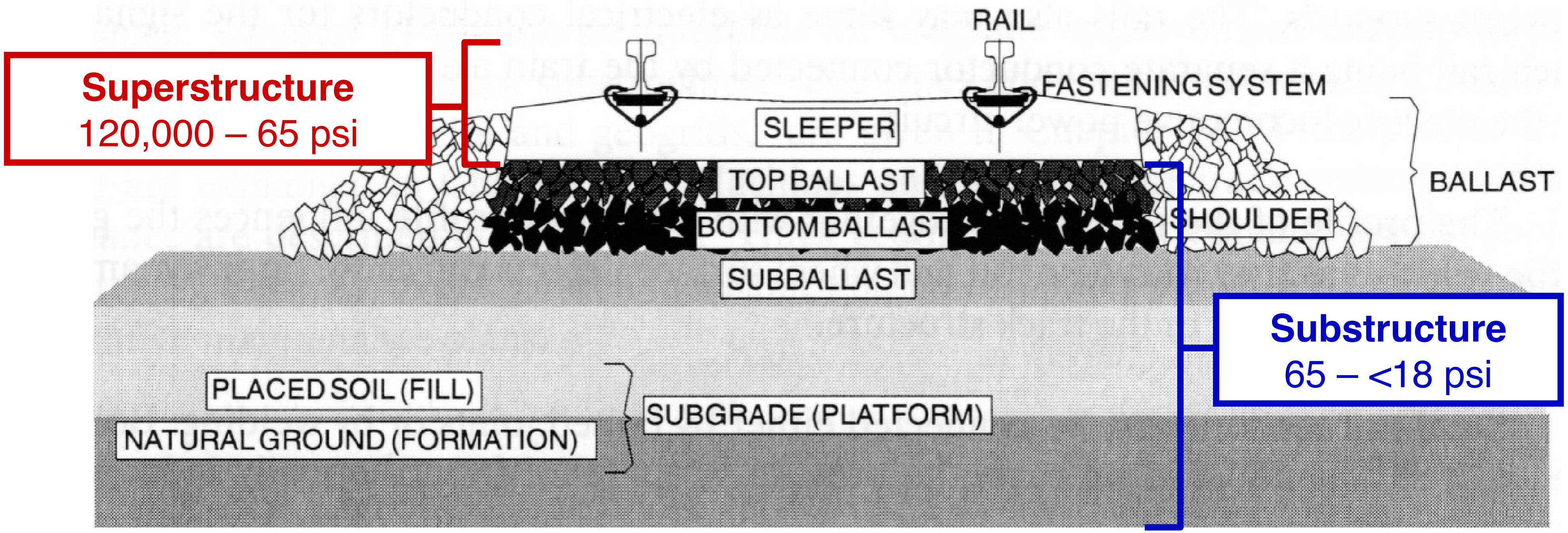
OUTLINE

1. Basics of Track Structure and Components
2. Horizontal Curvature, Superelevation, and Track Design
3. Track Standards and Regulations
4. FRA Mandated Track Inspections
5. The Track and Vehicle and as a System
6. Track Loading Environment

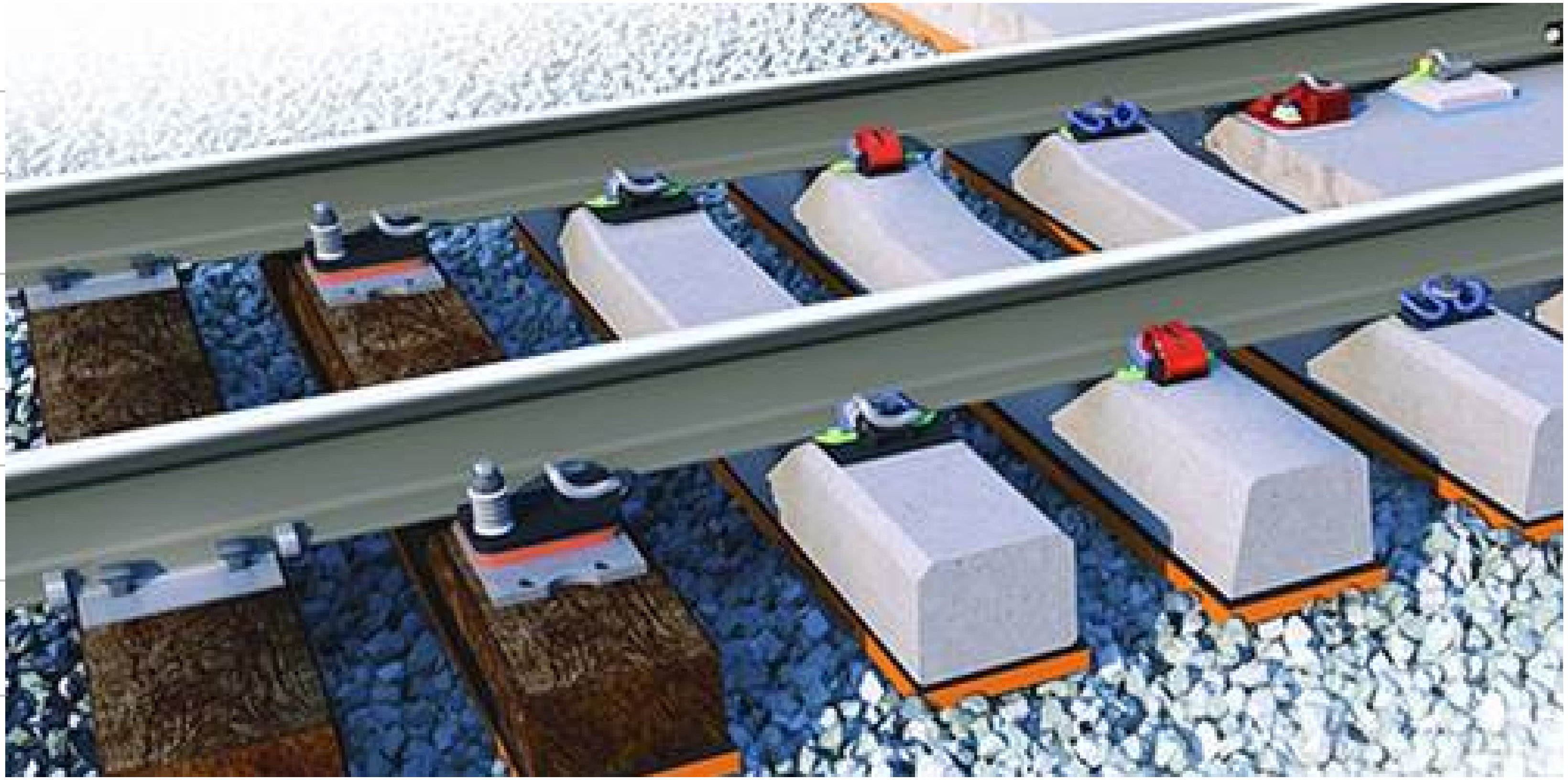
Basics of Track Structure and Components

Track Superstructure & Substructure



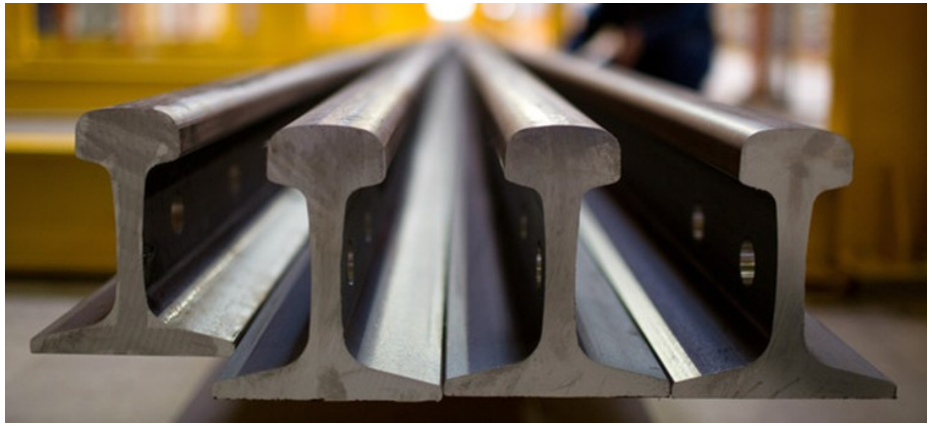
Track Components and Functions

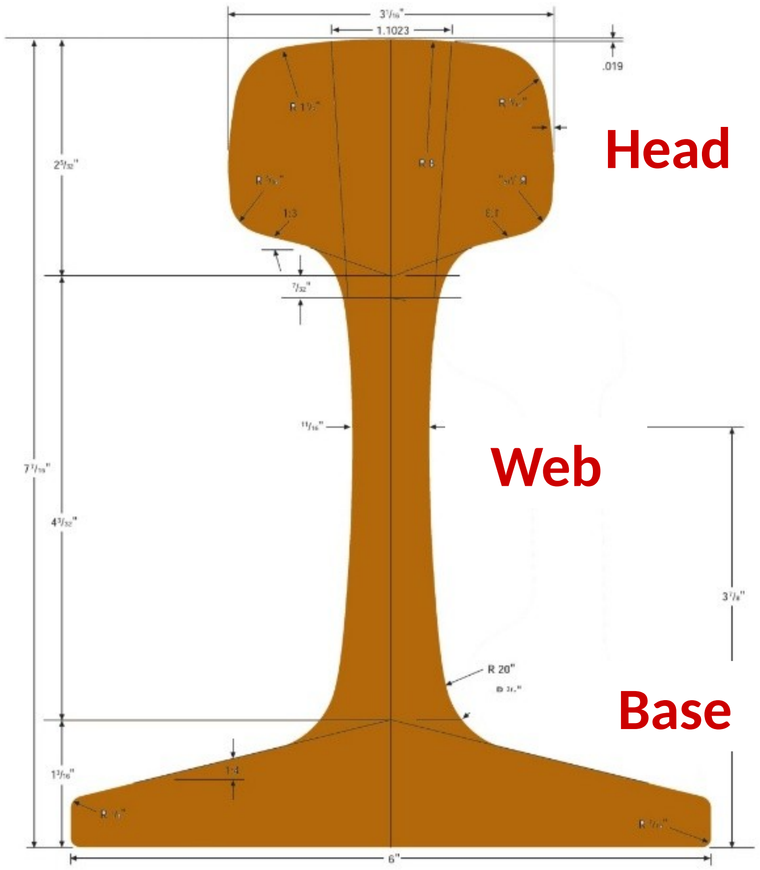
	Track Functions	Track Element or Component				
		Rail	Crossties	Fastening System	Ballast	Subballast
Primary	Support and Distribute Train Loads					
	Guide the vehicle					
	Provide adhesion at wheel-rail interface					
	Provide a smooth running surface					
	Facilitate drainage					
Secondary	Transmission of signal circuit					
	Broken rail detection					
	Path of ground return for traction power					



Rail Basics and Function

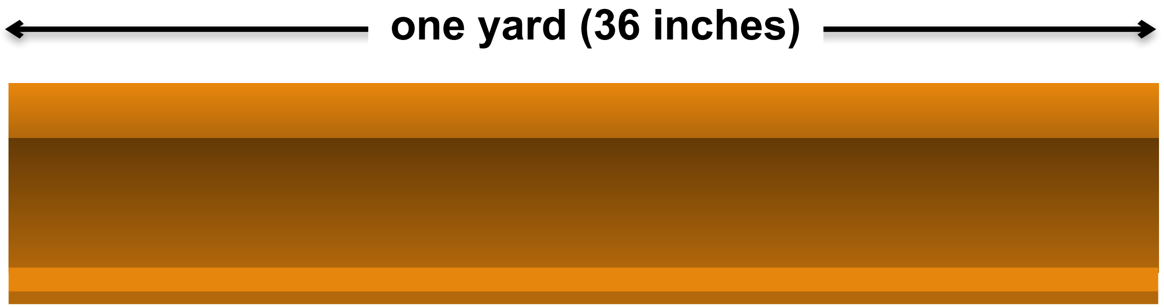
- Rail is the single most valuable asset owned by a railroad
- Rail is the most safety critical element of track system
- Provides a smooth, low-friction, running surface for trains
- Wide, flat base distributes the load across several crossties and allows fasteners and other stabilizing components to be attached
- Combined with fasteners and ties, provides a stable track gauge



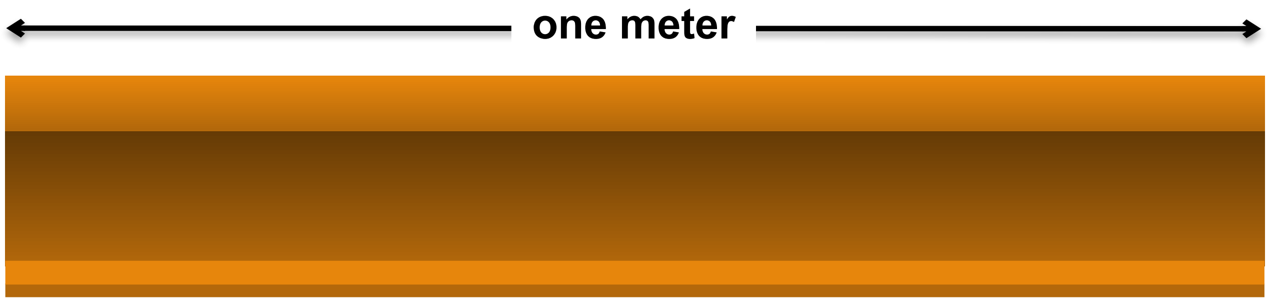


Rail size measurement

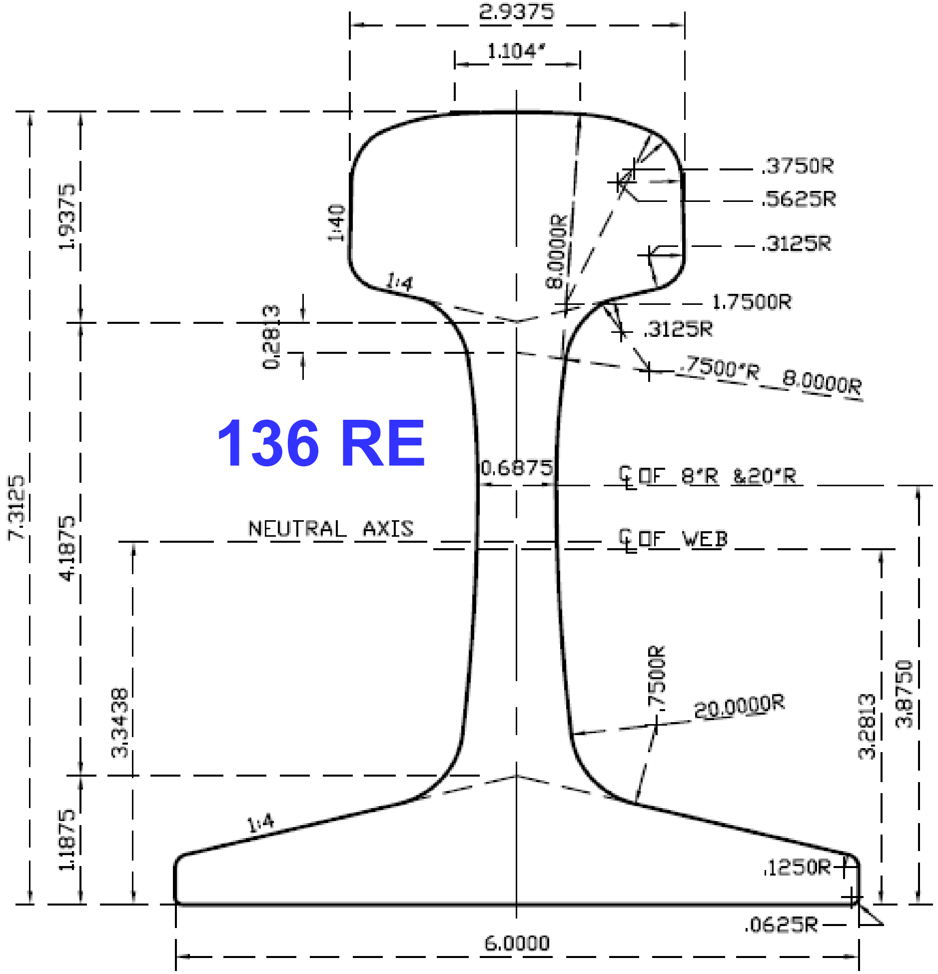
US, Canada & UK: Rail size measured in ***lbs per yard***



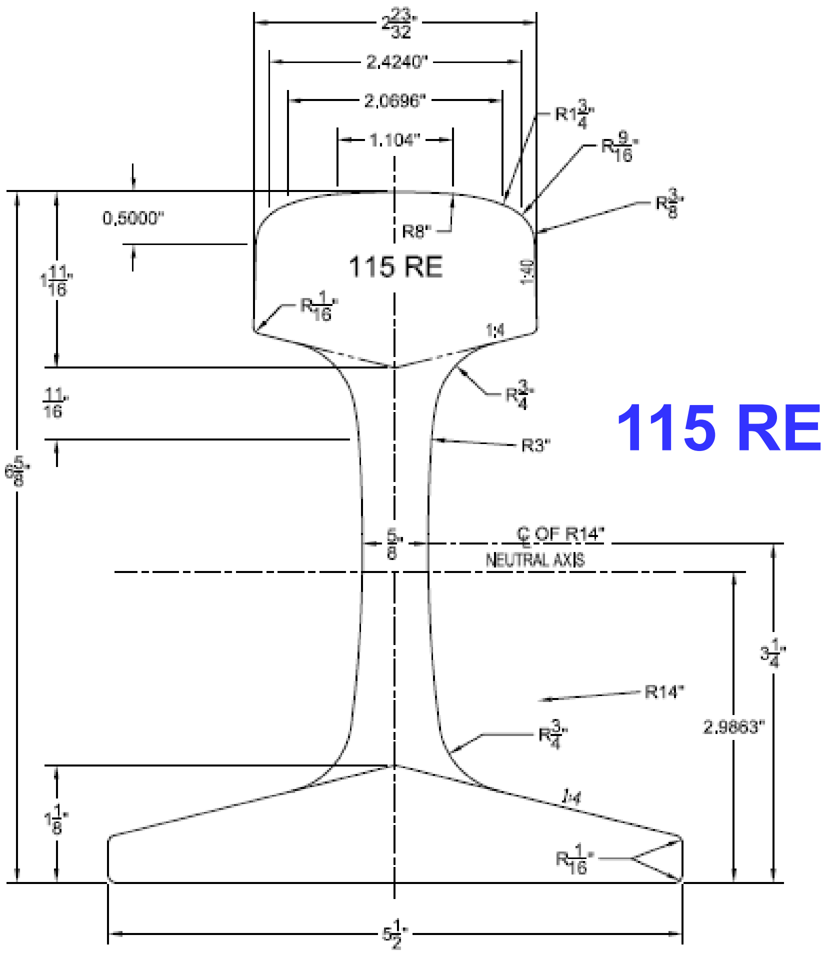
Elsewhere: Rail size measured in ***kg per meter***



Two common North American rail standards



~60% of N.A. Rail Rolled



~20% of N.A. Rail Rolled

Desirable Rail Properties

- ***High Wear Resistance***
  HARDNESS: the ability of a material to resist penetration, scratching, wear, abrasion and cutting
- ***High Yield Point***
  DUCTILITY: the ability of a material to undergo relatively large plastic deformations before fracture
- ***Resistance to Fatigue***
  TOUGHNESS: the ability of a material containing a crack to resist fracture

Summary of Rail Stresses & Effects

Contact Stresses *(static and dynamic wheel loads at the wheel-rail interface)*	**Bending Stresses** *(static and dynamic wheel loads, non-uniform temperature changes)*	**Axial Stresses** *(uniform temperature changes, train forces and rail creep)*
1) Rail wear *2) Rail fatigue & shelling* *3) Formation of plastic zone in contact region and rail corrugations*	*1) Selection of rail size* *2) Rail section at poorly maintained joint which may plastically deform*	*1) Track buckling or rail pull-aparts* *2) Selection of fastening system or distribution of rail anchors*

And one more… residual stresses

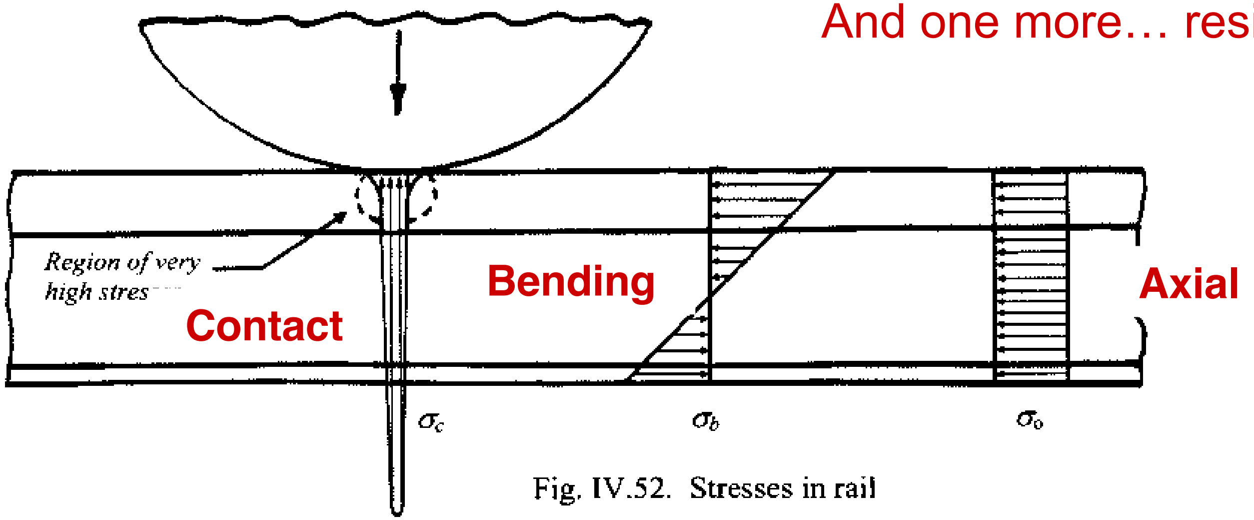
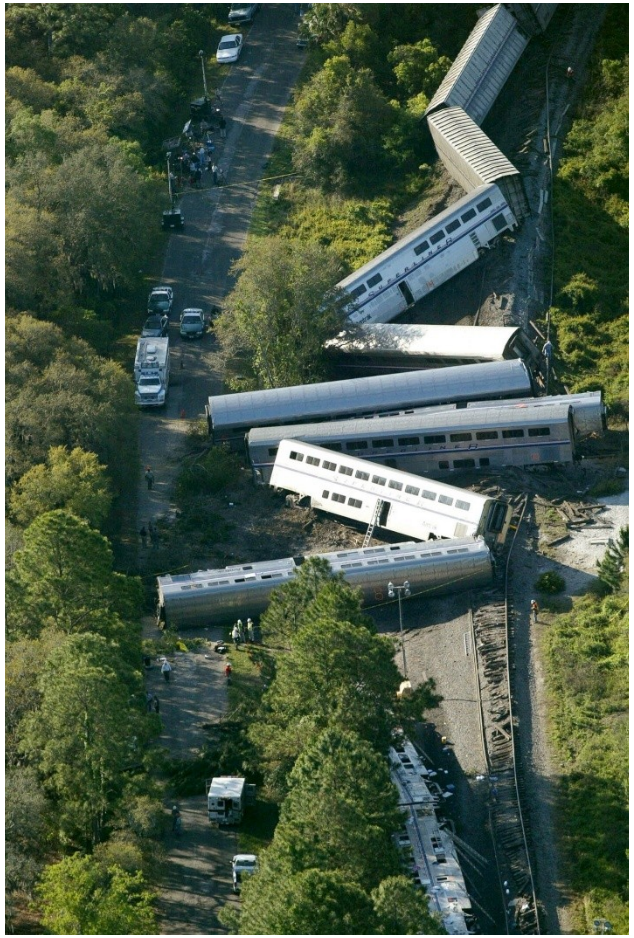


Fig. IV.52. Stresses in rail

Axial Stresses, Track Buckles, and Importance of Proper CWR Adjustment

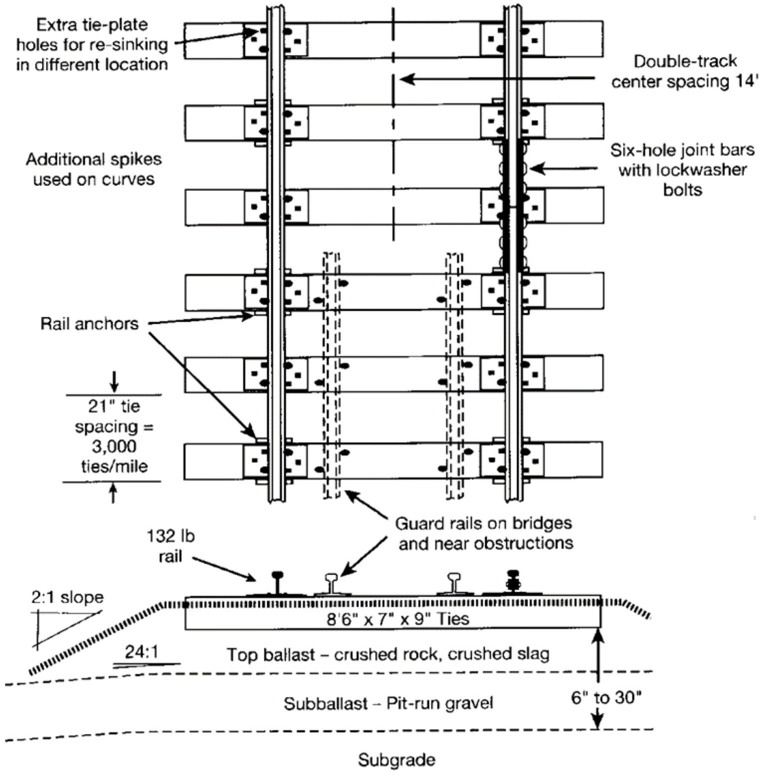
- Large differences between **rail temperature** and **Rail Neutral Temperature (RNT)** generate high levels of tension or compression in the rail.
- High compressive forces that exceed the lateral and longitudinal strength of track can cause buckles due to:
  - Thermal loads alone (i.e., static buckling) or
  - Thermal and vehicle loads (i.e., dynamic buckling)
- Proper rail stress management for continuous welded rail (CWR) can prevent track buckles or rail breaks.
- Opportunities for adjustment of RNT:
  - Proper stressing at rail installation to set RNT
  - Destressing activates and re-establishment of RNT

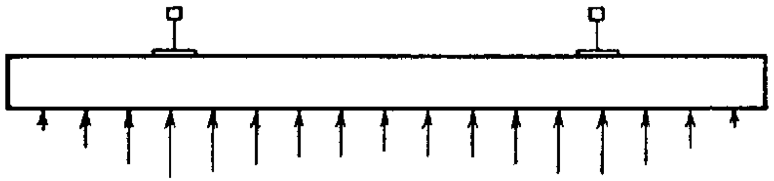


2002 Amtrak Auto Train Derailment on CSX (https://abcnews.go.com/US/timeline-major-train-crashes-us-2000/story?id=42450882)

Crosstie Basics and Function

- Maintain gauge
- Distribute wheel loads from the rails to the ballast
- Anchor track against lateral, longitudinal, & vertical movement
- Spacing typically ranges from about 18” to 30”
  - 24 inch spacing ≈ 2,640 ties per mile Common for Concrete
  - 19.5 inch spacing ≈ 3,249 ties per mile Common for Timber
  - Depends on tie material; tie size; ballast strength, joint spacing (supported or suspended) and loading





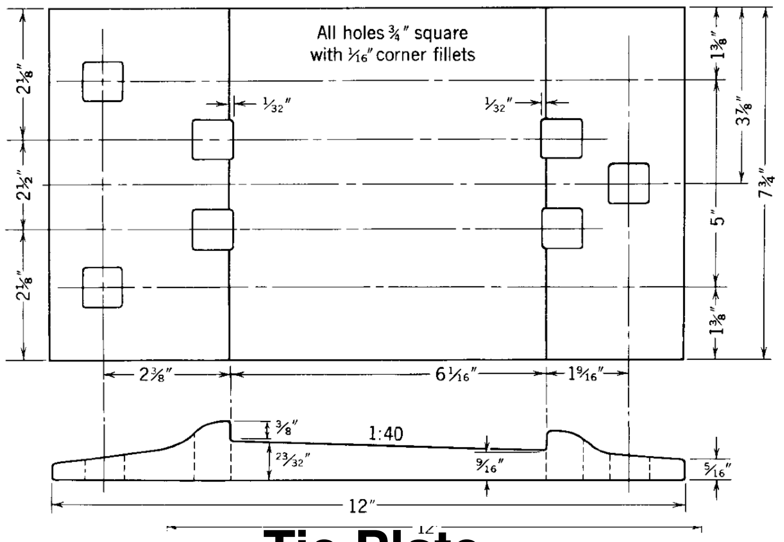
Types of Crossties
(700+Million in service in US)

Timber (90-92%) Concrete (6-8%)

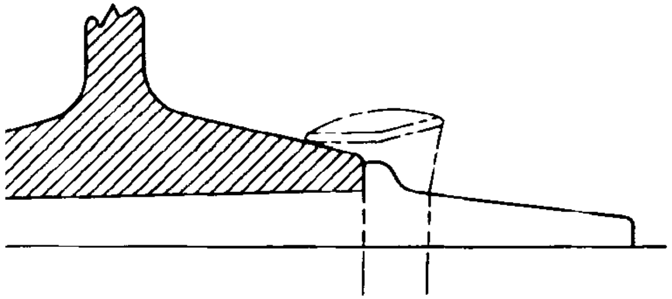
Composite (<1%) Steel (<1%)

Fasteners & Tie Plates

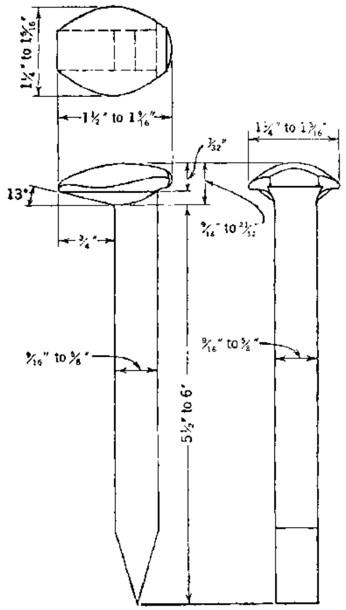
- The tie plate supports the rail and distributes the load over a larger section of the tie surface. It also provides lateral restraint to maintain gage.
- Fasteners (cut spikes are the most common type in N.A.) hold the track gage.
  (cut spikes do not provide much vertical restraint.)
- Along with fasteners, ties provide lateral, longitudinal and gage restraint and in turn further distribute the load into the ballast.



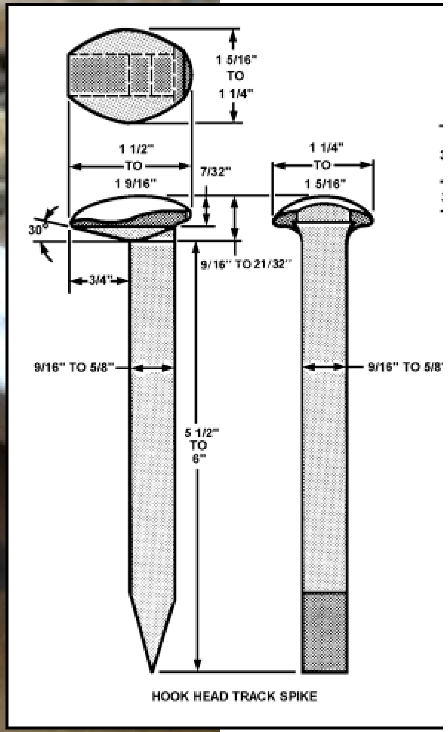
Tie Plate



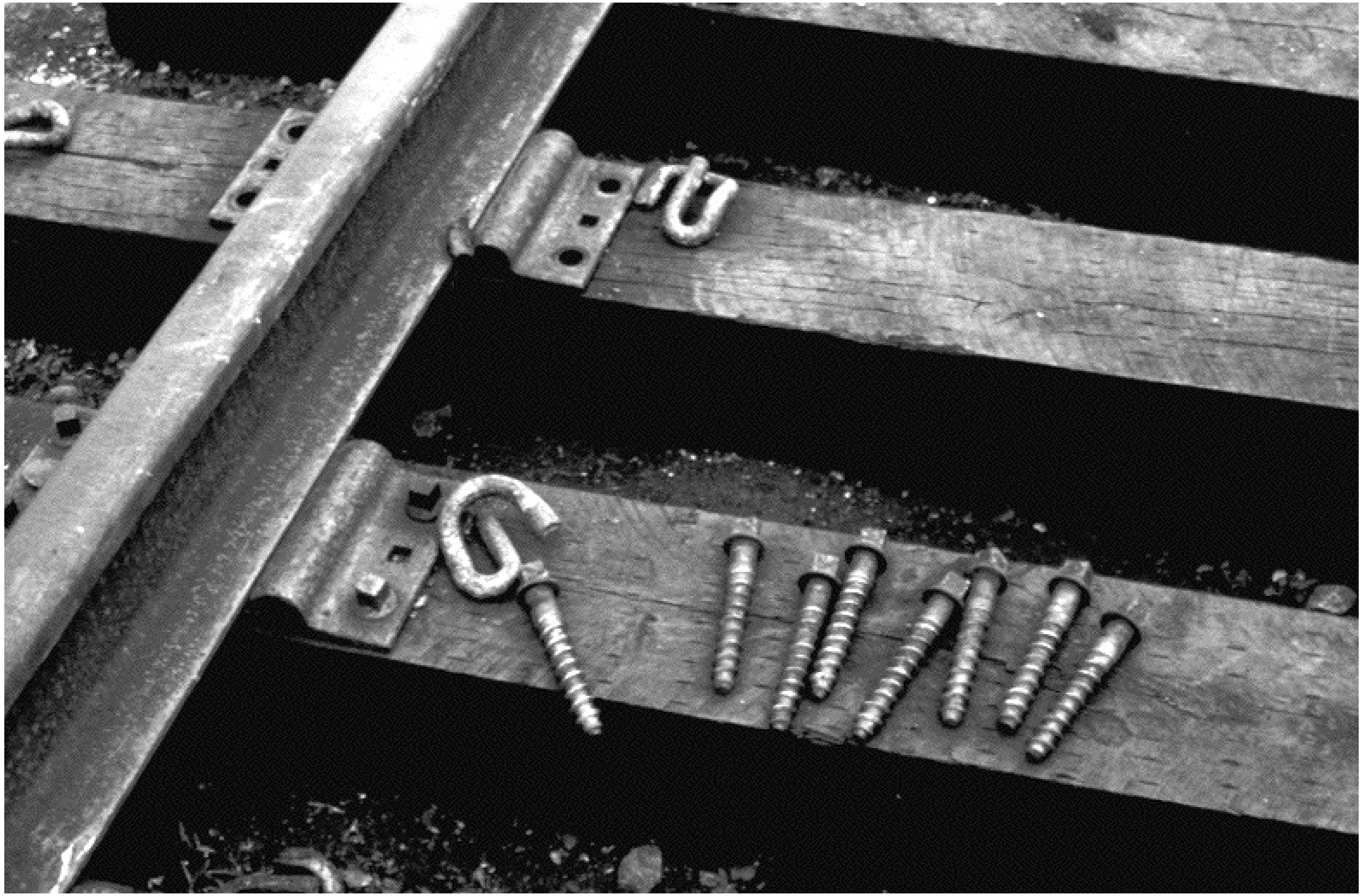
Standard "cut" spike

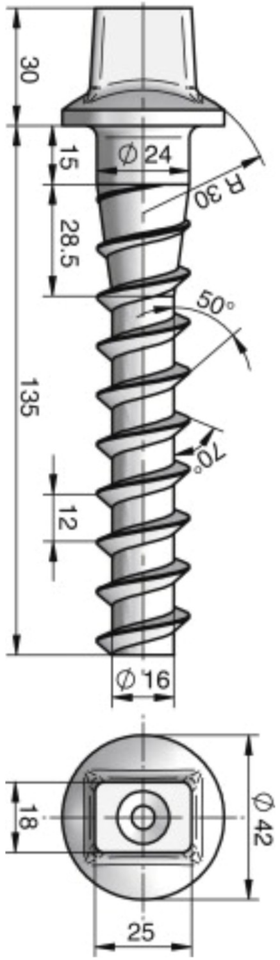


Most Common Wood Tie Fasteners
(~95% of timber track is cut spike and anchored)

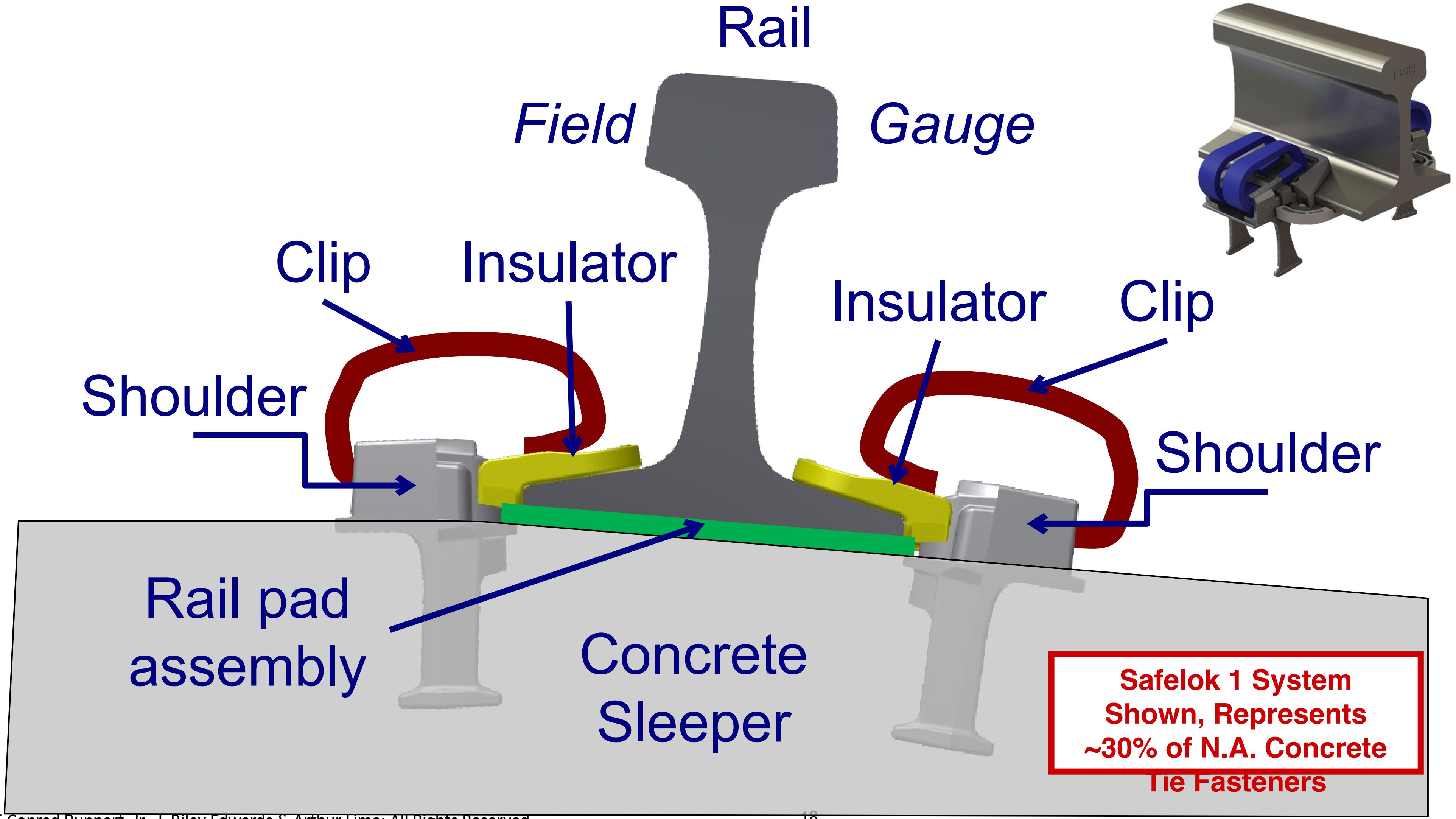


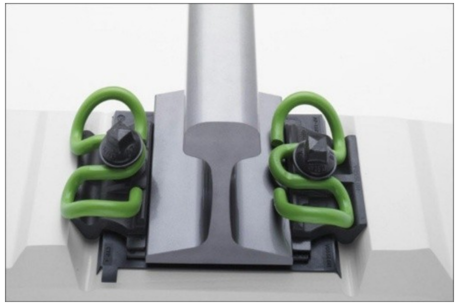
Screw Spikes and Elastic E-Clips
Premium Systems (~5% of timber tie track)

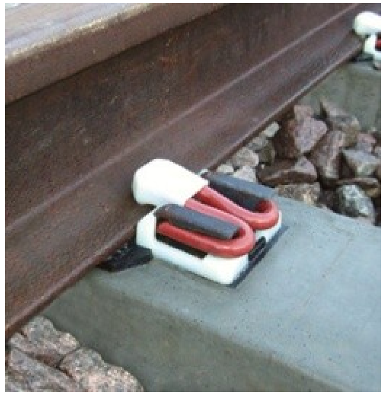




Concrete Crosstie Fasteners







Ballast & Sub-Ballast

- Ballast and sub-ballast are the final stages in load distribution
- Distributes vertical loads and maintains the longitudinal and lateral stability of track.
- Ballast and sub-ballast must provide adequate drainage.
- Ballast is subject to pulverization from loading as trains pass over, thereby generating fine particles that can clog the ballast and in turn inhibit drainage.

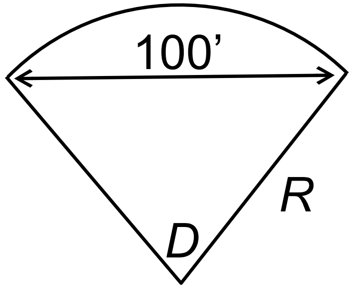
Ballast

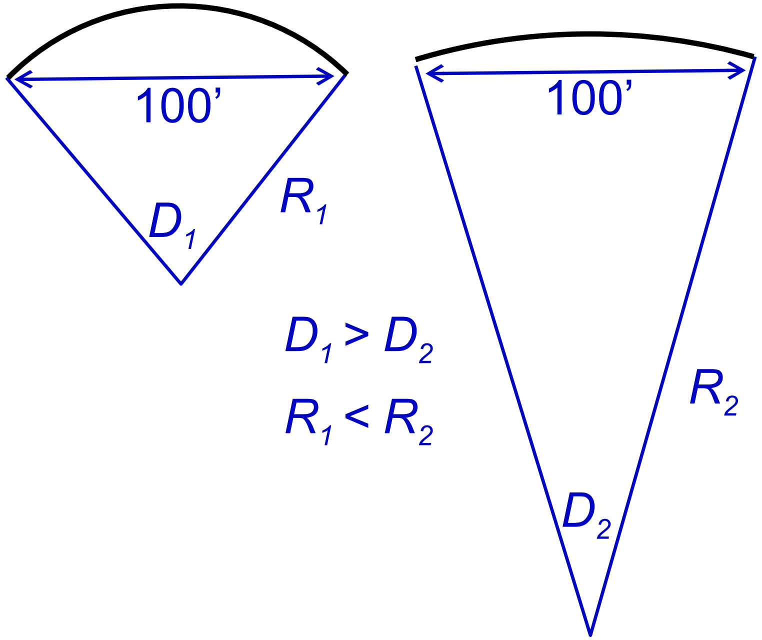
Subballast

Horizontal Curvature, Superelevation, and Track Design

Horizontal Curvature: Degree of Curve

- Lower degree of curve = larger radius = more gradual curve
- Railway – Chord Definition
  - Angle measured along the length of a section of curve subtended by a 100’ chord

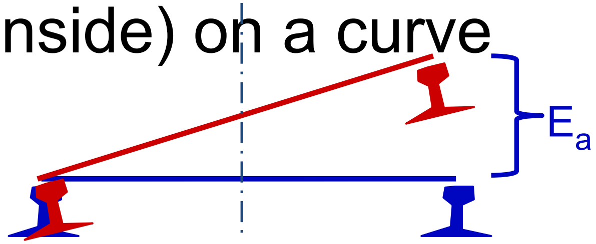




Application	Degree of Curve
Mainline (desirable)	< 2º
Mainline (typical)	< 4º
Secondary branchline (typical)	< 6º
Unit train facility (maximum)	< 7.5º
Industrial or yard track (desirable)	< 9.5º
Industrial or yard track (maximum)	< 12.5º

Superelevated Spiral Curves

- **Most** railway curves use superelevation and spiral transitions
- Actual superelevation "E_a" is inches of elevation difference between "high rail" (outside) and "low rail" (inside) on a curve

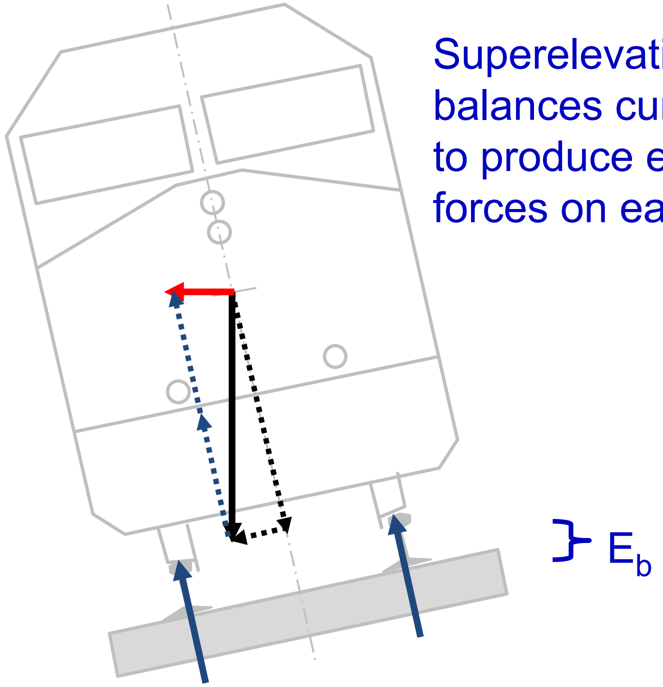


- Typical maximum value for E_a on freight lines is 4 inches
- Track is rotated about the low rail in curves
- Unlike highways which rotate about the centerline and the inside edge drops down
- Superelevation is established over a spiral transition between the tangent and the circular portion of the curve
- Circular portion of the curve is called the "curve body"

Balanced vs. Actual Superelevation

- E_a is a function of speed (V in mph), degree of curve (D) and E_u
- E_u is allowable unbalance (aka cant deficiency)
  - typically 1” to 2” for freight operations, depending on the railway

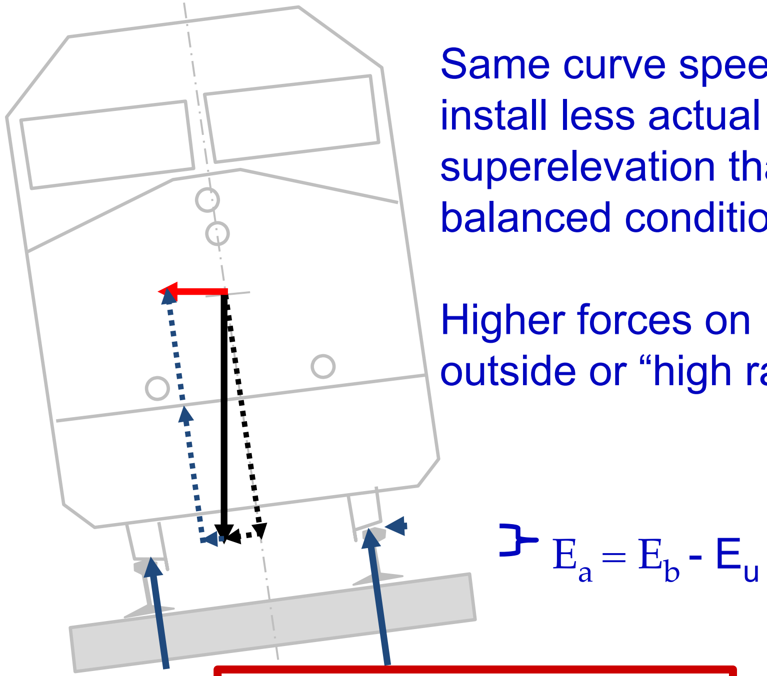
Balanced Condition



Superelevation exactly balances curving forces to produce equal wheel forces on each rail

$E_b = 0.0007V^2D$

Underbalance Condition



Same curve speed but install less actual superelevation than balanced condition

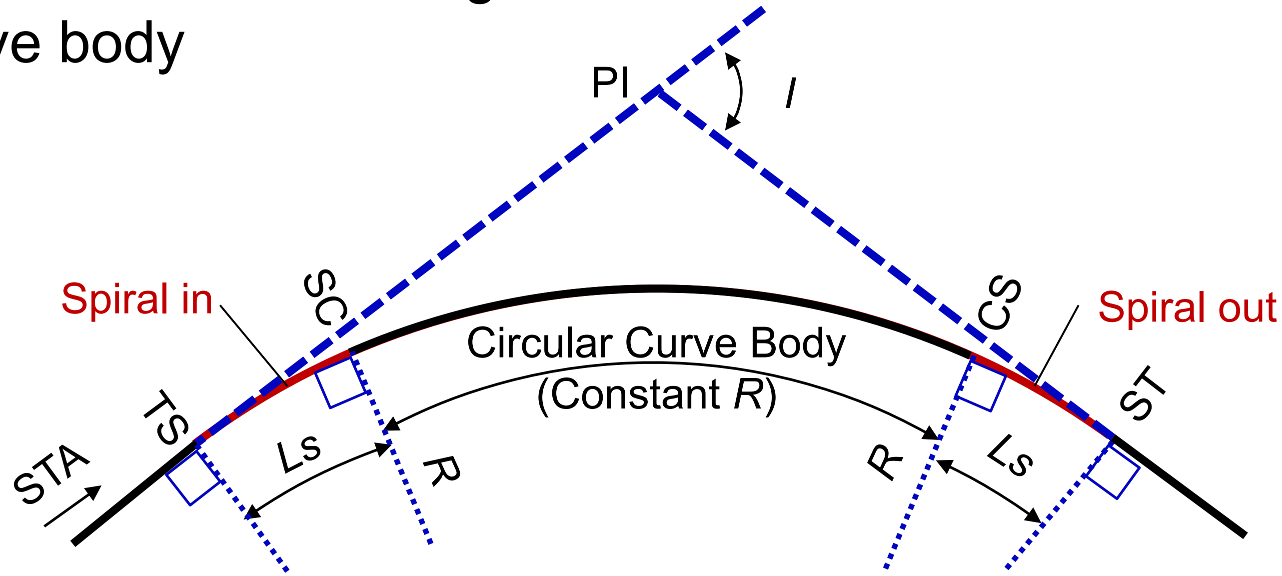
Higher forces on outside or “high rail”

$$\boxed{\mathbf{E_a = 0.0007V^2\mathit{D} - E_u}}$$

Resultant Force →
Wheel/Rail Forces →
Gravitational Force →

Spiral Transitions

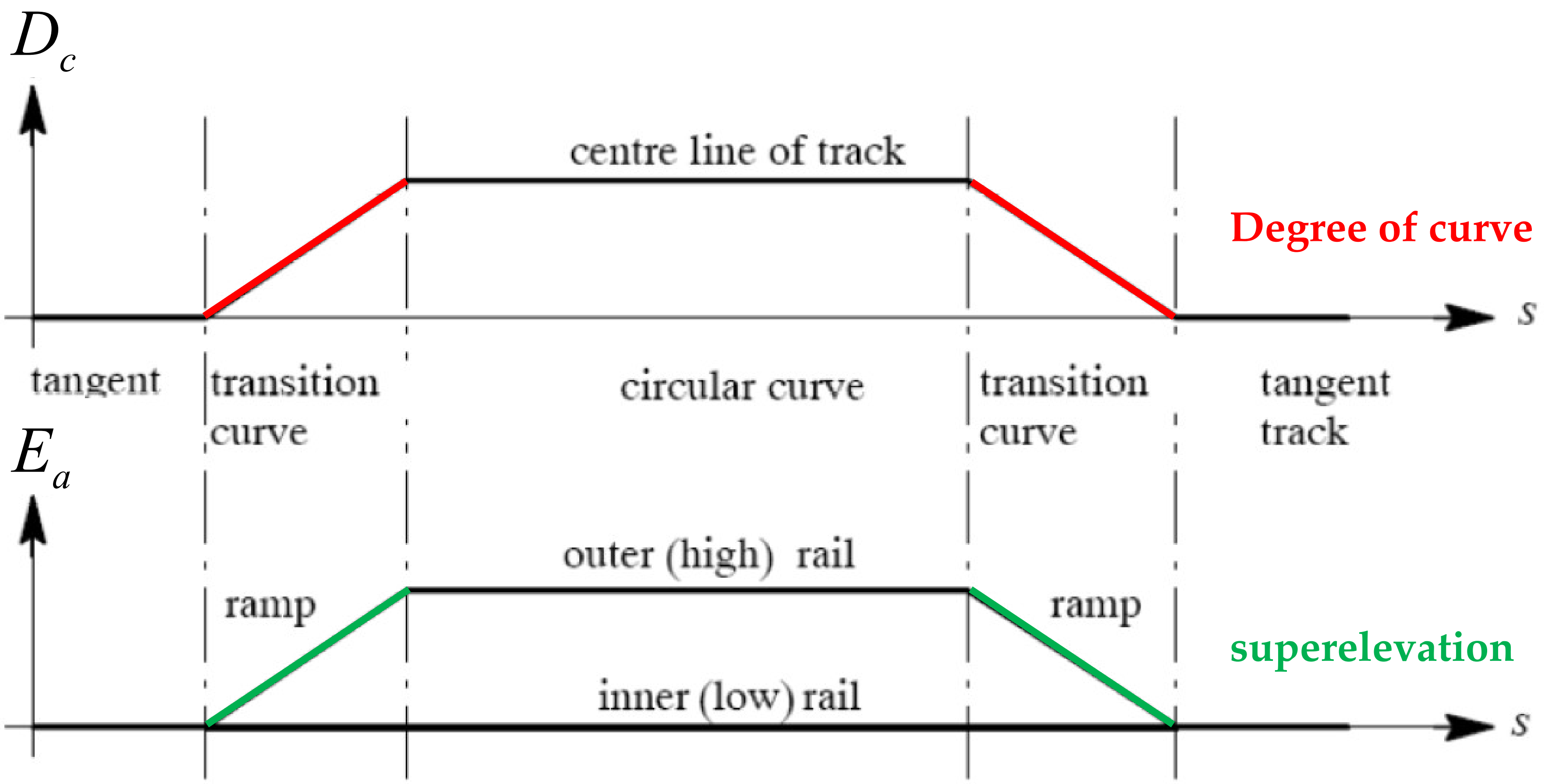
- Spiral transitions or “clothoids” are used to gradually “steer” railcars into curves and develop superelevation
- Spiral starts at tangent with infinite radius and then tightens until it matches the circular curve radius at the start of the curve body



- Spiral length (Ls) is a function of:
  - Design speed, actual superelevation Ea and suprelevation runoff rate
  - Railcar length (determines minimum spiral length to prevent car warp)
- Each railroad has its own process of calculating spiral length

Track Transitions – Spirals & Superelevation

Curvature and superelevation change **linearly** with distance along spiral

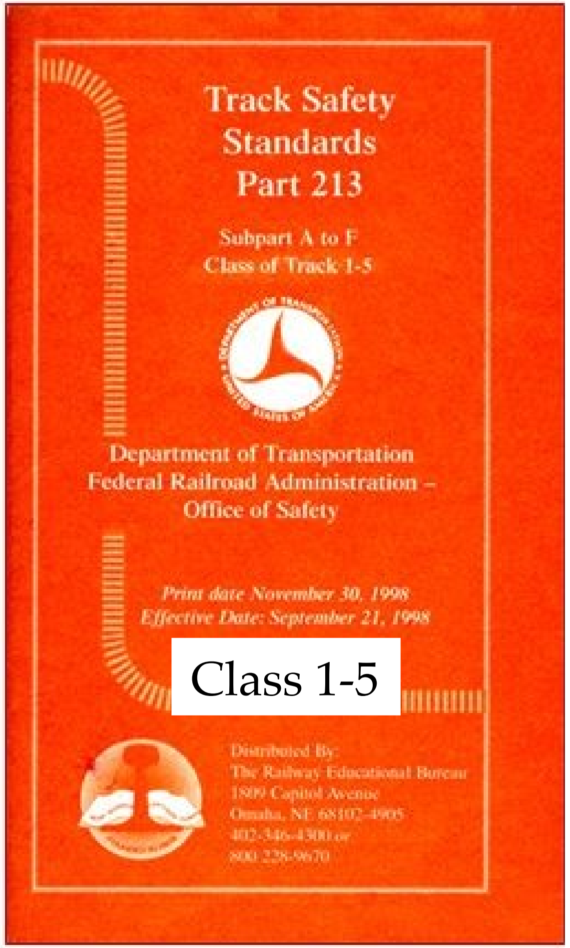


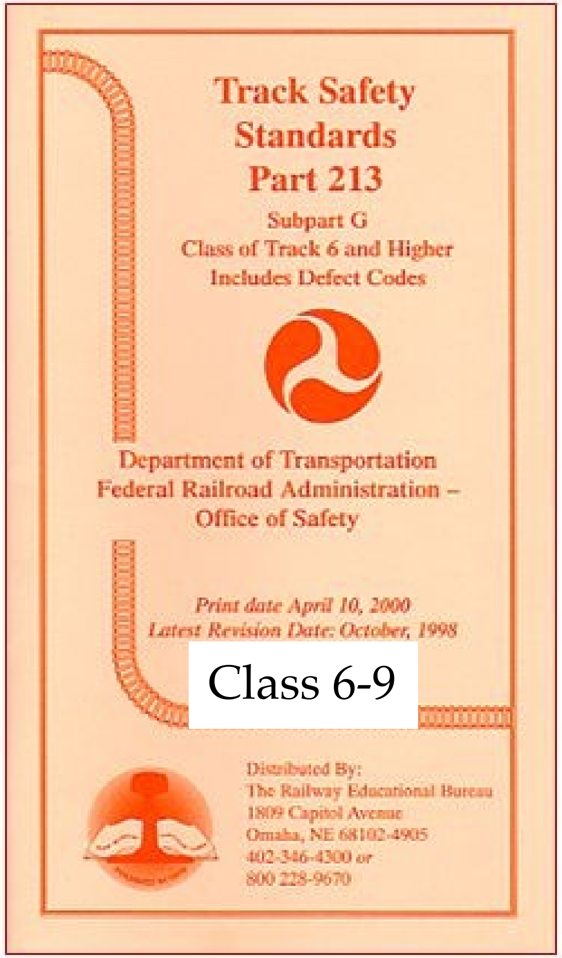
Track Standards and Regulations

Track Standards & Specifications

- Design Standards & Recommended Practices (Ideal)
  - desired structural capacity and geometric configuration
- Construction Standards & Specifications (Tolerances)
  - desire is to build to zero tolerance from the plans & specs.
  - in practice allowable tolerances are set to account for manufacturing limits, construction methods, etc.
- Maintenance Standards (Thresholds)
  - used to trigger maintenance or reconstruction actions.
- Safety Standards (Limits)
  - limits, once passed, that require the immediate repair of track, speed restrictions or removal from service.

FRA Track Safety Standards





FRA Compliance Manual

Track and Rail and Infrastructure Integrity Compliance Manual

Volume II Track Safety Standards
Chapter 1 Track Safety Standards
Classes 1 Through 5

January 2017

Office of Railroad Safety

U.S. Department of Transportation
Federal Railroad Administration

Federal Railroad Administration

Track and Rail and Infrastructure Integrity Compliance Manual

Volume II Track Safety Standards
Chapter 2 Track Safety Standards
Classes 6 through 9

January 2017

https://www.fra.dot.gov/eLib/Find#p1_z25_gD_lCM

FRA Track Safety Standards (49 CFR 213)

- Establish maximum speeds for railroad track.
  - Nine FRA track classes (each with corresponding speed limits for passenger and freight trains)
- Track must be maintained to a specified level to permit reasonably safe transit at the speeds associated with each Track Class.
- Track which does not comply with the standards for its posted Track Class **MUST** be fixed, protected or removed from service as soon as condition is found. (or operated at a lower track class / speed)

Reminder: THESE ARE NOT DESIGN STANDARDS!

FRA Track Class and Train Speed

- Maximum speeds are defined by FRA Track Class:

Class	Freight Trains	Passenger Trains
1	10 MPH	15 MPH
2	25 MPH	30 MPH
3	40 MPH	60 MPH
4	60 MPH	80 MPH
5	80 MPH	90 MPH

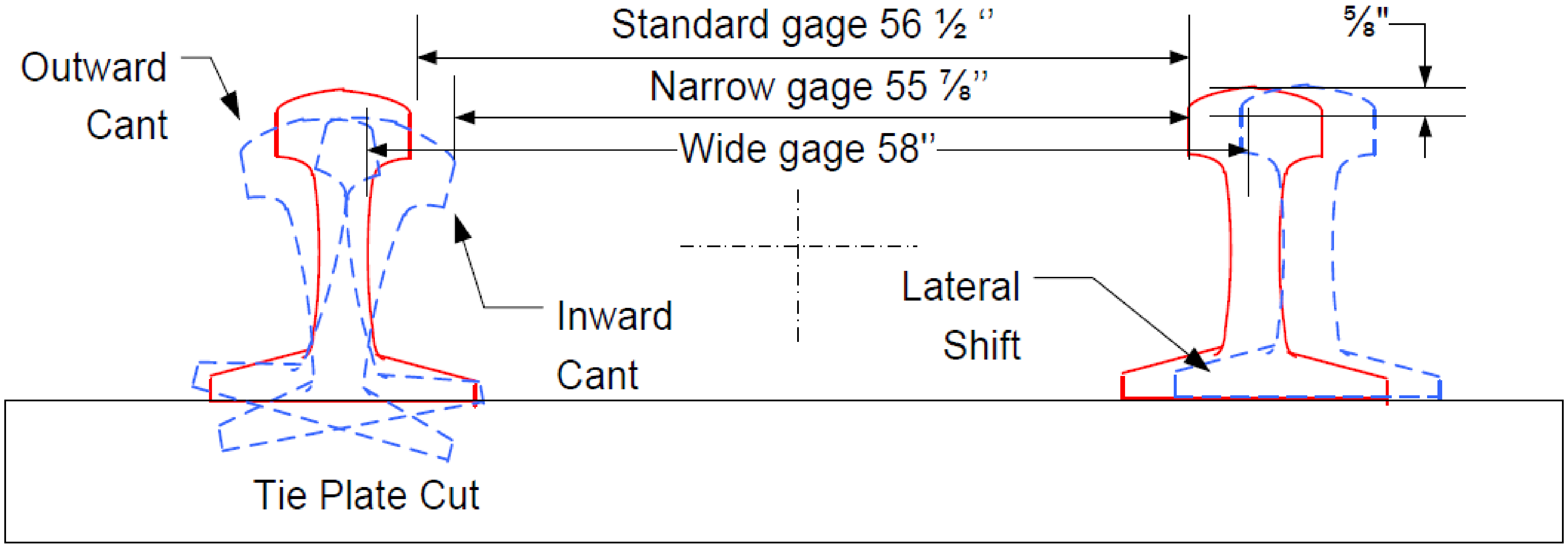
Why Track Irregularities Matter

- Variation along the track can cause dynamic vehicle response (more vehicle and track loading demands / degradation)
- Large amplitude irregularities may result in train derailments
- Ride comfort can be negatively affected
- Track and vehicle maintenance costs increase
- Must be kept small, particularly for High and Higher Speed Rail

Track Gage

§ 213.53 Gage

53(a) Gage is measured between the heads of the rails at right angles to the rails in a plane five-eighths of an inch below the top of the rail head.

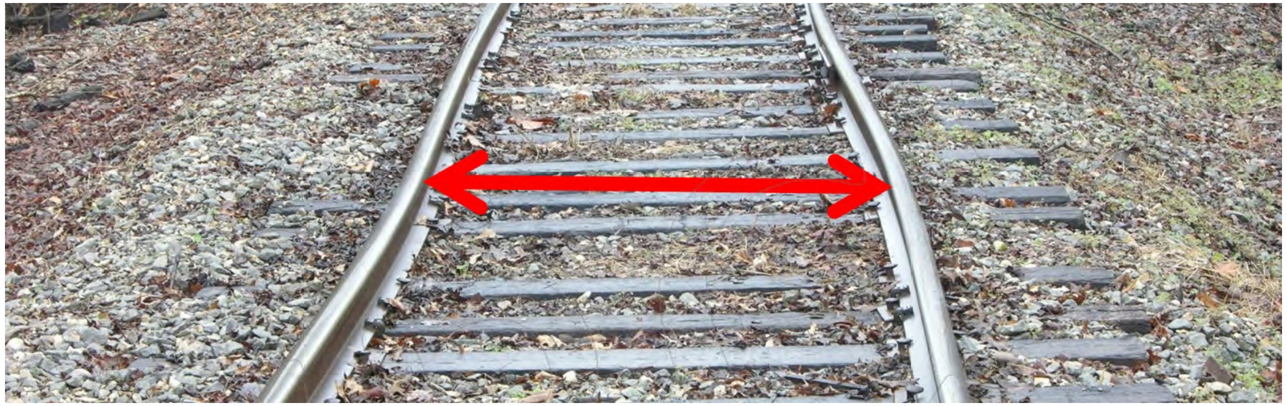


Track Gage

§ 213.53 Gage

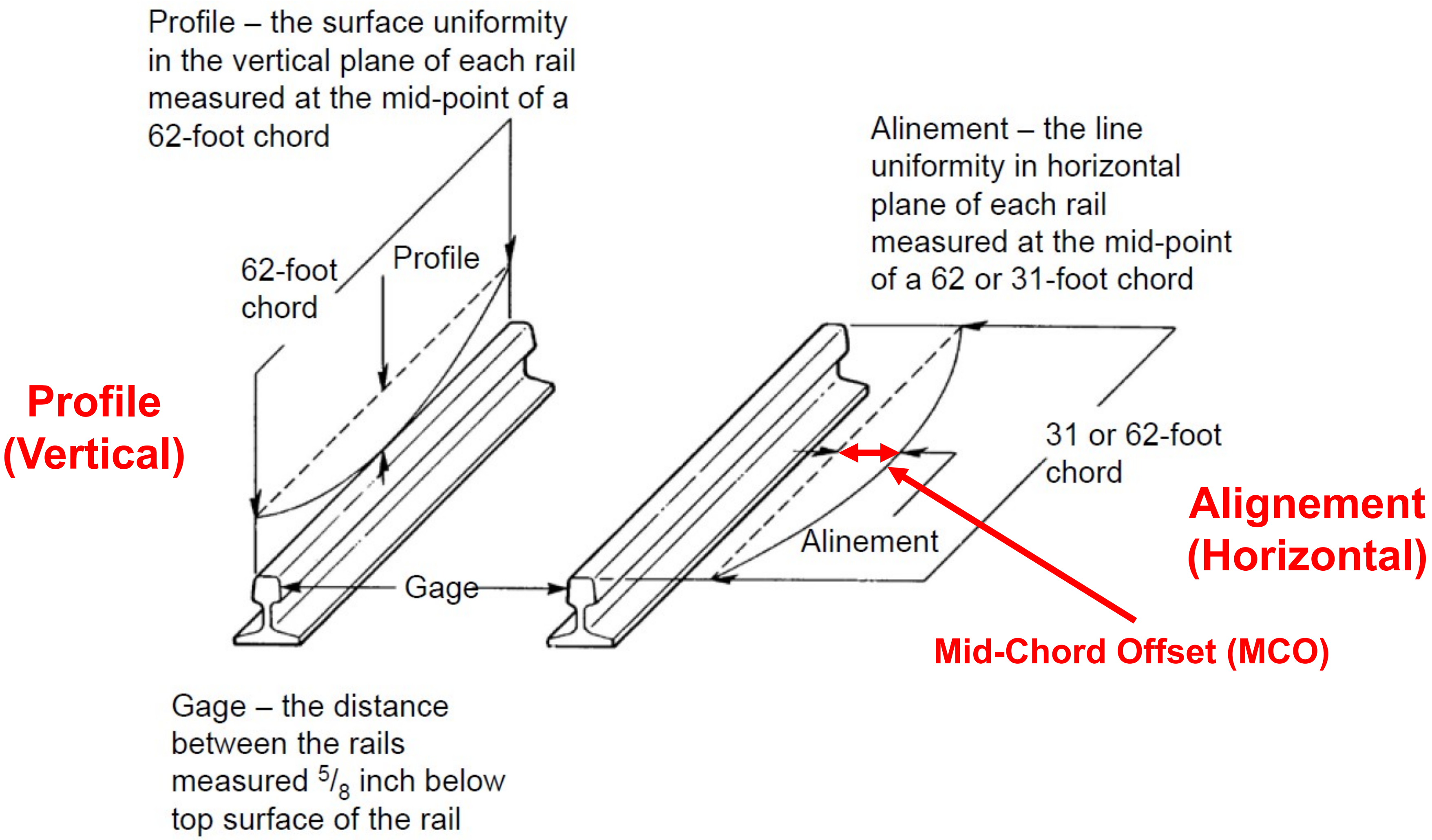
53(a) Gage is measured between the heads of the rails at right angles to the rails in a plane five-eighths of an inch below the top of the rail head.

Class of Track	***The gage must be at least -***	***But not more than -***
Excepted track	*N/A*	*4'10¼"*
Class 1 track	*4' 8"*	*4' 10"*
Class 2 and 3 track	*4' 8"*	*4' 9¾"*
Class 4 and 5 track	*4' 8"*	*4' 9½"*



(1" Wide)

Track Geometry Measurements



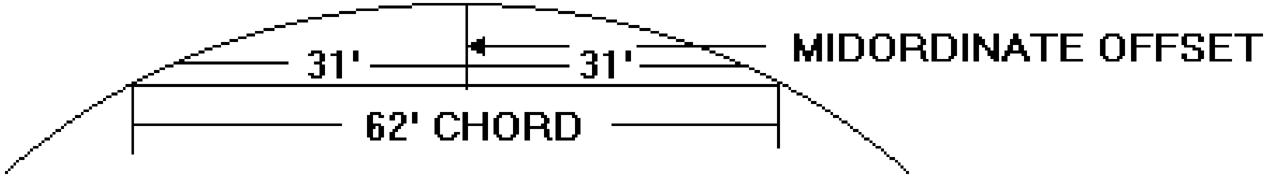

Alignment Measurement
(Stringlining a Curve)
Mid-Chord Offset
(MCO)

Track Alignment

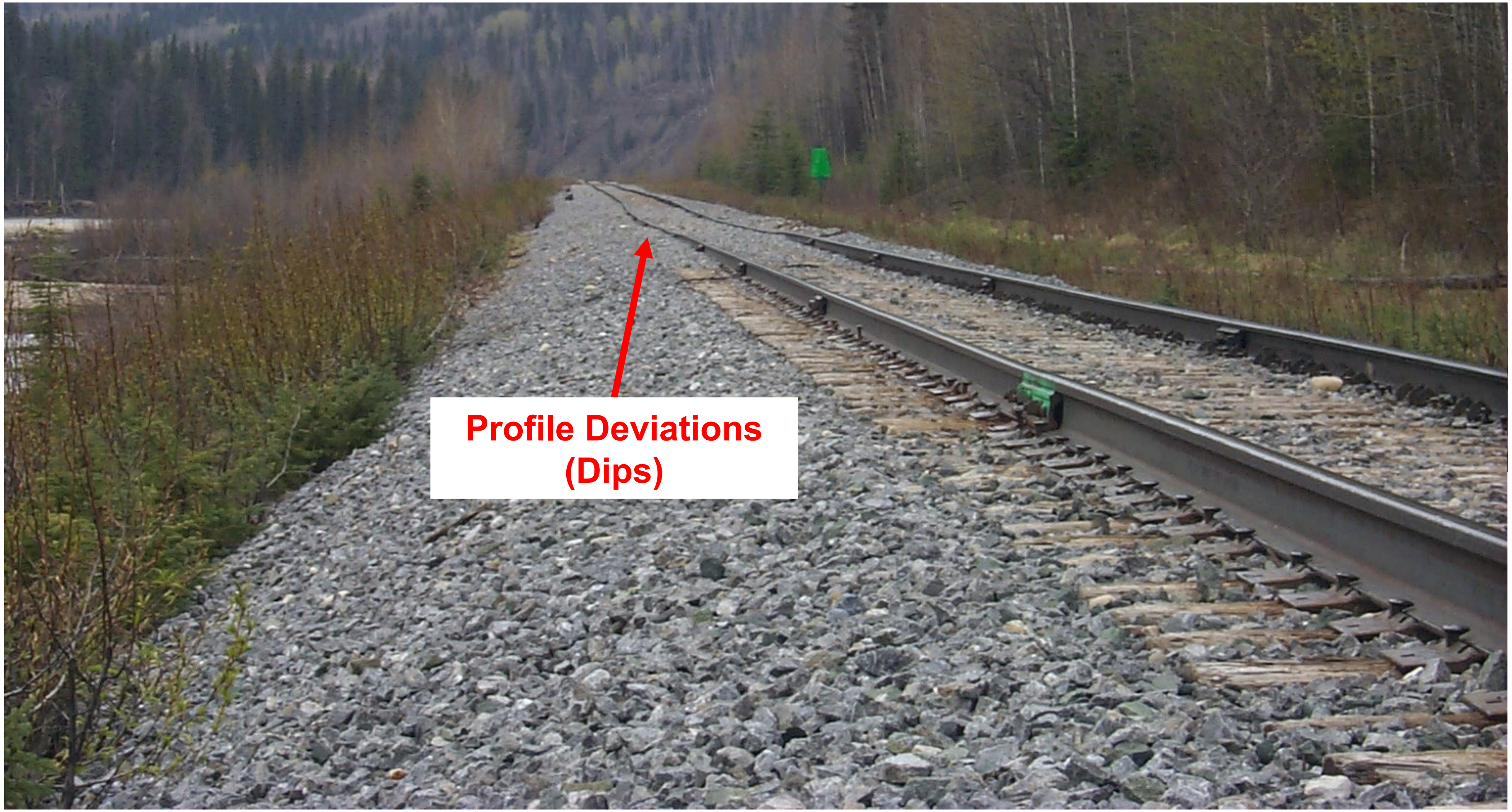
§ 213.55 Track alinement

55(a) Except as provided in paragraph (b) of this section, alinement may not deviate from uniformity more than the amount prescribed in the following table:

Class of Track	Tangent Track	Curved Track	
	The deviation of the mid-offset from a 62-foot line [1] may not be more than—(inches)	The deviation of the mid-ordinate from a 31-foot chord[2] may not be more than—(inches)	The deviation of the mid-ordinate from a 62-foot chord [2] may not be more than—(inches)
1	5	N/A [3]	5
2	3	N/A [3]	3
3	1¾	1¼	1¾
4	1½	1	1½
5	¾	½	⅝



Track Surface (Profile) Deviation



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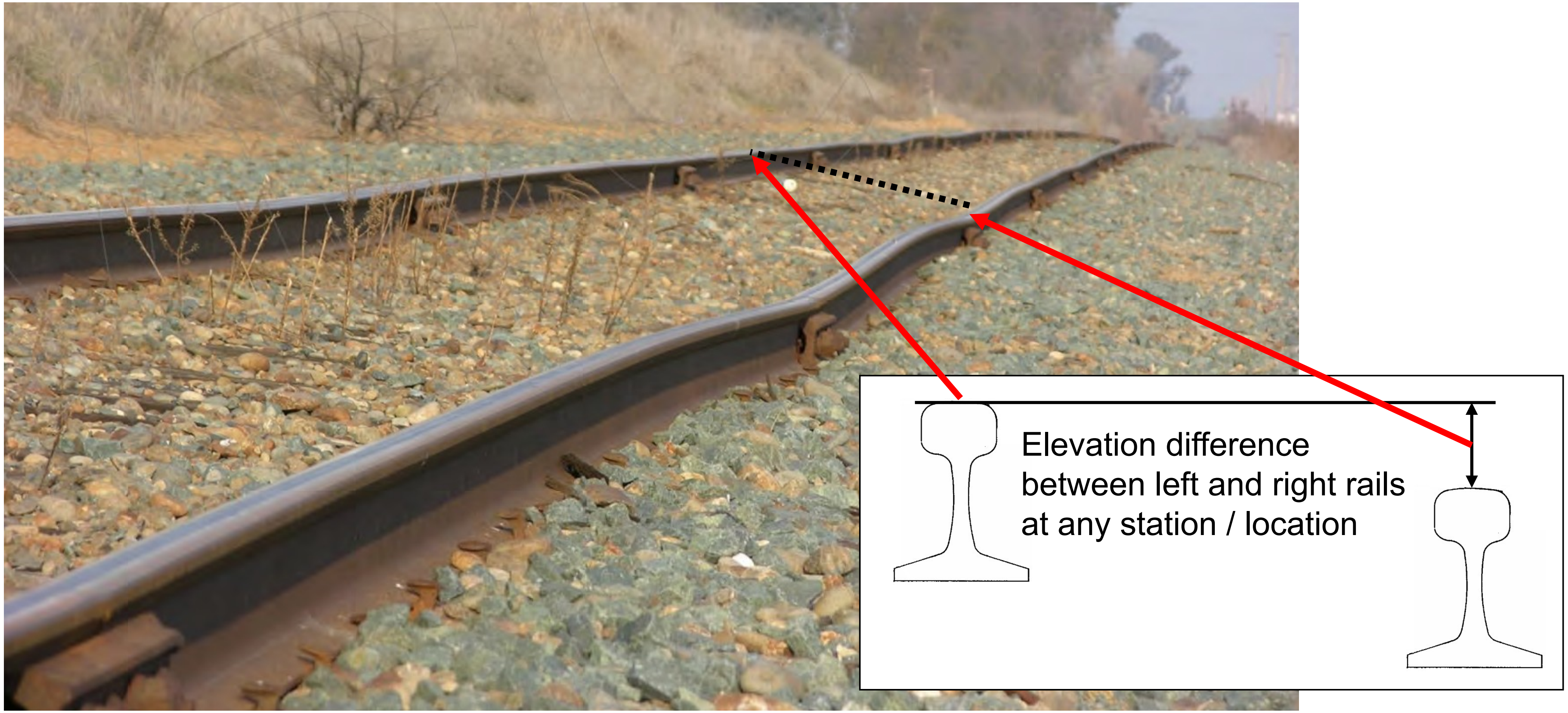
Track Surface

§ 213.63 Track Surface

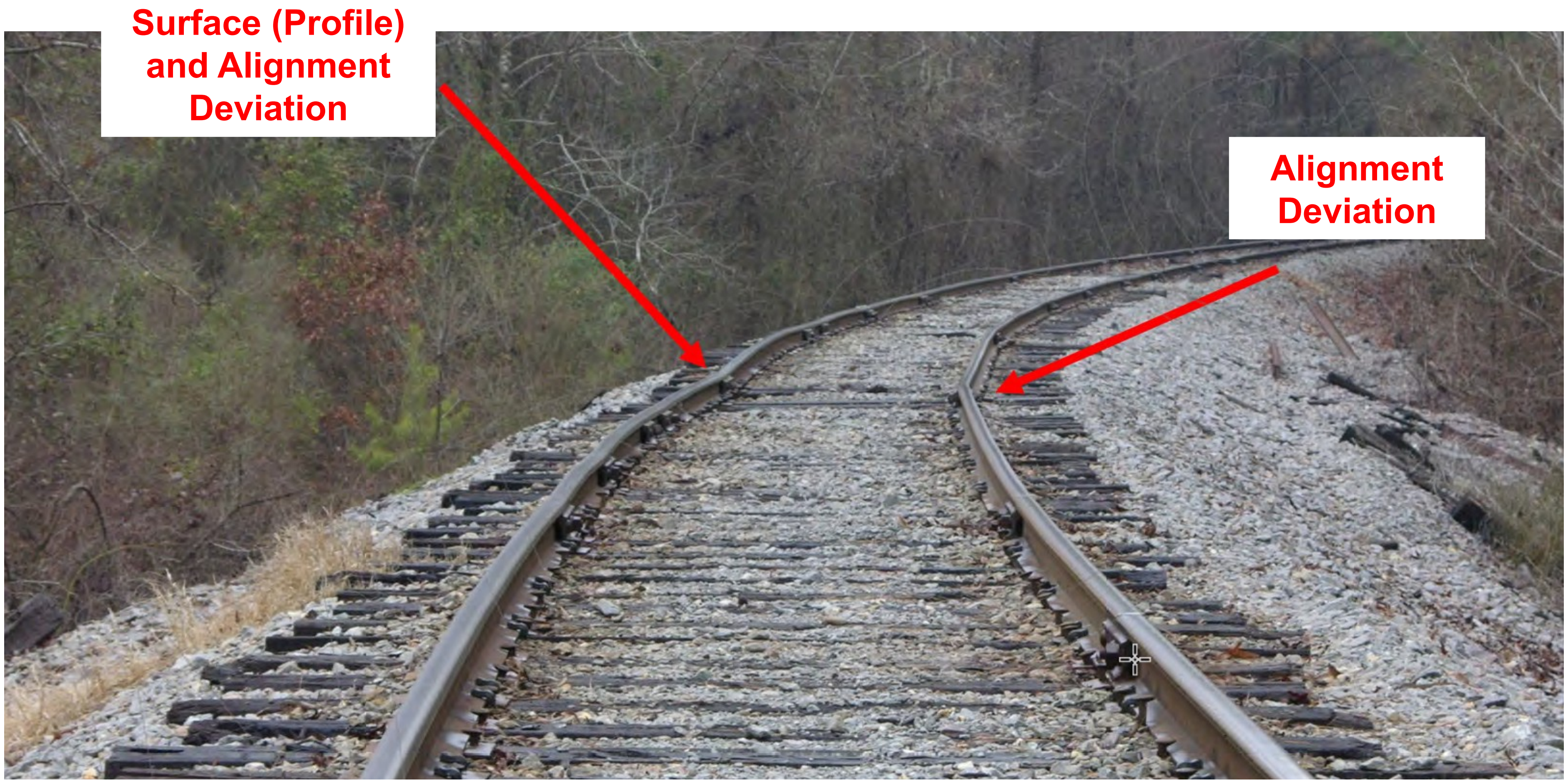
63(a) Except as provided in paragraph (b) of this section, each track owner shall maintain the surface of its track within the limits prescribed in the following table:

Track surface (inches)	Class of track				
	1	2	3	4	5
The runoff in any 31 feet of rail at the end of a raise may not be more than	3½	3	2	1½	1
The deviation from uniform profile on either rail at the mid-ordinate of a 62-foot chord may not be more than ...	3	2¾	2¼	2	1¼
The deviation from zero crosslevel at any point on tangent or reverse crosslevel elevation on curves may not be more than	3	2	1¾	1¼	1
The difference in crosslevel between any two points less than 62 feet apart may not be more than*1, 2	3	2¼	2	1¾	1½
*Where determined by engineering decision prior to June 22, 1998, due to physical restrictions on spiral length and operating practices and experience, the variation in crosslevel on spirals per 31 feet may not be more than.....................	2	1¾	1¼	1	¾

Crosslevel Deviation



Combined Surface & Alignment Deviations



Combined Surface & Alignment Deviations (Class 1-5)

§ 213.65 Combined track alinement and surface deviations.

On any curved track where operations are conducted at a qualified cant deficiency, E_u, greater than 5 inches, the combination of alinement and surface deviations for the same chord length on the outside rail in the curve, as measured by a TGMS, shall comply with the following formula:

$$\frac{3}{4} \times \left| \frac{A_m}{A_L} + \frac{S_m}{S_L} \right| \leq 1$$

Where—

A_m = *measured alinement deviation from uniformity (outward is positive, inward is negative).*

A_L = *allowable alinement limit as per § 213.55(b) (always positive) for the class of track.*

S_m = *measured profile deviation from uniformity (down is positive, up is negative).*

S_L = *allowable profile limit as per § 213.63(b) (always positive) for the class of track.*

$\left| \frac{A_m}{A_L} + \frac{S_m}{S_L} \right|$ = *the absolute (positive) value of the result of* $\frac{A_m}{A_L} + \frac{S_m}{S_L}$.

FRA-Mandated Track Inspection

FRA Inspection Requirements

§ 213.233 Track inspections

233(c) Each track inspection shall be made in accordance with the following schedule:

Class of Track	Type of Track	Required Frequency
Excepted track and Class 1, 2, and 3 track	*Main track and sidings*	Weekly *with at least 3 calendar days interval between inspections, or* before use, *if the track is used less than once a week, or* twice weekly *with at least 1 calendar day interval between inspections, if the track carries passenger trains or more than 10 million gross tons of traffic during the preceding calendar year.*
Excepted track and Class 1, 2, and 3 track	*Other than main track and sidings*	Monthly *with at least 20 calendar days interval between inspections.*
Class 4 and 5 track	....	Twice weekly *with at least 1 calendar day interval between inspections.*

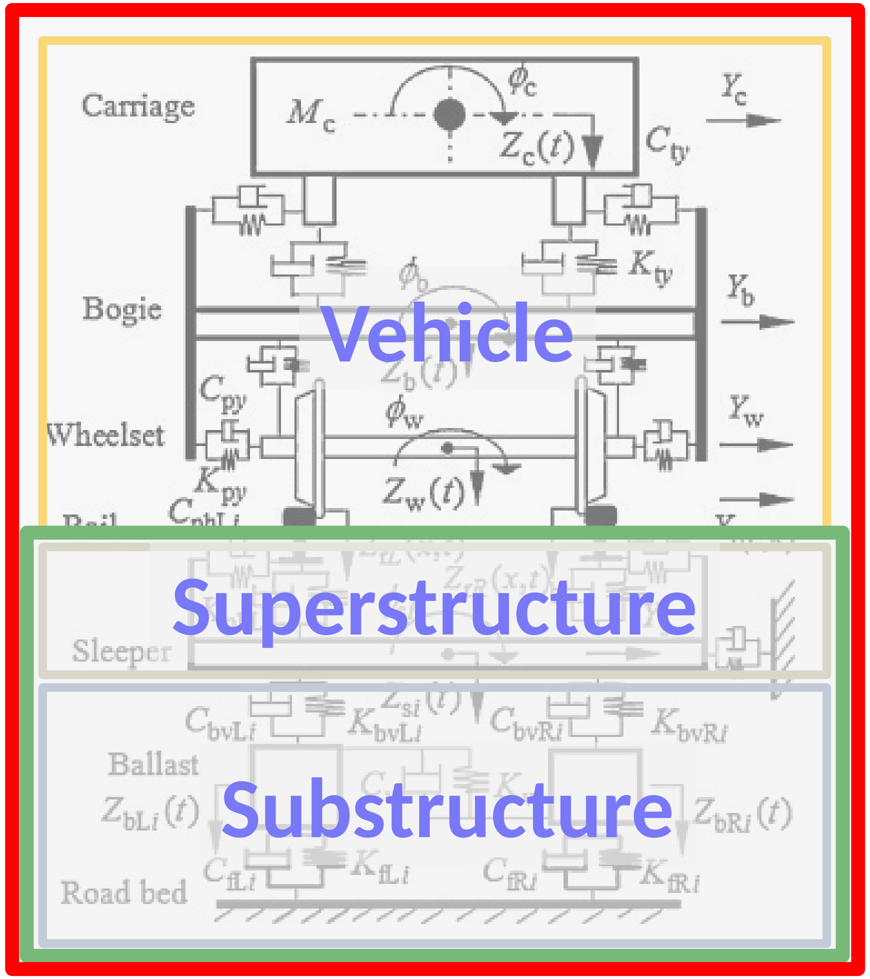
Other FRA Inspection Requirements

- Automated inspection of track constructed with concrete crossties (213.234)
- Inspection of switches, track crossings and lift rail assemblies or other transition devices on movable bridges (213.235)
- Inspection of rail (213.237 and 213.339)
- Special inspections (213.239)
- Automated vehicle-based inspection systems (213.333)

See the FRA *"Track and Rail and Infrastructure Integrity Compliance Manual – Volume II"* for more details

The Track & Vehicle as a System

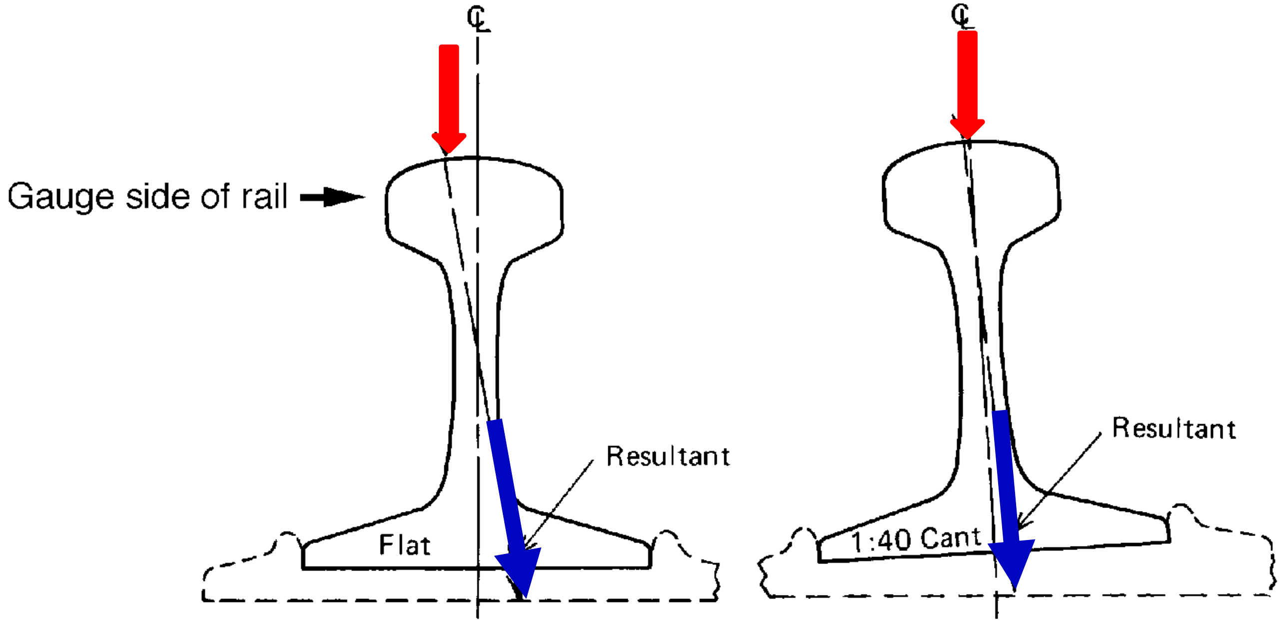
Understanding System Dynamics



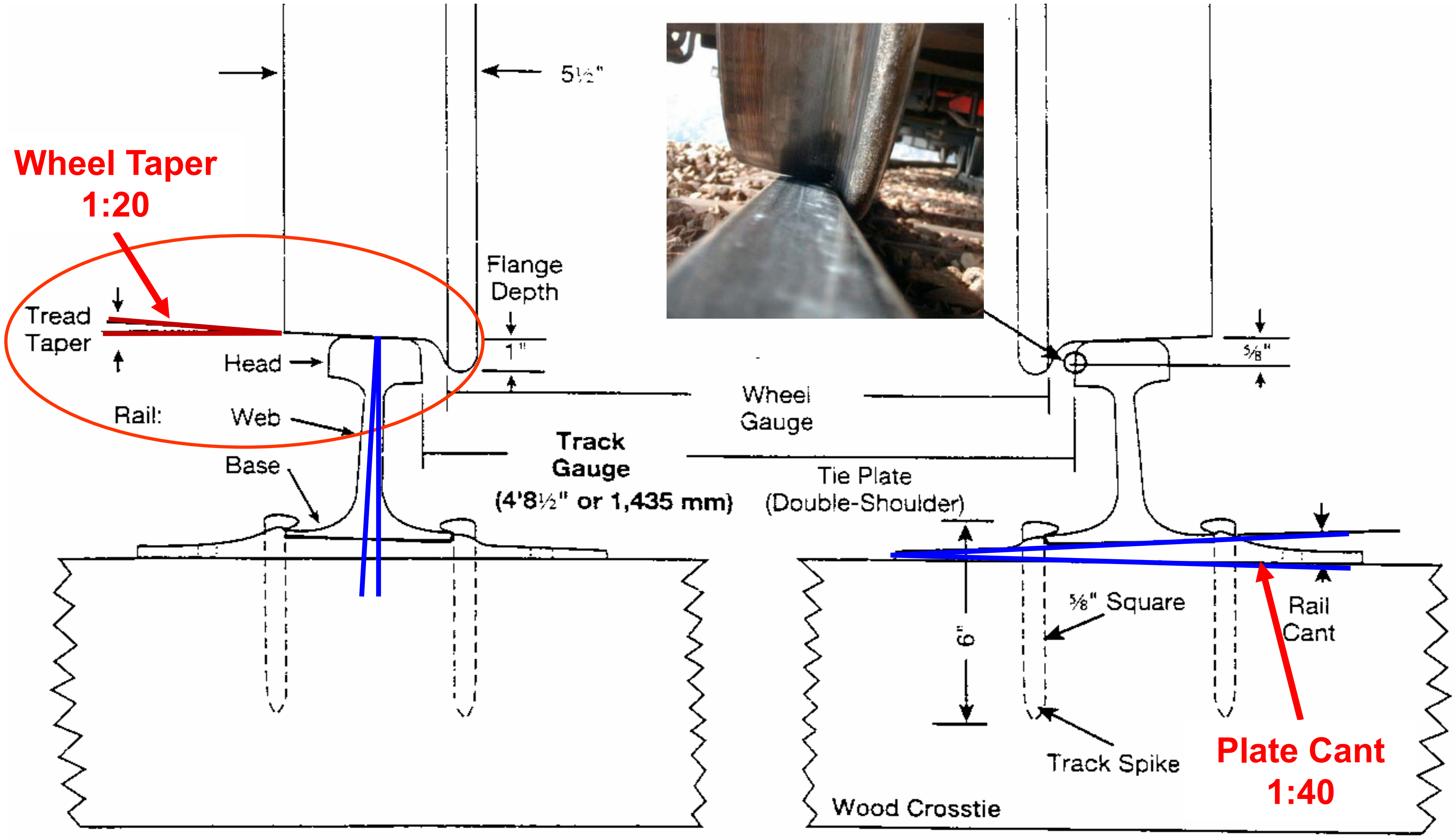
Wei Li,Guangwen Xiao,Zefeng Wen,Xinbiao Xiao,Xuesong Jin
Southwest Jiaotong University

Rail Cant

- Because the contact patch with a normal, tapered wheel is not at the center of the head of the rail, the rail is canted inward (toward the gauge side of the track) to give a better, more stable resultant load path through the web to the base.
- Typical North American practice is from 1:20 to 1:40 cant

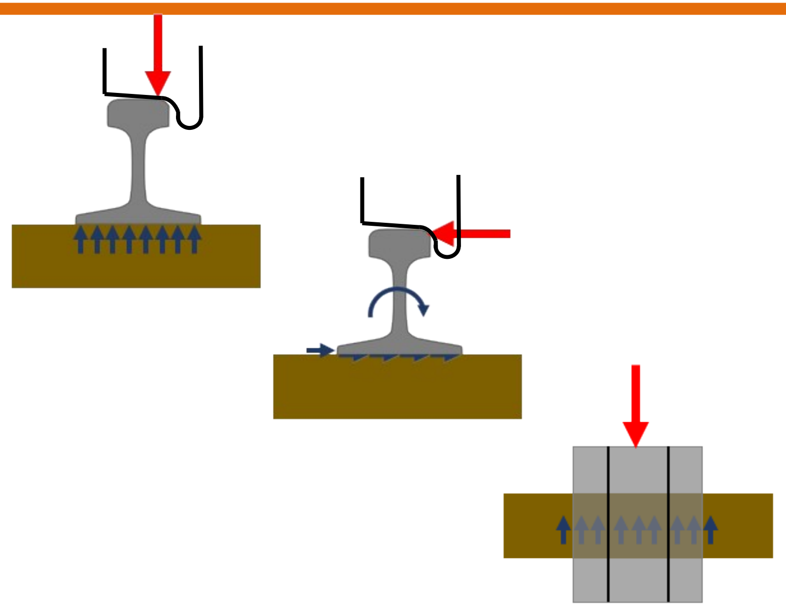


Wheel Tread Taper and Cant



The Track Loading Environment

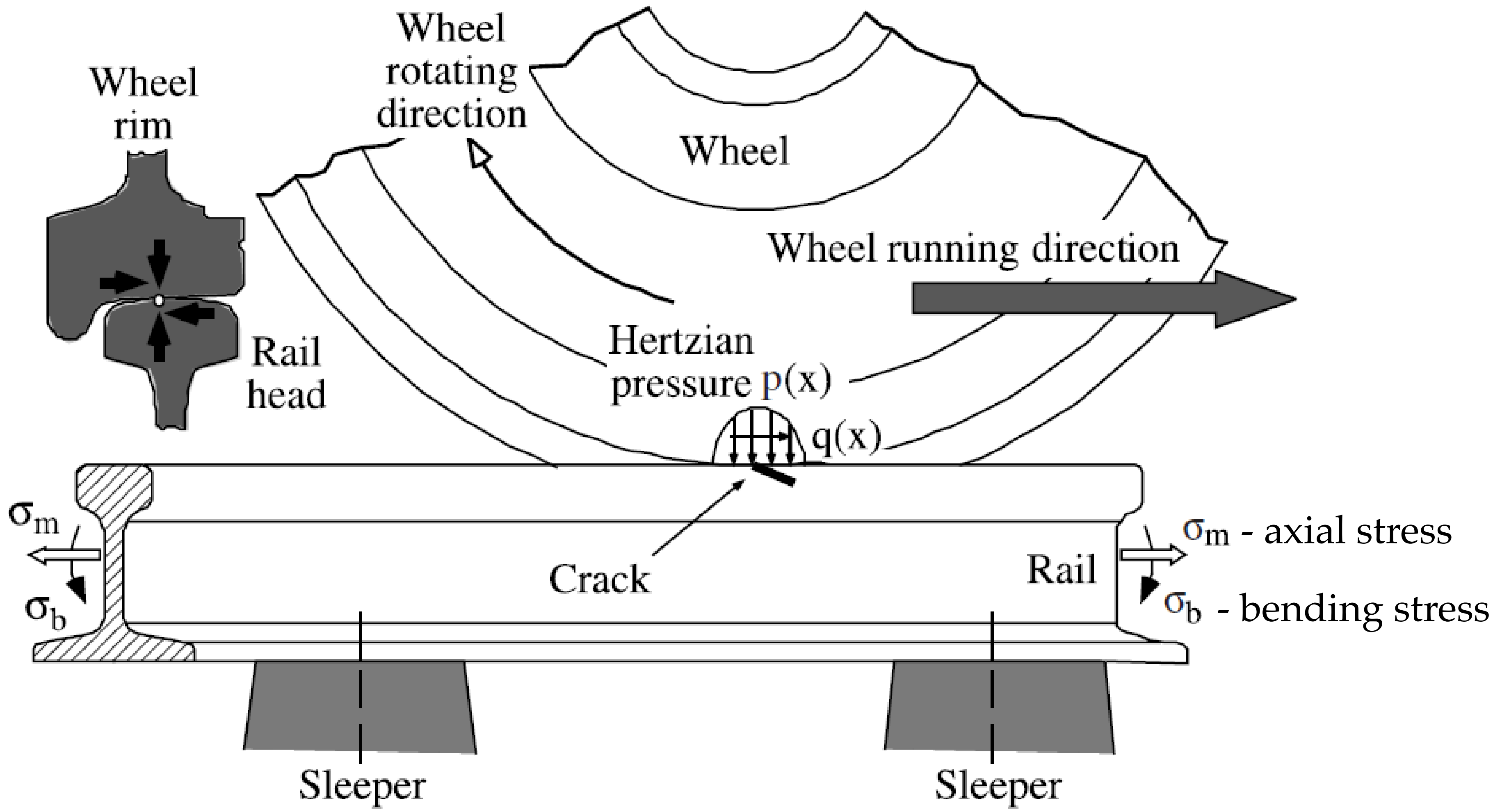
Forces Acting on the Track



- Load Direction and Orientation:
  - **Vertical** (P, Q or V)
  - **Lateral** (Y or L)
  - **Longitudinal** (T)

- Primary Types of Loading:
  - **Static** → Weight of vehicle at rest (level track)
  - **Dynamic** → Wheel rotation, minor track and wheel irregularities
    - ↳ Largely a function of the railcar in motion
  - **Impact** → Often related to discontinuities
    - ↳ Vehicle wheel-induced or track-related

Primary Loading Condition of Rail



Common North American Freight Car Sizes and Loads

Nominal Capacity (cargo weight)	Gross Rail Load (GRL) (vehicle PLUS cargo weight)	Axle Load (4 axles)	Wheel Load (8 wheels)
140,000 lbs (70 ton)	220,000 lbs	55,000 lbs (27. 5 tons)	27,500 lbs
200,000 lbs (100 ton)	263,000 lbs	65,750 lbs (32.9 tons)	32,875 lbs
220,000 lbs (110 ton)	286,000 lbs	71,500 lbs (35.8 tons)	35,750 lbs
250,000 lbs (125 ton)	315,000 lbs	78,750 lbs (39.4 tons)	39,375 lbs

"Heavy Axle Load" (HAL)

Vertical Forces Acting on the Track

- Vertical ($\boldsymbol{P}$, Q or V)

$$P_{total} = (P_{static} + P_{centering} + P_{wind}) + P_{dynamic}$$

quasi-static forces

where:

P_{static} = static wheel load measured on tangent track

$P_{centering}$ = wheel load due curvature and cant

P_{wind} = increase in wheel load due to wind

$P_{dynamic}$ = dynamic wheel load components from:

sprung mass (0-20 Hz); unsprung mass (20-125 Hz); & corrugations, weld, wheel flats (0-2000 Hz)

Impact Loads

- Caused by wheel defects, rail discontinuities, track transitions, etc.
  - Generally higher magnitude than cyclic dynamic loads
  - Flat or out-of-round wheels cause impact loadings in excess of 3X Static at the railhead and 4.5X Static in the subgrade

- Include high frequency vibrations referred to as P1 and P2 forces
  - P1 Force: High impact, short duration (rail, concrete ties)
  - P2 Force: High impact, long duration (ballast, track geometry)
  - P1 forces can be up to about 40% higher than P2 forces

Lateral Forces Acting on the Track

- Lateral (Y or L)

$$Y_{total} = \underbrace{(Y_{flange} + Y_{centering} + Y_{wind})}_{\textit{quasi-static forces}} + Y_{dynamic}$$

where:

Y_{flange} = lateral load from flanging on outer rail in curve

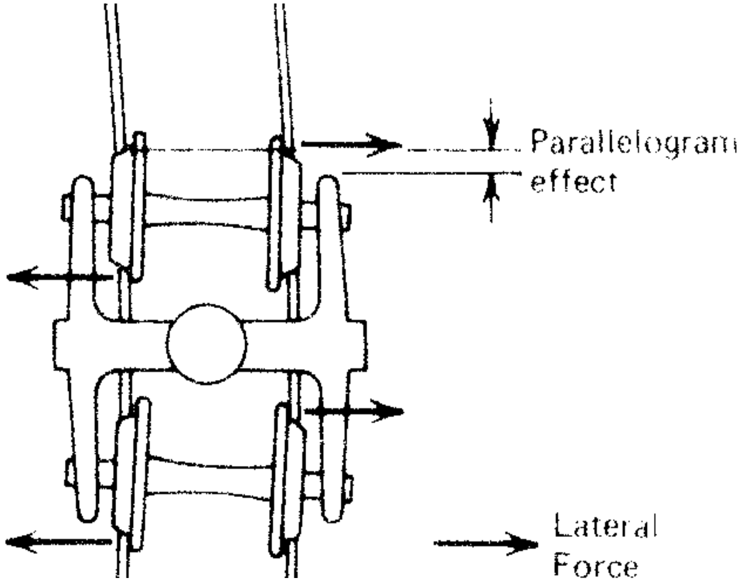
$Y_{centering}$ = lateral force due to non-compensated centrifugal force

Y_{wind} = lateral force due to cross wind

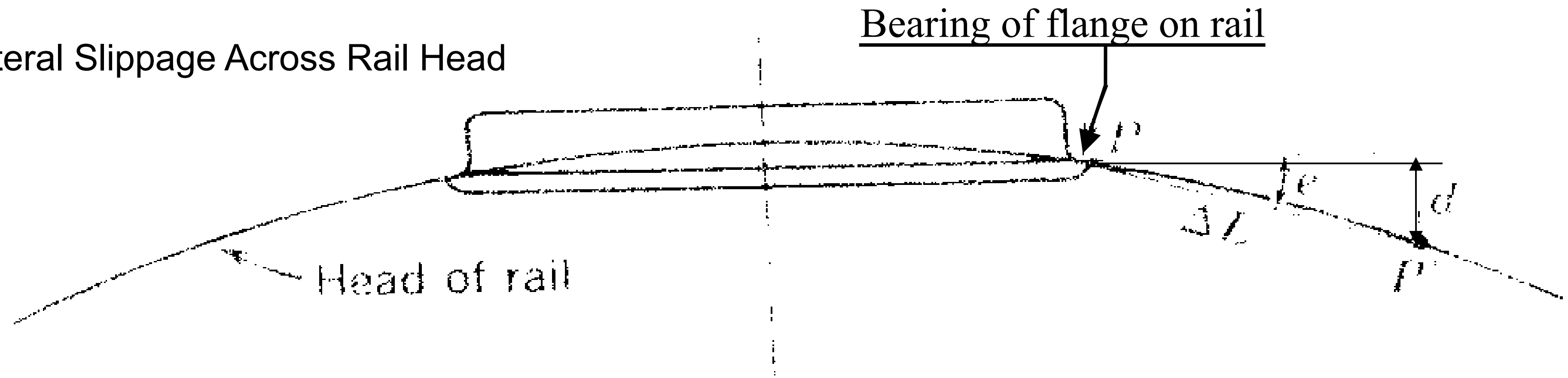
$Y_{dynamic}$ = dynamic lateral force component due to hunting or track alignment deviations

Lateral Forces

- Lateral component of wheel load
- Truck turning moments
- Wheel slip from worn wheels or rail
- Truck “parallelogram effect”
- Rail cant
- Wheel-rail Coefficient of friction
- Curve superelevation, train speed, and centrifugal force

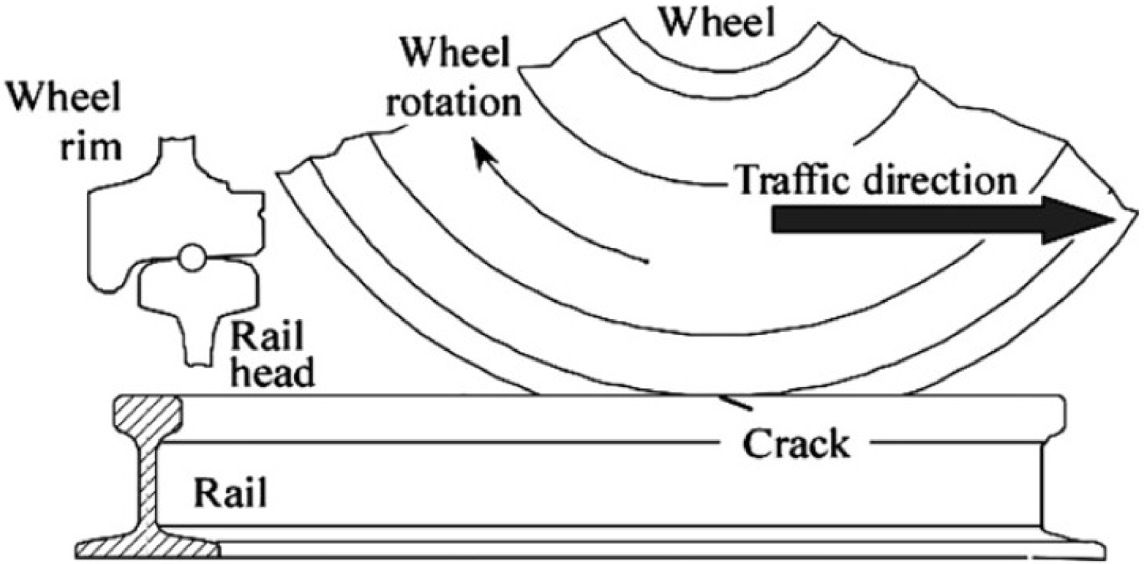


Lateral Slippage Across Rail Head



Longitudinal Force Acting on the Track

- **Thermal Force**
- Traction Force
- Braking Force

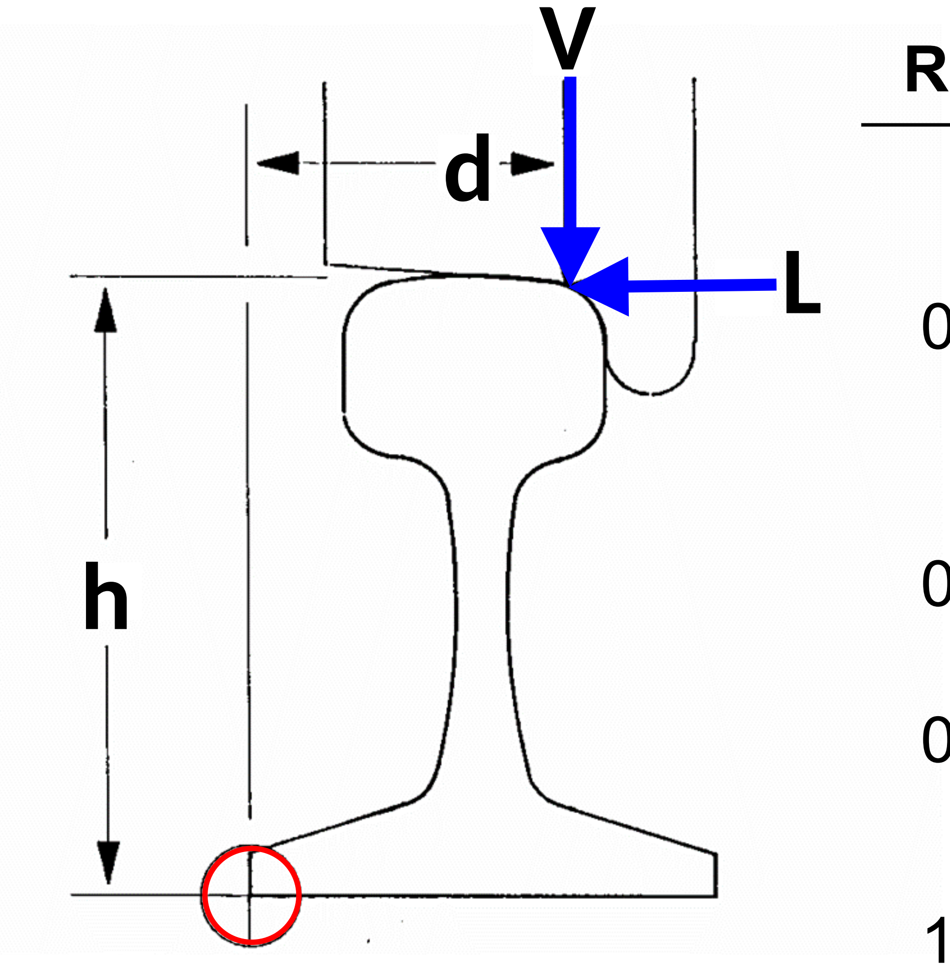


Thermal Forces

Track Forces and Influence

Force Direction	Load Magnitude (Single Wheel)	Load Amplification	Load Sharing (Stiffness)	Track Factors Influencing	Mechanical Factors Influencing
Vertical	32,000 – 40,000 lbs	1.0 - 1.5x Dynamic 2.0 - 4.0x Impact	5-7 Crossties	Stiffness / Modulus **Track Irregularity (e.g., profile, joint gap)**	Wheel Load / Condition
Lateral	10-20,000 lbs	1.0 - 2.0x	3-4 Crossties	Superelevation Balance / Unbalance Horizontal Curvature Spiral Design Curve Transition	**Truck Steering** Wheel Tread Condition Buff/Draft Forces
Longitudinal	Very Low to 20,000 lbs	Negligible	60-300 Crossties (100-500 ft)	Grade Longitudinal Resistance (Fasteners and Tie / Ballast) $\Delta T = T_{rail} - RNT$	AC vs DC Traction, Adhesion, Tractive Effort Buff/Draft Forces

L/V Ratio and Derailment Hazard



Rail can roll when: $\frac{L}{V} > \frac{d}{h}$

Ratio	Degree of Hazard
0.68	The resultant (making an angle of approximately 33°20′ with the vertical load) passes outside the base of the rail, indicating initial instability; an unrestrained rail may overturn.
0.75	A worn wheel flange may climb a worn rail.
0.82	The flange disengages from the rail; an outside wheel may lift from the rail on curves.
1.29	Derailing condition; wheel will climb a new rail; a new wheel lowers the wheel climb threshold.

Hay, 1991

Back to our case study site…

What do you see? (Photo taken near POD)

- Crossties and fasteners
  - Timber ties, cut spikes, and rail anchors
- Quality of ballast
  - Fouled / deteriorated
- Horizontal curvature
  - Shallow curve (superelevation?)
- Geometry
  - Profile and crosslevel deviations
- Proximity to grade crossing

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