William W. Hay Railroad Engineering Seminar

“Fundamentals and Selected Technical Issues for High Speed and Heavy Axle Railroad Engineering”

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University of Delaware

Date: Friday, April 21, 2017

Time: Seminar Begins 4:00PM

Location: Newmark Lab, Yeh Center, Room 1310
University of Illinois at Urbana-Champaign

Students welcome and encouraged to attend!

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Fundamentals and Selected Technical Issues High Speed and Heavy Axle Railroad Engineering

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Introduction

- Railroads have been the subject of technological innovation and engineering for nearly 200 years
- Track structure evolved through a combination of incremental improvements and technological innovation
  - Example- evolution of the rail section
    - Introduction of rolled steel sections led to “T” rail section
- The modern railway track structure introduced in the mid 19th century
- Continued to evolve through the introduction of more robust components, new materials, and improved component designs
- Upgraded to address heavier axle loading, higher speeds, and more intense operations.

Railroad Engineering

- Evolution of railroad track, and key components, paralleled by evolution in railroad engineering
- Early railroad engineering focused on “building” the railroad
  - Strong emphasis on construction techniques, bridge and tunnel engineering and route alignment engineering
- Modern railroad engineering focused on improved analytical tools, better designs, and improved maintenance procedures
  - Improve track structure’s strength and ability to carry heavy loads
  - To last longer and perform more efficiently
- Dependent of traffic type and characteristics
  - Axle load, Speed, Density of traffic

Railway Systems

- Freight
  - Conventional (Mixed Freight)
  - Heavy Axle Load
  - Unit Train
- Passenger
  - Interurban
    - Conventional
    - High Speed
  - Commuter Rail/Suburban
- Transit
  - Heavy Rail Transit
  - Light Rail Transit

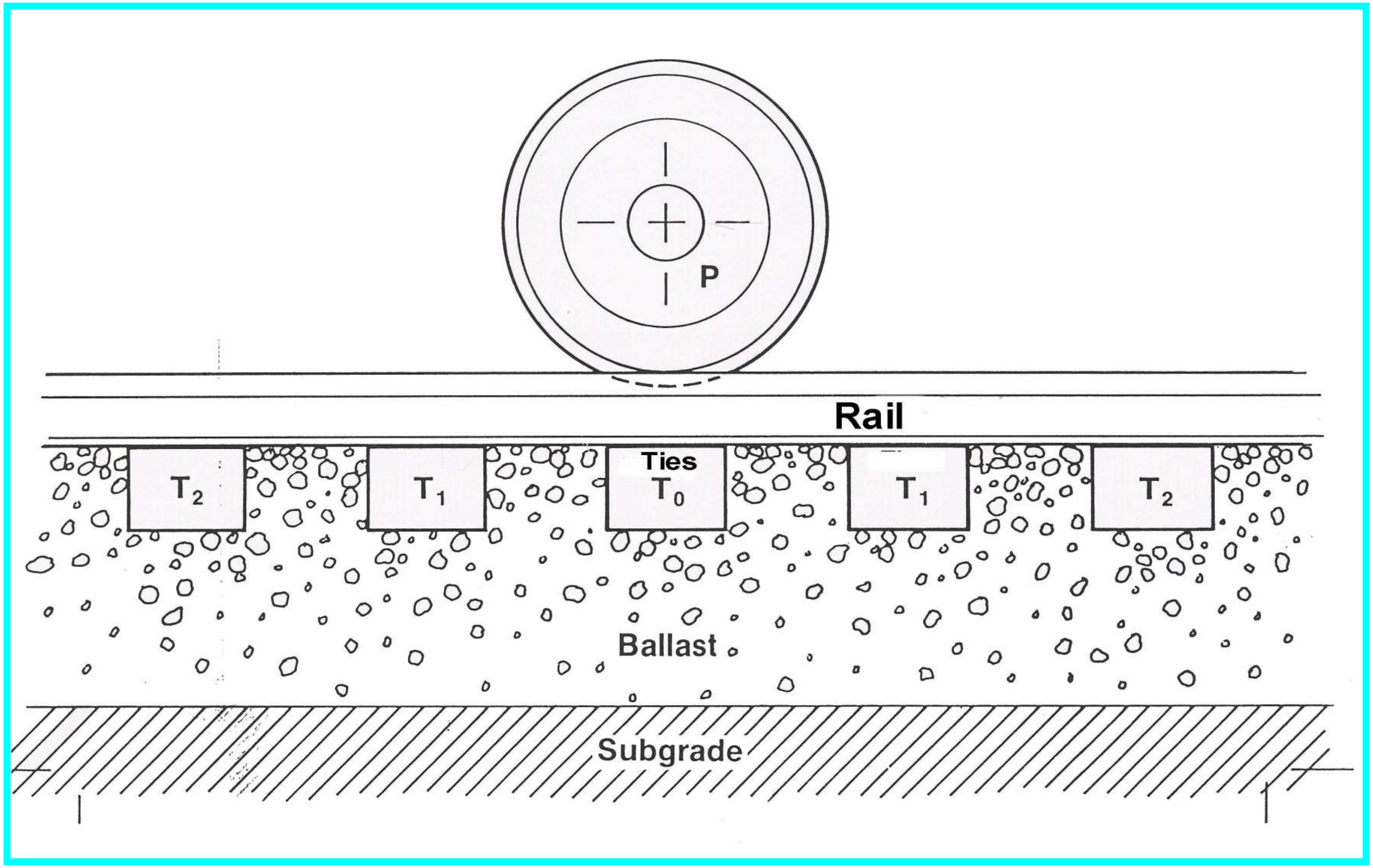
Purpose of Railroad Track Structure

- Support the loads of cars and locomotives
- Guide their movement

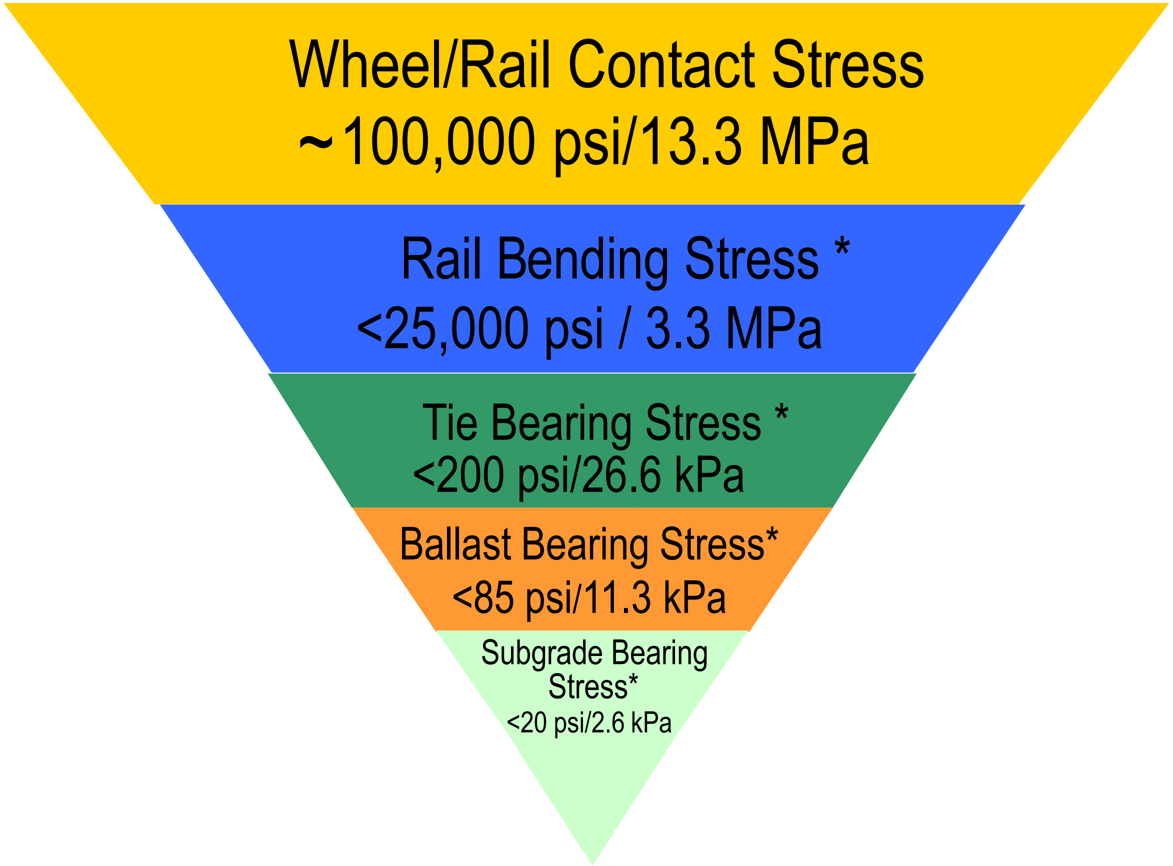
Track Types

- Ballasted Track
  - Cross-ties
    - Wood
    - Concrete
    - Steel
    - Plastic/composite
  - Longitudinal ties
  - Frames
- Non-ballasted Track
  - Slab track
    - Direct Fixation (DF) track on slab
    - Cast in place ties or tie blocks
  - Embedded track

Function: Withstand and Distribute Loads



Pyramid of Bearing Stresses



Wheel/Rail Contact Stress
~100,000 psi/13.3 MPa

Rail Bending Stress *
<25,000 psi / 3.3 MPa

Tie Bearing Stress *
<200 psi/26.6 kPa

Ballast Bearing Stress*
<85 psi/11.3 kPa

Subgrade Bearing Stress*
<20 psi/2.6 kPa

Focus of Engineering Analysis

- Strength of the track and its components
  - Ability to resist catastrophic failure
- Ability to resist long term degradation or deterioration
  - Maintain geometric integrity
  - Reduce/control maintenance requirements over extended periods
    - Extend the life of track components
    - Reduce/control rate of track degradation
    - Identify/rectify problems before catastrophic failure

Railroad Load Environment

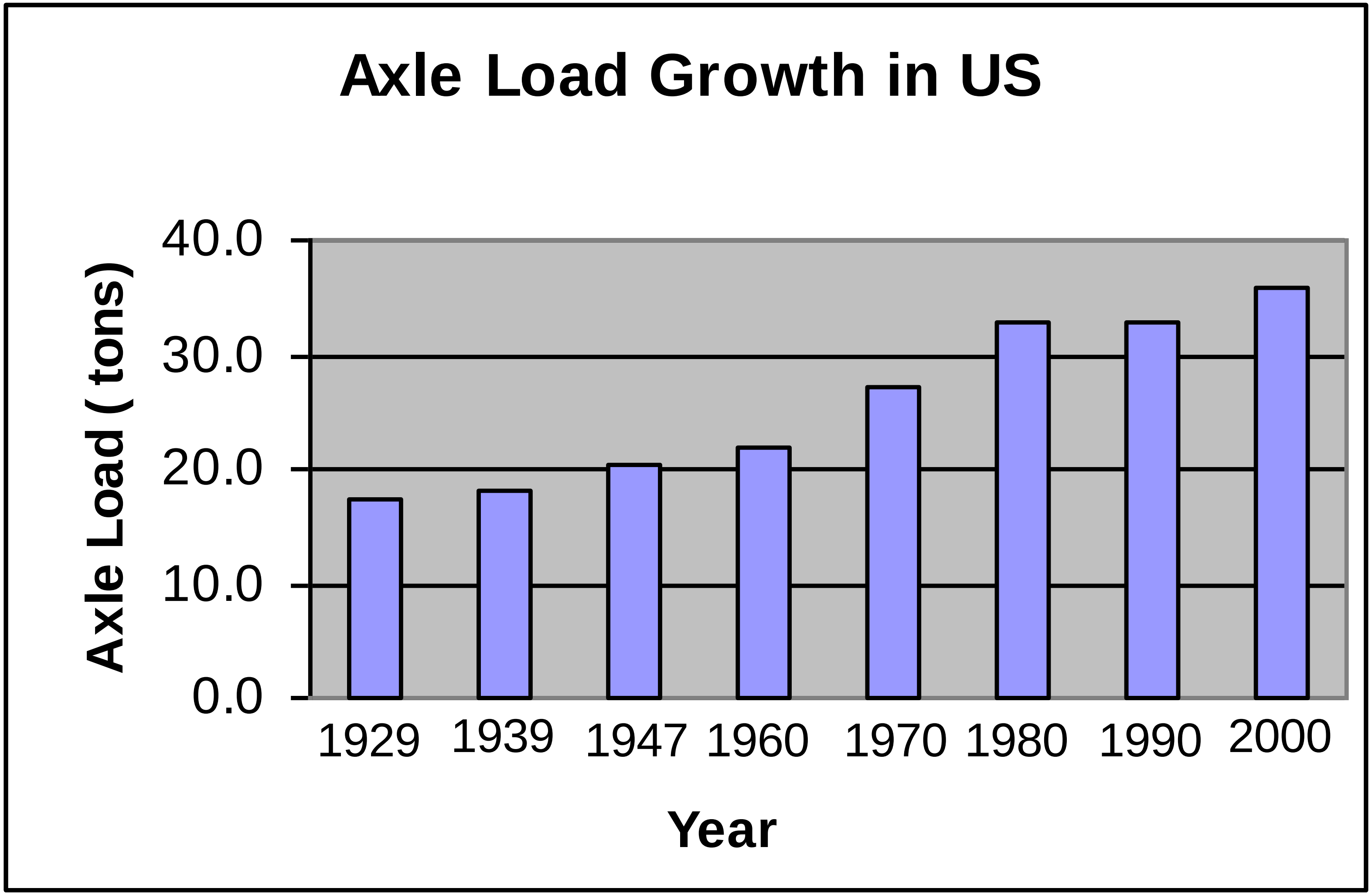
- Vertical Loadings
  - From railway vehicles
- Lateral Loadings
  - From railway vehicles
- Longitudinal Loadings
  - From railway vehicles
  - From environment (temperature effects)

Vertical Load

- Vertical wheel loading is primary load used in engineering of track
- Function of static axle load and speed
- Focus of major engineering changes to modern track structure
  - Growth in vehicle weight and associated vehicle loading has dominated engineering of track structure in last century
  - Quadrupling of wheel loads from turn of century (wheel loads of 8 Kips/4 tonnes) to today (wheel loads of 36 + Kips/16 tonnes)
  - Pace of growth in axle load (and car weight) set by ability of track structure to support load
- HS Rail loads related to speed and unsprung mass

Static Wheel Loads - Worldwide

Axle Load		Gross Weight of Cars		Traffic Type
Tonnes	Tons	kg	lb.	
8	**8.8**	**32,000**	**70,000**	**Light Rail Transit**
12	**13.2**	**48,000**	**106,000**	**Heavy Rail Transit**
17	**19**	**68,000**	**150,000**	**Passenger**
22.5	**25**	**90,000**	**198,000**	**Common European Freight Limit**
25	**27.5**	**100,000**	**220,000**	**UK+Select European Freight**
30	**33**	**120,000**	**263,000**	**BV (Sweden) limit on Ore Line**
32.5	**36**	**130,000**	**286,000**	**North America Free Interchange**
35.5	**39**	**142,000**	**315,000**	**Australia Iron Ore Lines +** **Very limited use in US**


Axle Load Growth in US
Axle Load (tons)
40.0
30.0
20.0
10.0
0.0
1929
1939
1947
1960
1970
1980
1990
2000
Year

Heavy Axle Load Freight Train

Operating Speed Ranges

Speed		Traffic Type
Kph	Mph	
80	**50**	**Transit**
75	**45**	**Heavy Axle Freight**
100	**60**	**Conventional Freight**
130	**80**	**Intermodal and High Speed Freight**
150	**90**	**Inter-urban Passenger and Commuter**
210	**125**	**Higher Speed Rail**
300	**180+**	**High Speed Rail**

High Speed Rail

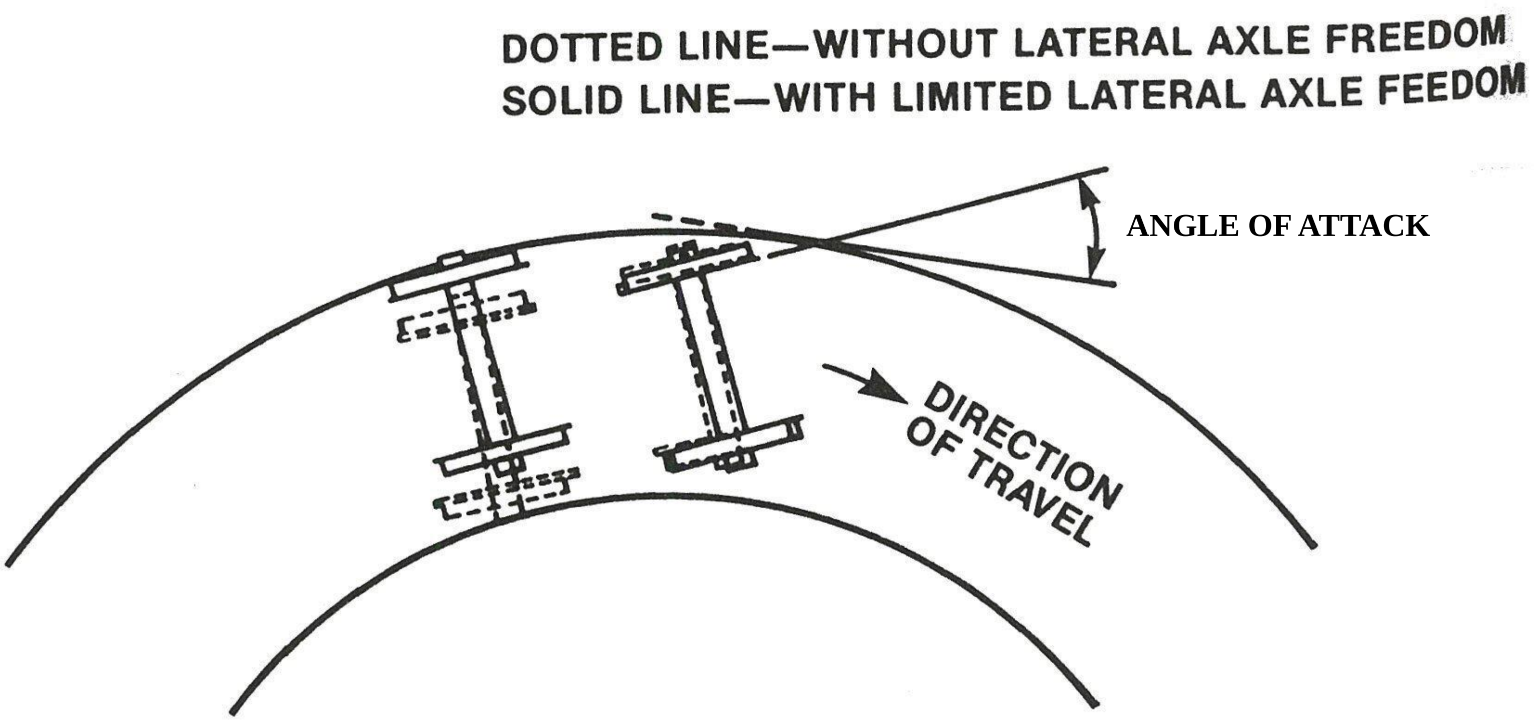
Vertical Loads: Dynamic

- Dynamic augments to static loads are significant
  - Due to dynamic effects of track geometry imperfections
  - Rail or wheel surface defects
  - Increased with increased operating speeds (and unsprung mass)
  - Stiffness transitions
- Dynamic impact factors of 4 and greater have been measured in the field
- Currently AAR limit is 90 Kips (41 tonnes)
  - Represents a factor of almost 3 times the static wheel load
  - European HS rail limits ≈ 3 times static load
- Recent field measurement of dynamic wheel loads :
  - 0.1% to 0.5% of all freight car wheels experience dynamic load levels exceeding 75,000 lbs (34 tonnes)
  - More than double the static load level

Lateral Load

- Lateral load is a major load condition, particularly in curves
- Railway vehicles have rigid axles
  - No independent turning of each wheel
  - During curving there is lateral and longitudinal slip
  - Coned wheel treads provide limited steering
    - For medium to severe curves there is flanging of wheels
    - Associated high wheel/rail lateral forces
- HS right of way limits curvature to < 2 degrees (2660" radius)
  - Significant curvature requires major reduction in speed
- Hunting at high speeds generates lateral loads

Standard Two-Axle Truck (Bogie)



Lateral Loads (Cont.)

- Lateral flanging force includes:
  - steady state curving forces
  - transient curving force
    - due to the dynamics of the wheel negotiating the curve
    - angle of attack between wheel and rail
- Lateral loads in the 30,000+lb (13.5 tonne) range have been measured on a low probability of occurrence basis
  - Loads in the 15,000+ lb (7 tonne) range occur on a more common basis
- Lateral loads act concurrently with vertical loads
  - Severe load environment on moderate to sharp curves
- L/V > 0.8 potential for wheel climb

Longitudinal Loads

- Longitudinal forces are input into track structure through two distinct mechanisms
  - Mechanical forces through train action
  - Thermal forces through changes in ambient temperature
- Mechanically induced longitudinal forces directly related to longitudinal train handling and operations (acceleration, braking, etc.)
  - Maximum mechanical forces of up to 60,000 lbs.(27 tonne) per rail
    - More typically these forces in range of 20,000 lbs.(9 tonne) per rail
- Thermally induced longitudinal rail forces caused by change in ambient (rail) temperature from “neutral” or “force free” temperature of rail
  - Forces either tensile or compressive
  - In curves, also results in significant lateral forces
  - 100 degree (F) temperature change can generate 250,000 lbs. of longitudinal force in 132 RE rail
    - 55 C temperature change generates 114 tonnes of force

High Speed Rail

- Speed has a major effect on loading and track system requirements
- Very High speed rail defined as speeds greater than 180 mph
  - Highest operating speeds 350 kph (210+mph)
  - Highest speed in US 150 mph (Amtrak NE Corridor)
- High speed rail is defined at 125 to 150 mph
  - FRA Class 8
- Higher Speed Rail category
  - Class 5 track with passenger train speeds up to 90 mph
    - Conventional signaling systems
  - Class 6 track operating at 90 to 110 mph
    - PTC or cab signals
  - Class 7 track operating at 110-125 mph
    - PTC
    - High performance freight equipment

High Speed Track Issues

- Design of track to allow for higher speed passenger traffic
  - Minimum curvature
    - Curves < 2 degrees (3000 foot radius)
  - High elevation (6 inches)
    - Issue for mixed passenger and freigth traffic
  - Tight track geometry requirements
  - Uniform track support
  - Enhanced grade crossing protection

- Track maintenance
  - Focus on track geometry maintenance
  - Significant costs necessary to maintain track for mixed higher speed passenger and freight operations

Curvature vs. Allowable Speed (cont)

4” unbalance (passenger equipment)

- Sensitivity to elevation

Curvature	Maximum Speed (mph)		
Elevation	6"	4"	3"
1 degree (5730'radius)	120	107	100
2	85	76	71
3	69	62	60
4	60	53	50
5	53	48	45
6	49	44	41

Railroad Engineering

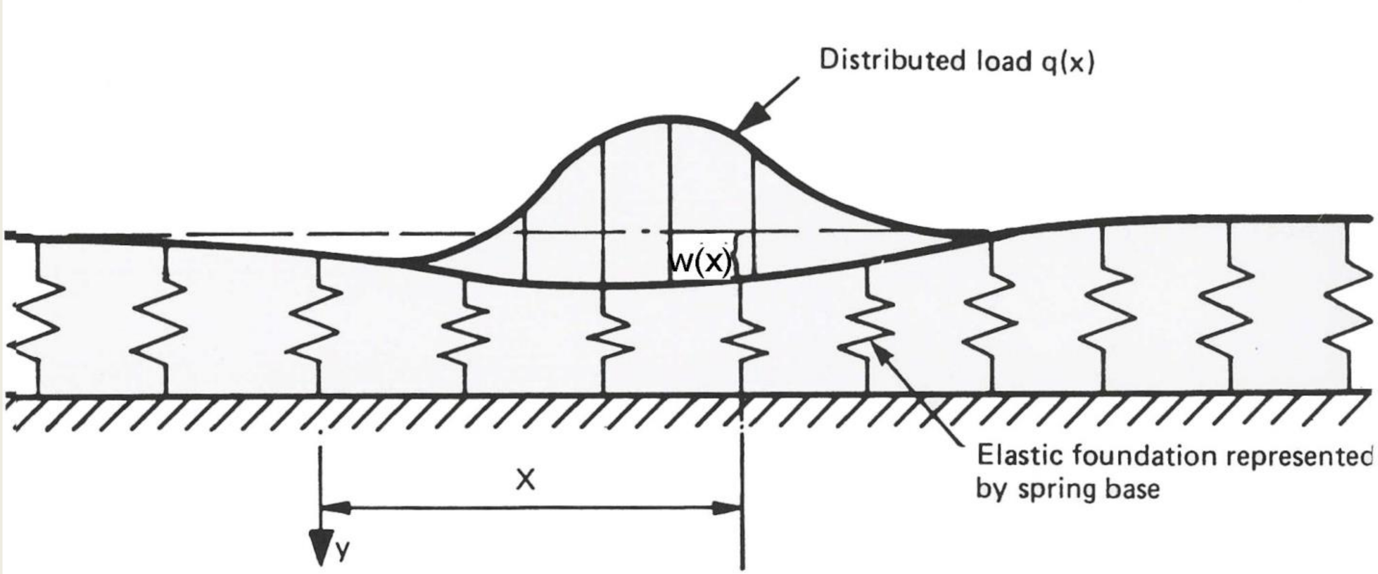
- Current practice can be divided into two broad categories
  - Design based engineering
  - Maintenance based engineering
- Difference in focus and approach
  - Railroad design engineers primarily concerned with former
  - Railroad maintenance personnel being primarily concerned with latter
    - Major focus today

Design Based Engineering:

- Design based engineering concerned with track systems, subsystems, or individual components
- “Standardized” tools presented by AREMA Manual for Railroad Engineering
- “Modern” railroad engineering starts with Beam On Elastic Foundation (BOEF) theory
  - Treats track structure as rail beam sitting on a continuous linear elastic foundation (k)
    - Representing the cross-ties, ballast and subgrade
  - Calculate rail stresses and deflections
  - Tie pressures
- Other track models use different foundation models
  - Rotational resistance effect
  - Spring and shear layer

Beam on Elastic Foundation Model

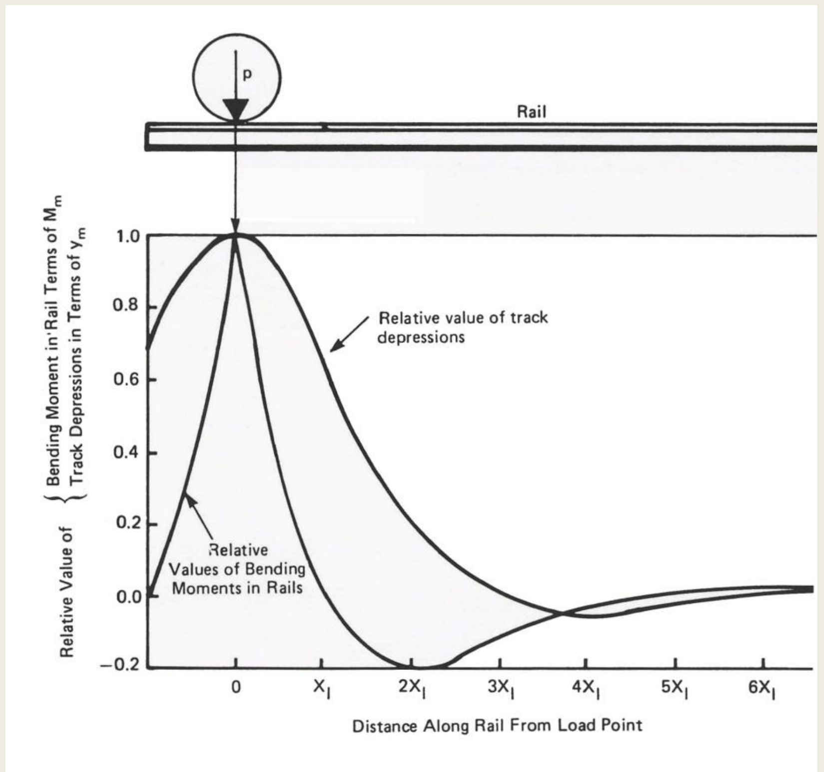
$$EI\frac{d^4w(x)}{dx^4} + kw(x) = q(x)$$



Solution of Classical BOEF Model

$$w(x) = \frac{P\beta}{2k} e^{-\beta x}\left[\cos(\beta x) + \sin(\beta x)\right]$$

$$M(x) = \frac{P}{4\beta} e^{-\beta x}\left[\cos(\beta x) - \sin(\beta x)\right]$$



Maintenance Based Engineering

- Maintenance based engineering is concerned with existing track and how to optimize its performance
  - long term railroad environment
  - increasing loads
- Focus is usually on specific component or subsystems
  - Different focus for HAL freight and high speed passenger
- Engineering analyses and studies in conjunction with empirical development of maintenance practices
- Maintenance engineering focus of last 40 years
  - Under heavy axle load operations, rail represents highest maintenance and replacement cost area for track structure
  - Under high speed passenger operations; track geometry represents highest maintenance cost area
- Safety is a major area of concern

Rail Stress Environment

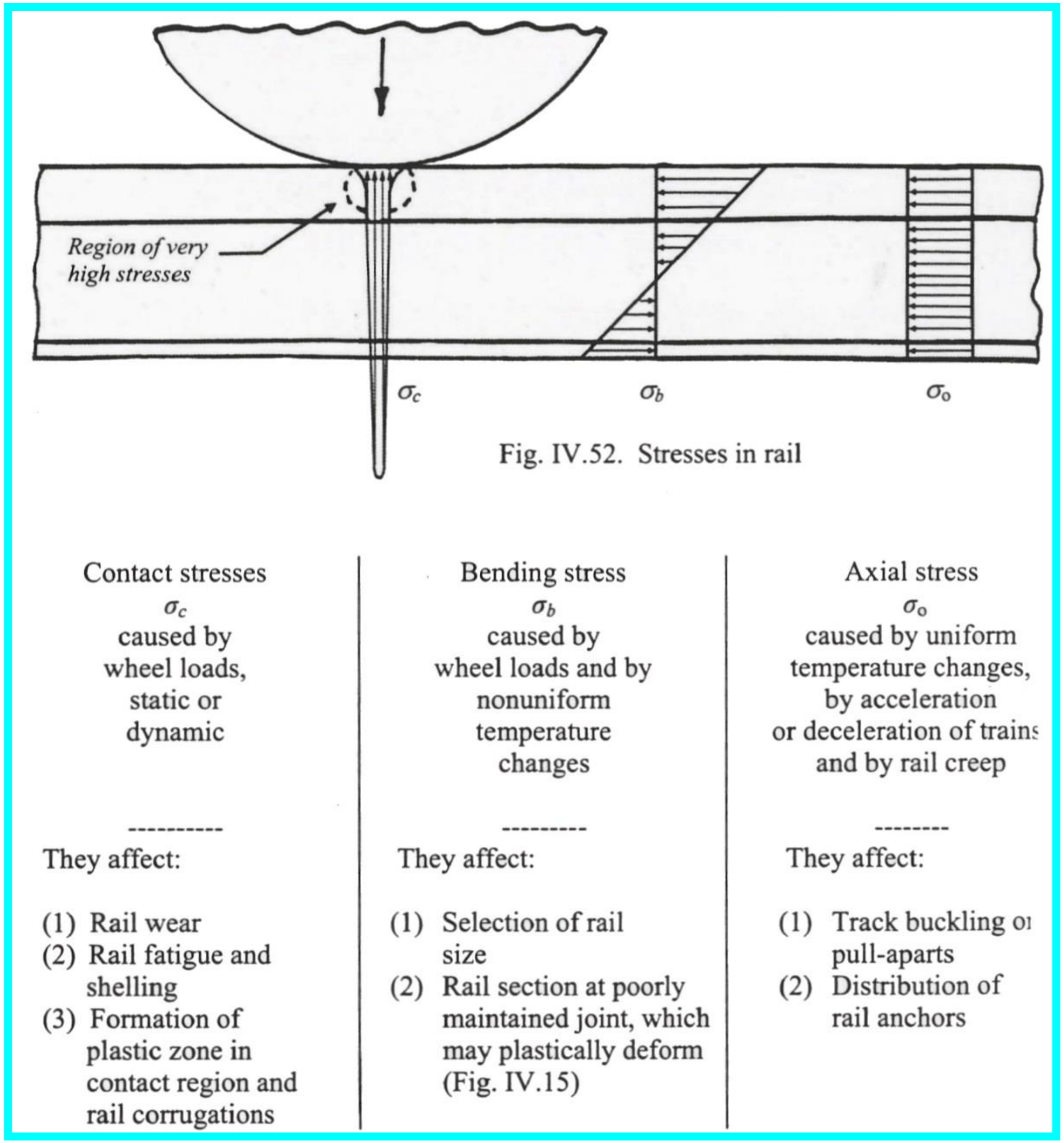


Fig. IV.52. Stresses in rail

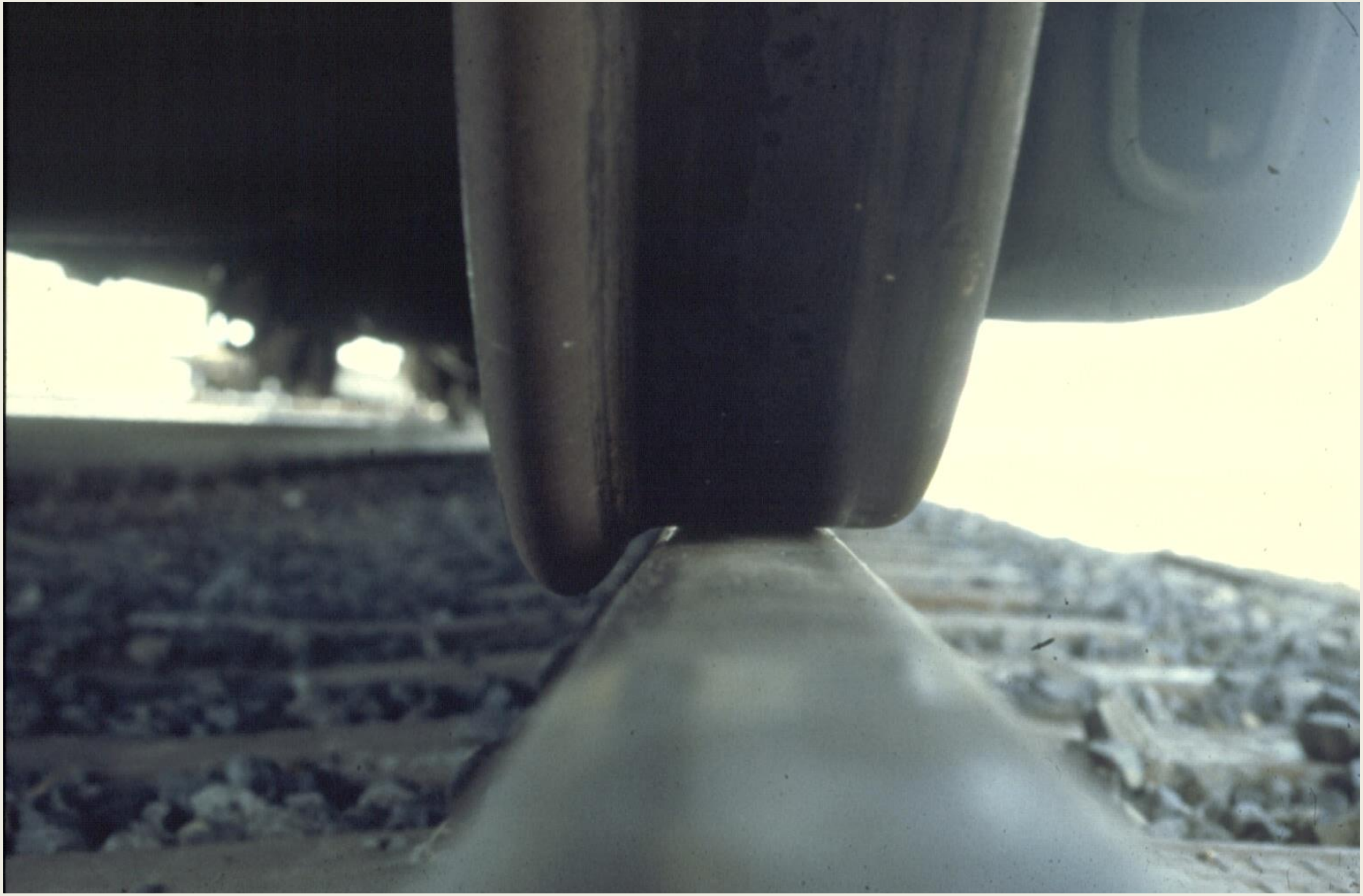
Contact stresses σ_c caused by wheel loads, static or dynamic	Bending stress σ_b caused by wheel loads and by nonuniform temperature changes	Axial stress σ_o caused by uniform temperature changes, by acceleration or deceleration of trains and by rail creep
----------	---------	--------
They affect:	They affect:	They affect:
(1) Rail wear (2) Rail fatigue and 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 (Fig. IV.15)	(1) Track buckling or pull-aparts (2) Distribution of rail anchors

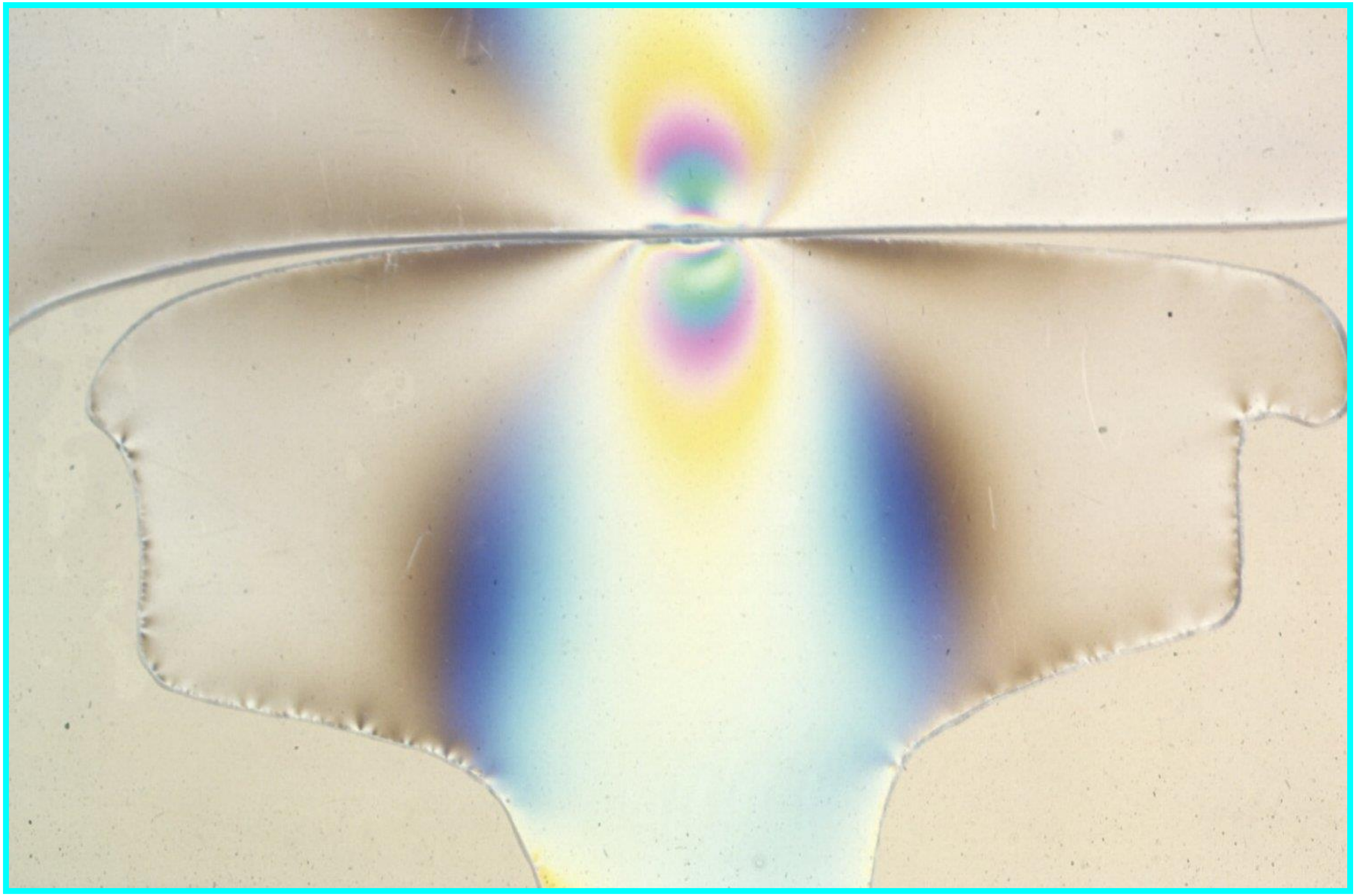
Rail Stress Environment

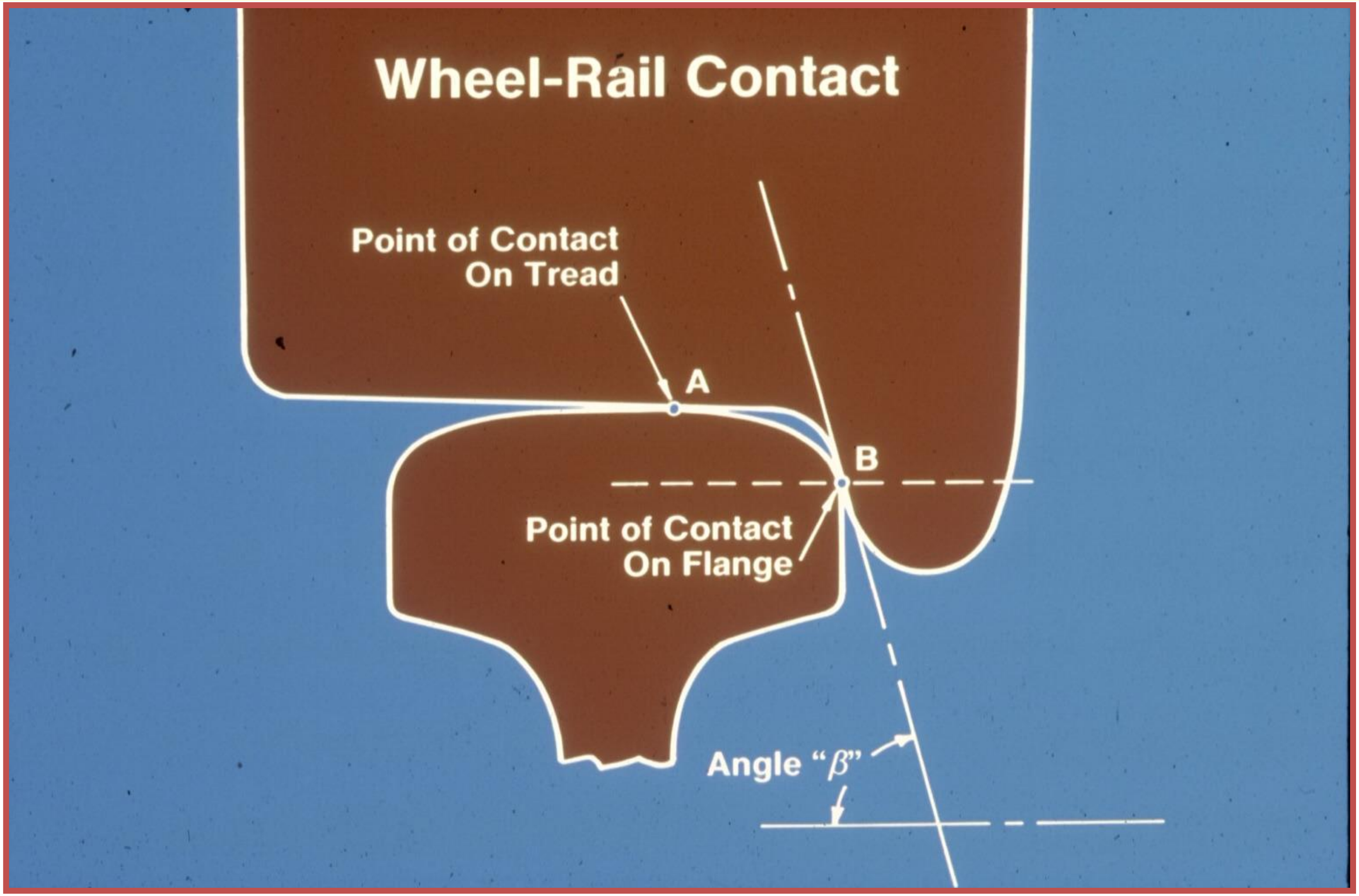
- Bending stresses play an important factor in rail design process
- Contact and longitudinal stresses are most important in maintenance engineering
  - Track maintenance policies and practices are strongly affected by these stresses and associated failure modes
    - Fatigue related problem, both surface and subsurface
    - Wear related problems
    - Pull-apart problems

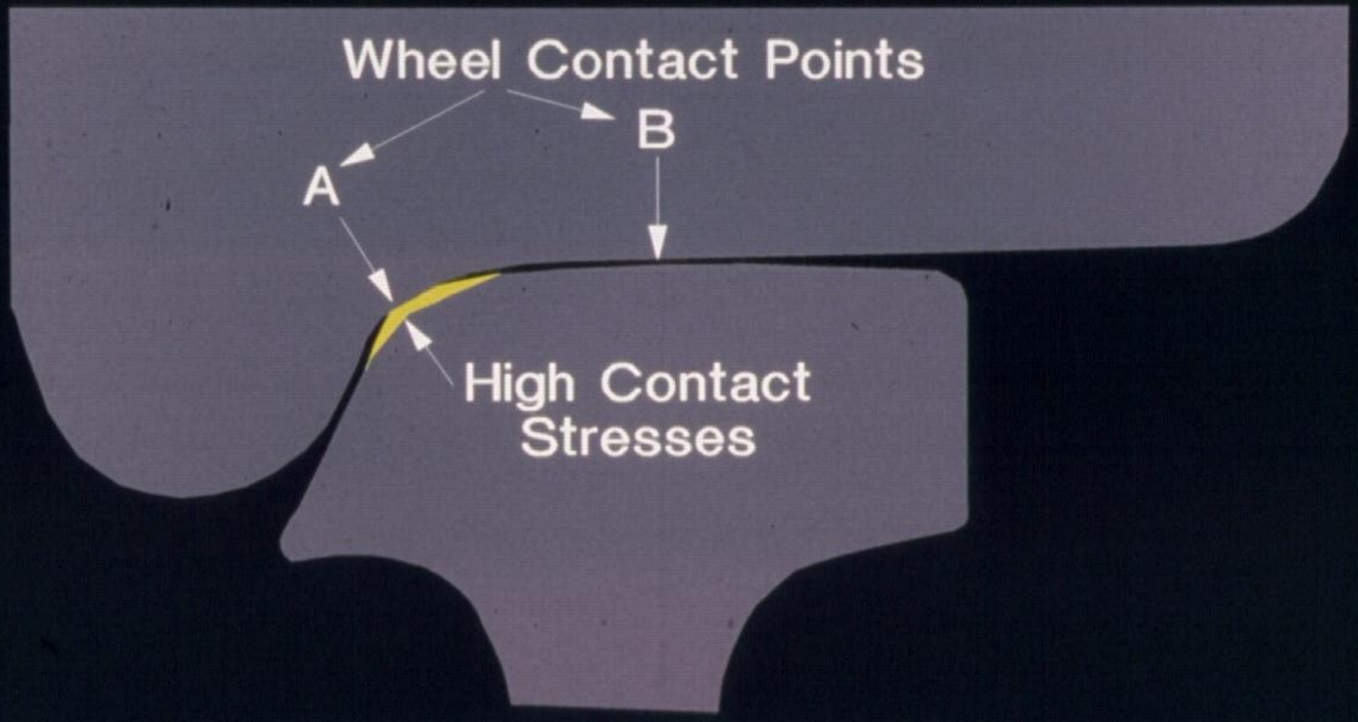
Wheel/Rail Contact Stress

- Generally defined using Hertzian Contact stress theory
- Directly related to the local interface geometry of the wheel and the rail
- Contact can be:
  - Centrally located on the rail head
  - Two point contact to include wheel flange contact on the side of the rail head
  - Contact at the gauge corner of the rail

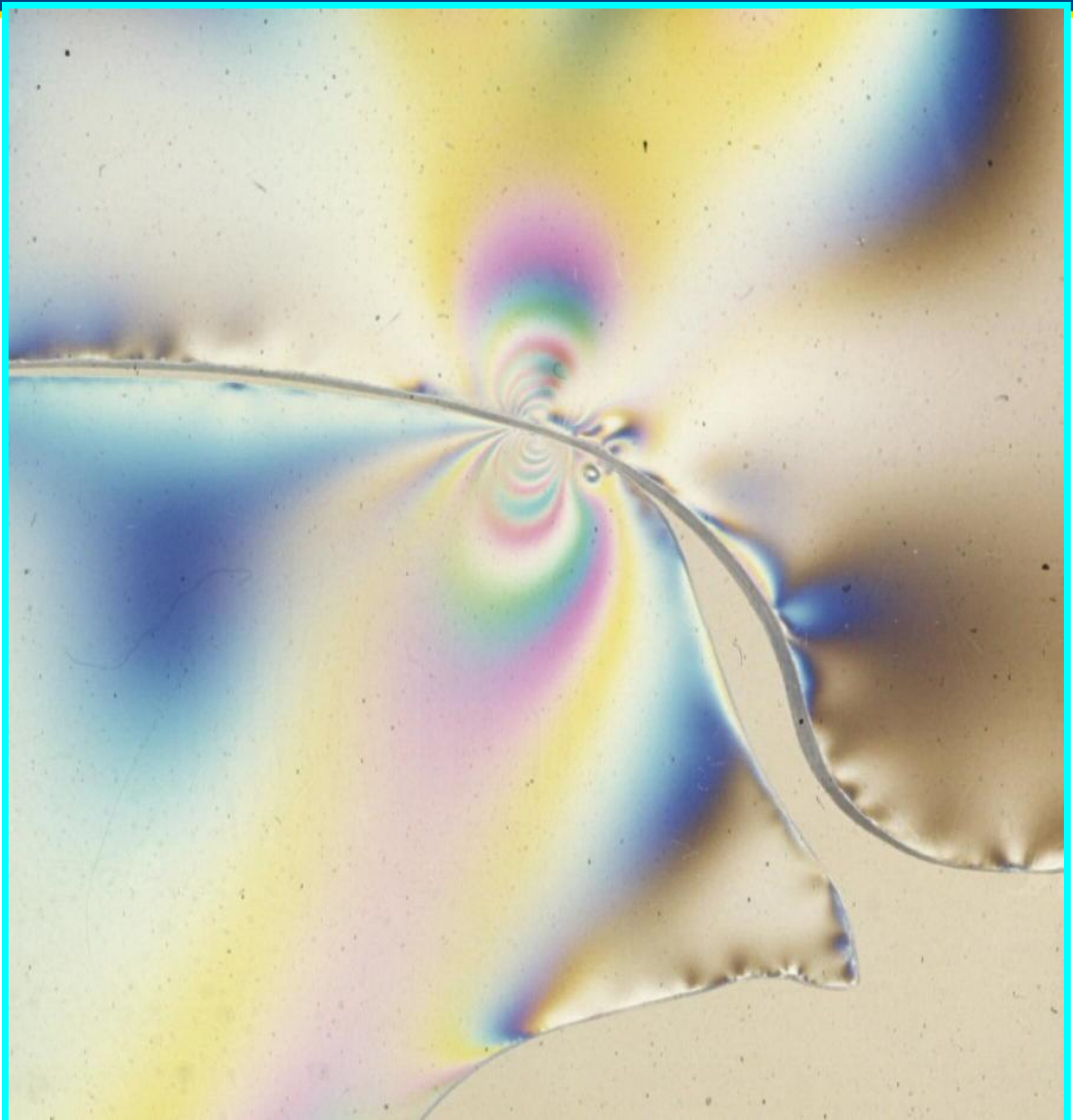





Wheel-Rail Contact
Point of Contact On Tread
A
B
Point of Contact On Flange
Angle "β"

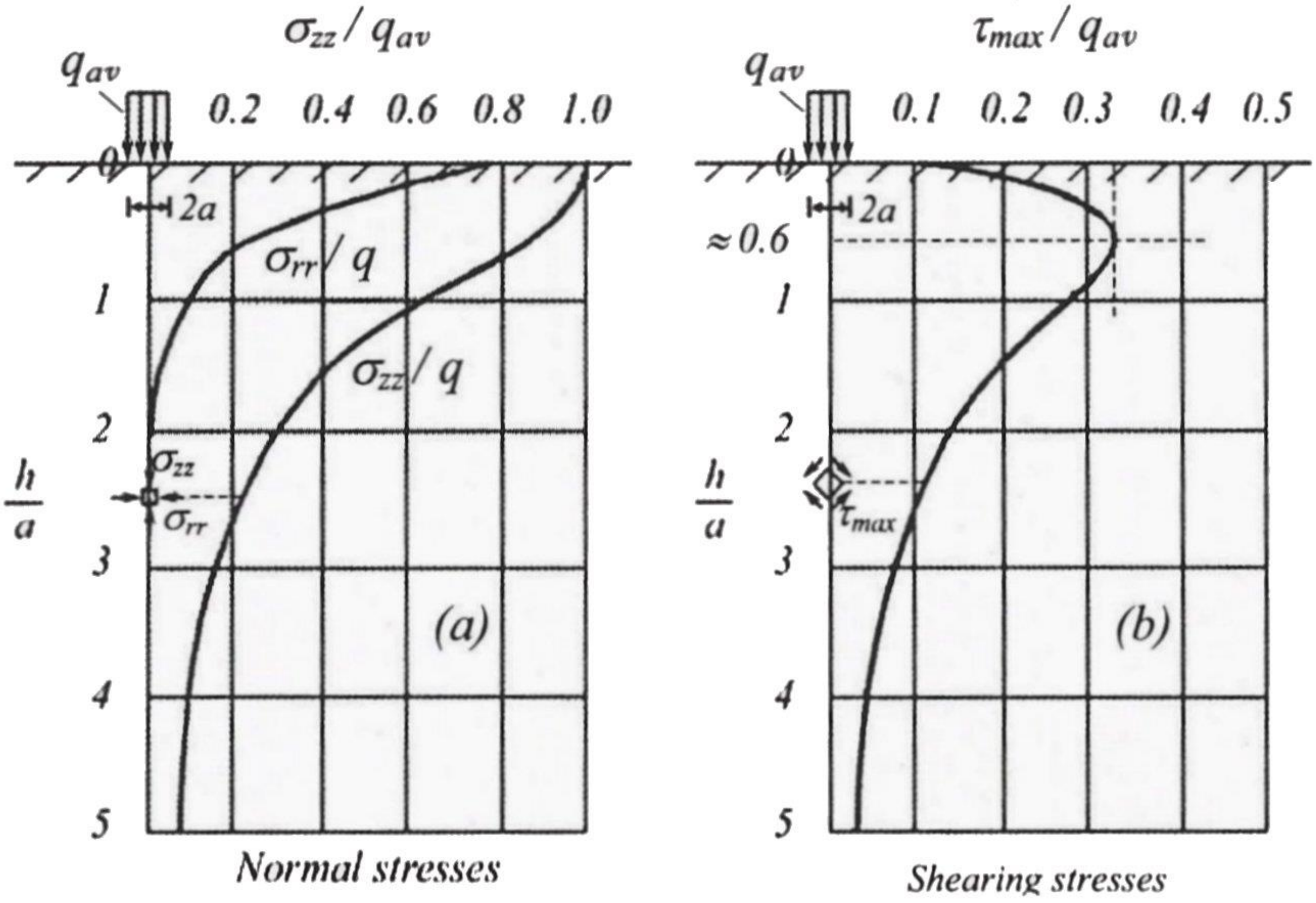


NEW WHEEL/WORN RAIL



Contact Stresses

- Contact stresses are local to the surface of the rail head
  - Decreases rapidly away from the surface
  - Related problems are local to surface of rail head or just subsurface at point of maximum shear stress
- By changing shape/profile of rail head, possible to control location and shape of wheel/rail contact zone and associated contact stresses
  - Allows for the “engineering” of optimum profiles



Normal stresses

Shearing stresses

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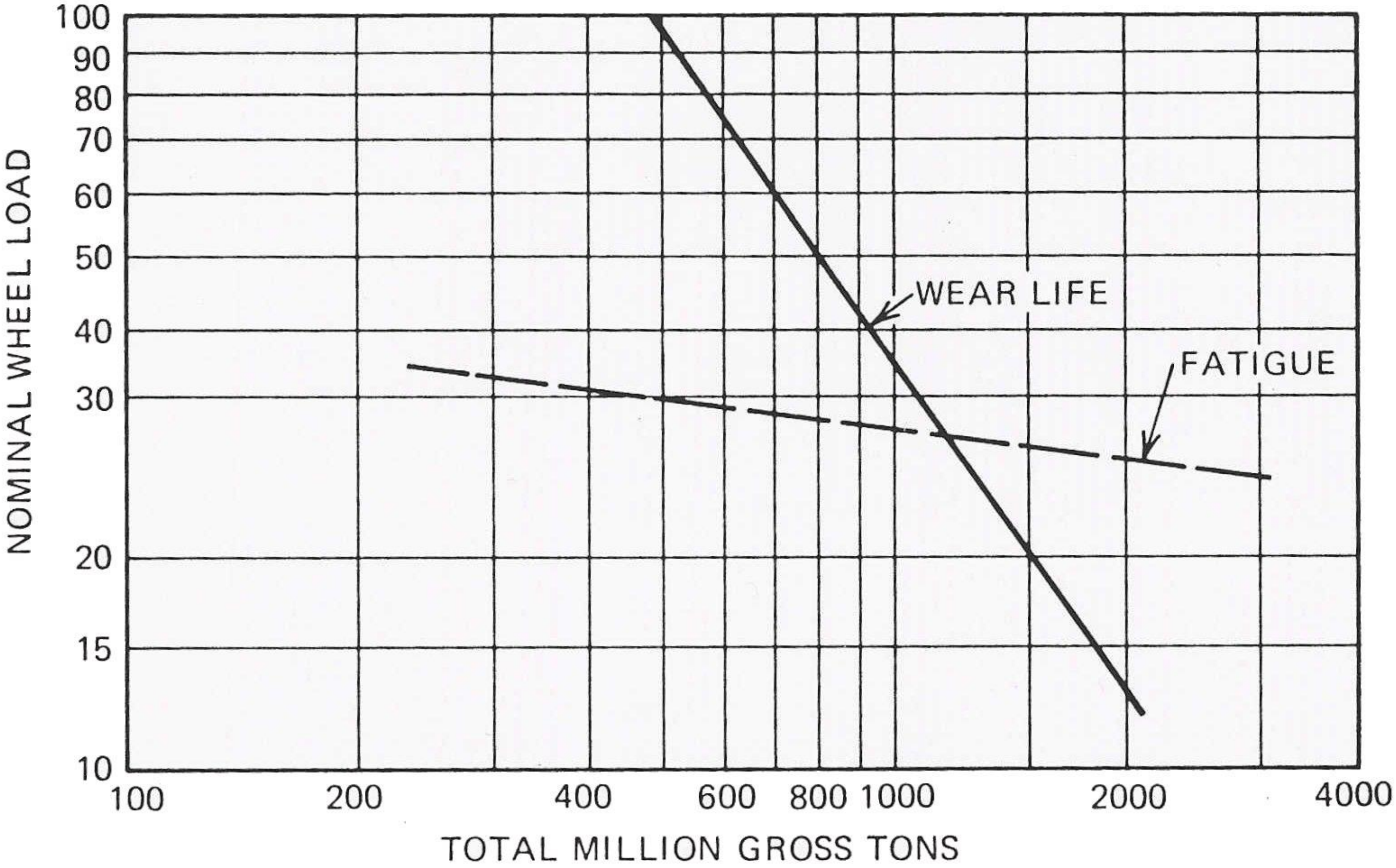
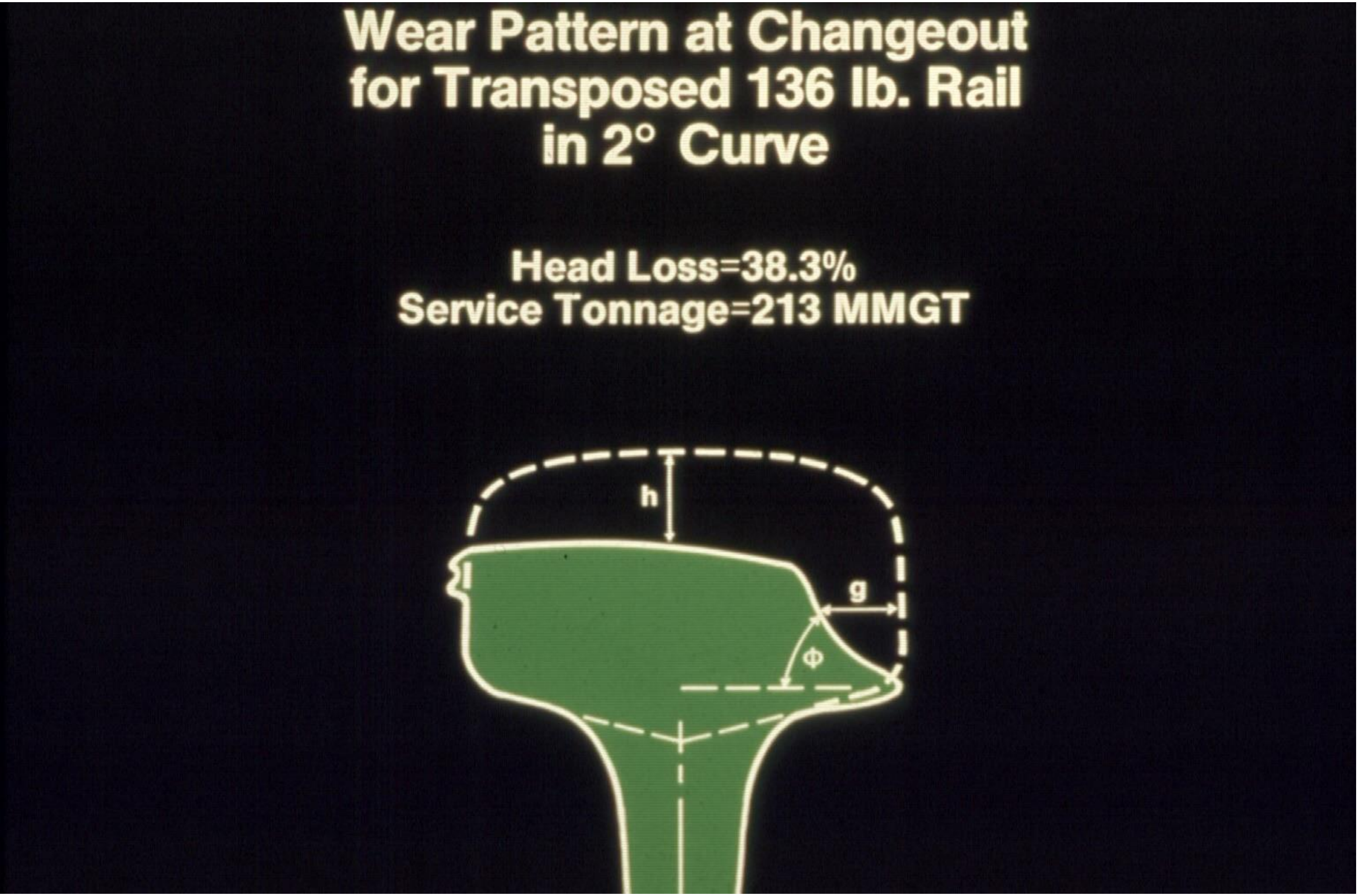
Wear Vs. Fatigue

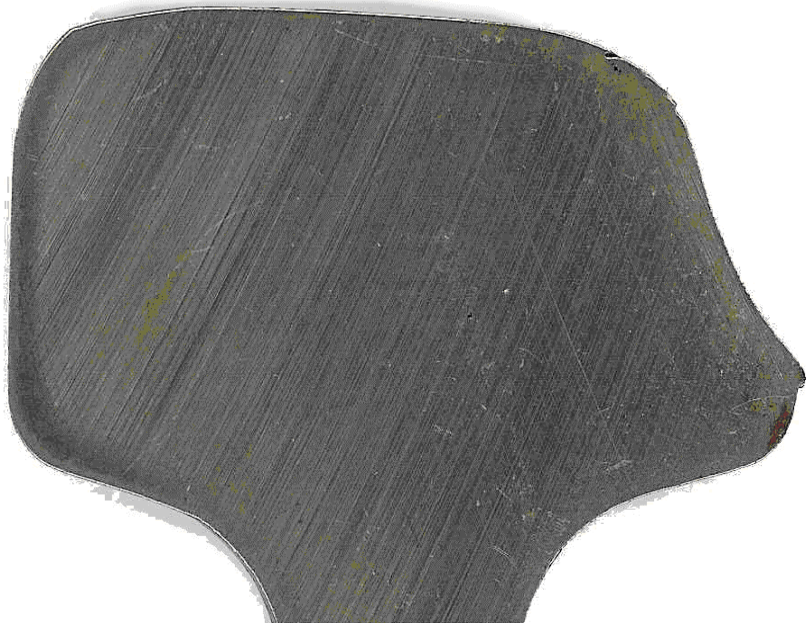




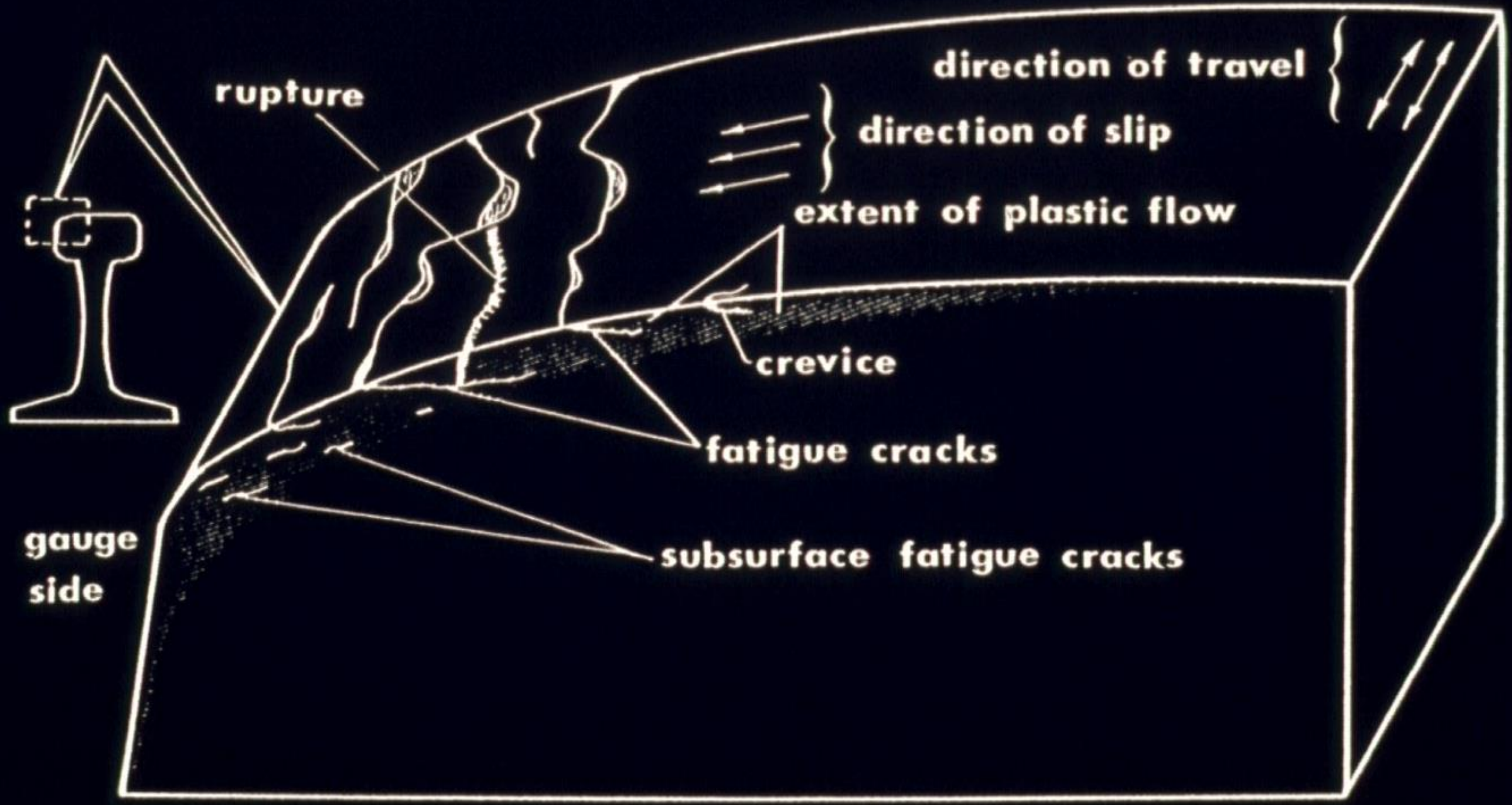
Wear Pattern at Changeout for Transposed 136 lb. Rail in 2° Curve

Head Loss=38.3%
Service Tonnage=213 MMGT

Rail Profile

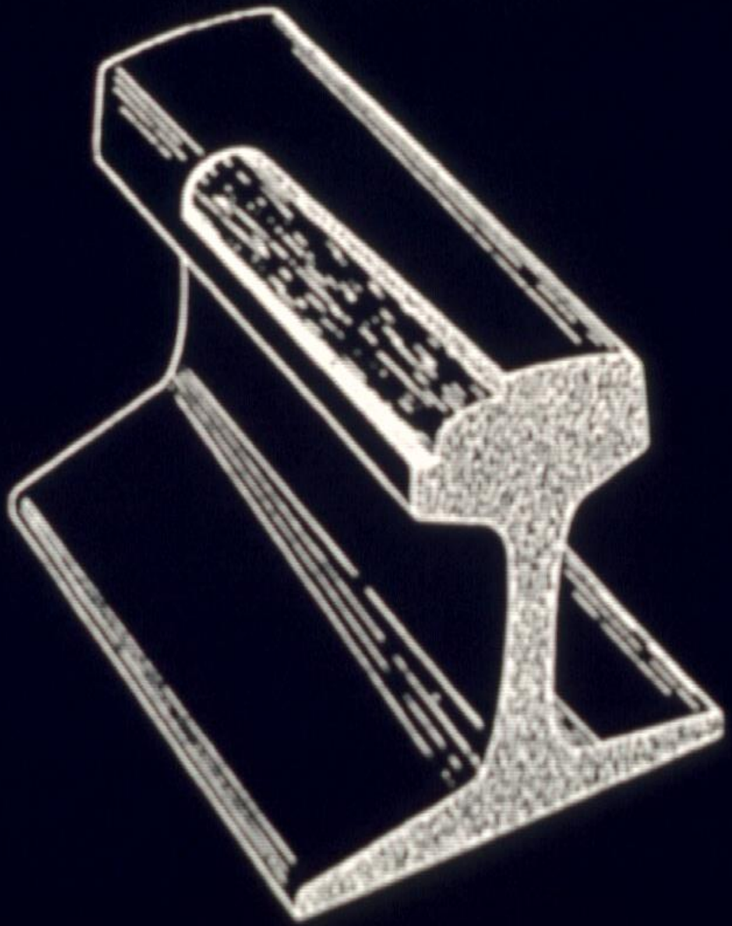


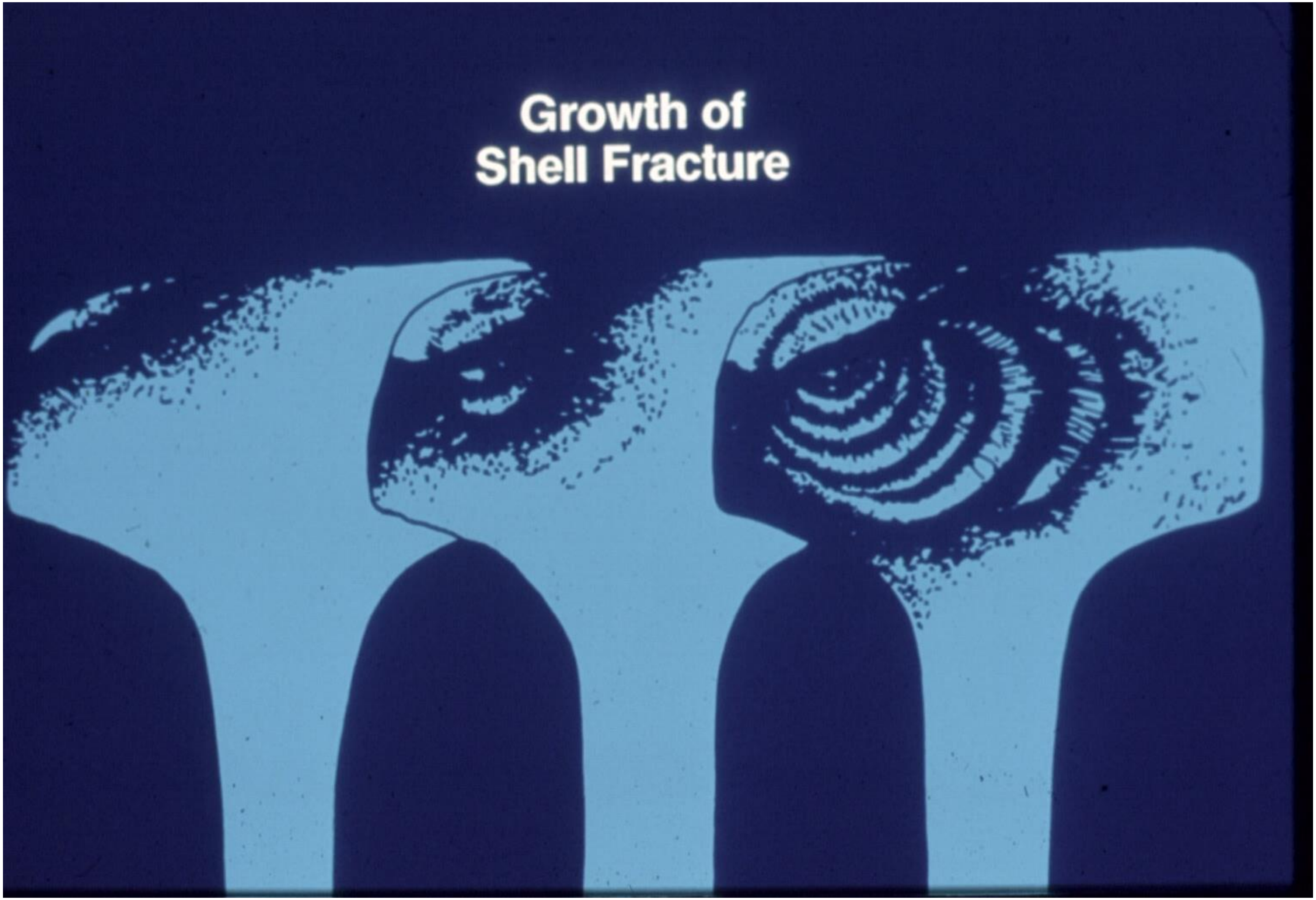
Schematics of Contact Fatigue Damage on the Outer Rail



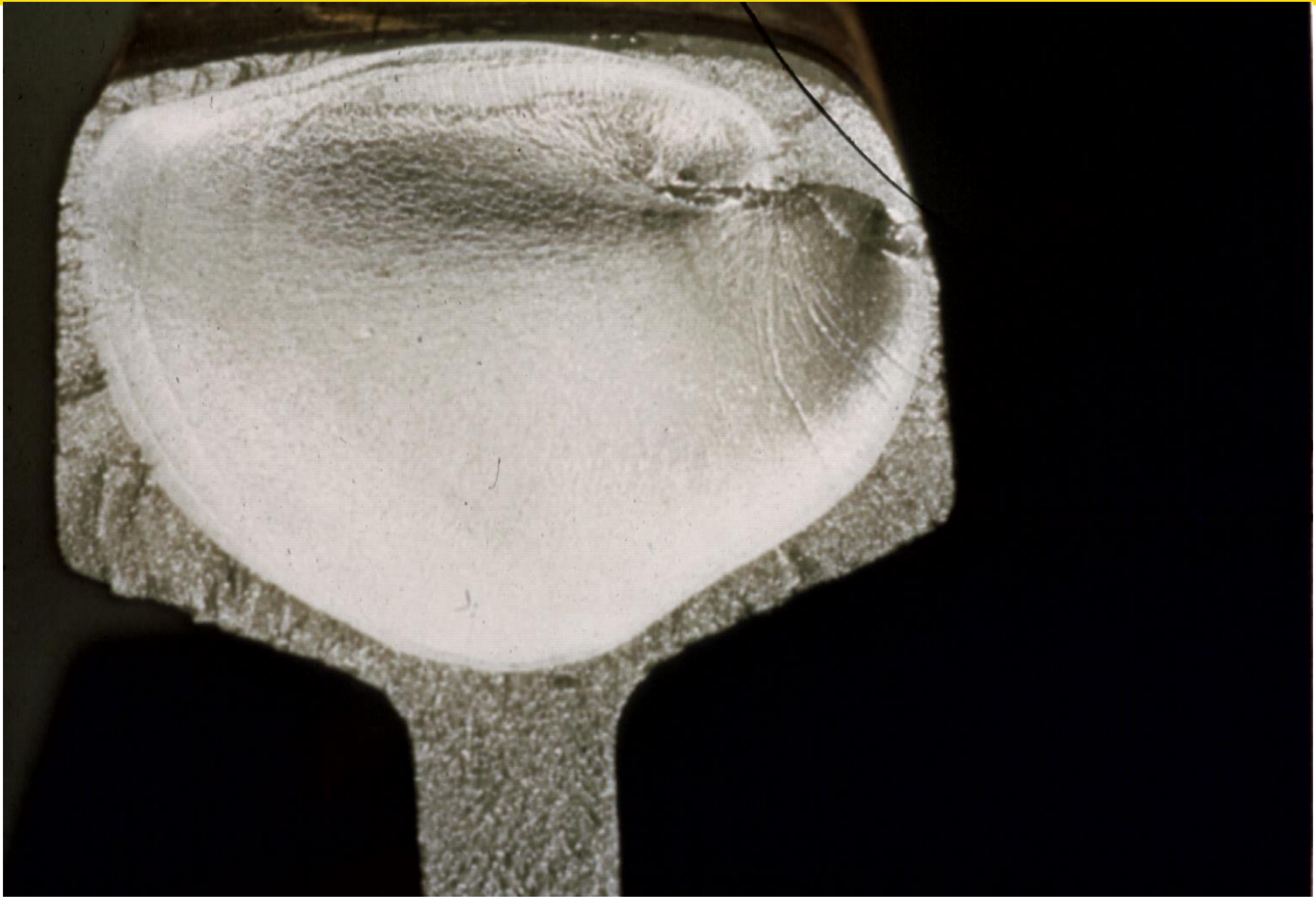
Spalling/Rolling Contact Fatigue

Shelling





Growth of Shell Fracture



Hatfield Derailment

October 2000 at Hatfield UK

- High speed intercity train derailed between London and Leeds
  - 115 mph speed at derailment
- 4 people killed, 70 injured
- Major disruption in Service
  - Major penalties for service disruption
  - UK£ 7 Billion
- Broken Rail Derailment
  - Rolling contact fatigue induced rail defect
  - Improper UT test procedure
  - Missed gauge corner defect
  - Broke under train

Hatfield Derailment

Hatfield Derailment

Derailment Cause

- Rail fractured when train passed over it
- Internal defect present; was not detected by UT testing
- The final proximate cause was "gauge corner cracking“ due to Rolling Contact Fatigue (RCF)

- Due to high contact stresses on the gauge corner of the railhead
  - Fatigue defect which grew with traffic (loading cycles)
  - When reaches critical size, the rail can fracture under a wheel load

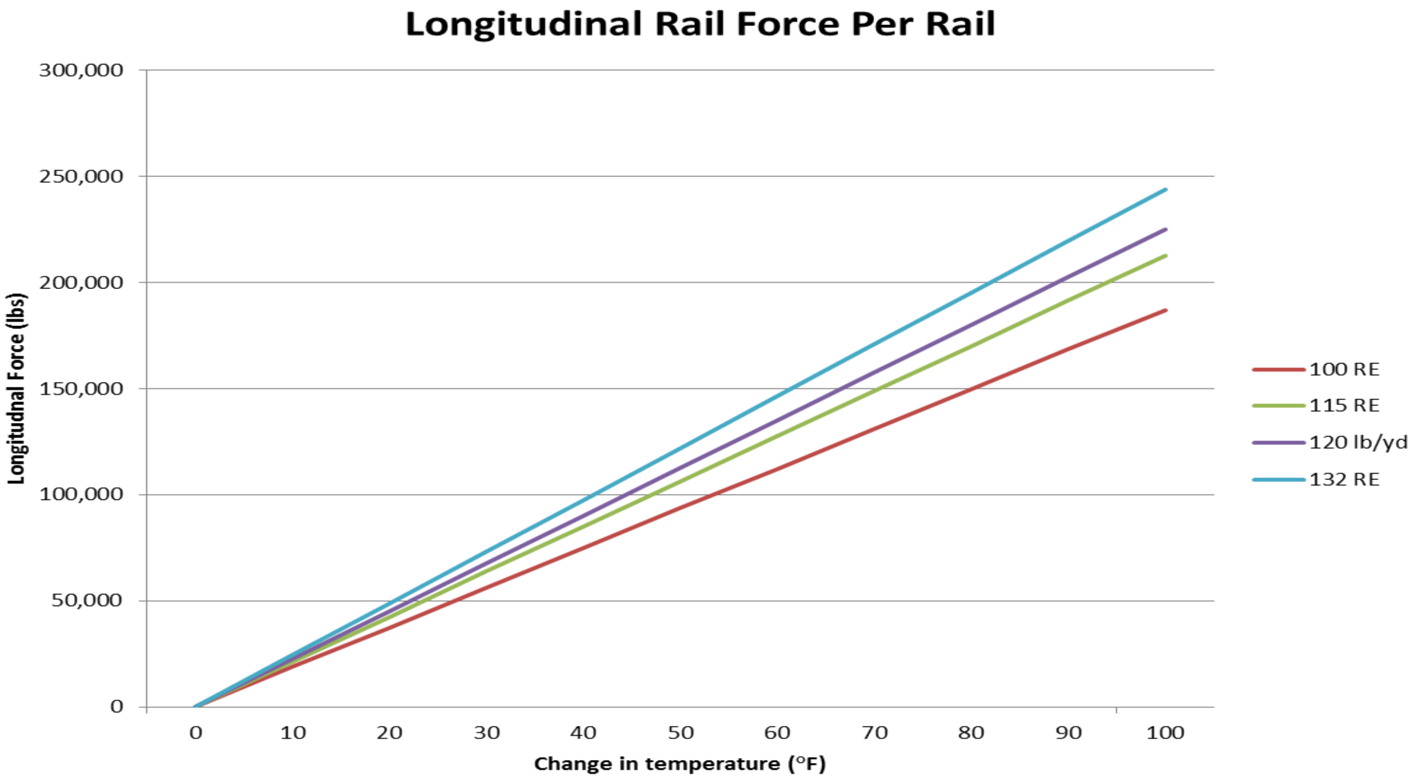
- Hundred of defects found throughout the system when properly tested

Rail Caused Derailments

- Major derailment category
- Approximately 200 rail caused derailments/year in US
  - 10 year average > 300 derailments/year
- Average derailment cost
  - FRA reported of $228,500 per derailment.
  - ‘True” cost of $410,000 per derailment
- Multiple rail failure modes
- Derailment rate of 0.0012 derailments/defect
  - 1 derailment for every 826 defects found

Thermal Loading Related Problems

- Thermally induced longitudinal rail forces due to change in ambient (rail) temperature from “neutral” or “force free” rail temperature
  - High tensile forces can result in rail “pull-aparts”
  - High compressive forces can result in track buckling



Track Stability (Pull-Apart)

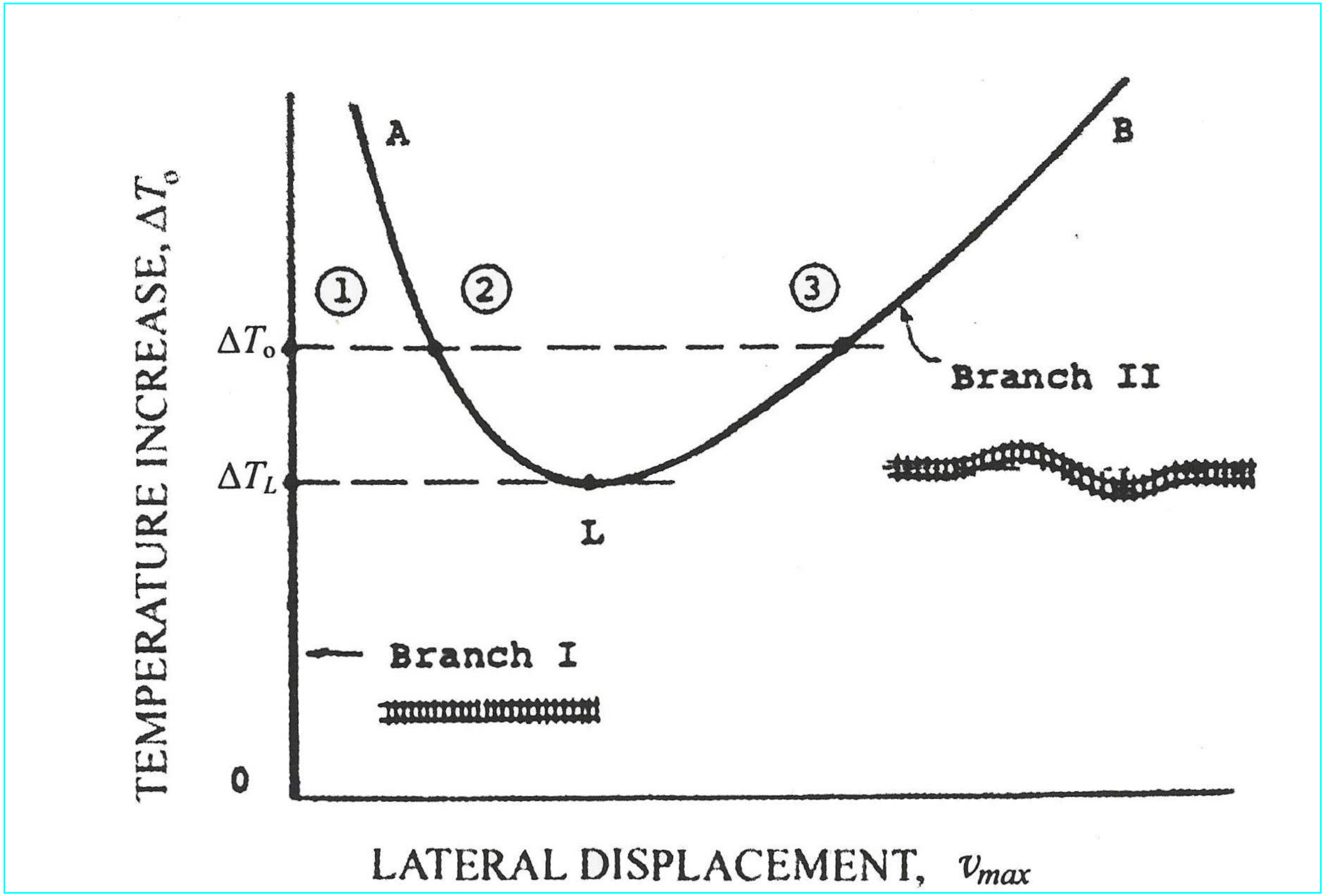
- Under high longitudinal tensile force, railroad rail can pull-apart
  - Forces due to drop in rail temperature from “neutral”
- Rail Stress/Failure Issue
- Factors include:
  - Improper (High) Installation temperature
  - Change in neutral temperature with time and traffic
  - Strength of rail (e.g. internal defect)
  - High impact load (e.g. wheel flat, rail surface defect, frozen track)

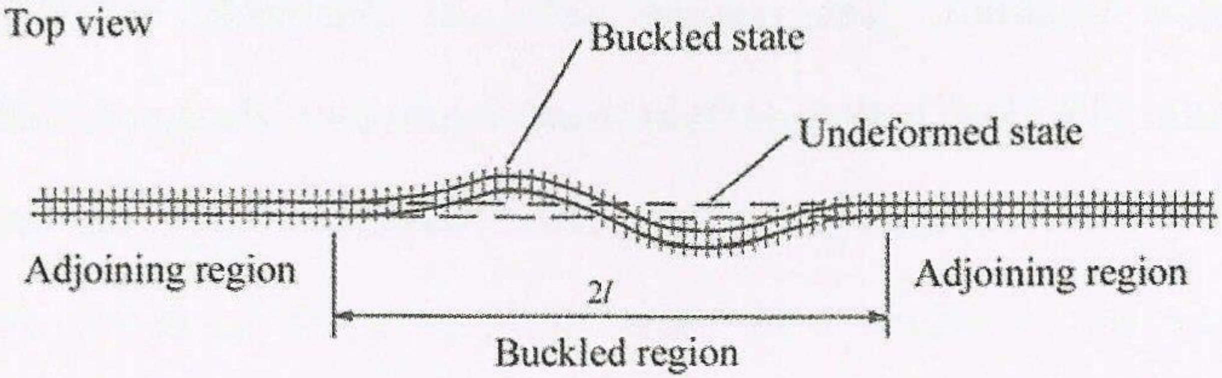
Track Stability (Buckling)

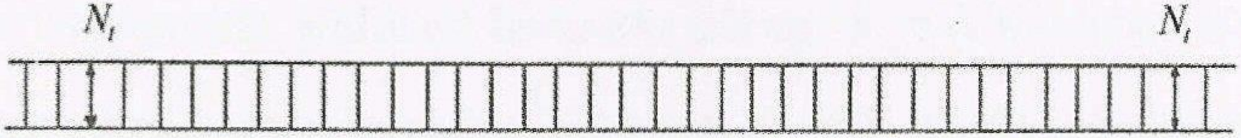
- Under high longitudinal compressive force, railroad track can buckle laterally
    - Forces due to change in rail temperature from “neutral”
- Stability Problem
- Factors include:
    - Improper (Low) Installation temperature
    - Change in neutral temperature with time and traffic
    - Strength of track structure
    - Maintenance practices and activities

Severe Track Buckle

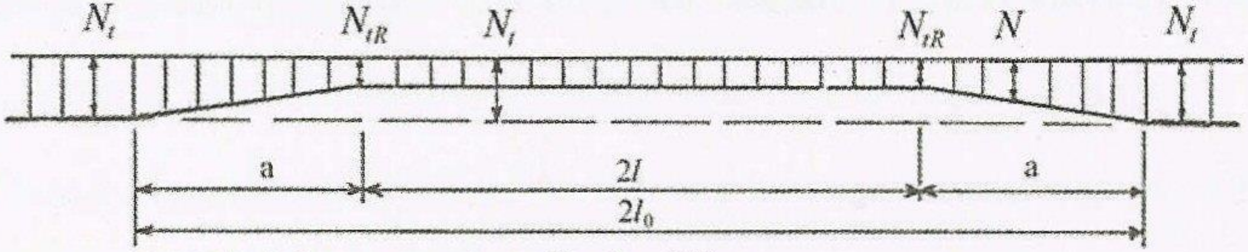
Track Stability (Kerr): Non-Bifurcation Buckling







(a) Axial compression force before buckling

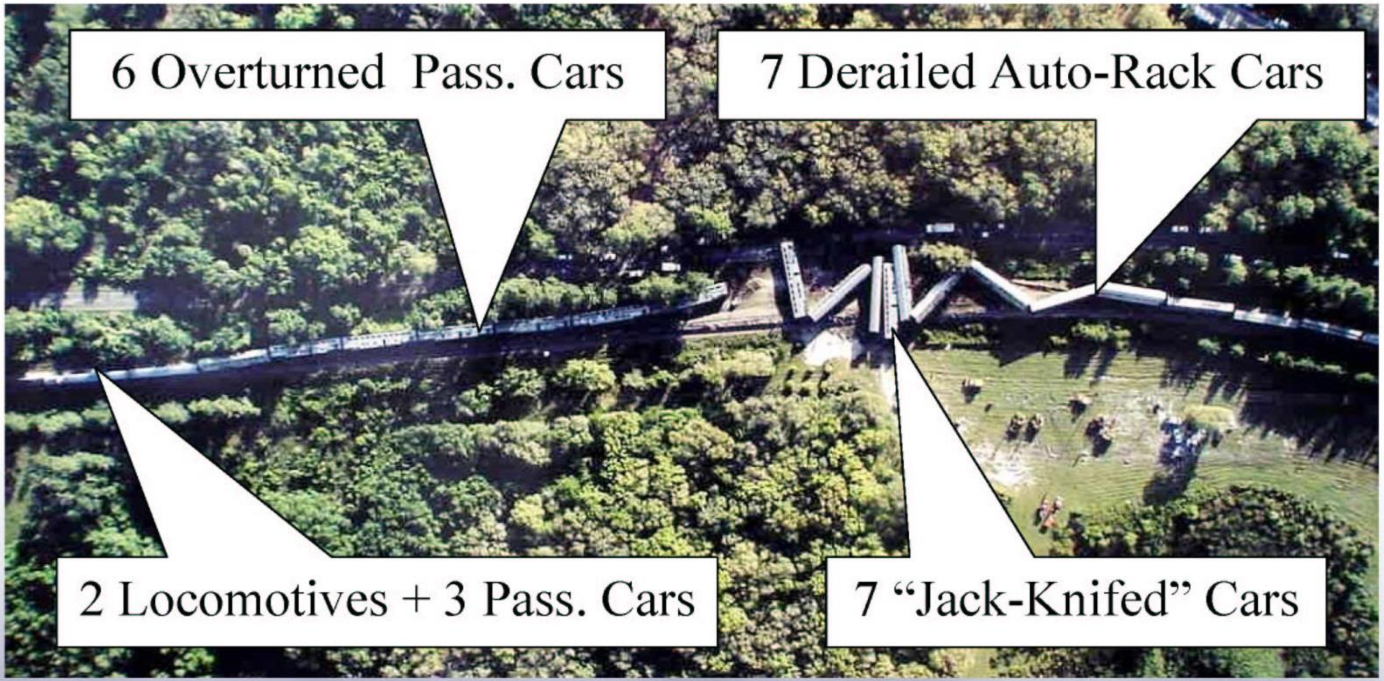


(b) Axial compression after buckling
[Note that in an actual track 'a' is several times larger than l]

Distribution of axial compression forces before and after buckling

Amtrak Derailment on CSX (Florida)

Derailment Configuration



6 Overturned Pass. Cars

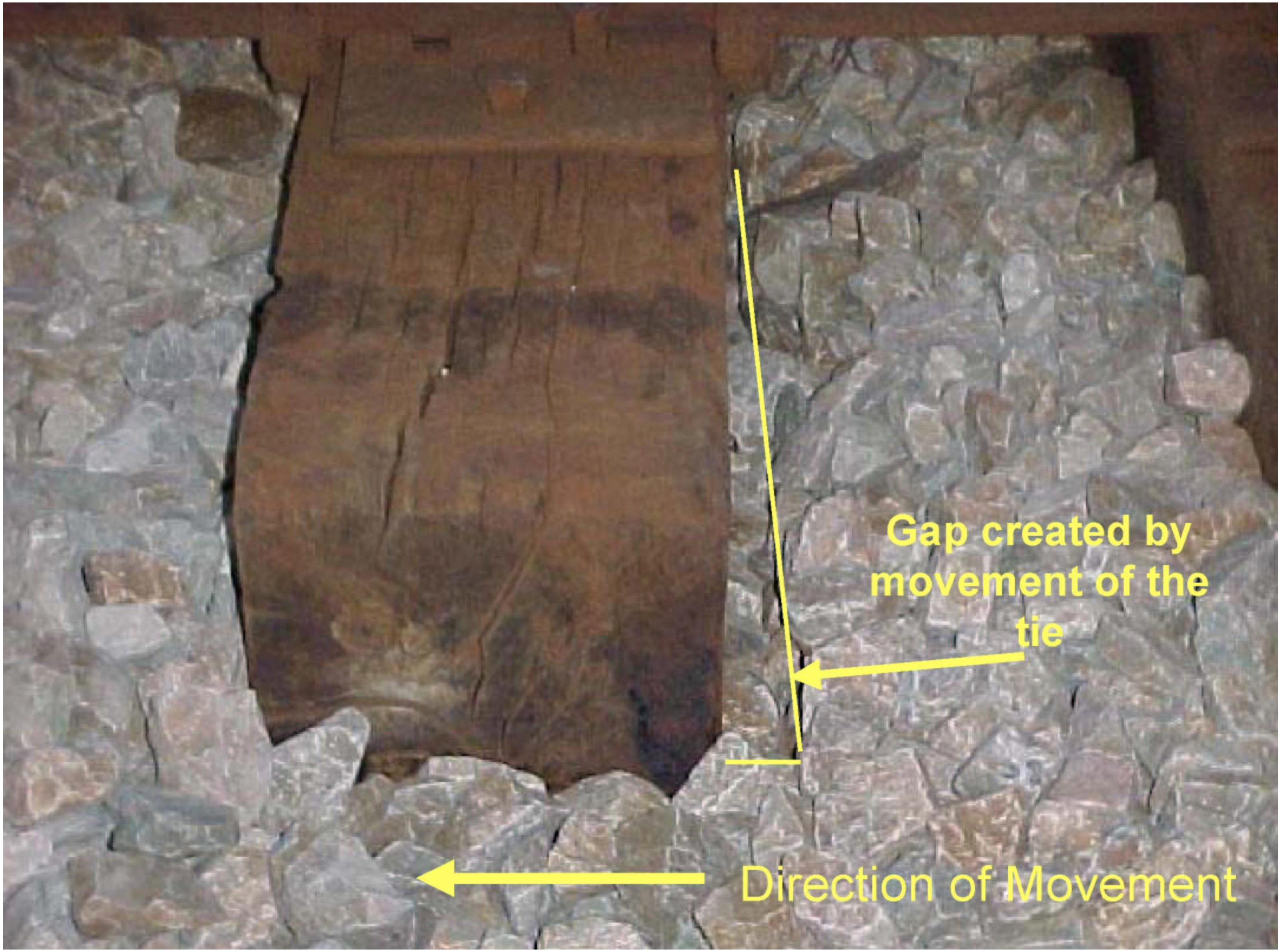
7 Derailed Auto-Rack Cars

2 Locomotives + 3 Pass. Cars

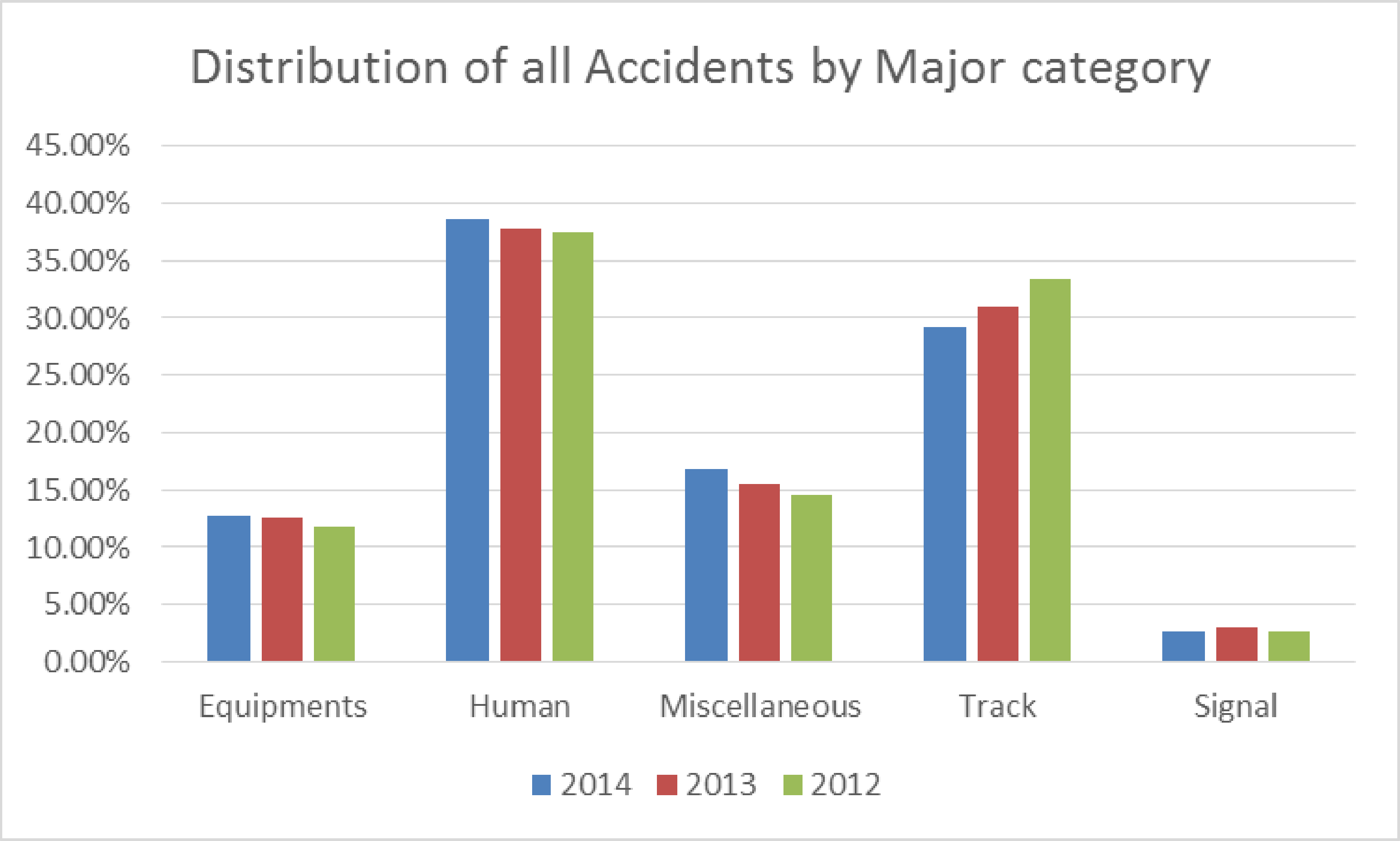
7 "Jack-Knifed" Cars

National Transportation Safety Board

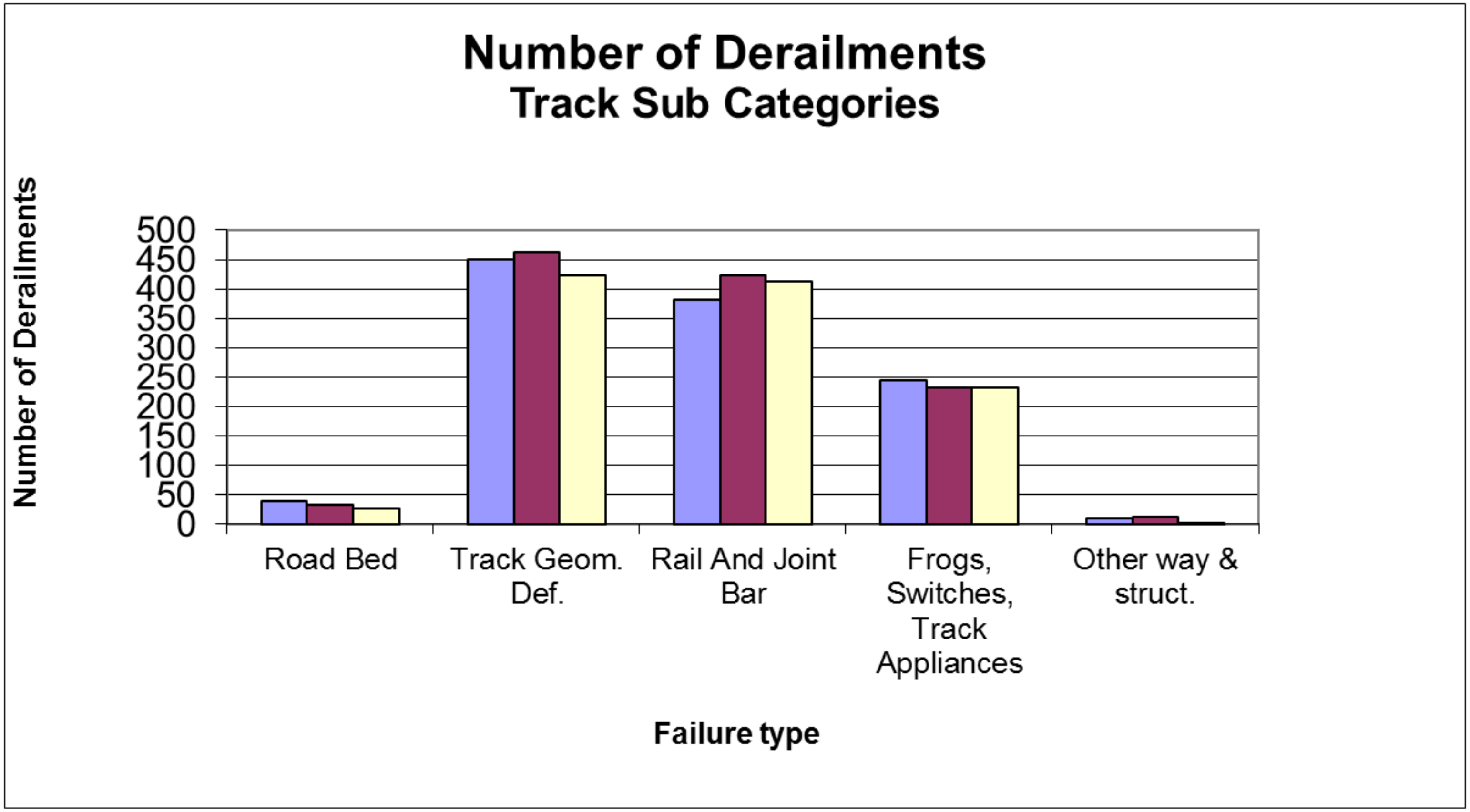
Ballast sloping off the ends of the ties


Gap created by movement of the tie
Direction of Movement

Distribution of All Accidents by Major Category



FRA Reported Derailment Causes



Top 10 FRA Reported Derailments 2005-2010

	Total Cost	Number of Derailments	cost/derailment	derailments/year
Rail defects/failure	$458,514,737	2,006	$228,572	334
Track geometry defects	$281,032,222	2,171	$129,448	362
Wheel failure	$92,680,571	350	$264,802	58
Axle and Bearing Failure	$89,127,954	276	$322,927	46
Frogs, Switches, Track Appliances	$73,836,950	1,087	$67,927	181
Train Handling and Makeup	$70,764,909	656	$107,873	109
General Switching Rules and Switching Operations	$57,549,113	1,209	$47,601	202
Improper Use of Switch	$50,465,185	1,152	$43,807	192
Road Bed Effects	$48,871,637	222	$220,143	37
Speed	$39,060,665	344	$113,548	57

Future of Railroad Engineering

- Factors most likely to influence the development of railroad track engineering
  - Continuing increased axle loads
  - High-speed passenger operations
  - Economics
- Track structure will continue to evolve with focus on “weak spots” that fail under traffic
- Potential for development of new improved track systems
  - Development of improved components and or materials
- Growth in high speed passenger operations and increasing axle load freight
  - 315,000 lb cars (39 ton axle loads)