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
<table>
<thead>
<tr>
<th>Axle Load</th>
<th>Gross Weight of Cars</th>
<th>Traffic Type</th>
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<tbody>
<tr>
<td>Tonnes</td>
<td>Tons</td>
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<tr>
<td>8</td>
<td>8.8</td>
<td>32,000</td>
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<tr>
<td>12</td>
<td>13.2</td>
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<tr>
<td>17</td>
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<td>22.5</td>
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<td>90,000</td>
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<td>25</td>
<td>27.5</td>
<td>100,000</td>
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<tr>
<td>30</td>
<td>33</td>
<td>120,000</td>
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<td>36</td>
<td>130,000</td>
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<tr>
<td>35.5</td>
<td>39</td>
<td>142,000</td>
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<table>
<thead>
<tr>
<th>Traffic Type</th>
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<tbody>
<tr>
<td>Light Rail Transit</td>
</tr>
<tr>
<td>Heavy Rail Transit</td>
</tr>
<tr>
<td>Passenger</td>
</tr>
<tr>
<td>Common European Freight Limit</td>
</tr>
<tr>
<td>UK+Select European Freight</td>
</tr>
<tr>
<td>BV (Sweden) limit on Ore Line</td>
</tr>
<tr>
<td>North America Free Interchange</td>
</tr>
<tr>
<td>Australia Iron Ore Lines +</td>
</tr>
<tr>
<td>Very limited use in US</td>
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</table>
Heavy Axle Load Freight Train
## Operating Speed Ranges

<table>
<thead>
<tr>
<th>Speed (Kph)</th>
<th>Speed (Mph)</th>
<th>Traffic Type</th>
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</thead>
<tbody>
<tr>
<td>80</td>
<td>50</td>
<td>Transit</td>
</tr>
<tr>
<td>75</td>
<td>45</td>
<td>Heavy Axle Freight</td>
</tr>
<tr>
<td>100</td>
<td>60</td>
<td>Conventional Freight</td>
</tr>
<tr>
<td>130</td>
<td>80</td>
<td>Intermodal and High Speed Freight</td>
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<tr>
<td>150</td>
<td>90</td>
<td>Inter-urban Passenger and Commuter</td>
</tr>
<tr>
<td>210</td>
<td>125</td>
<td>Higher Speed Rail</td>
</tr>
<tr>
<td>300</td>
<td>180+</td>
<td>High Speed Rail</td>
</tr>
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</table>
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)

DOTTED LINE—WITHOUT LATERAL AXLE FREEDOM
SOLID LINE—WITH LIMITED LATERAL AXLE FREEDOM

ANGLE OF ATTACK

DIRECTION OF TRAVEL
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 freight 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

<table>
<thead>
<tr>
<th>Curvature Elevation</th>
<th>Maximum Speed (mph)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 degree (5730'radius)</td>
<td>6”</td>
</tr>
<tr>
<td>2</td>
<td>120</td>
</tr>
<tr>
<td>3</td>
<td>85</td>
</tr>
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<td>4</td>
<td>69</td>
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<td>5</td>
<td>60</td>
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<tr>
<td>6</td>
<td>53</td>
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<tr>
<td></td>
<td>49</td>
</tr>
</tbody>
</table>
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

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

**Contact stresses**

\[ \sigma_c \]
caused by wheel loads, static or dynamic

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They affect:

1. Rail wear
2. Rail fatigue and shelling
3. Formation of plastic zone in contact region and rail corrugations

**Bending stress**

\[ \sigma_b \]
caused by wheel loads and by nonuniform temperature changes

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They affect:

1. Selection of rail size
2. Rail section at poorly maintained joint, which may plastically deform (Fig. IV.15)

**Axial stress**

\[ \sigma_o \]
caused by uniform temperature changes, by acceleration or deceleration of trains and by rail creep

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They affect:

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

Point of Contact On Flange

Angle \( \beta \)
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
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

- Rupture
- Direction of travel
- Direction of slip
- Extent of plastic flow
- Crevice
- Fatigue cracks
- Subsurface fatigue cracks
- Gauge side
Spalling/Rolling Contact Fatigue
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
Distribution of axial compression forces before and after 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]
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
Distribution of All Accidents by Major Category

Distribution of all Accidents by Major category

- Equipments
- Human
- Miscellaneous
- Track
- Signal

FRA Reported Derailment Causes

Number of Derailments
Track Sub Categories

- Road Bed
- Track Geom. Def.
- Rail And Joint Bar
- Frogs, Switches, Track Appliances
- Other way & struct.

Failure type

Number of Derailments
## Top 10 FRA Reported Derailments 2005-2010

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