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!

Sponsored by
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
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

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

<table>
<thead>
<tr>
<th>Speed (Kph)</th>
<th>Speed (Mph)</th>
<th>Traffic Type</th>
</tr>
</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>
</tr>
<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>
</tbody>
</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&quot;</td>
</tr>
<tr>
<td>120</td>
<td>107</td>
</tr>
<tr>
<td>2</td>
<td>85</td>
</tr>
<tr>
<td>3</td>
<td>69</td>
</tr>
<tr>
<td>4</td>
<td>60</td>
</tr>
<tr>
<td>5</td>
<td>53</td>
</tr>
<tr>
<td>6</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

Fig. IV.52. Stresses in rail

Contact stresses

$\sigma_c$
caused by
wheel loads,
static or
dynamic

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

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

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 Contact Points

A
B

High Contact Stresses

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
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

![Graph showing the relationship between temperature increase and lateral displacement.](image)
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
FRA Reported Derailment Causes

Number of Derailments
Track Sub Categories

<table>
<thead>
<tr>
<th>Failure type</th>
<th>Number of Derailments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Road Bed</td>
<td>50</td>
</tr>
<tr>
<td>Track Geom. Def.</td>
<td>450</td>
</tr>
<tr>
<td>Rail And Joint Bar</td>
<td>350</td>
</tr>
<tr>
<td>Frogs, Switches, Track Appliances</td>
<td>250</td>
</tr>
<tr>
<td>Other way &amp; struct.</td>
<td>50</td>
</tr>
</tbody>
</table>

UNIVERSITY of DELAWARE
## Top 10 FRA Reported Derailments 2005-2010

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