BCR2A'09
Railroad Track Design
Including Asphalt Trackbeds
Pre-Conference Workshop

Introduction to Railroad Track Structural Design

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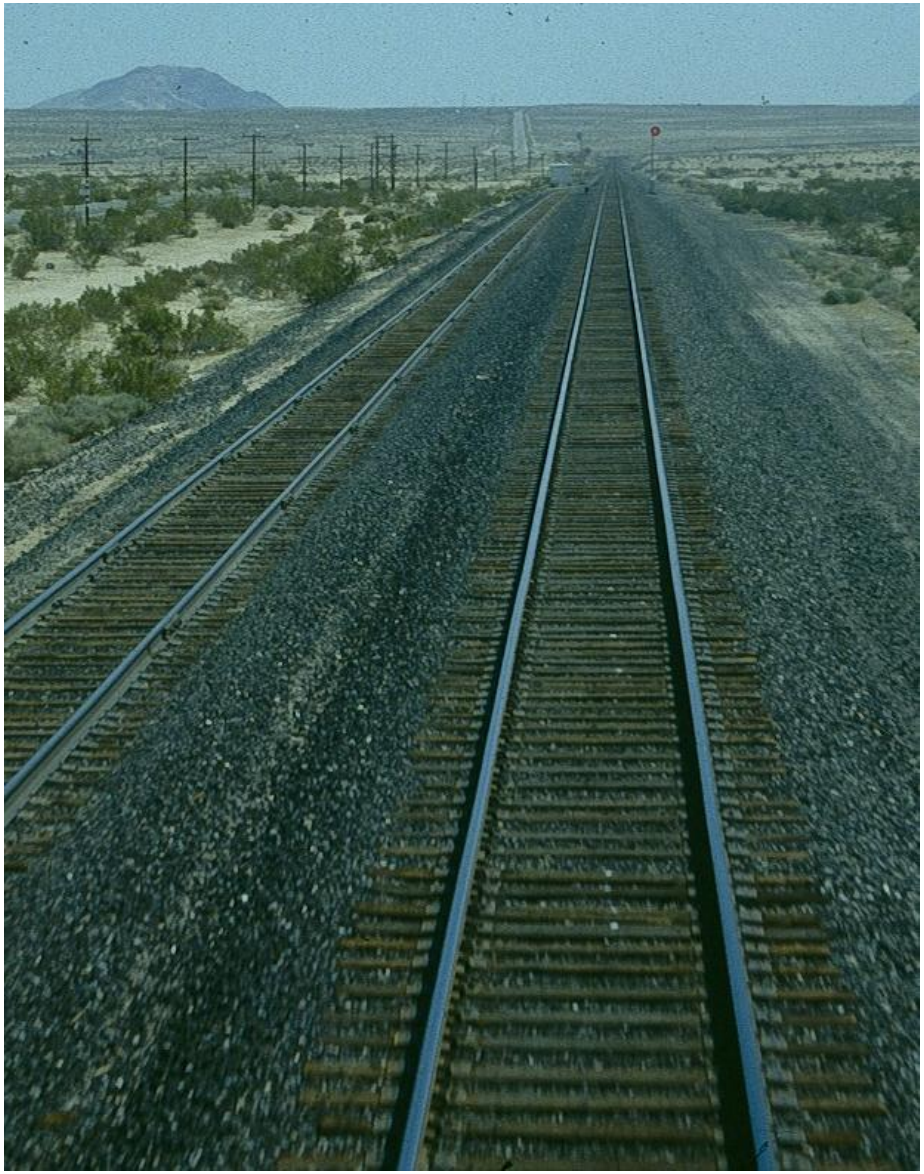


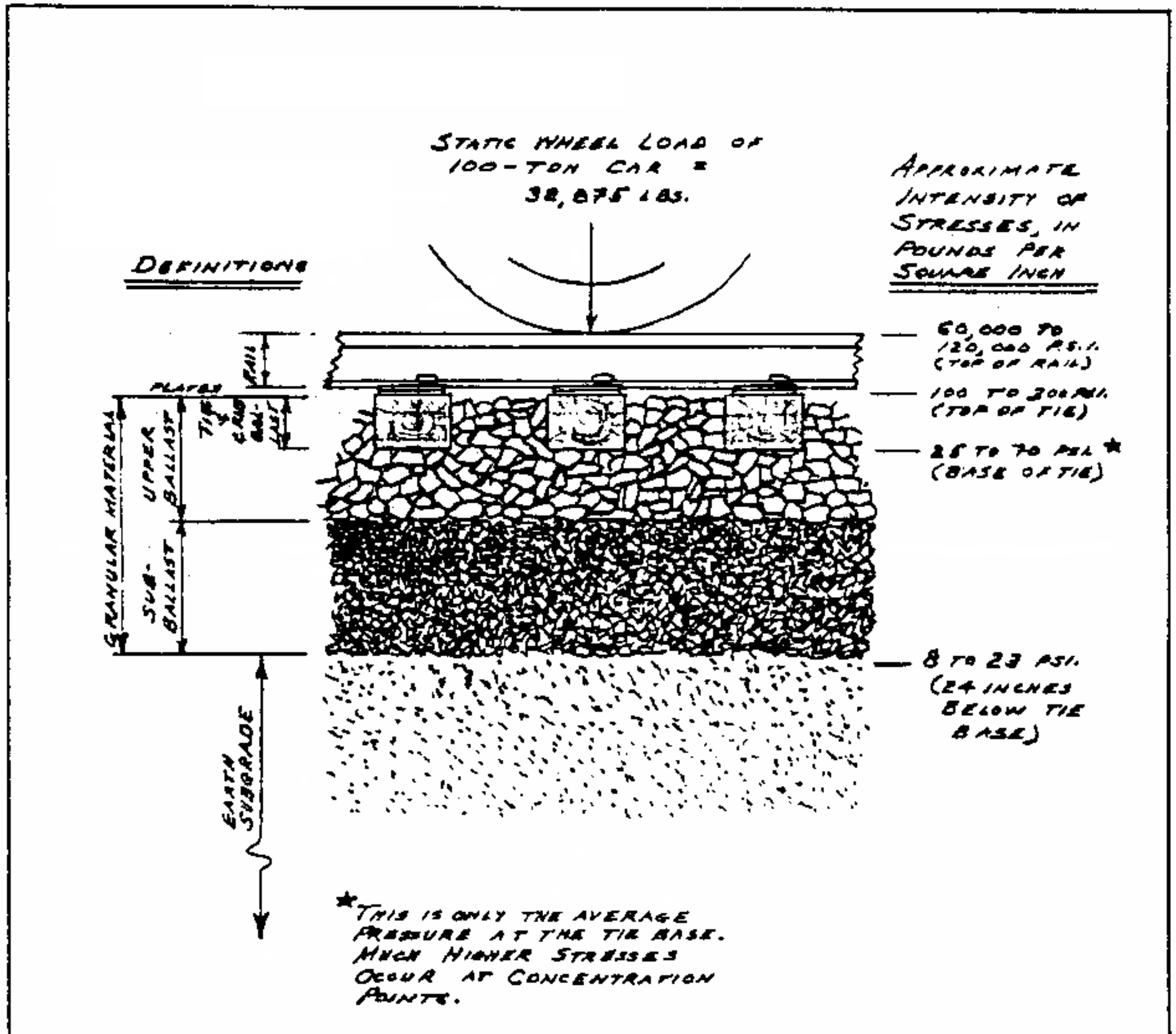
ILLINOIS
Railroad Engineering Program

Interaction, Vertical Load Distribution, and Deflections

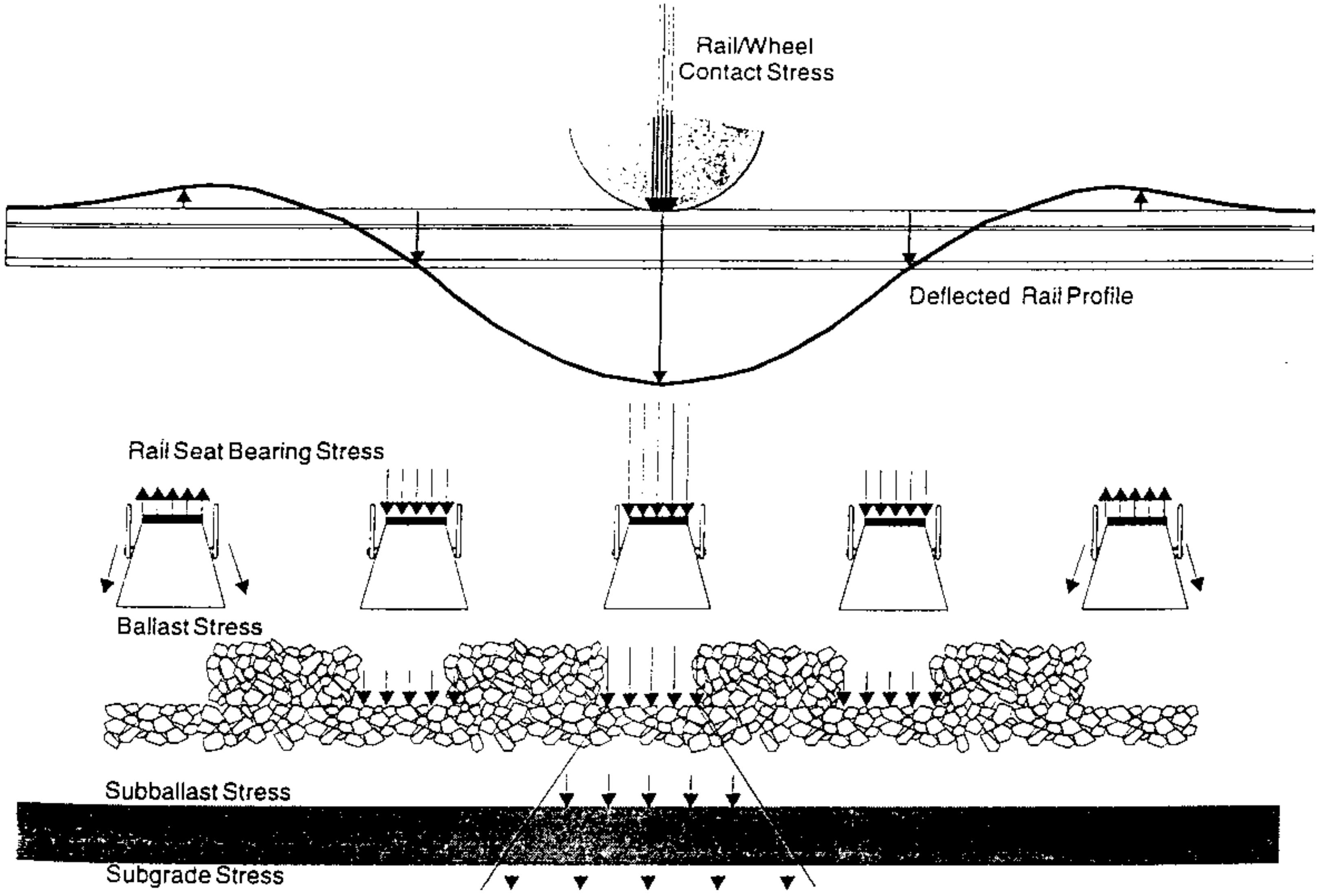
Stress Distribution

Components do not function independently!

Each component layer must protect the one below.



Deflection Profile



Source: Selig and Waters, Track Geotechnology and Substructure Management, 1994

Static vs. Dynamic Loads

- Dynamic loads higher
  - Acceleration from speed
  - Downward rotation of wheel
  - Smaller wheels, faster rotation, more acceleration
- Speed/wheel influence
  - $P_v = P + \theta P$ (AREMA)

    where P_v = Vertical Dynamic Load (lbs)

    $$\theta = \frac{D_{33} \times V}{D_w \times 100}$$

    D = Wheel diameter (in)

    V = Speed (MPH)

    P = Static Load (lbs)
  - Larger wheels impose less influence
- Additional dynamic loads from impacts such as caused by wheel flat spots, rail discontinuities (e.g. frog flangeways), track transitions (e.g. bridge approaches), track condition, etc.

Different Wheel Diameters

Track Stiffness

- Rail is assumed to be a beam on an elastic foundation
- Modulus of Track Elasticity, u (or k)
  (a.k.a. Track Modulus)

$$u = P/\Delta$$

where u = Modulus of Track Elasticity (lbs/in/in)

P = Wheel load per unit length of rail (lbs/in)

Δ = Unit of Track Deflection (in), less "play" or track "looseness"

or

$$u = P/S$$

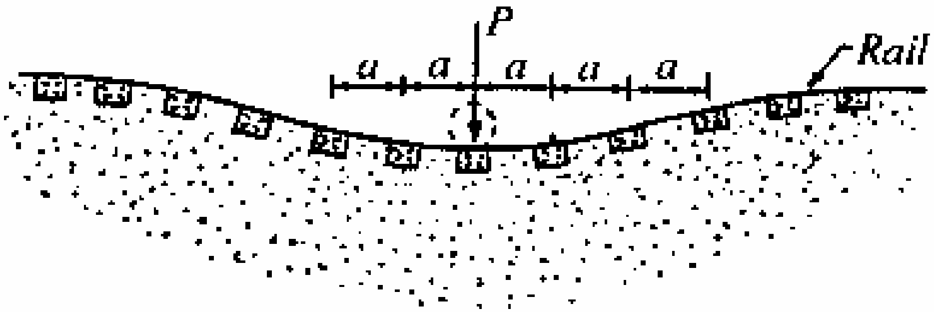
where u = Modulus of Track Elasticity (lb/in/in)

P = Wheel load (lbs) required to deflect the track 1 inch on one tie

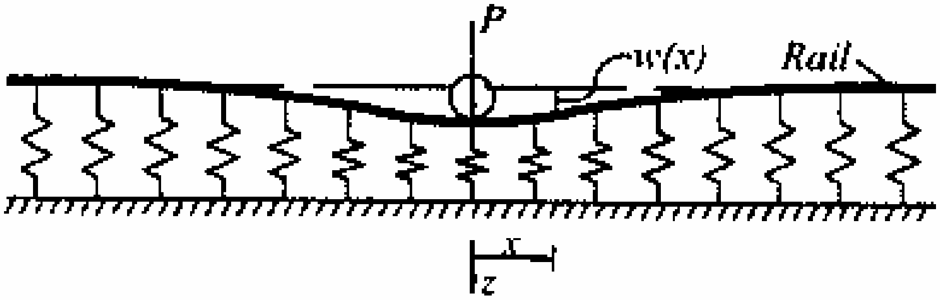
S = Tie spacing (in)

Classic Approach to Track Analysis and Design

- Continuously supported beam



(a) Physical problem



(b) Analytical model for rail analysis

Notes:
a = tie spacing "s"
w(x) = deflection "y"

Source: Kerr, A.D., Fundamentals of Railway Track Engineering, 2003

- Talbot equations

Rail Moment: $M_o = 0.318Px_1$

Deflection: $Y_o = 0.391P/ux_1$

Rail Seat Load: $Q_o = 0.391PS/x_1$ (Note: Q_o a.k.a. F_{max})

where: P = Wheel Load (lbs)

u = Track Modulus (lbs/in/in)

S = Tie spacing (in)

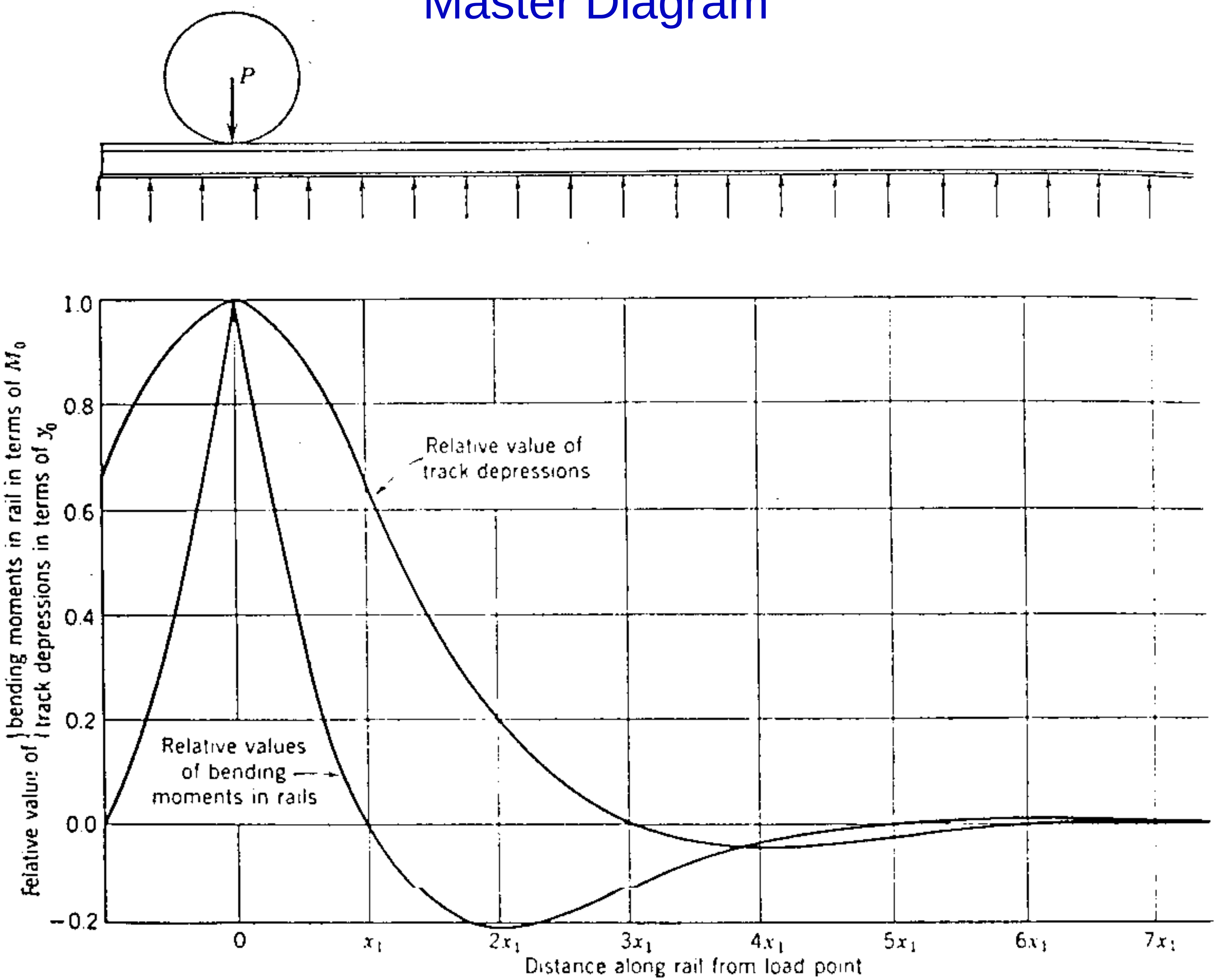
$x_1 = (\pi/4)(4EI/u)^{1/4}$ (in)

EI = Flexural rigidity of rail

with: E = Modulus of Elasticity of Rail (30×10^6 psi)

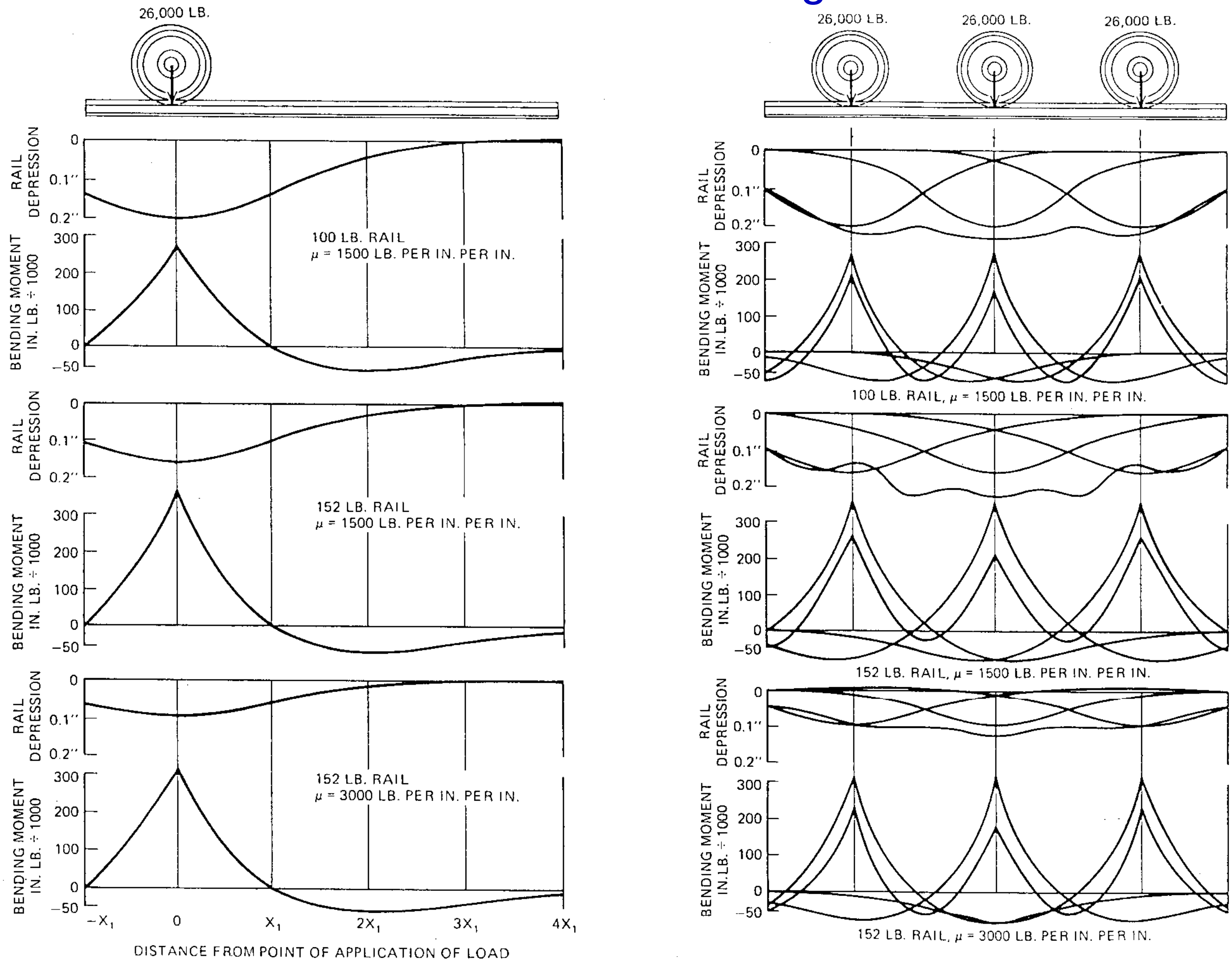
I = Rail Moment of Inertia (in^4)

Master Diagram



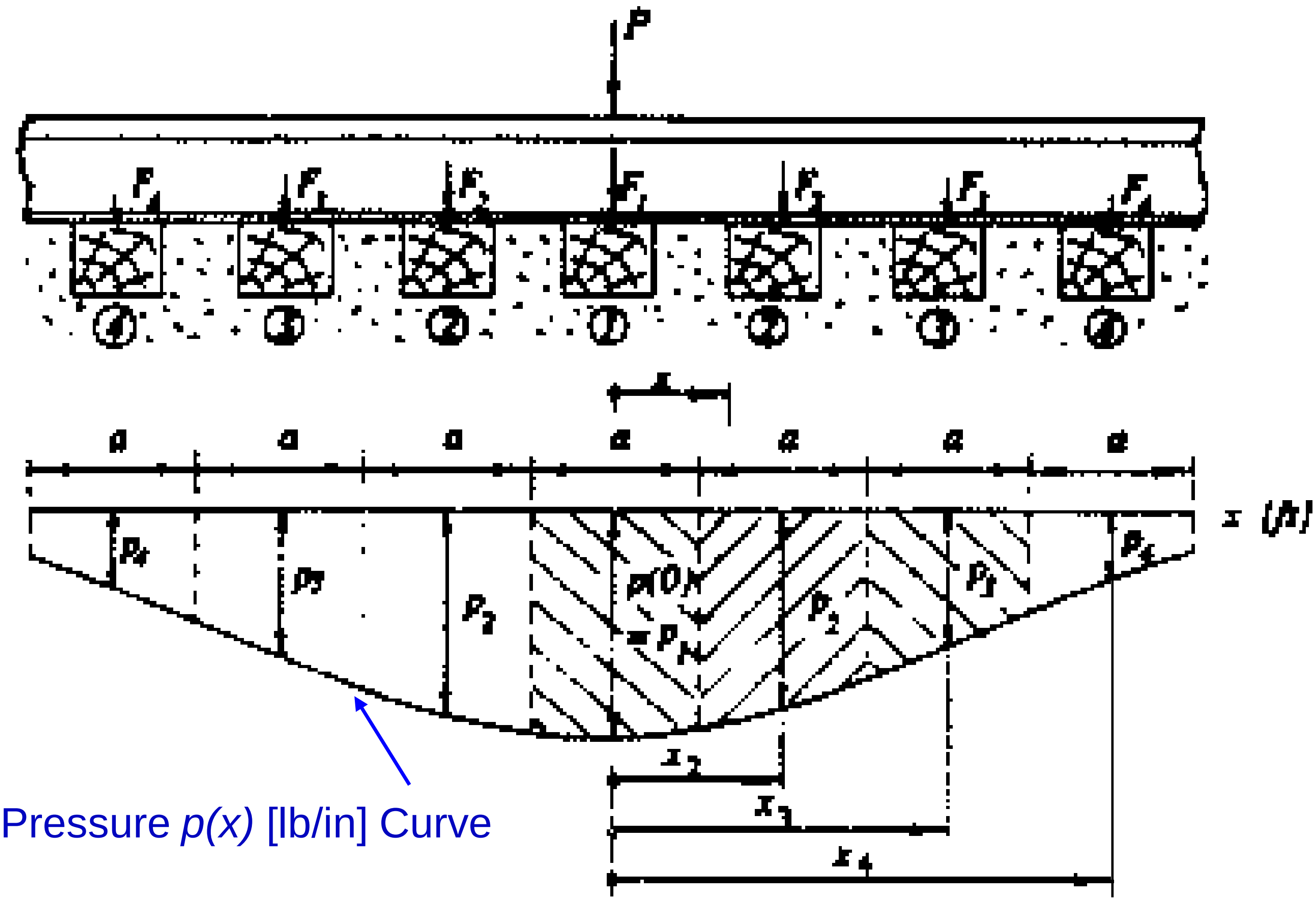
Source: Hay, W.W., Railroad Engineering, 1982

Load Deflections and Bending Moments



Source: Hay, W.W., Railroad Engineering, 1982

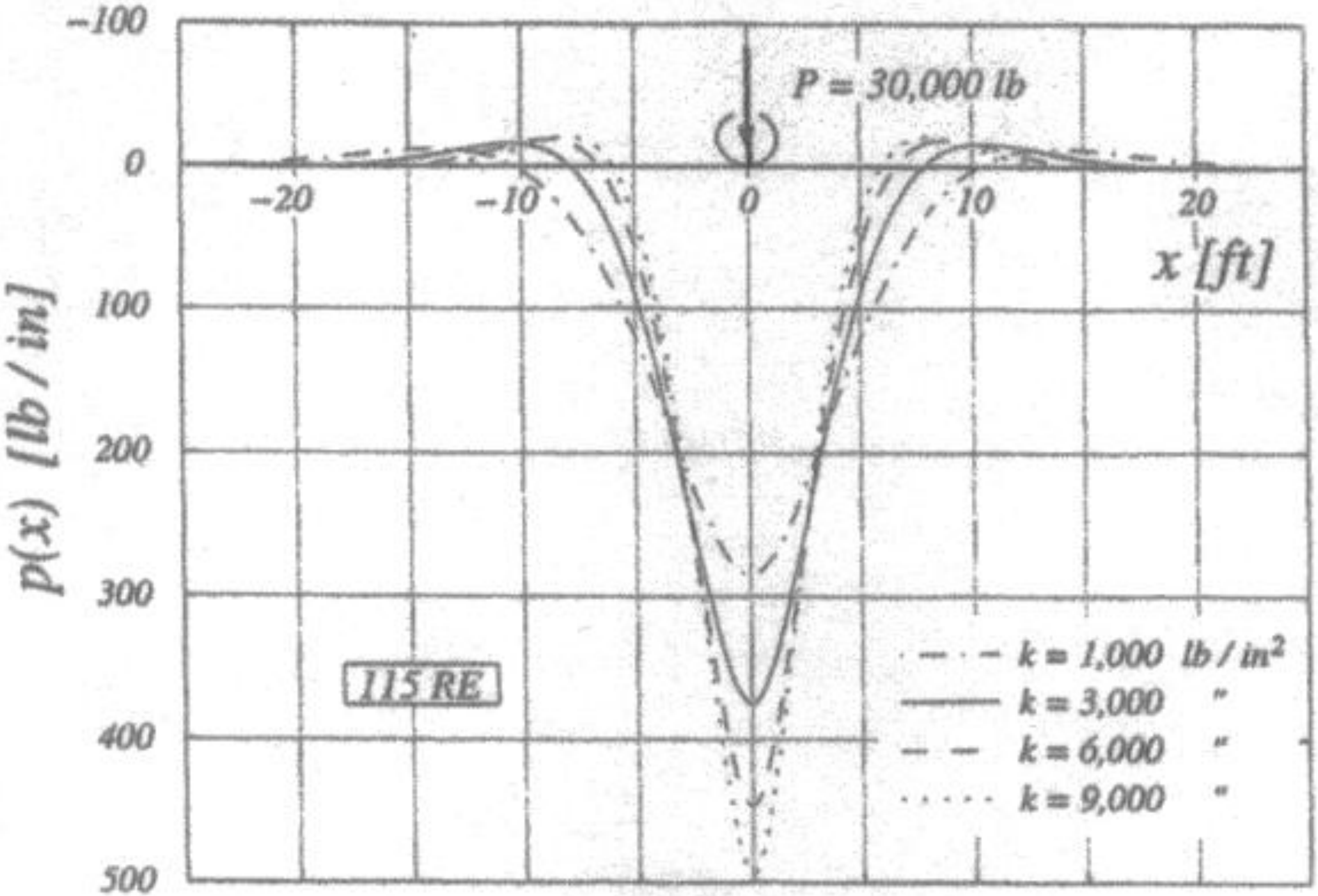
Determination of Rail Seat Forces (Q or F)



Pressure *p(x)* [lb/in] Curve

Source: Kerr, A.D., Fundamentals of Railway Track Engineering, 2003

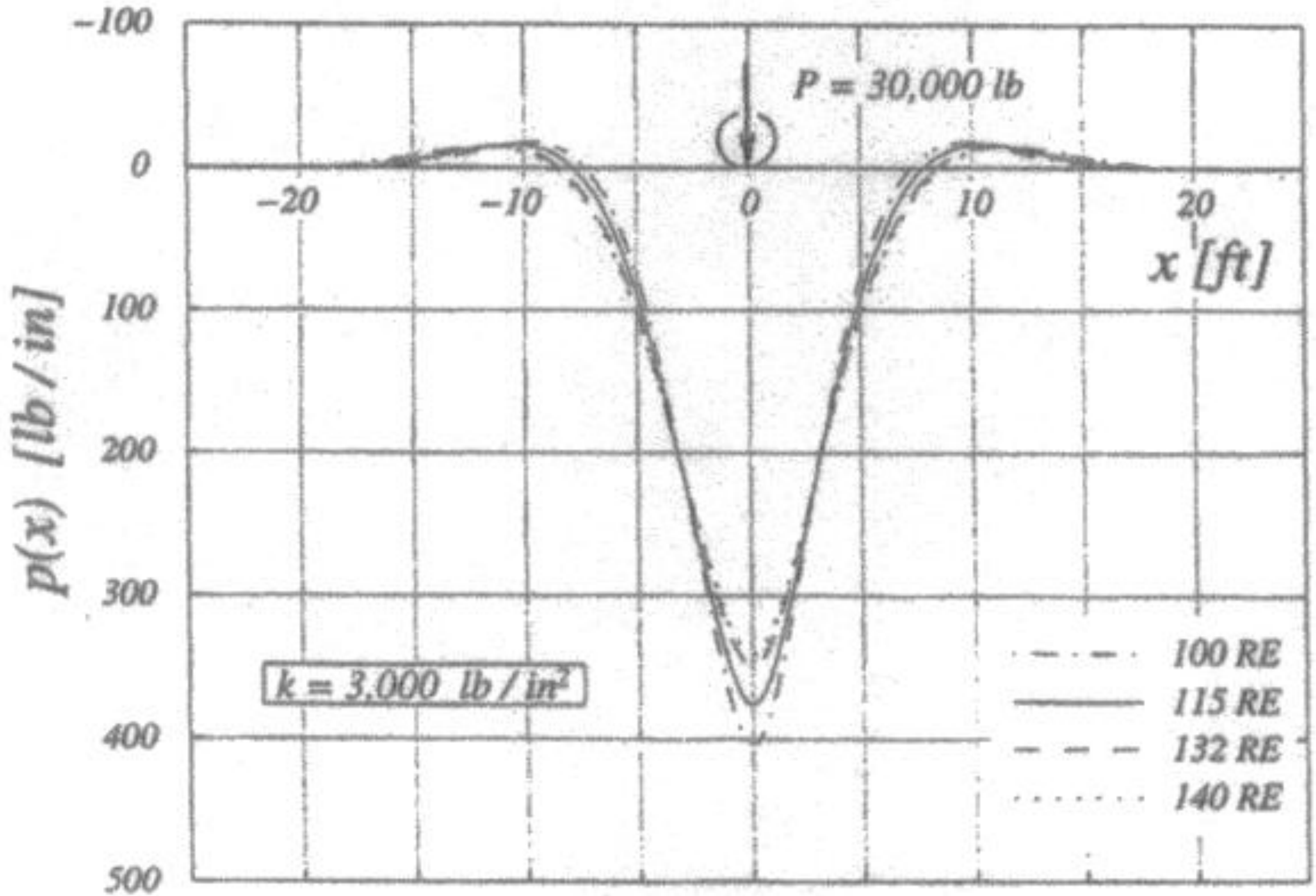
Pressure Distribution vs. Track Modulus



Pressure distribution for 115 RE rail and various *k*-values

Source: Kerr, A.D., Fundamentals of Railway Track Engineering, 2003

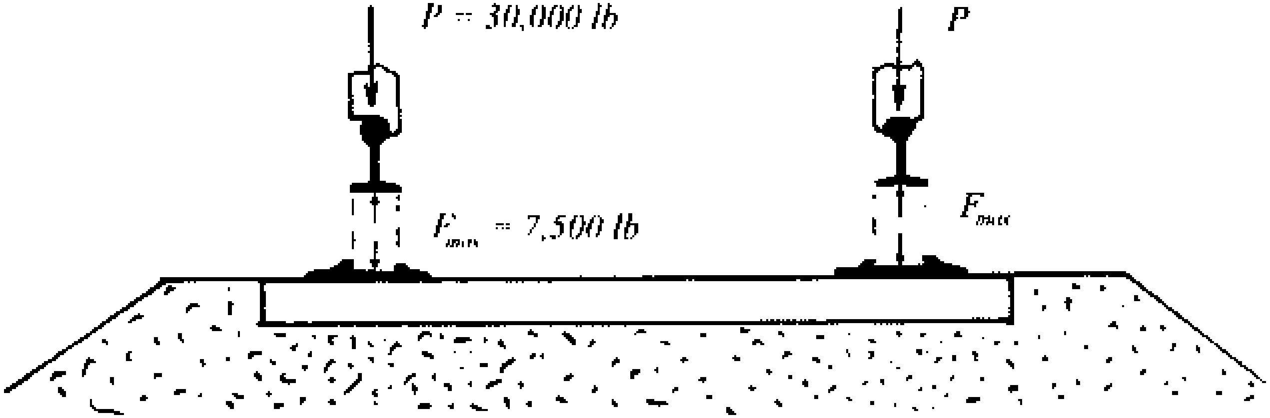
Pressure Distribution vs. Rail Weight



Pressure distribution for various rails and $k = 3{,}000\ lb/in^2$

Source: Kerr, A.D., Fundamentals of Railway Track Engineering, 2003

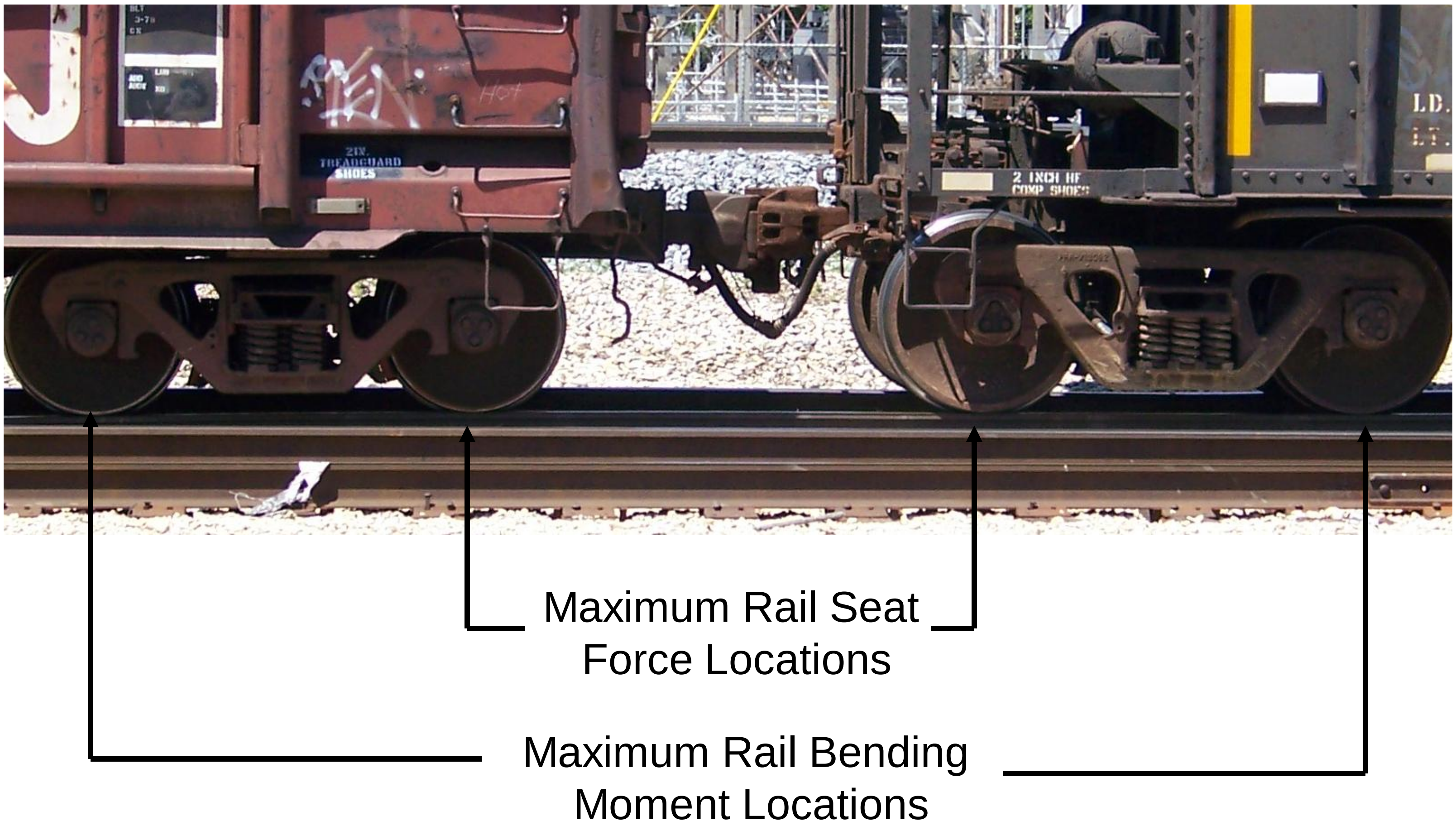
Relationship Between F_{max} (Q_o) and P



132 RE rail				
k [lb/in^2]	1,000	3,000	6,000	9,000
F_{max} [lb]	5,264	6,928	8,239	9,118
F_{max} in % of P	17.5	23.1	27.5	30.4

Source: Kerr, A.D., Fundamentals of Railway Track Engineering, 2003

Maximum Rail Moment and Rail Seat Force Locations



Design Steps (AREMA, U.S. DoD, and Others)
(Generalized)

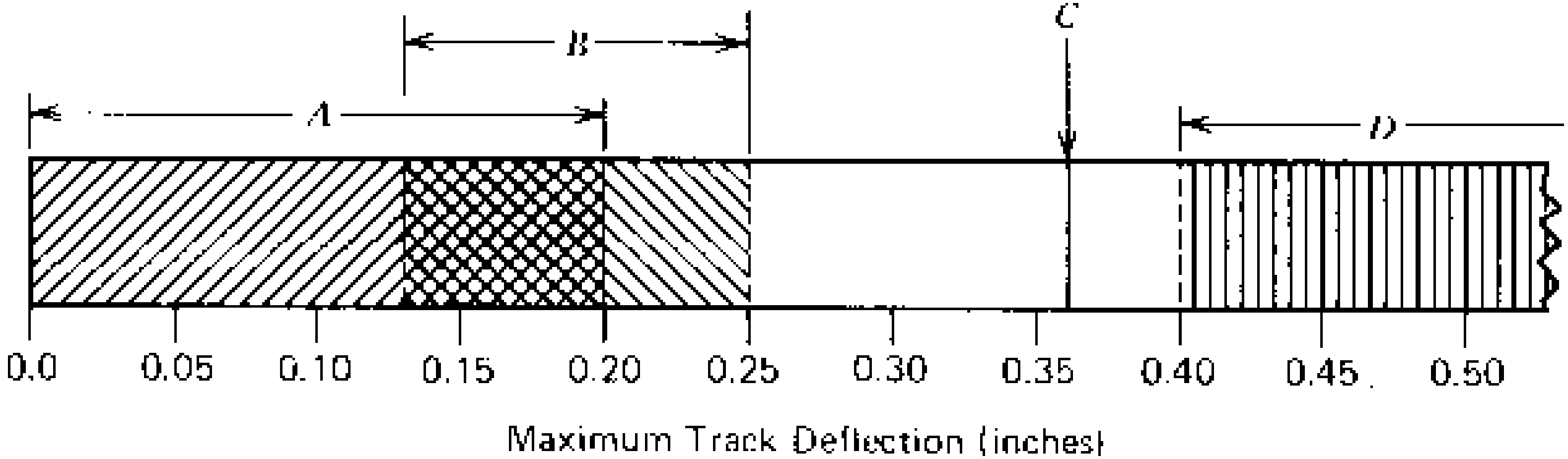
1. Select design wheel load based on most common, heaviest car and desired track speed. Consider all wheels in a truck and proximity of adjacent cars.
2. Select a Track Modulus, u or k, based on desired design deflection
3. Select rail size and section
4. Determine moment and loading coefficients
5. Check rail bending stress
6. Choose trial tie spacing and calculate maximum rail seat load

Design Steps (con't)

7. Select tie size
8. Check tie bending stress
9. Determine and select plate size based on minimum area
10. Determine ballast surface stress
11. Determine ballast depth based on allowable subgrade stress
12. Calculate track deflection under load and check on acceptability
13. If deflection is unacceptable, re-do design

Always consider economics!

Track Deflection vs. Track Performance



Range	Track Behavior
A	Deflection range for track that will last indefinitely
B	Normal maximum desirable deflection for heavy track to give requisite combination of flexibility and stiffness
C	Limit of desirable deflection for track of light construction (≤100 lb)
D	Weak or poorly maintained track that will deteriorate quickly

Source: Hay, W.W., Railroad Engineering, 1982

Track Modulus, u or k, Typical Values

- Well maintained wood tie track, ≈3000 lb/in/in
- Concrete tie track, ≈6000 lb/in/in
- Wood tie track after tamping, ≈1000 lb/in/in
- Wood tie track with frozen ballast/subgrade, ≈9000 lb/in/in
- Track on Ballasted Concrete Bridge Deck, ≈8000 to 12000 lb/in/in

Modulus higher during excessively dry periods and lower when subgrade at or near saturation.

Rail Analysis and Design
(weight and section selection)

- Many rail weights and sections have evolved by the efforts of various designers
  - American Railway Association (ARA) forerunner to Association of American Railroads (AAR) {branded RA or RB on rail}
  - American Society of Civil Engineers (ASCE) {branded AS}
  - American Railway Engineering and Maintenance of Way Association (AREMA) (formerly American Railway Engineering Association (AREA)) {branded RE}
  - International Union of Railways {branded UIC}
  - Railroads (many designations)

    Note: Sometimes numbers, not letters, are used to denote sections. Depends on manufacturer.

- Bending stress

  $S = M_o c/I$ or $S = M_o/Z$

  where S = Bending stress, psi

  M_o = Max bending moment, in-lbs

  c = Distance to base from neutral axis, in

  I = Moment of inertia of rail, in^4

  Z = Section modulus, I/c (properties of rail section)

- Allowable bending stress, typically is:
  - 32,000 psi for jointed rail
  - 25,000 psi for continuously welded rail (CWR)

- Maximum bending moment, M_o

  $M_o = P(EI/64u)^{1/4}$ ($M_o = 0.318Px_1$)

  where M_o = Max bending moment

  P = Max wheel load, lbs (static or dynamic)

  E = Modulus of elasticity = 30×10^6 psi

  I = Moment of inertia, in^4

  u = track modulus, lbs/in/in

  Note: Must account for moments from adjacent wheels. Compute from Master Diagram, computer code, or EXCEL.

- I and c are a function of design
  - Greater weight - greater I
  - Increase height - greater I (limiting factor is web height - thickness ratio)
- Must keep maximum bending stress less than or equal to allowable bending stress

TABLE 24.3 Properties of Typical Rail Sections

Section	Weight per Yard (lb)	Moment of Inertia	Base to Neutral Axis (in.)	Section Modulus (Base)	Area (sq in.)	Height (in.)	Base Width (in.)	Head Width (in.)	Head Radius (in.)
133 RE	133.4	86.0	3.20	27.0	13.08	$7\frac{1}{16}$	6	3	10
132 RE	132.1	88.2	3.20	27.6	12.95	$7\frac{1}{8}$	6	3	10
131 RE	131.2	89.0	3.20	27.0	12.90	$7\frac{1}{8}$	6	3	14
130 RE	130.0	77.4	3.03	25.5	12.71	$6\frac{3}{4}$	6	$2\frac{15}{16}$	14
120 RE	120.9	67.6	2.92	23.1	11.85	$6\frac{1}{2}$	$5\frac{3}{4}$	$2\frac{7}{8}$	14
115 RE	114.7	65.6	2.98	22.0	11.25	$6\frac{5}{8}$	$5\frac{1}{2}$	$2\frac{23}{32}$	10
112 RE	112.3	65.5	3.00	21.8	11.01	$6\frac{5}{8}$	$5\frac{1}{2}$	$2\frac{23}{32}$	14
110 RE	110.4	57.0	2.83	20.1	10.82	$6\frac{1}{4}$	$5\frac{1}{2}$	$2\frac{25}{32}$	14
100 RE	101.5	49.0	2.75	17.8	9.95	6	$5\frac{3}{8}$	$2\frac{11}{16}$	14
90 RA A	90.0	38.7	2.54	15.23	8.82	$5\frac{5}{8}$	$5\frac{1}{8}$	$2\frac{9}{16}$	14
75 AS	75.2	23.0	2.36	10.0	7.38	$4\frac{13}{16}$	$4\frac{13}{16}$	$2\frac{15}{32}$	12
106 CF&I	106.6	53.6	2.85	18.8	10.45	$6\frac{3}{16}$	$5\frac{1}{2}$	$2\frac{21}{32}$	14
119 CF&I	118.8	71.4	3.12	22.9	11.65	$6\frac{13}{16}$	$5\frac{1}{2}$	$2\frac{21}{32}$	14
136 CF&I	136.2	94.9	3.35	28.3	13.35	$7\frac{5}{16}$	6	$2\frac{15}{16}$	14
155 PS	155.0	129.0	3.38	36.7	15.20	8	$6\frac{3}{4}$	3	–
152 PS	152.0	130.0	3.50	37.0	14.90	8	$6\frac{3}{4}$	3	–
140 PS	140.6	97.0	3.37	29.0	13.80	$7\frac{5}{16}$	6	3	10

I c $Z = I/c$

Source: Hay, W.W., Railroad Engineering, 1982

Tie Analysis and Design
(size and spacing)

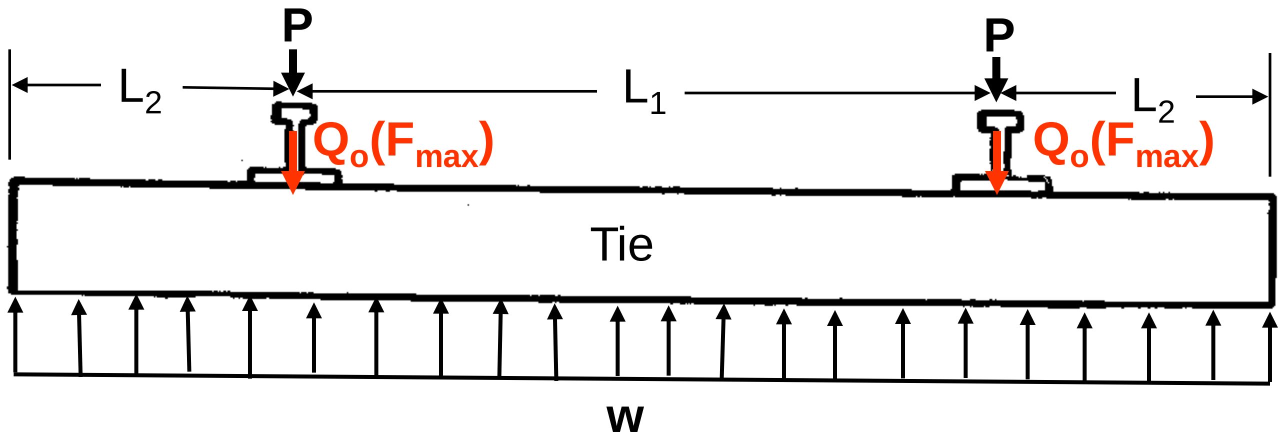
- Action under load
  - Early belief that tie reaction was uniform

  - Not so, Talbot found that stress concentrated under rail seat

Source: Hay, W.W., Railroad Engineering, 1982

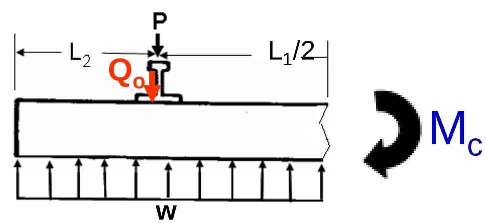
Theoretical Design

- Force diagram (close to center-bound condition)

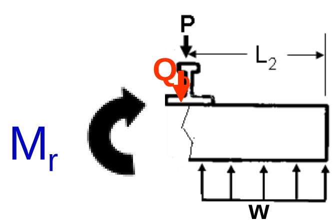


$L = L_1 + 2L_2$

- Look at bending moments under center and rail seat
  - $M_c = (Q_o/4)(L_1 - 2L_2)$



  - $M_r = -Q_oL_2^2/L$



Q_o must account for adjacent wheels. Recall, pressure distribution and principle of superposition.

- Maximum allowable bending moment
  - Simple beam moment

    $S = Mc/I$

    or

    $M = SI/c$

    where M = bending moment, inch-lbs

    I = moment of inertia = $bh^3/12$, in^4

    c = dist from base to neutral axis = $h/2$, inches

    S = allowable wood fiber bending stress, lb/in^2

    h = tie height, inches

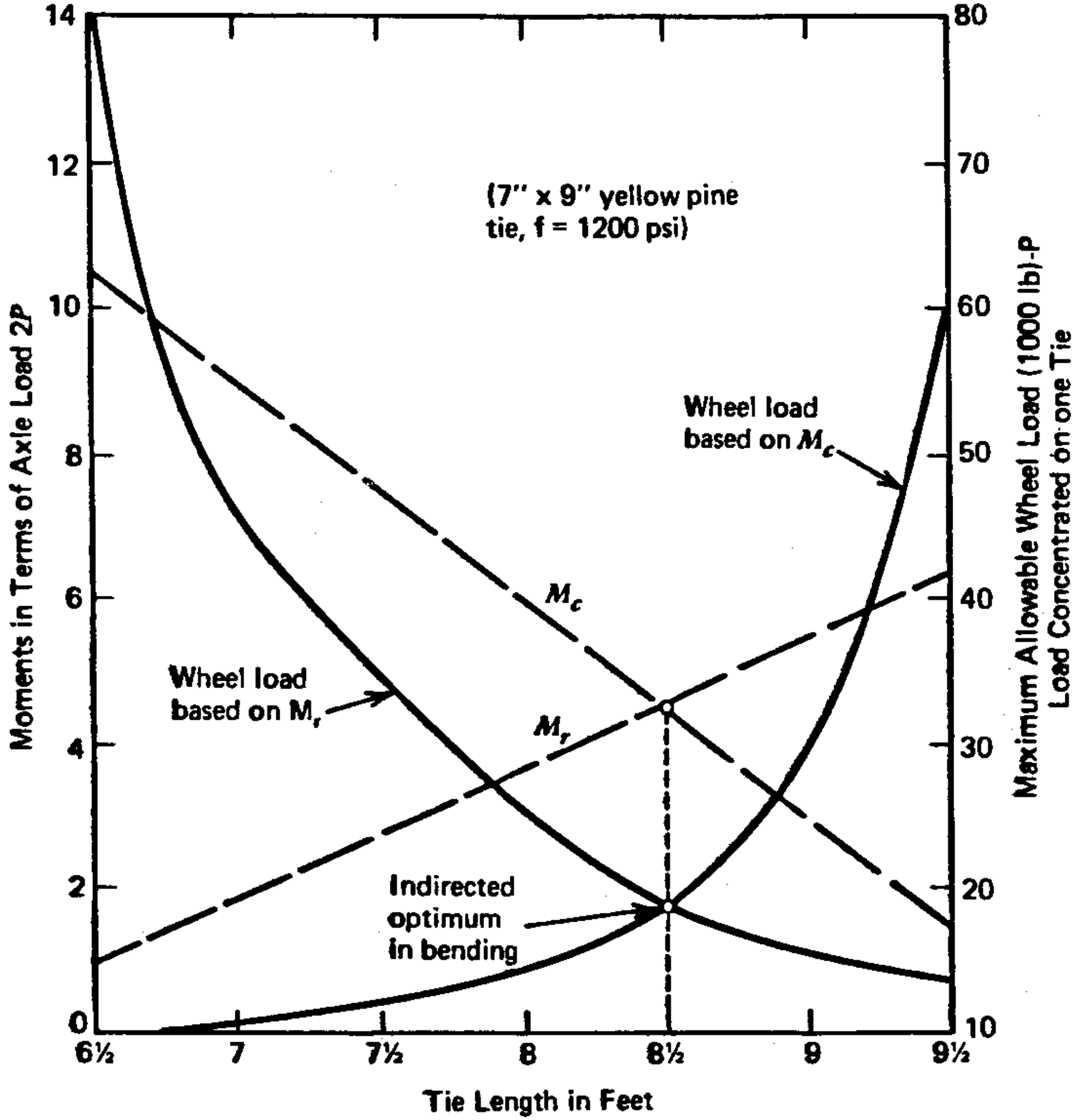
    b = tie width, inches

    then

    $$M = (bh^3S/12)/(h/2) = bh^2S/6$$

  - S varies by wood specie (e.g., 1000 psi for shortleaf yellow pine, 1200 psi for longleaf yellow pine, 900 psi for douglas fir, and 1400 psi for oak)

- “Optimal” tie length



Source: Hay, W.W., Railroad Engineering, 1982

Practical Design

- Load distribution
  - Bearing area is ⅔ of tie length (tamping zone), so

$A'_b = \frac{2}{3}Lb$

and unit load on ballast will be

$p_a = 2Q_o/A'_b$

thus $p_a = 3Q_o/Lb$

where p_a = unit tie pressure on ballast ($\leq$ 65 wood, $\leq$ 85 psi c

A'_b = total tie bearing area, in^2

L = tie length, inches

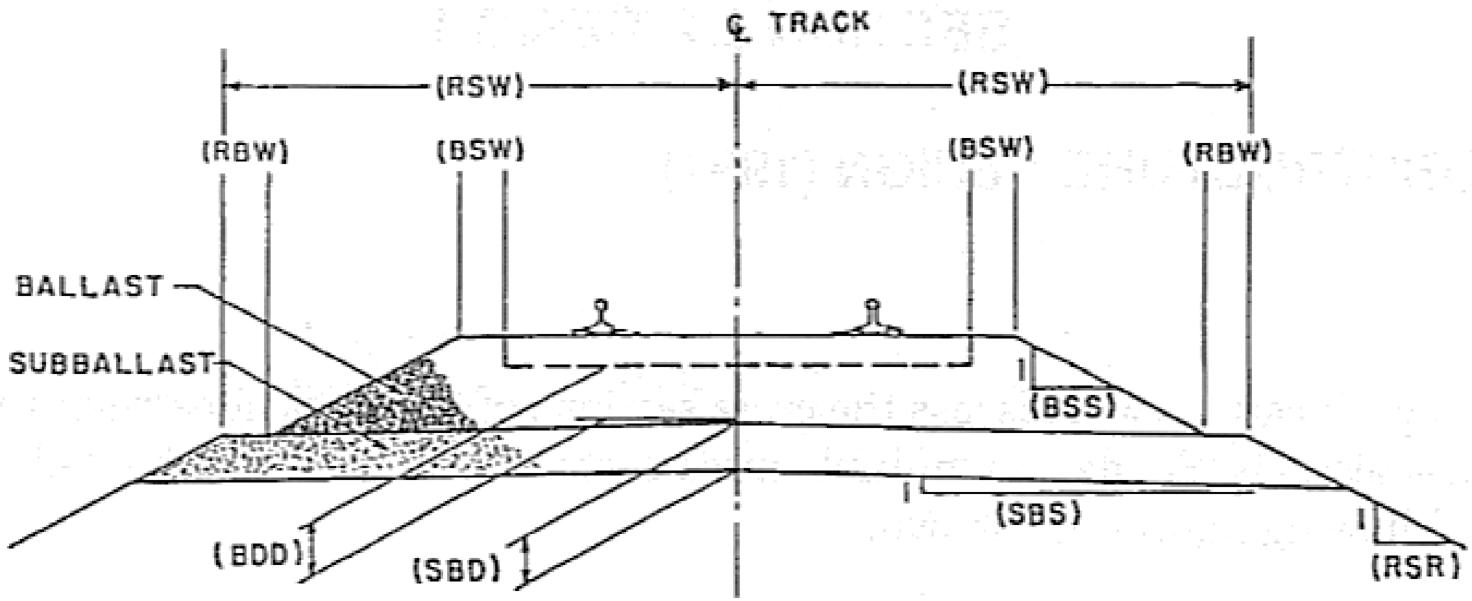
b = tie width, inches

Q_o = Rail seat load, lbs (static or dynamic), based on trial tie spacing

Plate Analysis and Design
(size selection)

- Two basic types
  - Single shoulder
  - Double shoulder
- Size
  - Width sized to fit tie
  - Length to keep stress on wood tie $\leq$ 200 psi
  - Stress = Q_o/Plate Area
  - Limited set of fixed sizes (generally choose smallest size possible for economics)
- Distance between shoulders (double shouldered plates) spaced to match rail base width

Ballast Analysis and Design
(depth determination)



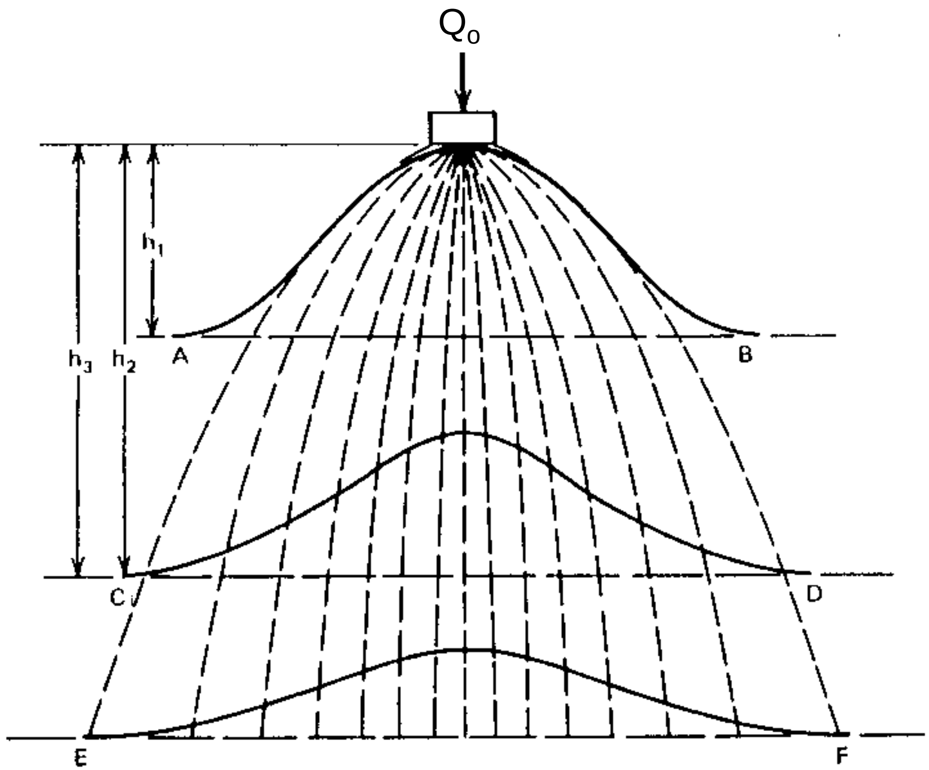
Ballast:
- BDD = Depth of Ballast
- BSW = Ballast Shoulder Width
- BSS = Ballast Side Slope Run

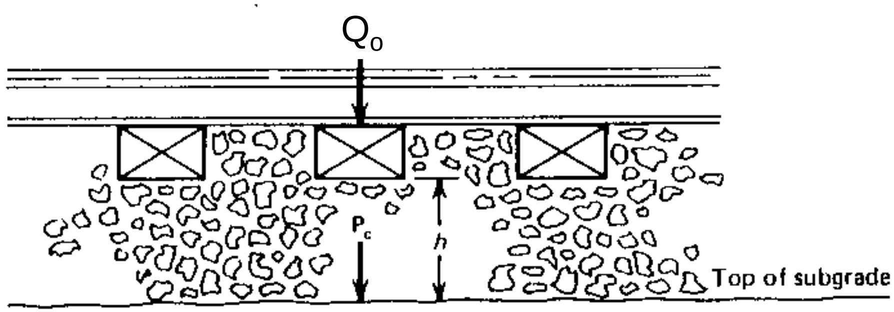
Subballast:
- SBD = Subballast Depth
- SBS = Subballast Side Slope Run

Roadbed:
- RSW = Roadbed Shoulder Width
- RSR = Roadbed Side Slope Run
- RBW = Roadbed Berm Width

Source: AREMA, Manual for Railway Engineering, Chapter 16, 2000

Gaussian Distribution Curves and Subgrade Pressure





Source: Hay, W.W., Railroad Engineering, 1982

- Ballast depth (ballast and subballast combined) = f(applied stress, tie reaction, and allowable subgrade stress)
  - Talbot Equation

    $h = (16.8p_a/p_c)^{4/5}$

    where h = Support ballast depth

    p_a = Stress at bottom of tie (top of ballast)

    p_c = Allowable subgrade stress

    Note: Stress distribution independent of material
  - Japanese National Railways Equation

    $p_c = 50p_a/(10+h^{1.25})$
  - Boussinesq Equation

    $p_c = 6P/2\pi h^2$ where P = wheel load (lbs)
  - Love's Formula

    $p_c = p_a\{1-[1/(1+r^2/h^2)]^{3/2}\}$

    where r = Radius of a loaded circle whose area equals the effective tie bearing area under one rail

- Ballast vs. subballast
  - New construction or reconstruction
    - Generally, half of overall ballast depth should be highest quality available
    - 6" minimum depth for subballast (AREMA)
    - Railroads may have own minimums (e.g. CN requires 12")
  - Existing track
    - All or some of the "old" ballast layer becomes "new" subballast layer when new ballast is added, but old material likely to be of marginal quality and layer function may be compromised
    - Bottom ballast and subballast differentiation becomes blurred
- "Ballast" layer often described as having a "top" ballast section and "bottom" ballast section. The "top" ballast section encompasses the tamping zone.

Subgrade Allowable Stress (Pressure)

- "Traditional" design value of 20 psi
- AREMA recommends limiting stress to 25 psi
- Using soil strength with a factor of safety
  - AREMA recommends a factor of safety of at least 2 and as much as 5 or more depending on the traffic (wheel loads and load repetitions) and soil conditions.
  - Company design standards will dictate (e.g. Army allows a design unconfined compressive strength (q_u) of 1.0 q_u for "normal" traffic levels - less than 5 MGT/yr - and design of 0.8 q_u when traffic levels exceed 5 MGT.)
  - Hay recommends factor of safety of 1.5 as applied to an ultimate bearing capacity of $\leq$ 2.5 q_u, thus allowable stress $\leq$ 1.67 q_u.

Allowable Subgrade Bearing Pressures

Table 10.4 Allowable subgrade bearing pressures

Subgrade Description	In-Place Consistency	Allowable Pressure below Track	
		psi	kPa
Well graded mixture of fine and coarse grained soils: glacial till, hardpan, boulder clay (GW-GC, GC, SC)	Very compact	65 - 100	450 - 690
Gravel, gravel-sand mixtures, boulder-gravel mixtures (GW, GP, SW, SP)	Very compact	55 - 85	380 - 590
	Medium to Compact	40 - 60	280 - 410
	Loose	25 - 50	170 - 350
Coarse to medium sand, sand with little gravel (SW, SP)	Very compact	30 - 50	210 - 350
	Medium to Compact	25 - 30	170 - 210
	Loose	15 - 25	100 - 170
Fine to medium sand, silty or clayey medium to coarse sand (SW, SM, SC)	Very compact	25 - 40	170 - 280
	Medium to Compact	15 - 30	100 - 210
	Loose	8 - 15	60 - 100
Fine sand, silty or clayey medium to fine sand (SP, SM, SC)	Very compact	25 - 30	170 - 210
	Medium to Compact	15 - 25	100 - 170
	Loose	8 - 15	60 - 100
Homogeneous inorganic clay, sandy or silty clay (CL, CH)	Very stiff to hard	25 - 50	170 - 350
	Medium to stiff	8 - 25	60 - 170
	Soft	4 - 8	30 - 60
Inorganic silt, sandy or clayey silt, varved silt-clay-fine sand (ML, MH)	Very stiff to hard	15 - 30	100 - 210
	Medium to stiff	8 - 25	60 - 170
	Soft	4 - 8	30 - 60

Source: Selig and Waters, Track Geotechnology and Substructure Management, 1994

Design Standards, Criteria, and Approaches

- Many railroads (including non-U.S. railroads) have established design standards and/or criteria
- Differences do exist between railroads. Examples include:
  - Some use ⅔ of wood tie length in analyses; some use entire length
  - Some use entire concrete tie length in analyses; some use ⅔ length
  - Some use a rail seat force of Q_o x 1.5
  - Allowable bending stress in rail may vary
  - Allowable rail seat load for determining plate size may vary. Depends on wood specie. Range about 250 – 400 psi. (AREMA recommends 200 psi).

- Differences (con't)
  - AREMA recommends a tie reaction of 65 lbs/in^2 under wood ties and 85 lbs/in^2 under concrete ties, but some railroads use the same for both (e.g. 75 lbs/in^2) – Stiffer track → Higher loads!
    - Why these values?
    - Ballast quality and ability to resist crushing forces (ballast degradation is the number 1 cause of ballast fouling)
  - Some railroads use different track modulus (u) values in design. For example, Spring u may be used for rail bending and ballast depth, but Winter u used for rail seat forces. Other railroads may use a single u value.

Canadian National Example

SPC 1301

TABLE 1

MINIMUM TRACK CONSTRUCTION STANDARDS

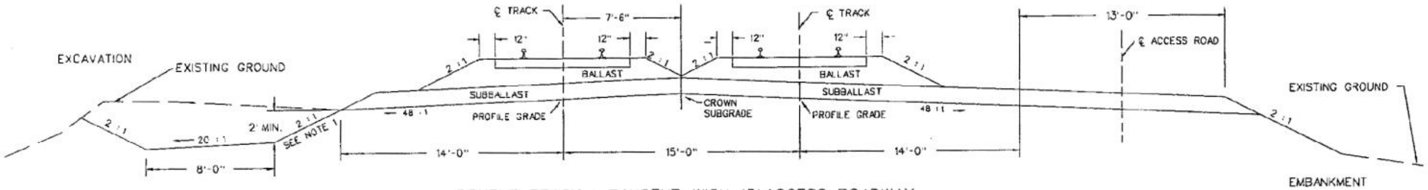
Description	Class 4 and Above	Class 2 & 3	Class 1 and Industrial
Rail Weight	Per SPC 3200 - Appendix "C" or as specified by the Division Engineer		
Rail (CWR or Jointed)	CWR	Class 3 - CWR Class 2 - Jointed	Jointed
Tie Plates	Per SPC 3600 100 %	Per SPC 3600 100%	Per SPC 3600 100%
Rail Anchors	Per SPC 3601	Per SPC 3601	Per SPC 3601
Fasteners	Elastic Fasteners Cut Spikes (per SPC 3604)	Cut Spikes (per SPC 3604)	Cut Spikes (per SPC 3604)
Ties Per Mile			
• Concrete	2640	2640	
• Wood No. 1	3110	3110	
• Wood No. 2			Class 1 - 2980 Industrial - 2840
Track Ties	Concrete (per SPC 3303) Hardwood	Concrete (per SPC 3303) Hardwood	Softwood or Hardwood
Switch Ties	Hardwood	Hardwood	Hardwood

CN SPC 1301 Table 1 (con't)

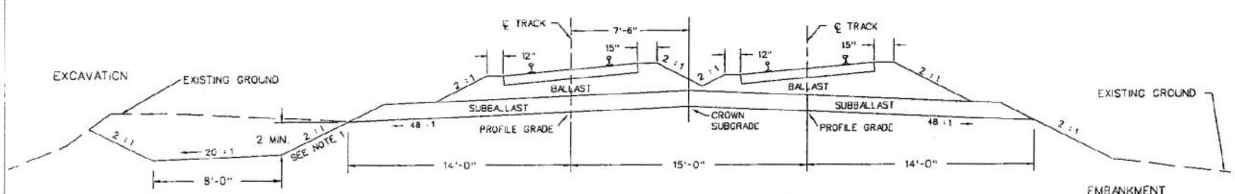
Ballast • Crushed Rock • Minimum Depth Below Bottom of Tie • Shoulder width • Walking Ballast*	 2-½" minus 12 inches CWR–12"	 2-½" minus or 2" minus 12 inches Jointed-6", CWR–12" AREMA Size No. 5	 2" minus or AREMA Size No.5 6 inches Jointed-6" AREMA Size No. 5
Sub-ballast • Minimum Depth • Maintained Top Width	 12 inches 22 ft.	 12 inches 22 ft.	 12 inches 22 ft.

* Where walking ballast is required, it shall be applied in a minimum 4" thick surficial layer

BNSF Standard Cross Section

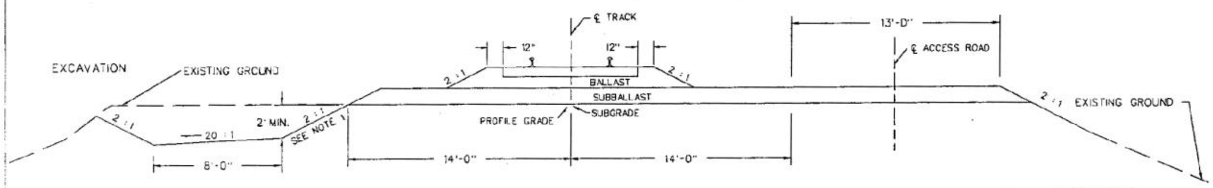


DOUBLE TRACK - TANGENT WITH 13' ACCESS ROADWAY

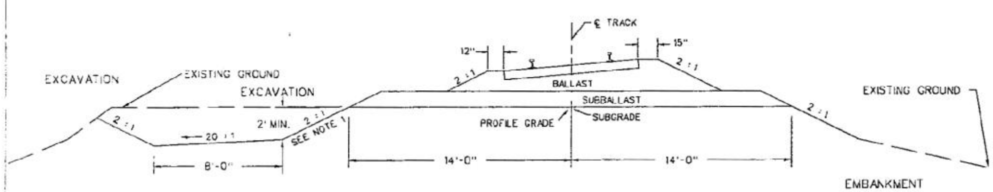


DOUBLE TRACK - CURVES

ROADWAY NOT SHOWN



SINGLE TRACK - TANGENT WITH 13' ACCESS ROADWAY



SINGLE TRACK - CURVES

ROADWAY NOT SHOWN

NOTES:

1. FILL AND CUT SLOPES SHALL BE AS INDICATED ON SITE EXPLICIT CONSTRUCTION PLANS AND PROFILES.
2. WHERE DOUBLE TRACK CROSSES A ROADWAY, ADJUST BALLAST SECTION TO PROVIDE UNIFORM ROADWAY PROFILE.
3. REMOVE AND REPLACE TOP SOIL TO DEPTH AS SHOWN ON PLAN AND PROFILE.
4. TRACK CENTERS ON DESIGNATED CORRIDORS WILL BE CONSTRUCTED AT 25'-0".
5. BALLAST DEPTH:
   WOOD TIE - 8" MIN.
   CONCRETE - 12" MIN.
6. SUBBALLAST DEPTH: 12" MIN.

CUBIC YARDS PER MILE OF TRACK			
TANGENT	8" BALLAST	12" BALLAST	12" SUB BALLAST
SINGLE TRACK	2750	3600	5775
DOUBLE TRACK	5500	7200	8475

BURLINGTON NORTHERN SANTA FE
STANDARD PLAN
ENGINEERING DEPT., FORT WORTH, TEXAS

MAINLINE AND MAJOR SPUR ROADBED SECTIONS (NEW CONSTRUCTION)

RAIL:

DATE: 02/26/97 | SCALE: NONE

DWG. NO. 1000 | SHEET NO. 02 | REV. NO. 03

Shortcomings and Things to Think About

- Design approach is part science, part “art”
- Track modulus is neither constant nor precise
- Relationship between track deflection and performance not exact
- Assumed Gaussian pressure distribution not entirely correct
- The challenge is in determining allowable ballast and subgrade stresses
- Design approach is not robust
  - Ballast and subgrade properties not adequately considered
  - Tonnage (MGT) and load repetitions considered only indirectly
  - Variability in ballast/subgrade properties abound
  - Design approach does not consider maintenance issues and track degradation affects
  - Cannot consider usage of HMA and/or other reinforcing layers in design
  - Others
- Standard designs sometimes misapplied or interpreted
- Others

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- Selig, E.T. and J.M. Waters, Track Geotechnology and Substructure Management, Thomas Telford Services Ltd, London, 1994