Track Buckling Prevention and Improved Rail Stress Management (Module 1)

Acknowledgement

This training course was developed by Dr. Andrew Kish of Kandrew Inc. Consulting Services. The material is based on over 30 years of Dr. Kish's US DOT/FRA/Volpe Center research, and over 30 industry CWR briefings, training seminars, and workshops on track buckling prevention conducted both domestically and internationally.

KANDREW
Consulting Services

Dr. Kish is an internationally recognized expert in rail and track mechanics with over 45 years of experience. His background includes research and testing in both the federal and private sectors, including over 30 years at the US DOT's Volpe Center and 16 years as a technical consultant with US railroads, AAR, FRA, industry rail suppliers, and international agencies.

Dr. Kish was a member of the Rail Safety Advisory Committee (RSAC) which developed the new CWR safety standards enacted in 2009.

Track Buckling Prevention and Improved Rail Stress Management

2023 FRA Training Course

Dr. Andrew Kish
Kandrew Inc. Consulting Services, USA

COURSE OBJECTIVE

- To present the fundamentals of track buckling prevention, rail stress, and rail neutral temperature (RNT) management for improving Continuous Welded Rail (CWR) safety and performance.

The training format supports both in-person class training as well as on on-line viewing as uploaded on Federal Railroad Administration's (FRA's) website.

Acknowledgement

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The John A. Volpe National Transportation Systems Center assisted with editing the course materials.

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U.S. Department of Transportation
Volpe Center

AGENDA

Module 1

❑ CWR Fundamentals
- Problem definition/track buckling basics
- CWR Plans/Procedures

❑ Key Governing Parameters
- Track lateral resistance
- Track curvature/line defects
- Train loads/dynamics
- Rail Neutral Temperature (RNT)

❑ Safety Concepts/Best Practice Guidelines
- Safety concepts and buckling prevention formula
- Best Practice Guidelines for CWR Management

Module 2

❑ Improved CWR Maintenance Practices
- The RNT problem and readjustment issues
- RNT readjustment after rail break/defect repairs
- Current best practice guidelines and applications: RNT-RESTORE
- Destressing of CWR

❑ Review and Summary

❑ Q&A, Discussion, and Closing Remarks

Introduction

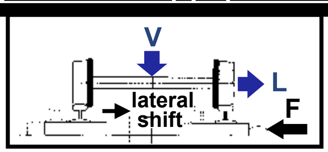
What is the Track Lateral Stability Problem?

<u>The Lateral Track Stability Problem</u>: How to effectively manage the vehicle and thermal loads to keep lateral geometry deviations within *"safe"* limits?

Track Lateral Stability Mechanism

Stage	Process	Major causal factors	Safety Criteria
1	Formation of initial "small" track lateral misalignments	1) High vehicle lateral to vertical (L/V) loads 2) Reduced local lateral resistance 3) Initial imperfections (welds), construction anomalies, and install errors	Construction and repair tolerances
2	Growth of misalignments (Track Shift)	1) Increase in L/V and thermal loads 2) Reduced lateral resistance 3) Track *"dynamic uplift"* 4) Many cycles of L/Vs	Max L/Vs and permissible line defects
3	Buckling	1) Misalignments generated by track shift 2) High thermal loads (reduced RNT) 3) Weakened lateral ballast resistance 4) Train loads and dynamics	Max thermal load or "safe" temp increase

<u>High Axle Load (L/V) Problem</u>



<u>Track Alignment Standards</u>

CFR 49 § 213.55; 213.327; 213.333

<u>(FRA Acc. Cause Code: T108)</u>

<u>High Thermal Load Problem</u>

<u>CWR Standards</u>

CFR 49 § 213.118 & 119 & 343

<u>(FRA Acc. Cause Code: T109)</u>

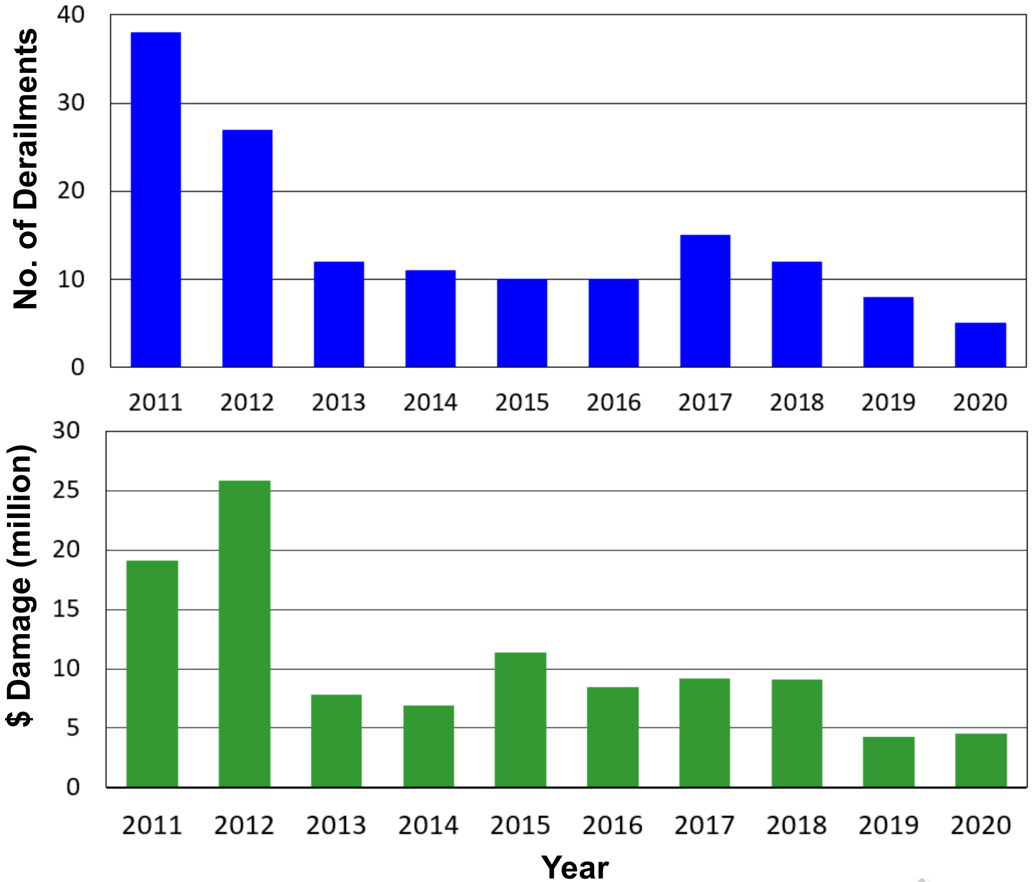
❑ **<u>Question</u>: Why is maintaining lateral stability a serious industry concern?**

Track Failure Caused Derailment Statistics

FRA Cause Code T109: Track alignment irregular (buckled/sunkink)
[All US Railroads/Mainline Track]

Year	$ Damage (million)	Count
2011	19.14	38
2012	25.83	27
2013	7.77	12
2014	6.86	11
2015	11.36	10
2016	8.45	10
2017	9.22	15
2018	9.09	12
2019	4.31	8
2020	4.58	5

$720,412 per derailment



- **Need more effective CWR procedures, training, and R&D to improve.**

What CWR Policies/Procedures?

CWR Track Safety Standards

October 2009: New FRA Track Safety Standards on CWR
[49 CFR § 213.118 & 213.119]

Requires CWR procedures and an annual training program

Requires compliance, and stipulates procedure's content

Rail Safety Advisory Committee (RSAC)

- Developed the provisions for § 213.118 & 119
- Developed a *Generic CWR Policy Document* for railroad use

Procedures for the Installation, Adjustment, Maintenance, and Inspection of CWR as Required by 49 CFR 213.118/119

Industry/FRA/Generic CWR Plan

Procedures for the Installation, Adjustment, Maintenance, and Inspection of CWR as required by 49 CFR §213.118 & 119: RSAC GENERIC CWR PLAN*

Chapter 1 CWR Installation Procedures
- 1.1 Neutral Temperature
- 1.2 Temperature Differential
- 1.3 Installing CWR

Chapter 2 Rail Anchoring Requirements When Installing CWR
- 2.1 Standard Box Pattern
- 2.2 Solid Box Pattern
- 2.3 Bridge Pattern
- 2.4 Legacy Patterns
- 2.5 Anchor Pattern After Repair

Chapter 3 Preventive Maintenance on Existing CWR Track
- 3.1 Maintaining Desired Rail Installation Temperature Range
- 3.2 De-Stressing Rail

Chapter 4 Monitoring Curve Movement Following Surfacing and Lining
- 4.1 Staking of Curves
- 4.2 Inspecting for Curve Movement

- Each railroad can use as template to customize to individual needs; also see an updated FRA version!

Chapter 5 Placing Temporary Speed Restrictions Account Work
- 5.1 General Requirements
- 5.2 Responsibility for Placing Speed Restrictions
- 5.3 Speed Restriction Length
- 5.4 Speed Restrictions for Track Work

Chapter 6 Rail Joint Inspections
- 6.1 Class of Track
- 6.2 Frequency of Inspections
- 6.3 Identification of Joints

Requires More Effective CWR Neutral Temperature (RNT) Management as per [§213.119 – (a)(1)(2);(d);(f)(2);(g)]

Chapter 8 Training

Chapter 9 Recordkeeping
- 9.1 Report of CWR Installations
- 9.2 Report Maintenance Work in CWR

Industry/FRA/Generic CWR Plan

Procedures for the Installation, Adjustment, Maintenance, and Inspection of CWR as required by 49 CFR §213.118 & 119: RSAC/FRA GENERIC CWR PLAN

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7.1 Hot Weather Ins
7.2 Cold Weather Inspe

Chapter 8 Traini

Chapter 9
9.1
9.2

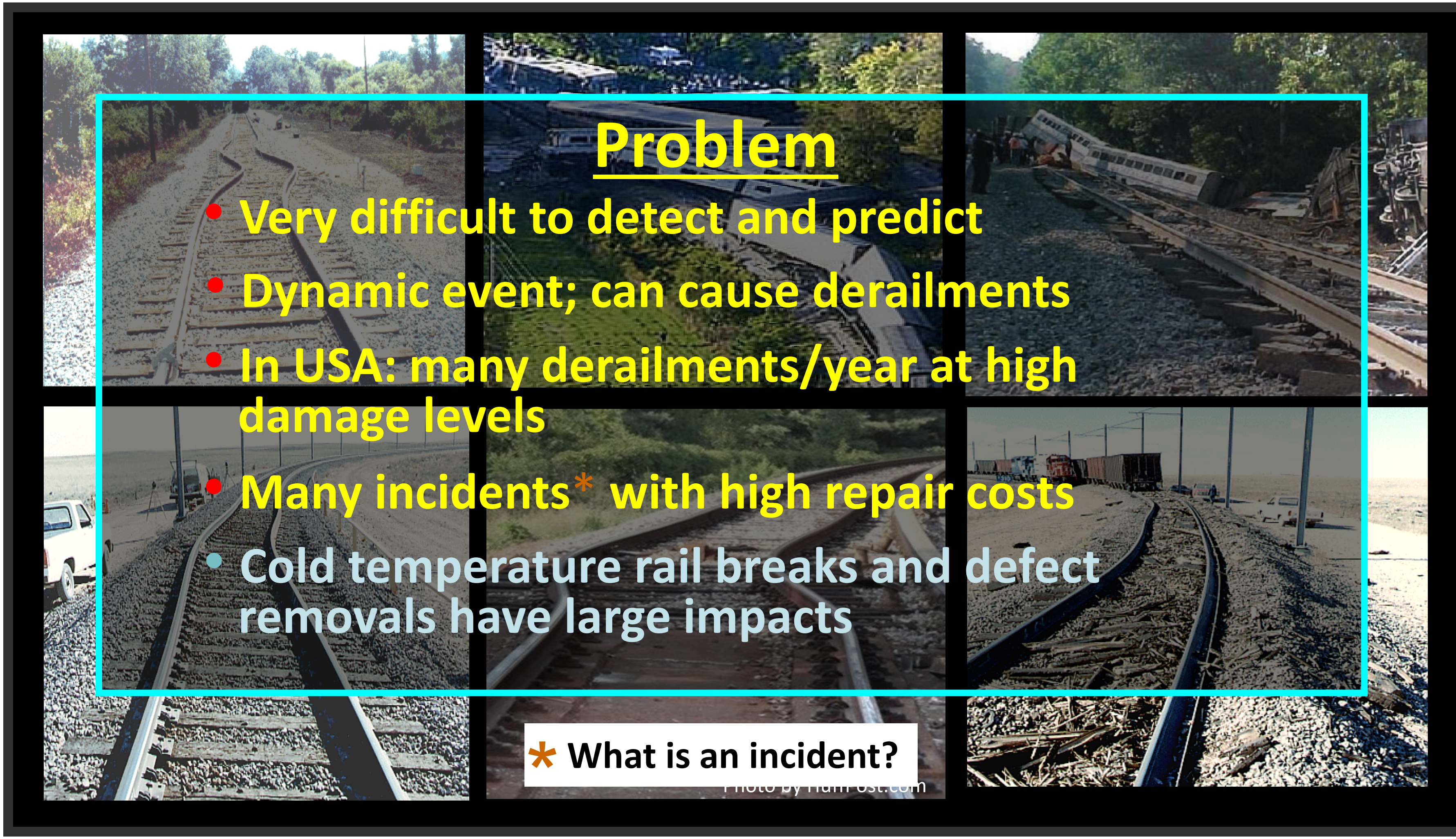
REQUIREMENT: rail that has broken or cut must be readjusted to the subdivision's desired rail neutral temperature (DRNT) minus a safe range (usually between 0 - 20°F) within the time/temperature specified by the RSAC readjustment TABLE

ISSUE

WHAT METHODOLOGY?

"RNT-RESTORE" or other sound engineering approaches

The Track Buckling Problem

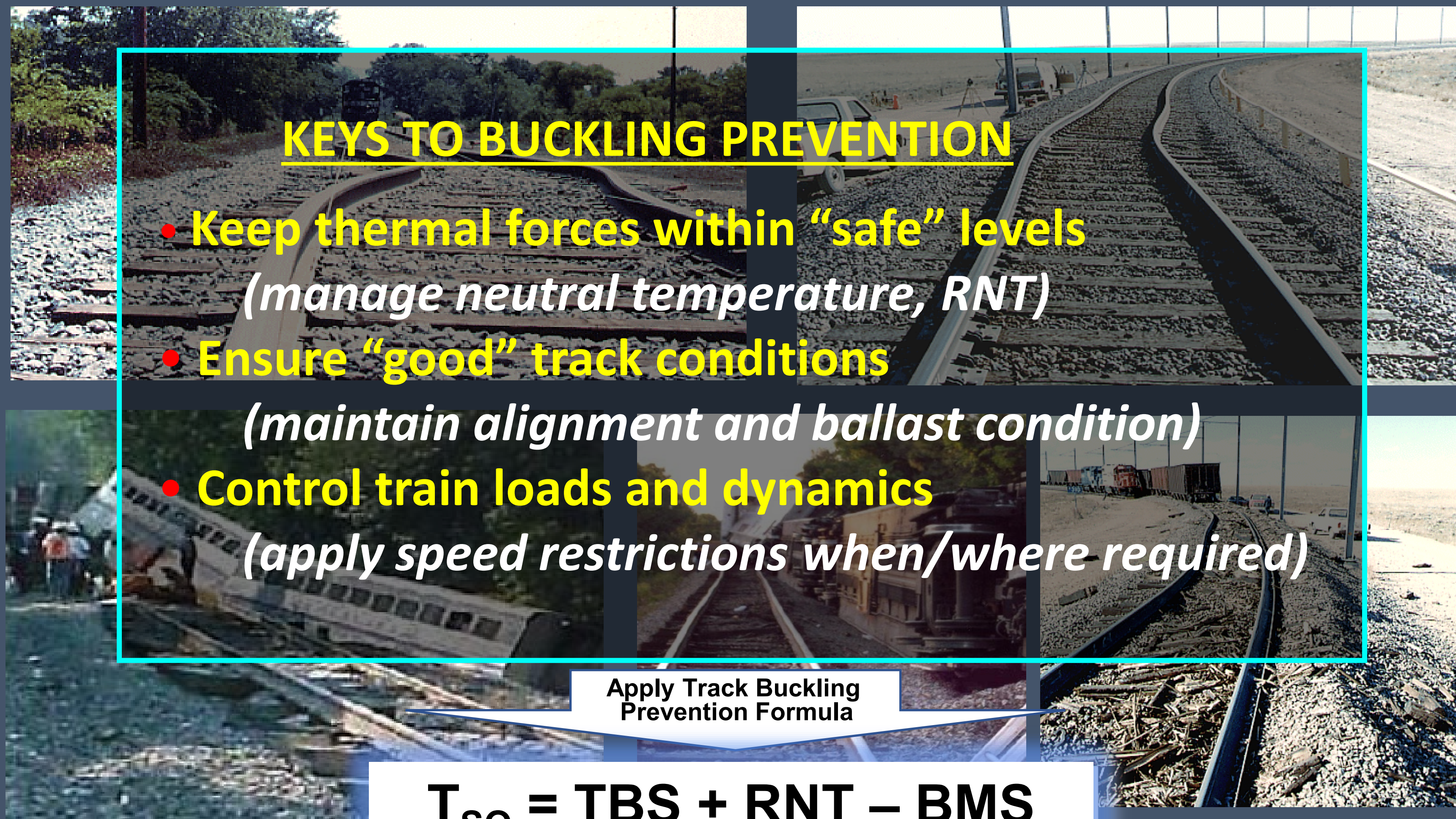


Problem

- Very difficult to detect and predict
- Dynamic event; can cause derailments
- In USA: many derailments/year at high damage levels
- Many incidents* with high repair costs
- Cold temperature rail breaks and defect removals have large impacts

* What is an incident?

How to Prevent?



KEYS TO BUCKLING PREVENTION

- Keep thermal forces within "safe" levels
  (manage neutral temperature, RNT)
- Ensure "good" track conditions
  (maintain alignment and ballast condition)
- Control train loads and dynamics
  (apply speed restrictions when/where required)

Apply Track Buckling Prevention Formula

$$T_{SO} = TBS + RNT - BMS$$

The Buckling Prevention Formula

$$T_{SO} = TBS + RNT - BMS$$

- Safe Rail Operating Temperature
- Track Buckling Strength
- Rail Neutral Temperature
- Rail Operator Defined Safety Factor

PERFORMANCE STATEMENT

- If CWR is installed, adjusted, and maintained in line with the above track quality-based safety criterion, the track's buckling potential is expected to be at a minimum

Science and data driven; risk based safety performance standard for CWR

*Note: the RNT in the buckling prevention formula refers to a *"track RNT"* i.e., the average of two rail's RNTs!

- APPLICATION: requires knowing TBS, RNT, and BMS* in the formula! (*BMS is often referred to as the *"Buckling Margin of Safety")*

The Buckling Prevention Formula

$$T_{SO} = TBS + RNT - BMS$$

- Safe Rail Operating Temperature
- Track Buckling Strength
- Rail Neutral Temperature
- Rail Operator Defined Safety Factor

APPLY: 60°F : 80°F : 100°F CRITERION

weak | average | strong

Weak (60ºF)	Higher degree curves (3 deg or higher); Class 3-4 alignment deviations; recently maintained to partially consolidated ballast
Average (80ºF)	Tangent to 3 degree curves; Class 4-5 alignment deviations; "standard" ballast lateral resistance
Strong (100º)	Tangent, well consolidated, high quality track; Class 5-6 alignment deviations
Based on over 1000 buckling calculations + 14 track buckling tests	

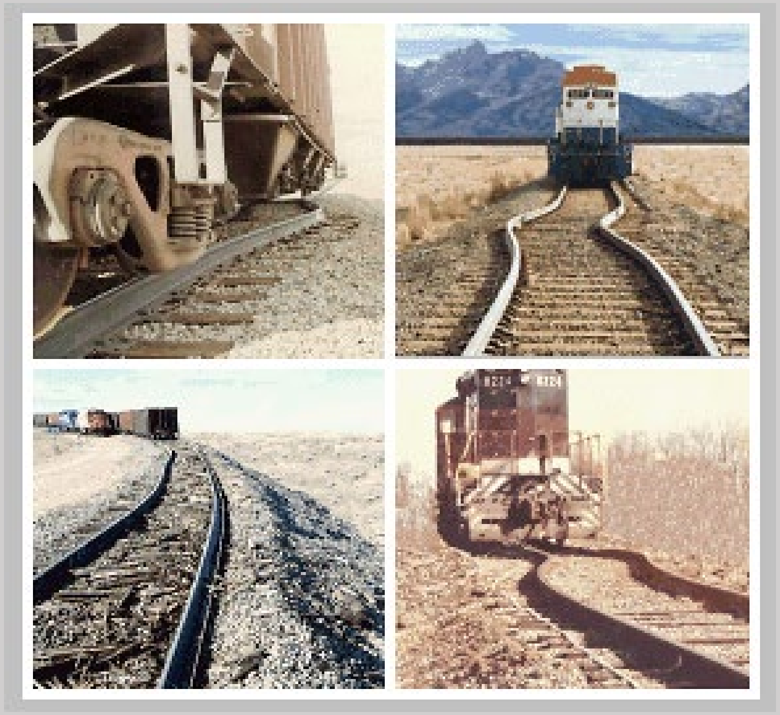
- HIGHLY VARIABLE!
- DIFFICULT TO MEASURE!
- DIFFICULT TO MANAGE!

Need Best Practice Guidelines/Procedures to Maintain Within a Desired Safe Range!

Track Buckling Prevention

U.S. Department of Transportation
Federal Railroad Administration

Track Buckling Prevention: Theory, Safety Concepts, and Applications



DOT/FRA/ORD-13/16

Final Report
March 2013

Document available on the FRA website:
www.fra.dot.gov

CWR Fundamentals

CWR Fundamentals

What is CWR?

- CWR is rail welded together that exceeds 400 feet
  - Rail installed as CWR remains CWR, regardless of whether a joint or plug is installed at a later time
  - Temperature variations produce constrained thermal expansions and contractions resulting in tensile or compressive forces

Pull-aparts/Rail Breaks

High Tensile Forces

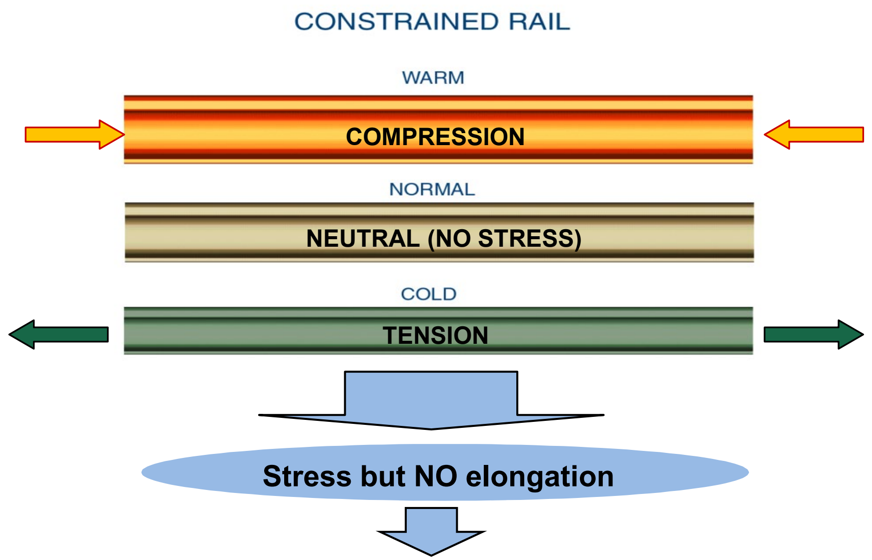
Buckling

High Compressive Forces

How do these forces develop?

How do forces develop in CWR?

With temperature increase/decrease, the rail wants to expand/contract; but it can't because it's constrained, so instead it develops longitudinal forces (referred to as *"forces due to constrained thermal expansion"*



- Note 1: A 1440 ft (36 rail lengths) string of unrestrained (free) rail will grow by 5⅝ inches with a temperature increase of 50°F!
- Note 2: If in track (constrained), a longitudinal force of 130,000 lbs will develop in each rail (136 lb.) for 50°F temp increase

Rail Movement (inches) = Rail Length (inches) x Temperature Differential (°F) x 0.0000065 → **Used in CWR Destress Tables**

Buckling Occurrence Summary: When, Where, and Why?

Occurrence	Reason
40-60% in April/May/June	Early heat coupled with winter condition Impacts; reduced neutral temperature; weakened ballast resistance due to spring thaw and winter curve movement
More on curves than tangent *(however, tangent buckles are more severe)*	Increased *"buckling proneness"* due to curvature effects; loss of alignment, resistance and neutral temperature after winter/spring string-lining
Under the train, with a large percentage of buckles in the rear half of the train	Train loads cause misalignment growth (track shift) under the train to *"critical"* sizes, triggering buckles

HOW TO PROTECT AGAINST EARLY HEAT? →

SOME CWR Procedures: apply 40 mph if T_{AMB} change is 40°F or more in a 12-hour period!

Buckling Occurrence Summary (con't)

Occurrence	Reason
On track segments where CWR was laid in *"cold temperatures"*	Reduced rail neutral temperature (RNT) due to rail laid well below preferred rail laying temperature (PRLT) and NOT destressed prior to "warm" temperatures
In areas of recent maintenance involving ballast and rail	Inadequate consolidation to restore ballast resistance, inadequate RNT adjustment when repairing broken or defective rail
Large percentage near fixed points (50% within 400 ft)	High longitudinal force (reduced RNT) due to rail "shoved" toward rigid/fixed structure

- **RNT Management is the Most Important Aspect of CWR Maintenance**

Key Parameters Influencing Track Buckling

Key Track Buckling Parameters

5 Key Parameters Influencing Track Buckling

- *Track resistance*
- *Alignment deviations*
- *Track curvature*
- *Train loads and dynamics*

\+

Rail neutral temperature (RNT)

$$T_{SO} = TBS + RNT - BMS$$

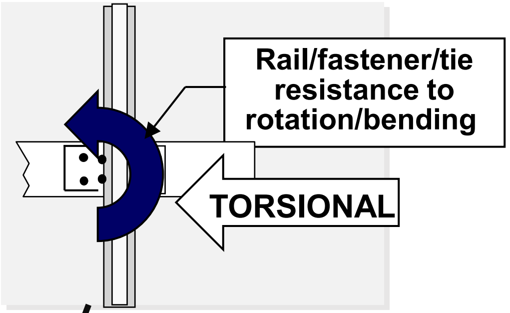
Track Resistance

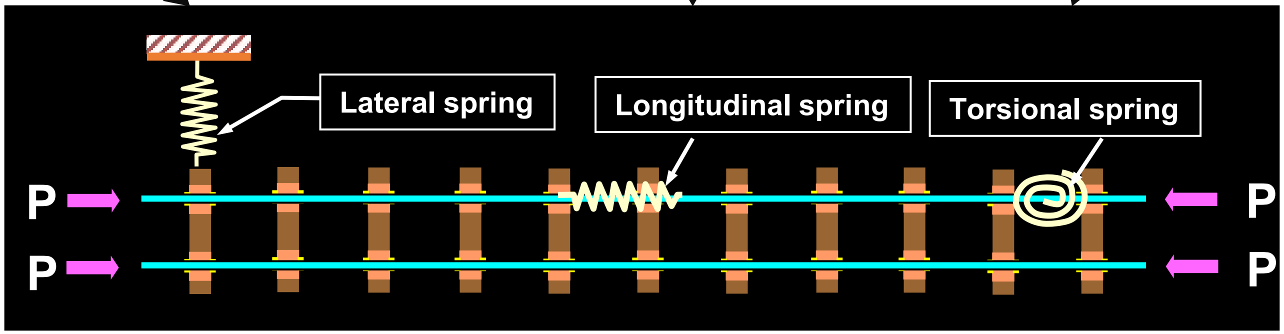
Track Resistance Components

- *Lateral resistance (ballast – lateral)*

- *Longitudinal resistance (fasteners/ballast-longitudinal*

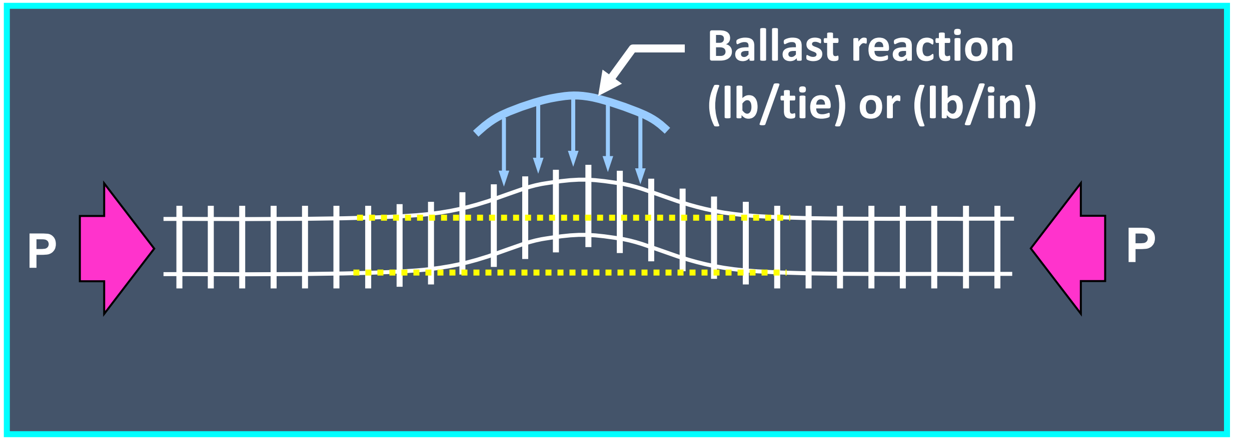
- *Torsional resistance (fasteners/ties/ballast – in plane bending)*





Track Lateral Resistance (TLR)

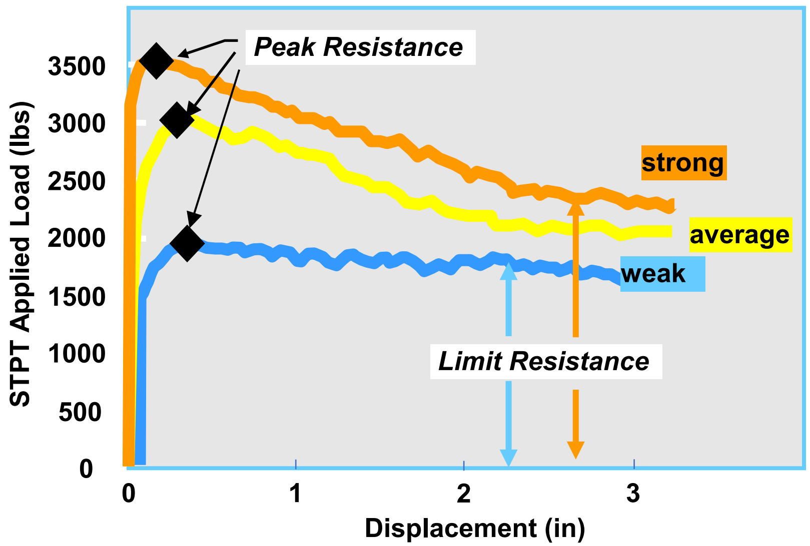
- Definition: TLR is the reaction offered by the ballast to the rail-tie structure against lateral movement



- TLR is a key parameter for track stability retention; it provides lateral strength against buckling.
- How to measure/quantify: *Single Tie Push Test (STPT)*

Track Lateral Resistance: *Measurement and Quantification*

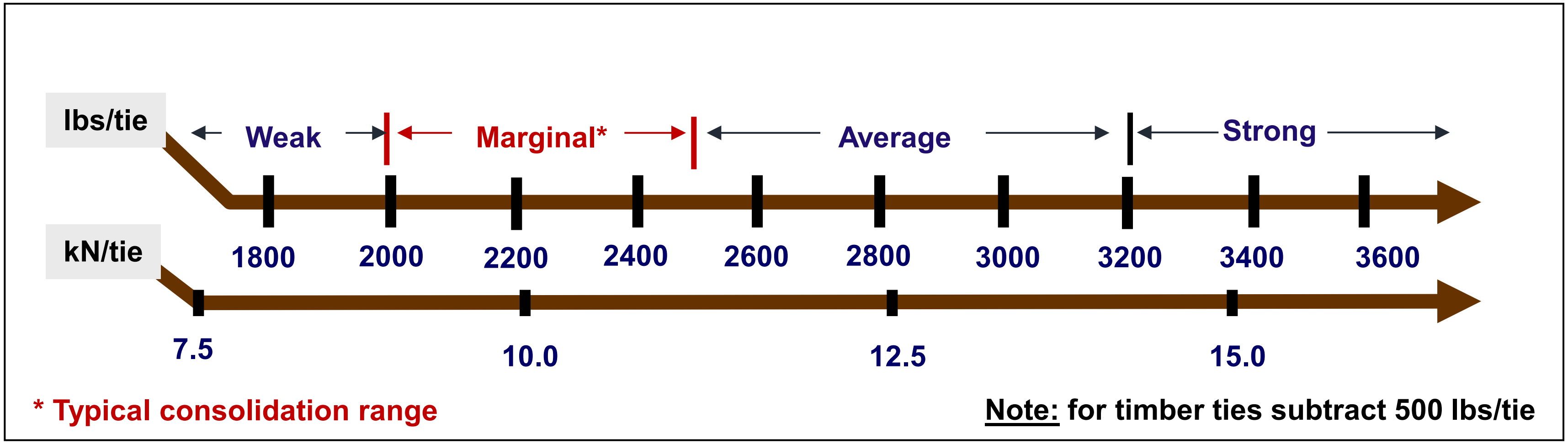
Single-tie push test *(STPT)* measurement for lateral resistance evaluation



Over 1200 VOLPE/FRA STPT Measurements to Quantify Ballast Lateral Resistance Behavior

Track Lateral Resistance: *Influencing Factors and Typical Values*

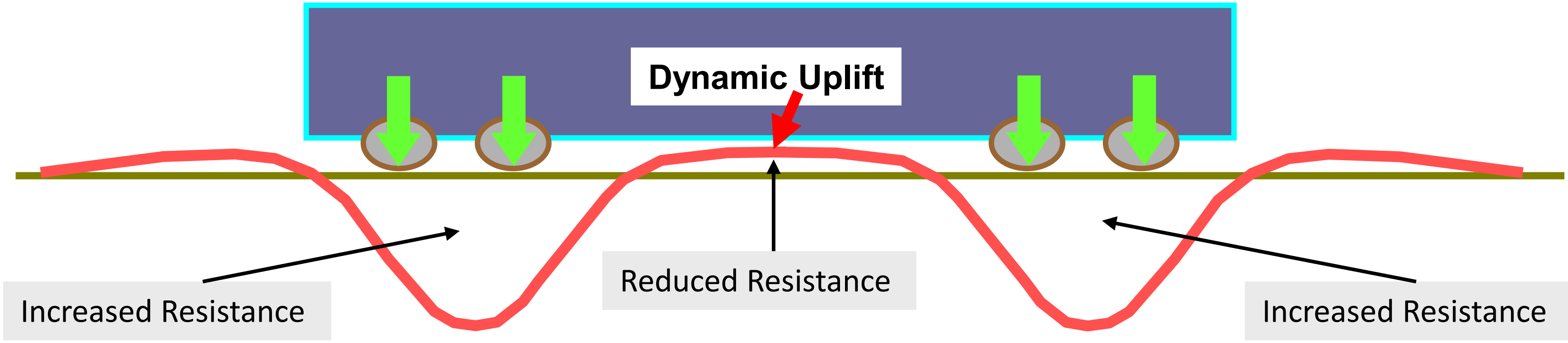
- **Typical concrete tie peak values (static/unloaded):**

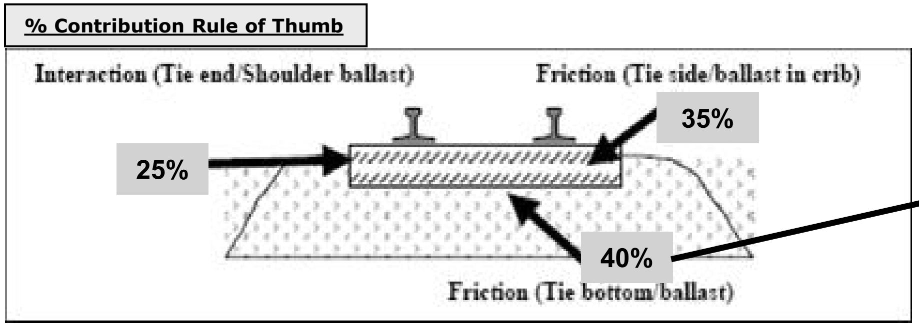


- **Factors influencing lateral resistance:**
  - Tie type, weight, shape and spacing; ballast type and condition (fouled, frozen, etc.), shoulder width, crib content; maintenance, degree of consolidation, and vehicle loads (dynamic uplift)

Track Lateral Resistance: *Dynamic Resistance*

- ***"Dynamic resistance"***: **reduced or increased resistance due to train loads; it is a key component of both track buckling and track shift evaluations**



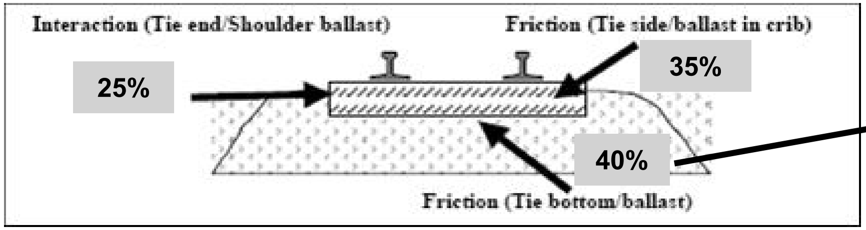


Can result in up to 40% loss of lateral resistance

Track Lateral Resistance: Shoulder Width

Why is shoulder width important?

(a)

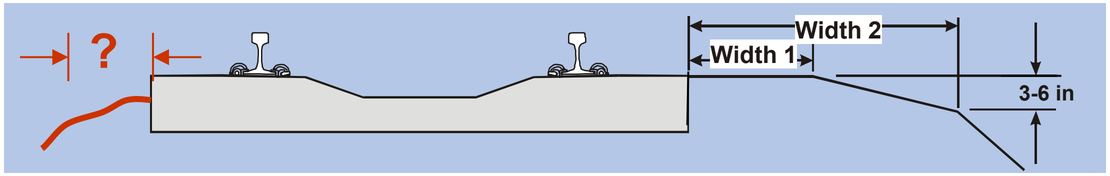


When losing up to 40% resistance due to dynamic uplift, the shoulder width contribution becomes important

Reduced shoulder

(b) To limit curve "string-lining," thereby mitigating line defect generation and neutral temperature variation ➡ don't neglect shoulders on low rail side!

Question: what is an "optimum" shoulder width?



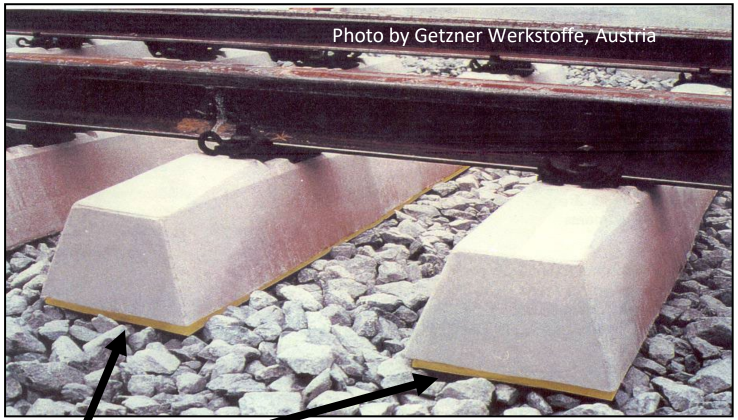
Track Lateral Resistance: Other Influences

<u>Improved Tie Designs to Increase Lateral Resistance</u>

- Concrete tie lateral resistance is higher than wood *(~500 lbs/tie)* <u>but</u> wider tie spacing and lower tie/ballast friction coefficient tend to *"equalize"* lateral strength benefits

- Some concrete tie designs employ "roughened bottoms," "scalloped" sides, and special design features to increase lateral resistance

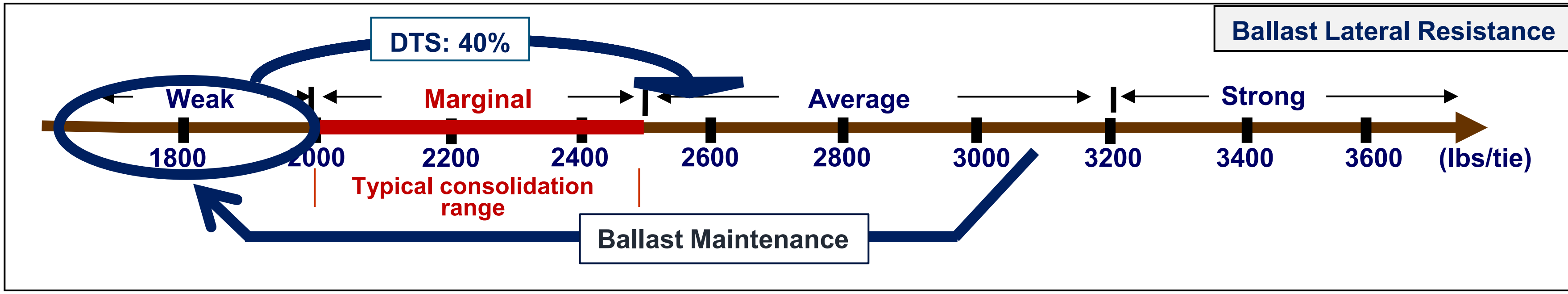
- New tie design concept: under tie (sleeper) pads (USPs) to increase tie/ballast interface contact and friction coefficient
  - Improved track quality
  - Better vertical and lateral stability
  - Improved geometry at bridge/track transitions
  - Reduced ballast maintenance



Under tie pads

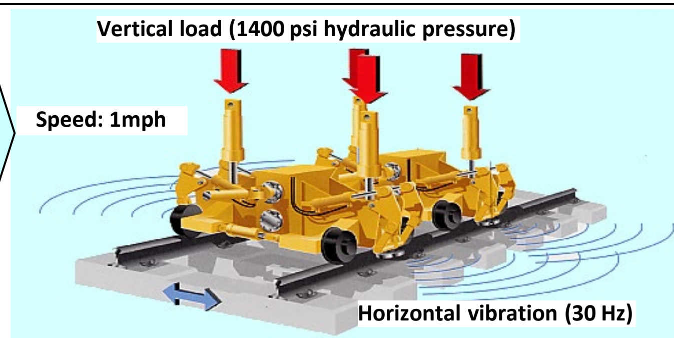
Track Lateral Resistance: Influence of Ballast Maintenance

- Ballast maintenance typically reduces TLR to the *"Weak"* range; requires consolidation either by dynamic track stabilization (DTS) or traffic tonnage. DTS can immediately restore 40%; traffic consolidation may require <u>over</u> 0.1 MGTs (100,000 tons) of slow ordered traffic to produce the equivalent 40% DTS restoration.



DTS principle*: a quick restoration of the tie bottom friction component of lateral resistance by applying vertical load coupled with horizontal vibration (i.e., *"rubbing"* track into ballast)

*Riessberger, K. & Wenty, R. *"40 Years of Dynamic Track Stabilisation."* EIK 2015, pp. 55 – 76



Photos by www.plasseramerican.com

Tonnage Principle: the application of many axle loads at slow speeds produces consolidation, but the mechanism and the rate are unknown.

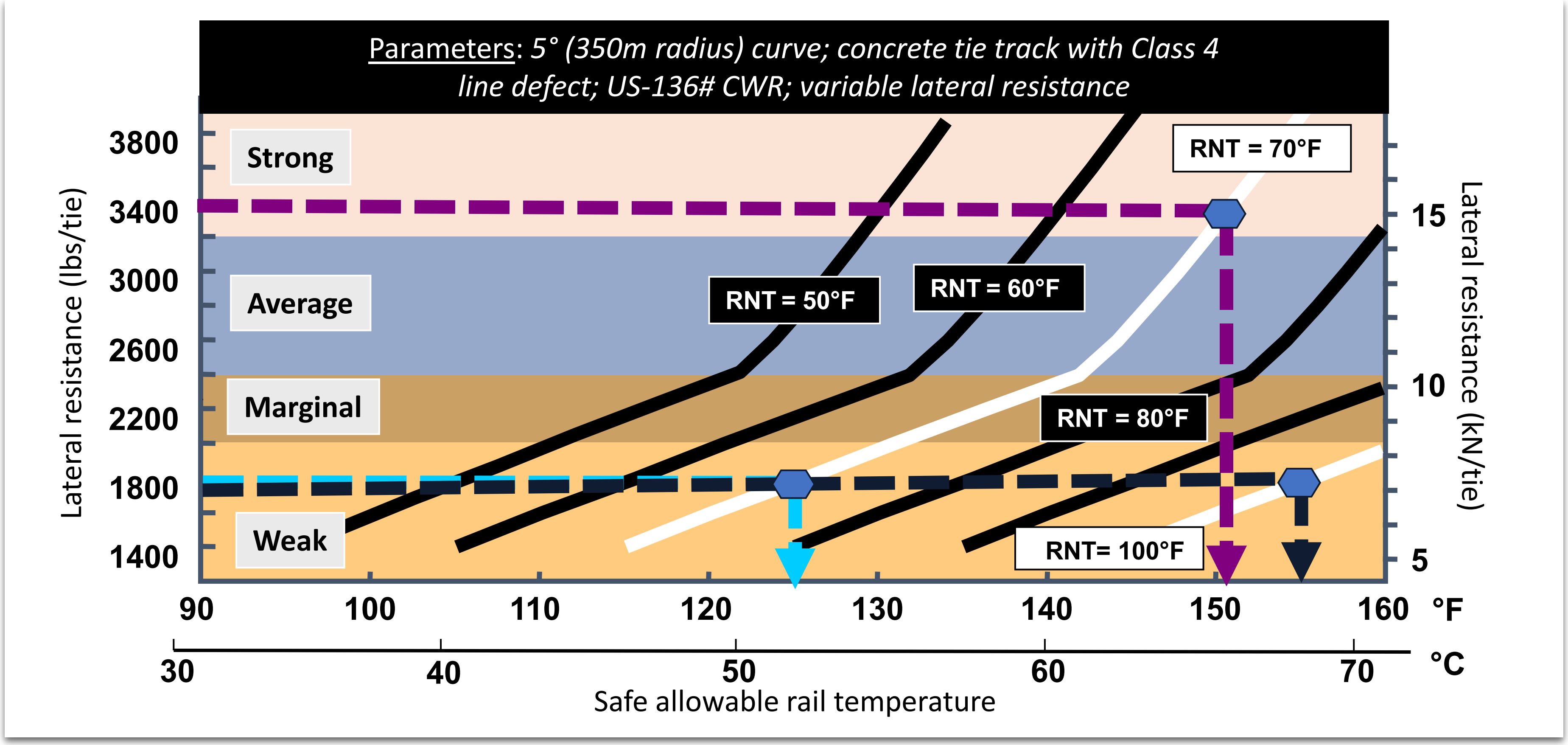
ASSUMPTION

0.1 MGT (100K tons) = 30 - 40% DTS increase

More R&D is needed to better quantify the 0.1 MGT benefits.

Track Lateral Resistance: Impact on Buckling Temperatures

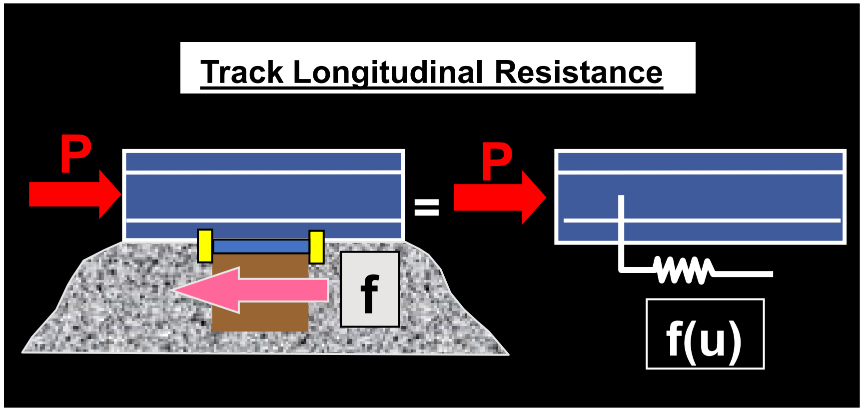
Ballast Strength versus Buckling Potential

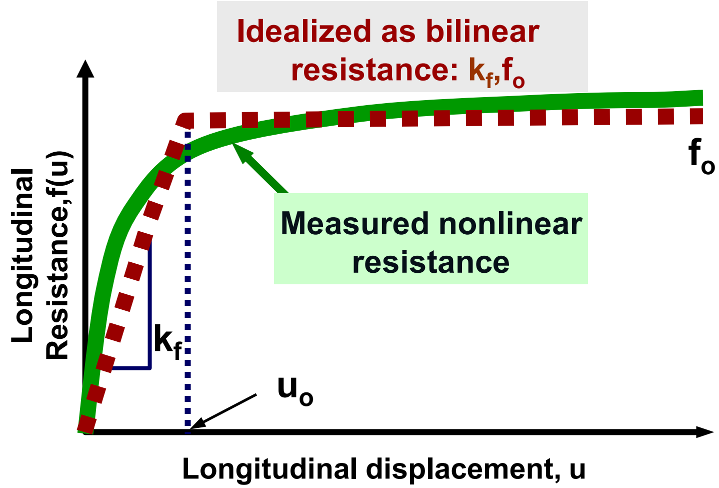


Note: for more details on buckling strength characteristics and parametric studies, refer to Kish & Samavedam: *"Track Buckling Prevention: Theory, Safety Concept and Applications"* [DOT/FRA/ORD-13/16]

Longitudinal Resistance

- Track longitudinal resistance is the restraint offered by the rail/tie structure against longitudinal movement by *(1) ties moving through the ballast, and (2) rails moving through anchors/fasteners. The composite behavior is a non-linear interaction of the two movement's "mechanics."*





Why an Important Parameter?

- Loss of track longitudinal resistance *(resulting in rail/tie longitudinal movement)* is a key contributor to a change in rail neutral temperature.
- Loss of track longitudinal resistance can also result in larger rail gaps in breaks/defect cuts causing more difficult repairs/RNT readjustments.

Track Curvature Issues

<u>Influence of Track Curvature</u>

- As curvature increases, buckling occurs at lower temperatures but the buckle amplitudes are smaller. Hence, tangent buckles have more serious derailment consequences.

  - ❑ **BUT** more incidents on curves than tangents due to:
    - Tensile force induced string-lining (*radial breathing*) in curves results in loss of neutral temperature, lateral resistance, and lateral alignment → higher buckling potential.

☑ Effective management of curve stability is a key part of track buckling prevention!

- **<u>New curve stability problem</u>: long train dynamics and track lateral shift**
  - ❑ High net axle lateral loads due to long train distributed power applications (especially in curves) causing track lateral shift, i.e., excessive alignment deviations

Influence of Lateral Alignment Defects

- Lateral alignment defects reduce buckling temperatures and *"trigger"* buckling, i.e., buckles occur at line defects

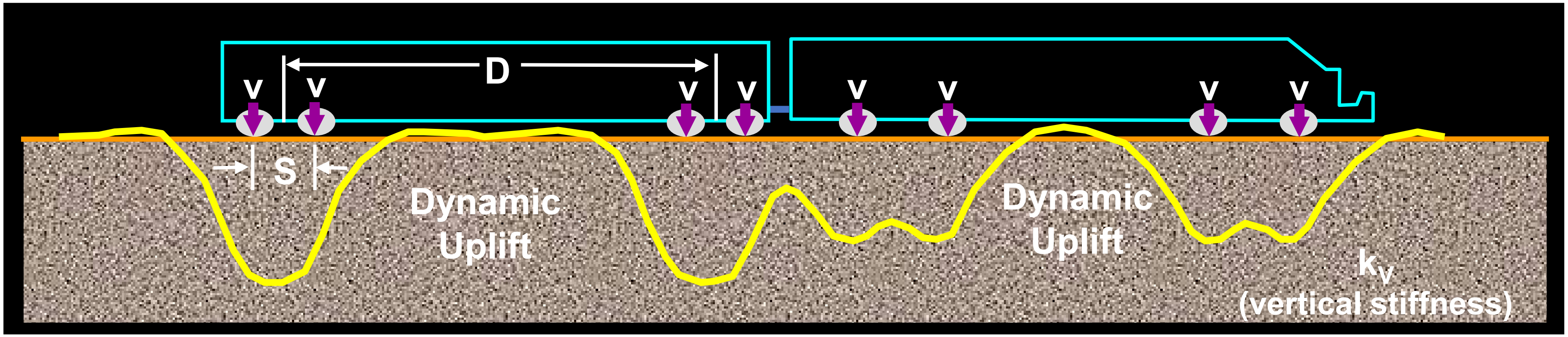
All things being equal, a track with FRA Class 3-line defects will buckle at a LOWER temperature than one with Class 5-line defects

- Mechanism: line defects tend to grow under the train (dynamic uplift and multiple axle passes) to a "critical" size which then creates a buckling prone condition

Take-Away: the better the track's lateral line defect condition, the higher its buckling strength (or buckling temperature.)

Track Loads/Dynamics Issues

Train Loads, Dynamics, and Parameters



- Under dynamic uplift, lateral resistance is reduced in the uplift zone, hence the amount of uplift becomes a factor in the buckling process.
- D,S,V, and k_v become influencing parameters in buckling predictions
- High train loads coupled with dynamic uplift can cause misalignment growth under the train leading to track shift or buckling
- Train speed, length (mass), and loads impart "dynamic energy" into the track structure and impact its buckling potential → key part of hot-weather speed restrictions

Take-Away: train loads, speeds, car parameters, and overall track/train dynamics also contribute to track's buckling potential.

Track Buckling Due to Other Energy Sources

<u>What Caused These?</u>

Guerrero – Oaxaca earthquake, Mexico 2012

Photo Source by Clarin Internacional

Canterbury earthquake, New Zealand, 2010

Photo by Malcolm Teasdale of Kiwirail

5 Key Parameters Influencing Track Buckling

- *Track resistance* √
- *Alignment deviations* √
- *Track curvature* √
- *Train loads/dynamics/uplift wave* √

- ***Rail neutral temperature (RNT)***

The most important parameter in CWR safety and buckling prevention!

What is Rail Neutral Temperature?

Rail Neutral temperature (RNT) is the rail temperature at which the net longitudinal force in the rail is zero. It is often associated with the rail *"installation"* or *"fastening"* temperature. It has a relationship to the force (P) in the rail:

$$P = EA\alpha(T_{RAIL} - RNT)$$

E is rail steel modulus of elasticity; A is rail cross section area; α is rail steel coefficient of thermal expansion

$EA\alpha$ (lbs/°F)
$2185_{115\#}$
$2600_{136\#}$

$$RNT = T_i - RF_k - RF_m$$

Installation Temperature

DRNT vs. Actual Laying Temp

Reduction Factor due to Rail Kinematics

Rail/track movement longitudinally, curve shifting laterally, and track vertical settlement

Reduction Factor due to Rail Maintenance

Relay, realignment, broken/defective rail repair, incorrect destressing

<u>NOTE</u>: many buckled-track-caused derailments can *ONLY* be explained if *"large"* reductions in RNT are present.

<u>Note:</u> *DRNT – Desired Rail Neutral Temperature*

Neutral Temperature Issues/Factors

What is the RF_k Reduction Factor?

- Experimental data indicate that neutral temperature reductions due to rail kinematics are typically in the range of 20°- 30°F (11-17°C) under "normal conditions."

Note: **for estimating purposes the rule-of-thumb RNT reduction factor for *normal* conditions (no breaks/cuts or excessive curve movement) is**

30°F (17°C)

[Rail Safety Advisory Committee (RSAC) on CWR Safety Standards]

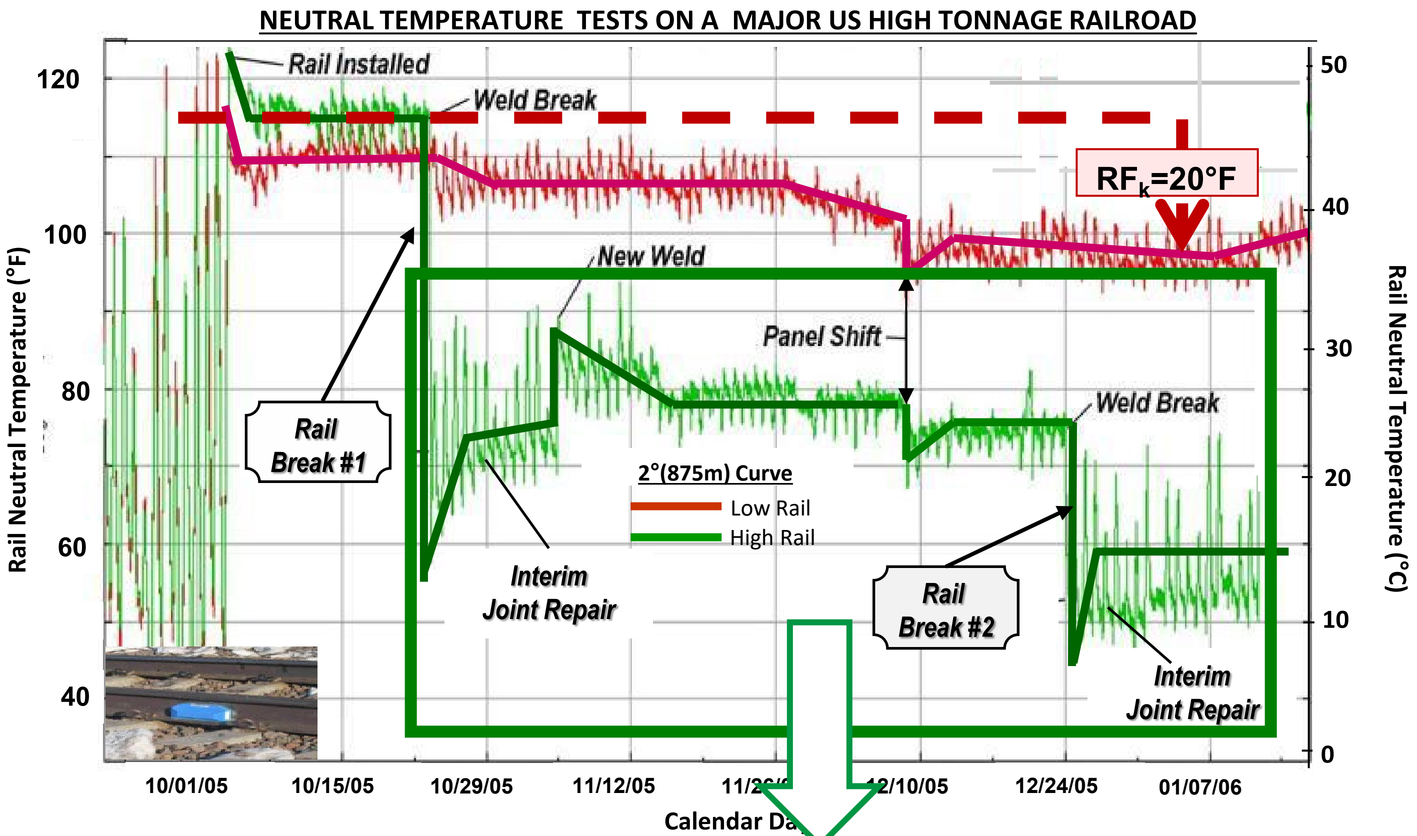
Consequence: if rail is installed at 100°F (38°C), a reasonable estimate is that after some time/tonnage the RNT is 70°F (21°C)

ISSUE

…but what if in line with most CWR Policy's requirements where RNT is readjusted to DRNT-20?

Neutral Temperature Issues/Factors

RNT Revenue Service Tests

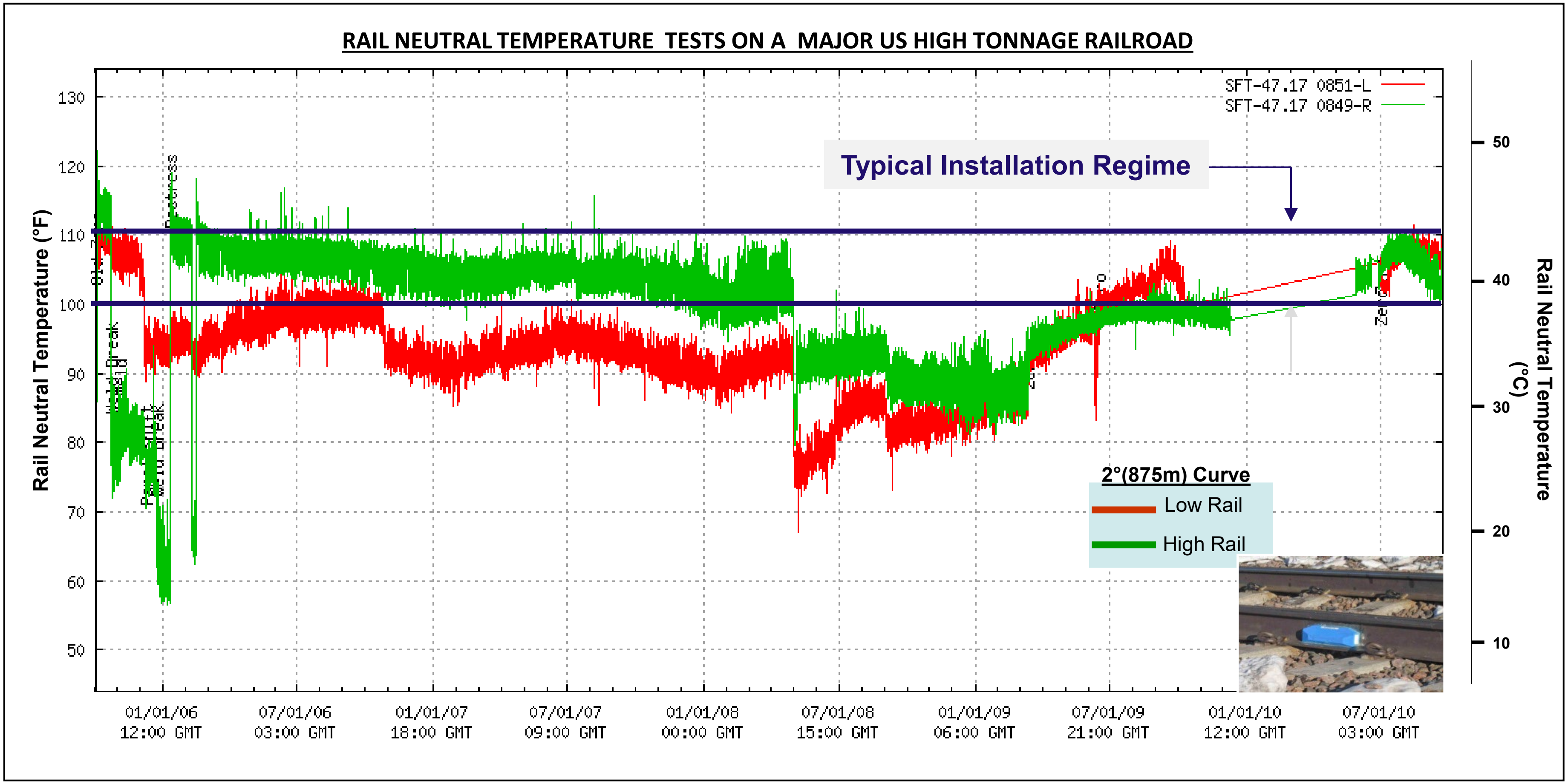


RNT = $T_i - RF_k - RF_m$

RNT's RF_m component typically can't be estimated!

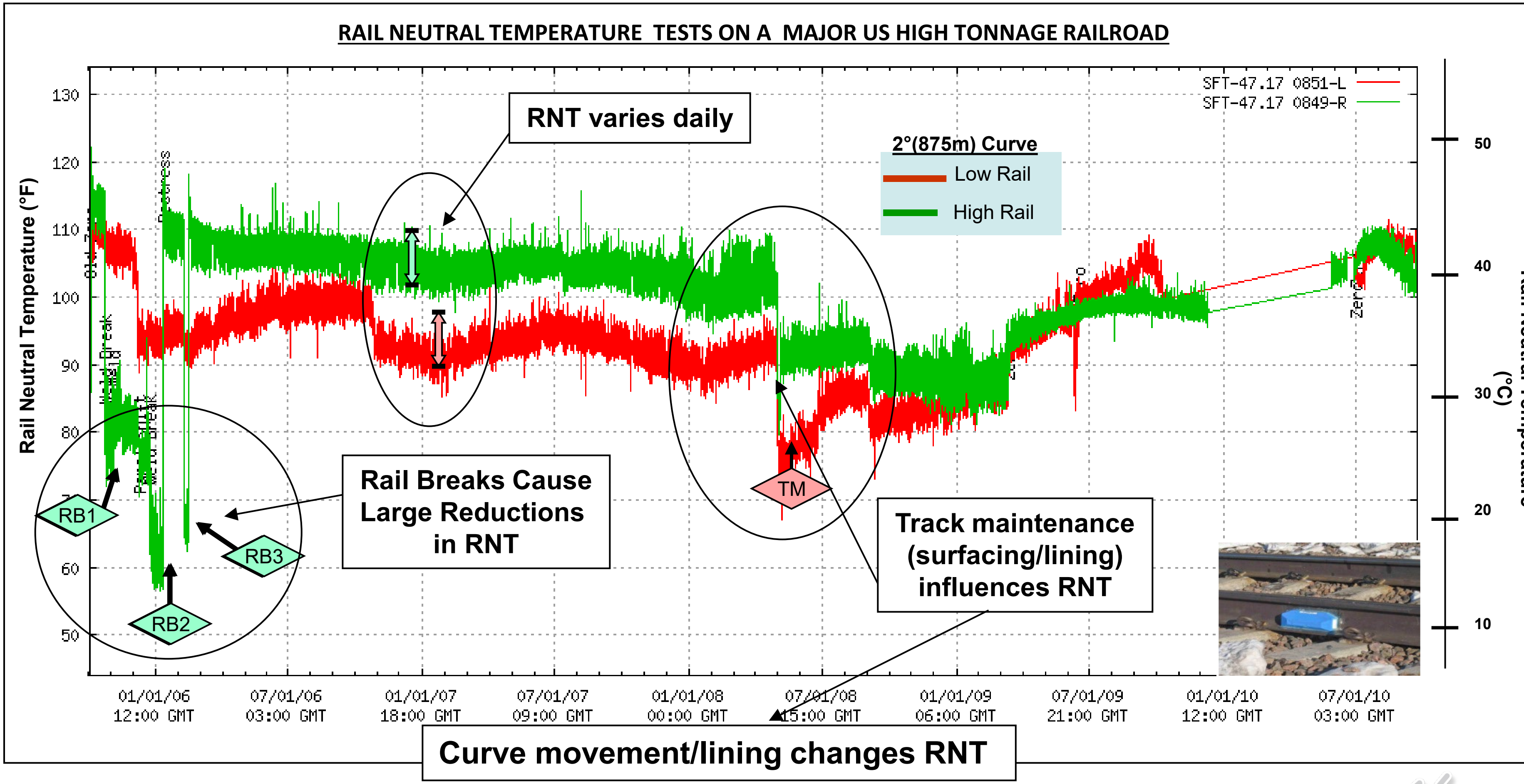
Rail Neutral Temperature Tests

5 Years of RNT Data on a US High Tonnage Test Site



Neutral Temperature Tests

5 Years of RNT Data on a US High Tonnage Test Site



5 Years of RNT Data on a US High Tonnage Test Site: Key Summary Points

- Tests confirmed the high variability of RNT

Key contributors: rail breaks/cuts; track maintenance; rail movement/breathing; and rail installation anomalies

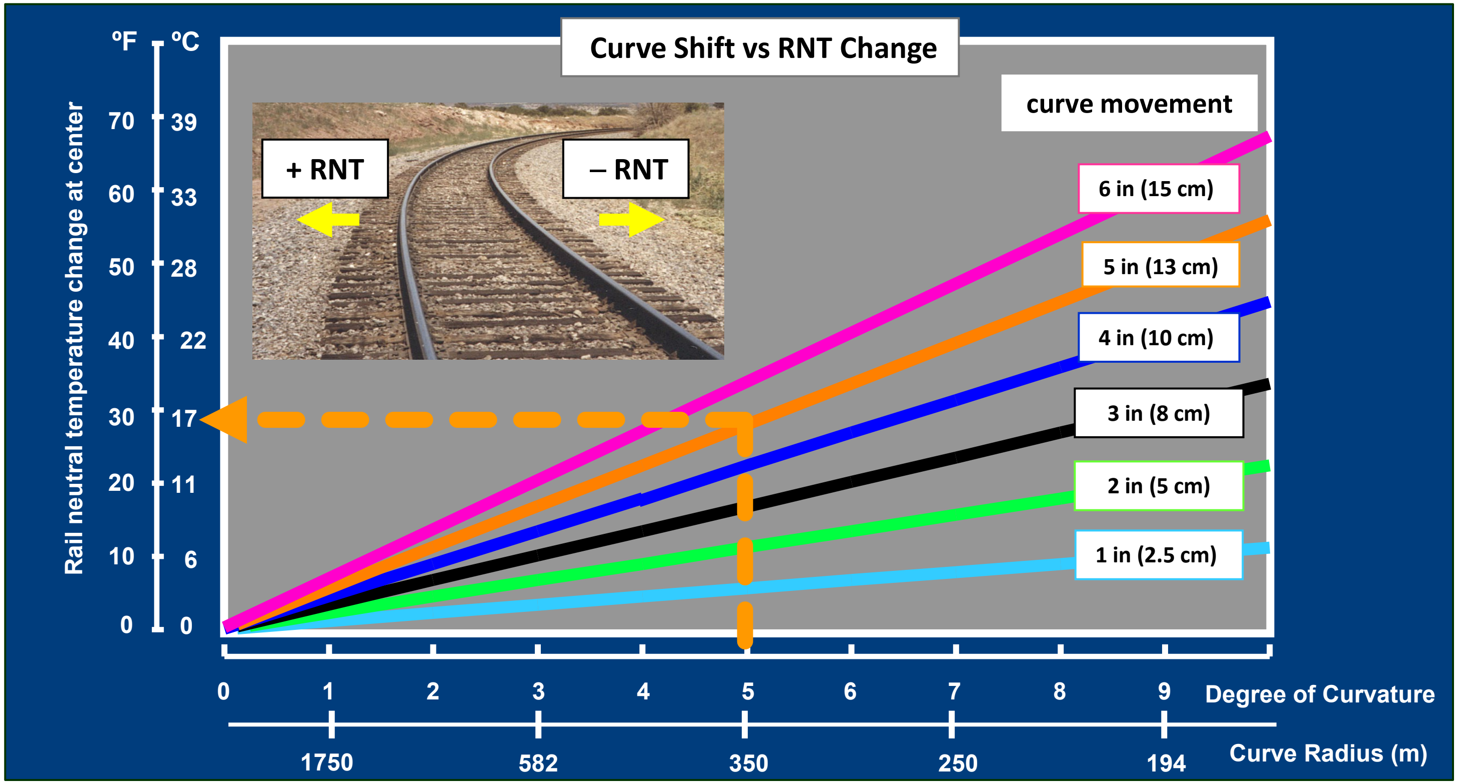
- Recalling RNT's three components:

$$\mathbf{RNT = T_i - RF_k - RF_m}$$

Although RF_k variation may be estimated by the 30°F RSAC safety factor, the RF_m component is highly rail break/cut and track maintenance dependent, and can only be evaluated via measurements.

Rail Neutral Temperature on Curves

Curve Shift and *"Lining Track In-Out"* Influence on RNT Change



Curve movement ⇛ reduced RNT + reduced lateral resistance + increased line defects ⇛ Buckling Prone Track

Effective management of curve movement is critical to maintaining curve stability.

Rail Neutral Temperature Summary

<u>Key RNT Summary Points</u>

- RNT of <u>both</u> rails govern buckling potential
- Track RNT (average of two rails) acceptability "Rule of Thumb":

unacceptable	marginal	fair	good

50°F(10°C) | 70°F(21°C) | 90°F(32°C)

- 20-30°F (11-17°C) decrease in RNT due to rail kinematics is typical; much larger RNT reductions in rail break/cut scenarios
- RNT is highly variable: $RNT = T_i - RF_k - RF_m$
- Many track buckle derailments can ONLY be explained through *reductions in RNT*

Major Impediment

- **RNT is very difficult to measure accurately, nondestructively, and continuously**

Stress/RNT Measurement Issues

RNT Measurement Concepts

Concepts Researched

- Mechanical/electrical resistance strain gage
- Rail uplift
- Rail vibration
- Vibrating wire/filament
- Ultrasonic wave
- Acoustic wave
- Electromagnetic/acoustic wave
- Magnetic permeability:
  (Barkhausen noise)
  (Magnetostriction)
- X-ray diffraction
- Fiber optics
- Moiré - fringe interference

- Have accuracy issues: (sensitivity to rail microstructure, residual stresses, track parameters; hard to get RNT from stress; *"zeroes"* required)
- Don't provide real-time, continuous data output
- Not nondestructive and not easily deployable
- Not railroad cost effective

Examples of Systems in USA: Salient Rail Stress Module (RSM); Rail Uplift (VERSE)

RNT Measurement Systems (USA)

Salient System's RSM

Continuous, real-time data; has **buckle hazard warning** and rail break detection capability; requires a "zero" calibration

VERSE

One time measurement; works in tension only; does not work in curves >3 deg; needs unfastening 100 ft of rail; may need rail profile measurement; no zero calibration

- **The development of a non-destructive, accurate, continuously monitoring system for RNT evaluation is a high-priority industry need**

How Can We Manage Something We Can't Measure?

Image by kaldy2508 | Published 23.5.2014
https://drahy.wordpress.com/2014/05/23/ze-zivota-zeleznicaru/schienen-von-der-rolle/

- INDUSTRY APPROACH: In the absence of reliable RNT measurement capability, develop/apply best practice guidelines to more effectively manage CWR.

Safety Concepts and Best Practice Guidelines

Track Buckling Safety Concept

What Are *"Safe"* Temperatures for Buckling Prevention?

- Track parameters and conditions

\+

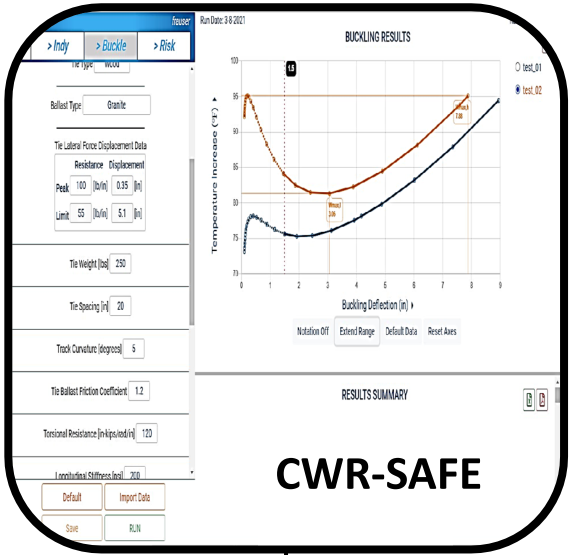
- Theory, models, and tests to evaluate buckling temperatures

\+

- Safety criterion (Thermal Force < Buckling Force)

- Rail properties
- Tie properties/spacing
- Curvature
- Alignment defect
- Track resistance:
  - (a) *Lateral*
  - (b) *Longitudinal*
  - (c) *Torsional*
- Tie/ballast friction coefficient
- Track modulus
- Vehicle type/characteristics

\+



"Safe" Temperature Increase Values (TBS)

Track Buckling Prevention Formula

$$T_{SO} = TBS + RNT - BMS$$

The Buckling Prevention Formula

$$T_{SO} = TBS + RNT - BMS$$

- T_{SO}: Safe Rail Operating Temperature
- TBS: Track Buckling Strength
- RNT: Rail Neutral Temperature
- BMS: Rail Operator Defined Safety Factor

PERFORMANCE STATEMENT

- If CWR is installed, adjusted, and maintained in line with the above track quality-based safety criterion, the track's buckling potential is expected to be at a minimum

Science and data driven; risk based safety performance standard for CWR

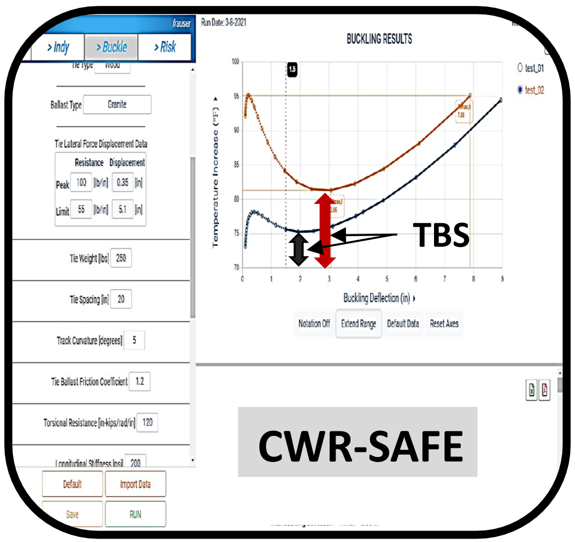
*Note: the RNT in the buckling prevention formula refers to a "track RNT," i.e., the average of two rail's RNTs.

<u>QUESTION</u>: What are TBS, RNT, and BMS and how to apply formula?

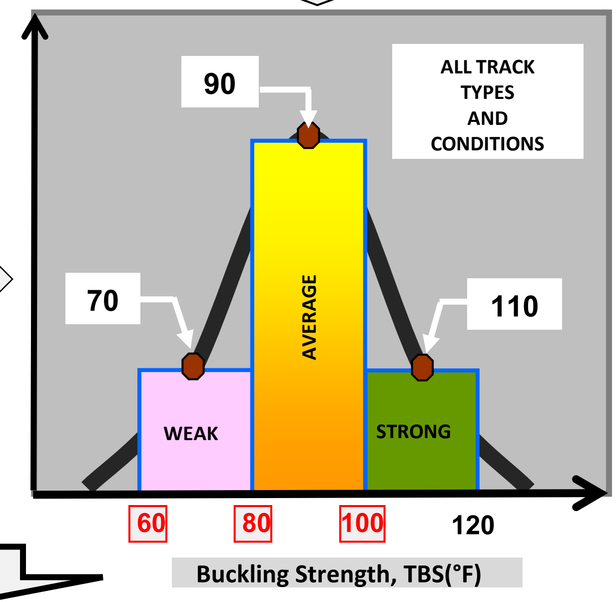
What Is TBS in the T_{SO} Equation?

<u>Definition:</u> Track Buckling Strength (TBS) is the *"lowest" or "safest"* rail temperature increase above neutral to prevent buckling.

- It is analytically determined
- It is track-type/condition dependent



Over 1000 Buckling Calculations



<u>TBS RULE OF THUMB</u>: 60°F : 80°F : 100°F CRITERION

weak	average	strong

Buckling Strength Characterization

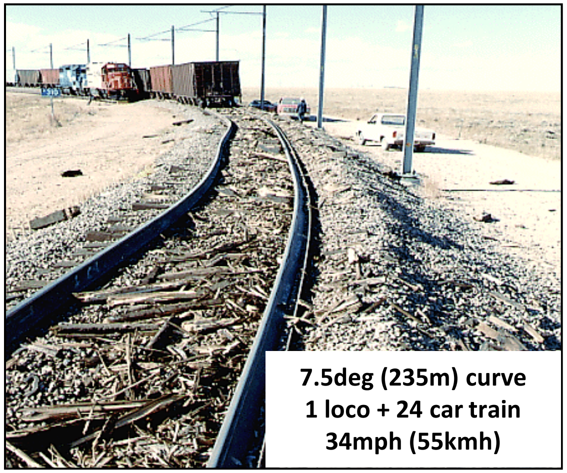
Buckling Strength (TBS) *"Rule of Thumb"* Descriptors

Weak (60°F)	Higher degree curves (> 3 deg); typically, Class 3-4 alignment deviations; recently maintained to partially consolidated ballast
Average (80°F)	Tangent to 3 deg curves; Class 4-5 alignment deviations; "standard" ballast lateral resistance
Strong (100°F)	Tangent, well consolidated, high-quality track; Class 4-6 alignment deviations
Based on over 1000 buckling calculations + 14 track buckling tests	

Proof Examples:

(1) a full-scale dynamic buckling test representing "weak" track conditions [7.5 deg curve; 136# rail; tamped ballast; Class 4 alignment deviations]; track buckled under the train at **62°F** above neutral.

(2) RSAC/FRA assumed **70°F** as "weak" buckling strength in developing the new CWR standards under CFR 49 § 213.119 (October 2009). [See RSAC 70:70 Rule]



7.5deg (235m) curve
1 loco + 24 car train
34mph (55kmh)

Note: For details on buckling strength characteristics, parametric studies, and tests, refer to Kish & Samavedam: *"Track Buckling Prevention: Theory, Safety Concept and Applications"* [DOT/FRA/ORD-13/16]

RNT Determination for T_{SO} Equation

$$T_{SO} = TBS + RNT - \boxed{BMS}$$

Measure

Direct RNT Monitoring
via
RSM Technology

Install RSMs either localized or territory wide and use actual measured RNT data in T_{SO} equation to dictate remedial actions

Estimate

Industry Experience
+
Test Data on RNT

RNT Reduction Factor:

30°F from RLT (RSAC)

Example: If CWR installed at 100°F, it's effective RNT is 100-30=70°F

Calculate

Industry CWR Policy
+
RNT Recording

Most CWR Policies require recording RNTs when rail breaks or is cut for defect removal

BMS

Since RNT is only *"approximate,"* need to apply a safety factor, BMS

Current US rule of thumb for BMS: between 0 and 20°F (depending on railroad's risk acceptance, track type/condition, and maintenance)

T_{SO} Equation Applications

T_{SO} EQUATION APPLICATION EXAMPLES

- Establish *"critical neutral temperature"* based maintenance limits
- Determine hot-weather speed restriction temperatures

See Kish & Clark IHHA 2015 Paper

- Evaluate rail break/defect repair temperatures

See RSAC Table in Generic Plan

- Develop "Buckling Hazard" warnings

$BMS = TBS + RNT_{MEAS} – T_{MEAS}$

The RNT_{CRIT} Concept for Maintenance Intervention

Question: What is a minimally acceptable track RNT?

Answer: As defined by the T_{SO} equation:
$[T_{SO} = TBS + RNT – BMS]$

Max Rail Temp

Track Buckling Strength

Safety Factor (Buckling Margin of Safety)

$$RNT_{CRIT} = T_{MAX} – TBS + BMS$$

EXAMPLE: 70°F 140°F 80°F 10°F

INTERVENTION CRITERION:

Destress/readjust those locations exhibiting $RNT < RNT_{CRIT}$

T_{SO} Equation Applications

The RNT_{CRIT} Concept for Maintenance Intervention

RNT Evaluated from Rail Break Data

Month	# of Service Defects	T_{Br} (deg F)	RNT_{PBr} (deg F)	ΔT Causing Break (deg F)	RNT Change (from install)
January	22	19	60	41	40
February	7	19	67	[illegible]	33
March	5	48	57	[illegible]	43
April	1	38	83	45	17
August	2	55	78	23	22
September	3	44	101	57	-1
October	11	37	84	47	19
November	15	27	77	50	23
December	20	19	74	55	26
TOTAL	86	26	72	46	28

DESTRESS in line with RNT_{CRIT} criterion!

Avg Rail Break Temp

Avg Subdivision RNT

Avg Temp Difference Causing Break

Avg RNT Decrease From DRNT

T_{Br} – Rail temperature at the time of separation
RNT_{PBr} – Prebreak rail natural temperature

U.S. Department of Transportation
Federal Railroad Administration

The Buckling Temperature Concept

How to Determine Buckling Temperatures (BTs)?

(BT = TBS + RNT)

TBS RULE OF THUMB: 60 : 80 : 100 CRITERION

weak | average | strong

TRACK RNT

unacceptable	marginal	fair	good
	50°F	70°F	90°F

Track Buckling Strength	Buckling Temp [Rail(°F)]
Weak (60)	130 (54°C)
Average (80)	150 (66°C)
Strong (100)	170 (77°C)

What is T_{RAIL} vs T_{AMB}?

Buckling T_{AMB} [US: $T_{RAIL} = T_{AMB} + 30°F$]
100 (38°C)
120 (49°C)
140 (60°C)

NOTE: a more correct formula is $T_{RAIL} = T_{AMB} + 30°F + (T_M)$ → **(Mechanical heating)**

BEST PRACTICE GUIDELINES FOR BUCKLING PREVENTION: *"THE 5 RULES"*

1. Know/Understand the Track's Buckling Strength
2. Maintain Rail Neutral Temperature in the Desired Range
3. Ensure Adequate Track Lateral Resistance
4. Maintain Good Lateral Alignment Condition
5. Perform Track Inspections and Remedial Actions

Industry's CWR policies/procedures/training programs play key roles in effective applications of best practice guidelines

BEST PRACTICE GUIDELINES FOR BUCKLING PREVENTION

1. Know/Understand the Track's Buckling Strength: Rudimentary knowledge of the CWR track's buckling strength, parameters and safety concepts are important.

Key Parameters

- *Track resistance*
- *Alignment defects/curvature*
- *Train loads/dynamics*
- *Rail neutral temperature*

Temp Increase "Rule of Thumb" To Cause Buckling

Track Buckling Strength	"Safe" Temperature Increase Above Neutral, TBS (°F)
Strong	100-120
Average	80-100
Weak	60-80

Track Buckling Prevention Formula

$$T_{SO} = TBS + RNT - BMS$$

BEST PRACTICE GUIDELINES FOR BUCKLING PREVENTION

2. Maintain Rail Neutral Temperature in the Desired Range: **Maintaining RNT at a high, stable, and uniform level is the most important facet of track buckling prevention.**

- Prevent rail creep by ensuring effective anchors/fasteners
- Limit/monitor curve movement to reduce RNT change
- Have QC on installation of CWR to ensure preferred RLT and its uniformity; if rail laid cold, MUST readjust prior rail temps approaching the RLT range
- Monitor/record rail break/defect repairs for RNTs and added rail conditions
- When making final repairs to defective/broken rails, be sure to perform RNT readjustment prior to the onset of warm weather
- Have/develop effective rail repair procedures to facilitate "correct" readjustment of RNT

Requires Effective Installation, Restressing, and Destressing Procedures!

BEST PRACTICE GUIDELINES FOR BUCKLING PREVENTION

3. Ensure Adequate Track Lateral Resistance: Have effective ballast maintenance practices

- Provide/maintain full ballast section (i.e., full cribs and shoulders in line with railroad specs)
- Provide adequate ballast consolidation after ballast work such as surfacing, lining, and tamping:

  (a) via Dynamic Track Stabilization (DTS)
  (b) via reduced speed traffic for a minimum of 0.1 MGTs (100,000 tons)
- Monitor curves for excessive chording-in-out; provide/maintain adequate shoulders on low rail side
- Be aware of *"fouled"* ballast condition which can create drainage problems leading to geometry degradation, "soft" (reduced resistance) ballast, and winter- time frozen ballast (which upon thawing can reduce lateral resistance)

BEST PRACTICE GUIDELINES FOR BUCKLING PREVENTION

4. Maintain Good Lateral Alignment Condition: Preserve alignment geometry to required limits

- Ensure good lateral geometry condition, especially at the onset of warm weather and after ballast maintenance
- Monitor curve line defects resulting from non-uniform movement, especially after a winter pull-in condition and during/after surfacing curves in cold temps (may require programmed curve staking – see RSAC rule)
- During hot temperatures, monitor/inspect for increased alignments, especially after train passage (Note: Often one train can create a misalignment or a small amplitude buckle, leaving the next train vulnerable to a buckling derailment)

BEST PRACTICE GUIDELINES FOR BUCKLING PREVENTION

5. Perform Track Inspections and Remedial Actions: Both hot and cold weather inspections are essential to identify buckling prone conditions. (Note: Cold temperature rail defect/break repairs can influence the track's buckling potential at warm temperatures.)

- Inspect for substandard ballast, alignment, and excessive rail movement attributable to substandard anchor/fastener conditions
- Inspect for adverse track conditions after maintenance, which disturbs ballast
- Conduct hot weather inspections for wavy, kinky, tight rail conditions and remediate
- Perform cold weather inspections for broken rails, bent bolts, pull-aparts, curve movements, wide gap between rail-ends, canted rail, cracked or broken joint bars, and frozen ballast → re-inspect after spring thaw
- Apply remedial actions (such as RNT readjustments and/or speed restrictions) when/where warranted.
- Inspect approaches to "fixed" points for evidence of degraded conditions on anchor/fastener, ballast, and alignment

Guidelines Summary Issues

❑ **Inspect at approaches to *"rigid"* structures:**

D
E
G
R
A
D
E
D

- RNT condition
- ballast condition
- alignment condition

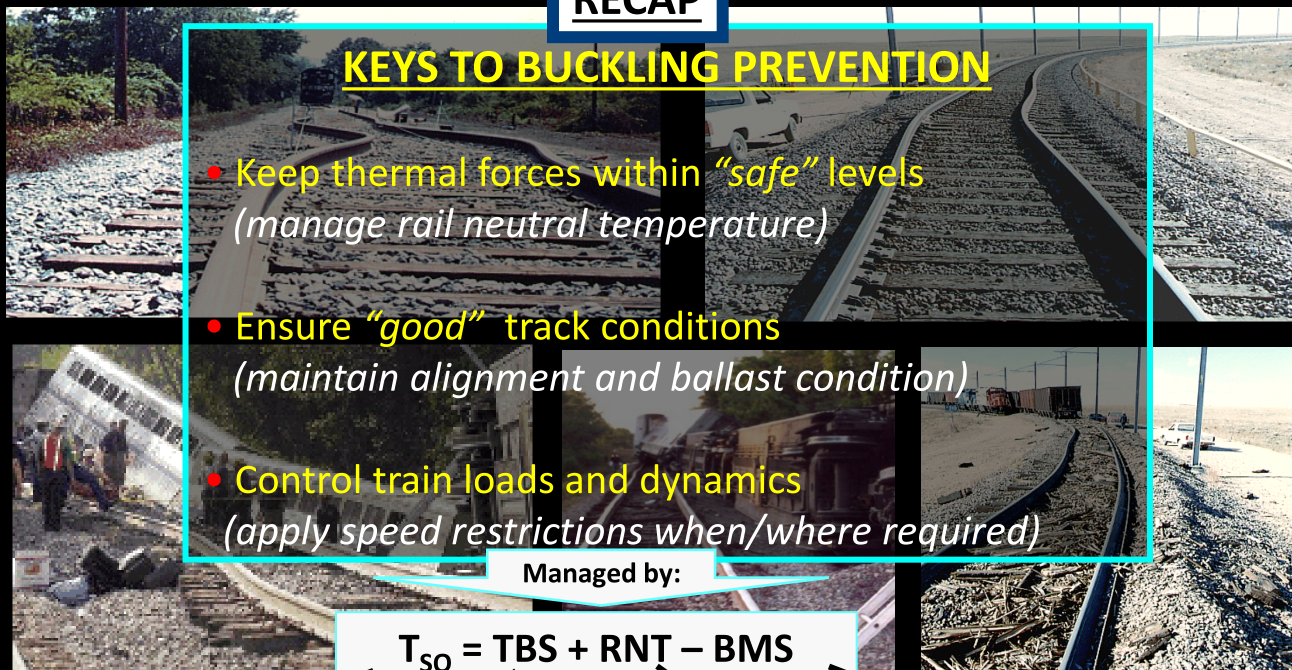
BUCKLED TRACK

WHY IMPORTANT? – Because 50% of T109 derailments occur within 400 ft of fixed structures.

Track Buckling Prevention and Improved Rail Stress Management

SUMMARY

RECAP



KEYS TO BUCKLING PREVENTION

- Keep thermal forces within *"safe"* levels
  (manage rail neutral temperature)
- Ensure *"good"* track conditions
  (maintain alignment and ballast condition)
- Control train loads and dynamics
  (apply speed restrictions when/where required)

Managed by:

$$T_{SO} = TBS + RNT - BMS$$

- **Safe Rail Operating Temperature**
- **Track Buckling Strength** → **Well Understood!**
- **Rail Neutral Temperature** → **More R&D Required!**
- **Rail Operator Defined Safety Factor**

KEY BENEFITS

Performance Based Safety Standard

If CWR is installed, adjusted, and maintained in line with the track buckling prevention formula, the track's buckling potential is expected to be at a minimum.

Improved safety, Capacity, and revenue!

Abbreviations

BMS	Buckling margin of safety	**L/V**	Lateral to vertical force ratio
CFR	Code of Federal Regulations	**MGT**	Million gross tons
CL	Curve length	**P**	Force in rail
CM	Curve movement	**PRLT**	Preferred rail installation temperature
CTEF	Concrete ties, elastic fasteners	**RNT**	Rail neutral temperature
CWR	Continuous welded rail	**RF**	Reduction factor
D	Degree of curvature	**RLT**	Rail laying temperature
DRNT	Desired rail neutral temperature	**RSAC**	Rail Safety Advisory Committee
DTS	Dynamic track stabilizer	**RSM**	Rail stress module
EOTA	Every other tie anchored	**RTLR**	Rail-track longitudinal resistance
ERA	Effective rail added	**STPT**	Single tie push test
ETA	Every tie anchored	**T**	Temperature
FRA	Federal Railroad Administration	**TBS**	Track buckling strength
IR	Interim repair	**TLR**	Track lateral resistance
L	Length	**USP**	Under sleeper pad

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