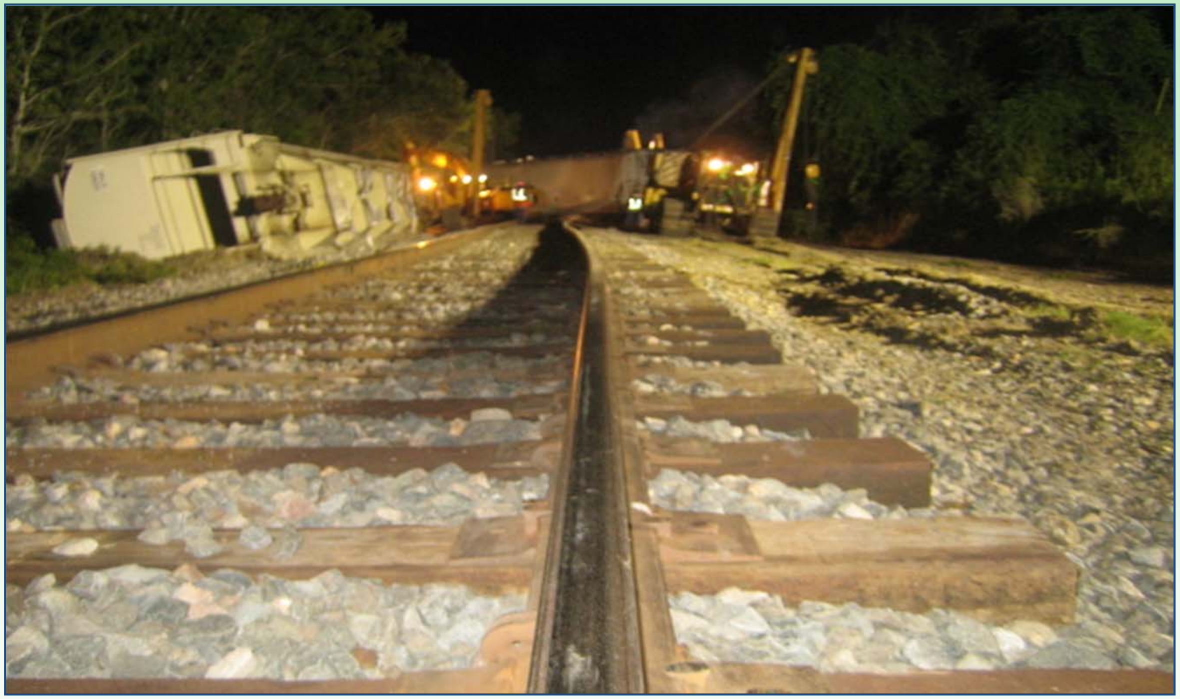
Ballast Strength and Track Lateral Stability



Dr. Andrew Kish
Kandrew Inc. Consulting Services
Peabody, MA, USA

Presentation Themes/Outline

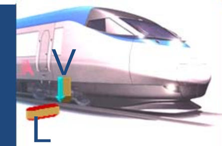
How Is Ballast Relevant to WRI and Vehicle/Track Interaction?

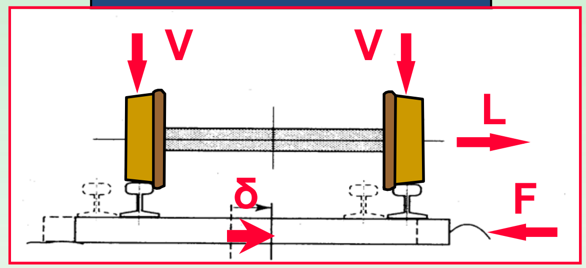
High Thermal Load Problem

$P = AE\alpha\Delta T$

Ballast is a Key Parameter in Providing Track Lateral Stability

High Axle L/V Problem





- **Effective management of lateral stability requires determination of minimum requirements on ballast lateral strength**

Questions:

(1) What are minimum requirements on ballast?

(2) Have we reached the limit of ballast strength required to maintain lateral geometry to "safe" levels?

FRA Track Failure Caused Derailment Statistics

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ACCIDENTS IN DESCENDING FREQUENCY BY CAUSE

ALL US MAINLINE TRACK (2010-2013)

Track / Derailment / Main (through November, 2013)

	Accident Cause [T-Codes: 65 Total]	No. of Accs.	% Total	2010	2011	2012	2013
#1	**T109 Track alignment irreg. (buckled / sunkink)**	**105**	**14.7**	**29**	**37**	**27**	**12**
	T110 Wide gage (defective / missing crossties)	61	8.5	18	11	16	16
	T207 Detail fracture - shelling / head check	59	8.2	14	19	17	9
	T220 Transverse / compound fissure	55	7.7	21	14	13	7
	T001 Roadbed settled or soft	44	6.1	16	12	7	9
	T221 Vertical split head	42	5.9	9	13	7	13
	T102 Cross level track irreg. (not at joints)	34	4.7	5	14	8	7
	T314 Switch point worn or broken	27	3.8	11	8	6	2
	T210 Head and web sep. (outside of bar limit)	23	3.2	9	5	5	4
	T202 Broken base of rail	22	3.1	5	4	7	6
	T101 Cross level of track irregular (joints)	21	2.9	6	10	3	2
#12	**T108 Track alignment irreg. (not buckled / sunkink)**	**19**	**2.7**	**4**	**3**	**5**	**7**
	T111 Wide gage (spikes / other rail fasteners)	15	2.1	1	9	2	3
	T299 Other rail and joint bar defects	15	2.1	2	5	3	5
	T002 Washout / rain / slide / etc. dmg - track	14	2.0	5	6	.	3

- **Track buckling caused derailments rank #1 in BOTH the number of derailments and $$$ damage/derailment ⇒ a high-priority industry goal to improve!**

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Talking Points

- What is ballasted track lateral resistance (TLR) and key parameters, and how to measure?
- What factors influence ballast lateral resistance?
- What are minimum requirements for consolidation after ballast work?
- What is the US data on influences of ballast maintenance and consolidation – and do we need more?
- What impacts on track buckling and track shift?
- What research needs?

What is track lateral stability?

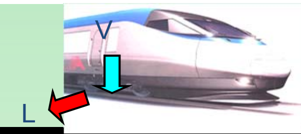
<u>Track Lateral Stability:</u> is managing the vehicle and environmentally induced loads (L-V-P loads) to keep track geometry within "safe" limits

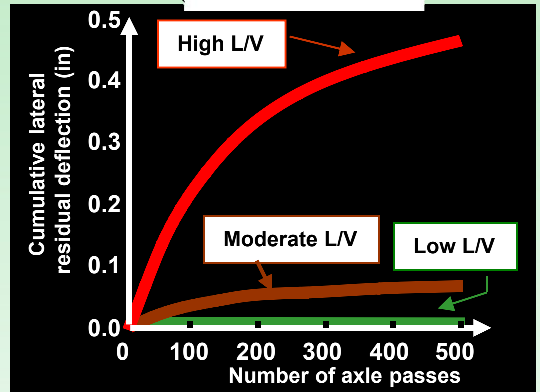
Track Lateral Stability Mechanism

Step	Event	Major causal factors
1	Formation of initial track misalignments	1) High L/V's 2) Reduced local lateral resistance 3) Initial imperfections (welds), construction anomalies, and install errors
2	Growth of misalignments (Track Shift)	1) Increase in L/V, and high longitudinal forces 2) Reduced lateral resistance at line defects 3) Track *"dynamic uplift"* 4) Many cycles of L/V's
3	Buckling	1) High longitudinal force 2) Reduced T_N (stress-free temperature) 3) Weakened lateral resistance 4) Train loads and dynamics 5) Misalignments generated by track shift

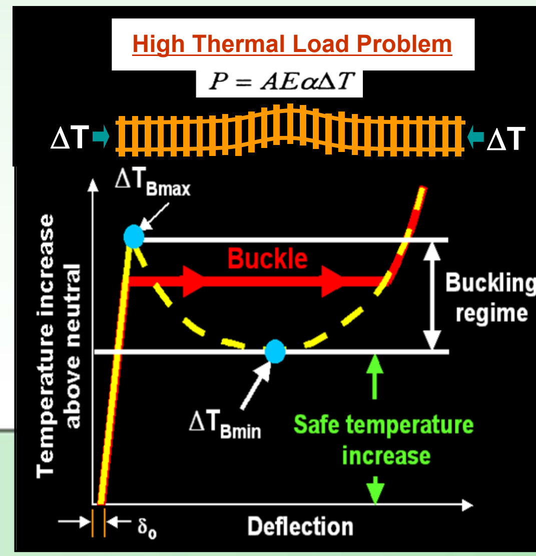
CWR-SAFE

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



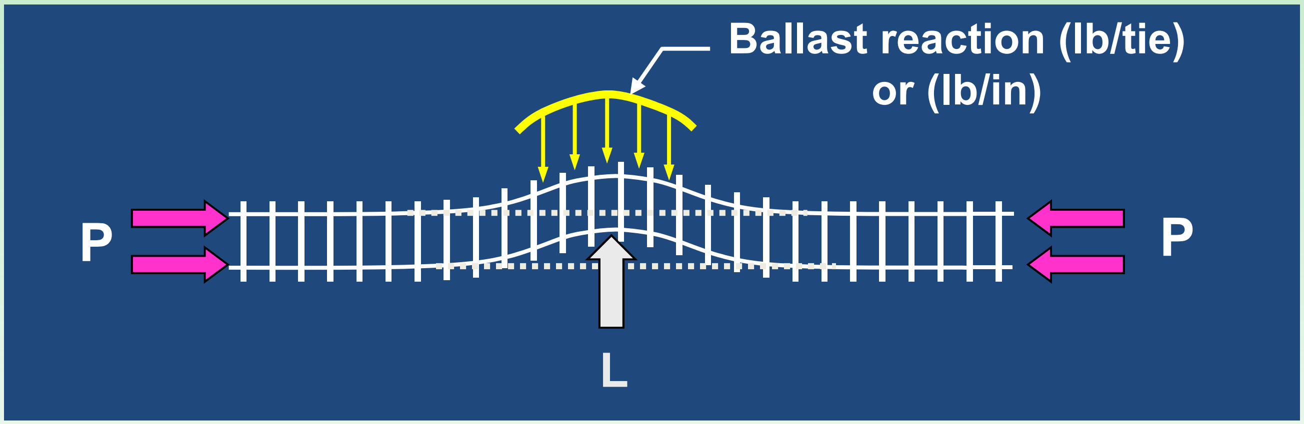


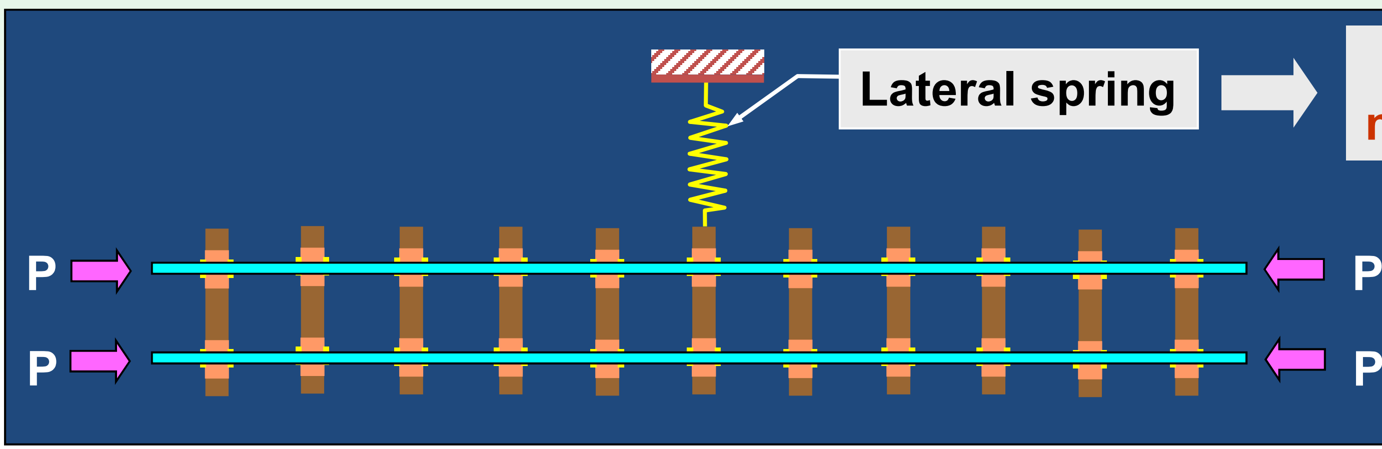
TREDA



What is track lateral resistance (TLR)?

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





How to measure?

How to Measure?

Measurement Methods

- single tie push test (STPT) √
- discrete cut panel pull test
- track lateral pull test (TLPT)
- analytic empirical model (CWR-SAFE)*
- continuous dynamic measurement (Plasser – DTS)

* Model "trained" by over 1000 STPT measurements to provide lateral resistance based on inputs of: tie type, shoulder width, crib content, and consolidation level.

Typical Behavior and Values

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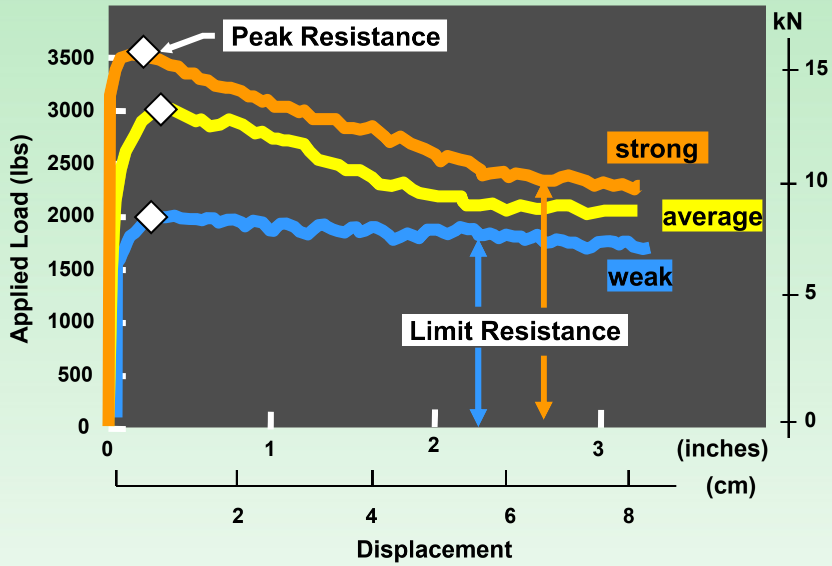
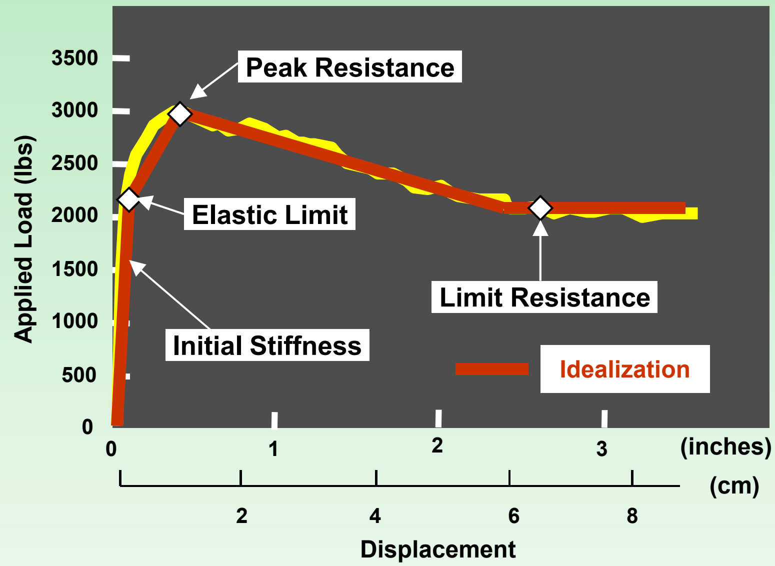
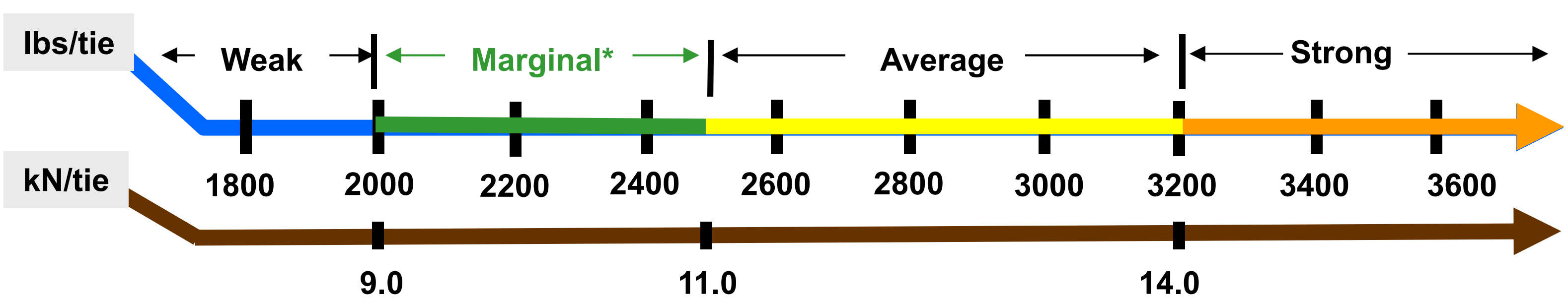
What is an STPT Signature?





Typical concrete tie peak values (static)

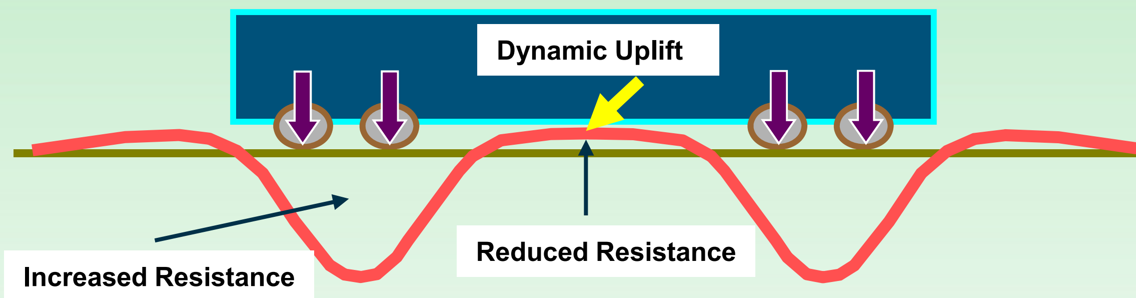


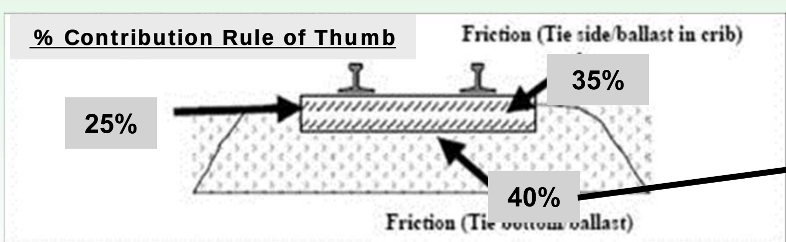
* Typical consolidation range

Note: for wood ties subtract 500 lbs/tie (2.2 kN/tie)

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)





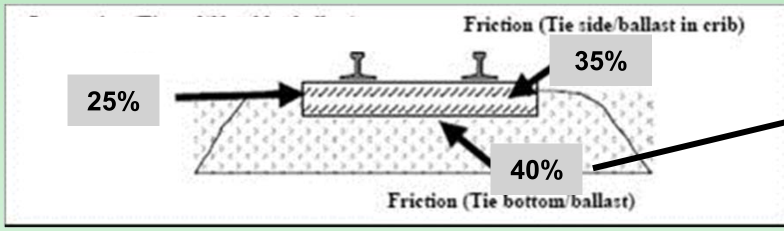
Can result up to 40% loss of lateral resistance

Key Points:

- Track stability analyses require both loaded and unloaded resistances
- Do not neglect the importance of the 25% shoulder width contribution

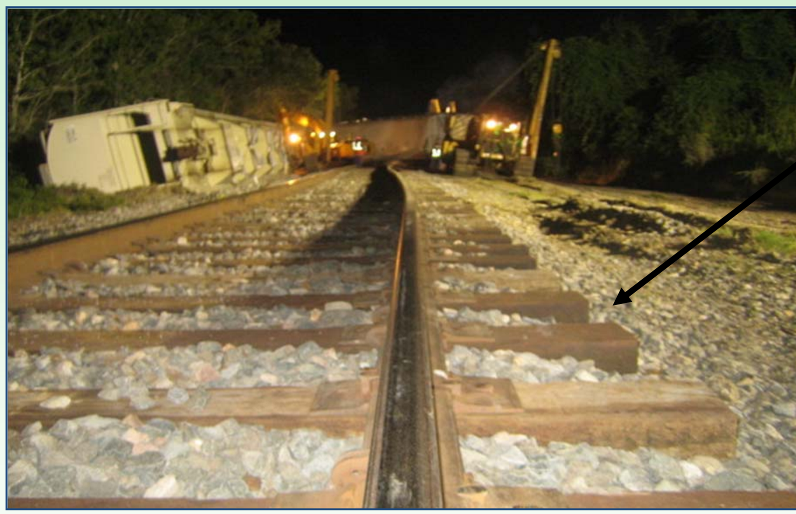
Factors Influencing Lateral Resistance

Question: why is shoulder width important?



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

Reduced shoulder



Answer:

(1) To "compensate" for dynamic uplift induced loss of resistance

(2) To keep curves from moving under cold temperature tensile forces

Lateral Resistance Problem in Curves

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- Curves “breathe” (move in-and-out) under temperature changes. This results in neutral temperature (RNT) change.

- As curves pull in ballast at tie ends get voided thereby reducing lateral resistance. Also there can be line defects formed due to non-uniform curve movement.

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

❑ Take-away: maintain good ballast shoulders on both the low and the high sides of curves + destress to readjust RNT

Dynamic Lateral Resistance

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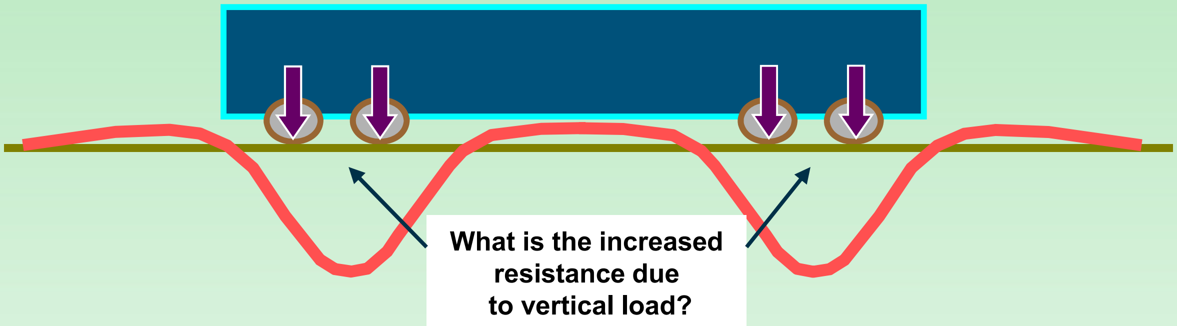
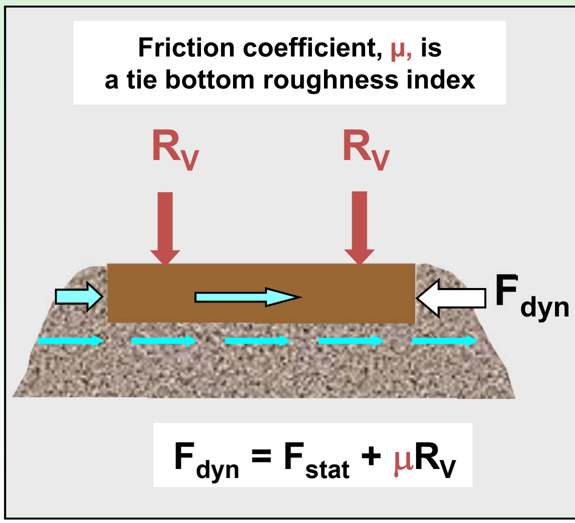
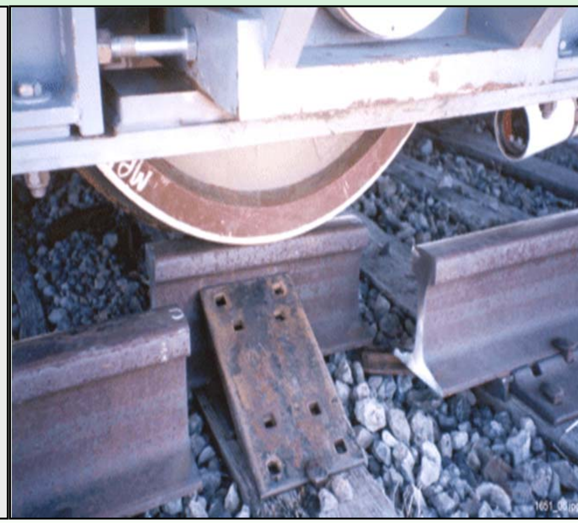
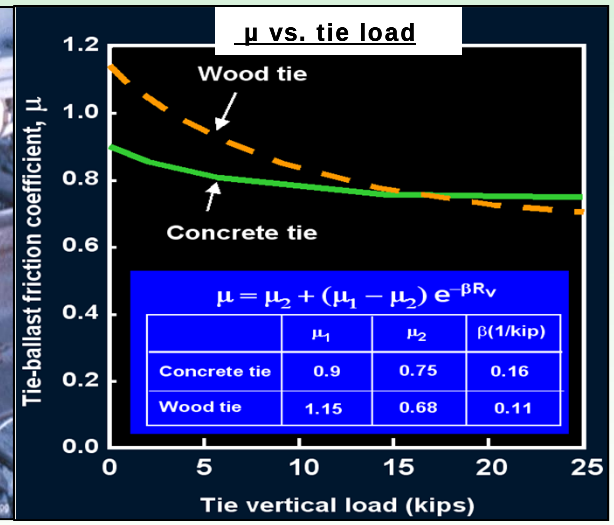
The Tie/Ballast Friction Coefficient Concept









- Friction coefficient μ is a key parameter in lateral stability analyses

Factors Influencing Lateral Resistance

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- **Tie type, weight, shape and spacing; ballast type and condition (fouled, frozen, etc.); shoulder width, crib content; vehicle loads, and maintenance and consolidation**

- **Ballast maintenance (surfacing, tamping, lining) can reduce TLR by 40 - 60%; requires consolidation either by dynamic track stabilization (DTS) or traffic tonnage.**

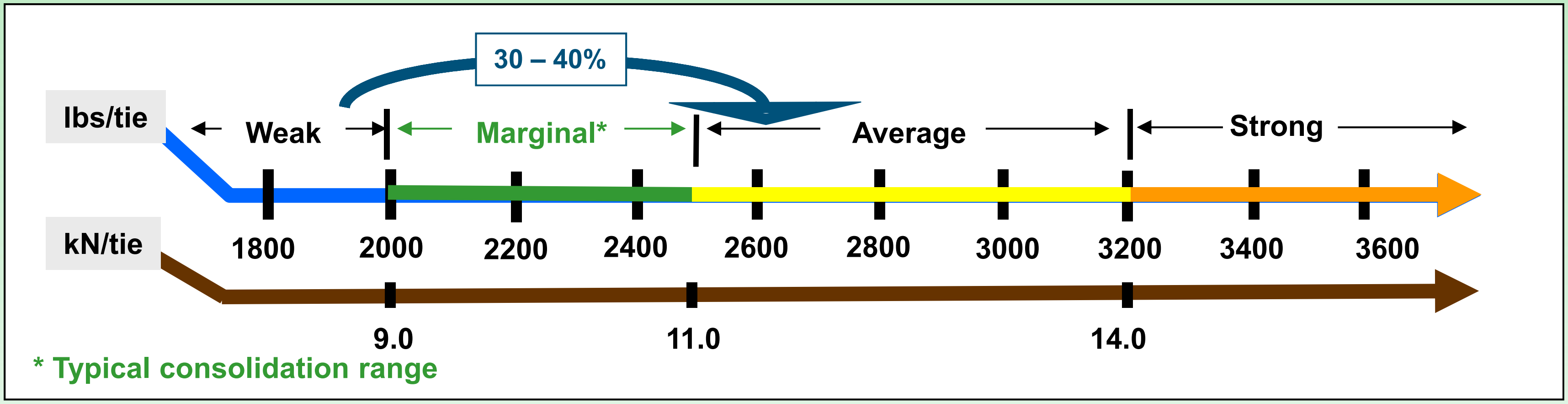
- **DTS can increase the reduced TLR by 30 – 60%; traffic consolidation may require over 0.1 MGTs (million gross tons) of traffic at reduced speeds to produce at least a 30% DTS equivalent.**

Question: how much TLR recovery is required to ensure lateral stability?

Answer: a minimum of 30-40% (although some track conditions may require more).

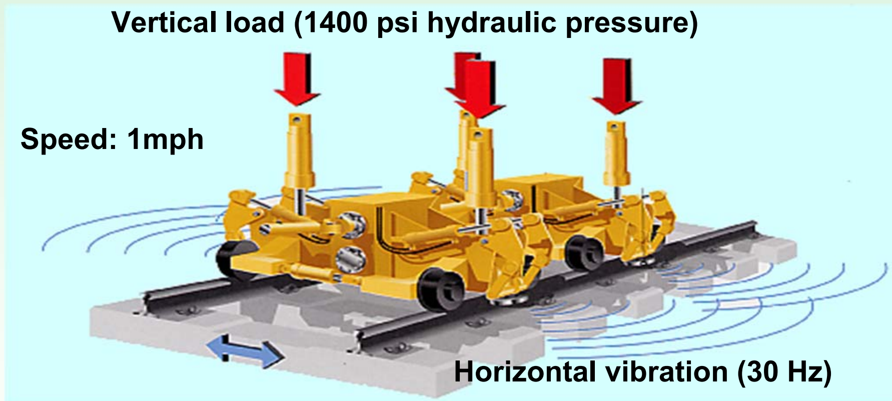
TLR Recovery After Ballast Maintenance

Question: how much TLR recovery is required to ensure lateral stability?



DTS principle - vertical loads coupled with horizontal vibration:

- restores a large part of the ballast particle's interlocking capability, and
- increases the tie bottom/ballast friction coefficient. Test results indicate an immediate 30-60% TLR recovery.



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

ASSUMPTION

0.1 MGT = 30 - 40% DTS increase

This equivalence has NOT been demonstrated in the US [more R&D is needed to evaluate]

US Data on Ballast Consolidation

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AREMA 2011 PAPER

AAR/TTC Tests – wood ties (1990 – Trevizo, [9])
- Tangent: 17% recovery after 0.1MGT; 32% after 1MGT
- 5° Curve: 9% recovery after 0.1MGT; 21% after 1MGT

Volpe/FRA Tests at TTC - wood and concrete (1987-1990; Kish, et al, [10])
- Wood - tangent: 26% recovery after 0.1MGT
- Concrete – 5° Curve: 52 % reduction due to tamping
- Concrete – 5° Curve: 22% recovery after 0.1MGT

Volpe/Union Pacific Tests – concrete (2000-Sluz, [11])
- Concrete (new-scalloped) - 17% recovery after 0.35MGT
- DTS increase: 33%

Volpe/Amtrak/FRA Tests – concrete (2001- Kish, et al, [12, 13])
- 43% reduction due to surfacing with ½ inch lift
- DTS increase: 31%

UP/Foster-Miller Tests – wood/concrete/old/new (2001-Samavedam [14])
- 39-70% reduction due to tamping/surfacing
- 0.1MGT had negligible influence on wood after tamping; 0.2MGT was 28%
- Heavy rain/wet ballast: 20% decrease in lateral resistance on wood

UP/TTCI Tests – concrete/tangent/high tonnage (2010-Clark & Read @ IHHA 2011)
- Over 70% reduction due to surfacing
- 0.1MGT increase: 49%
- DTS increase: 60%
- Tonnage after DTS reduced TLR by 11%

DTS Increase: 31 – 60%

US Data on Ballast Consolidation

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0.1 MGT traffic DOES NOT not produce the DTS equivalent, but LOWER!

More R&D is required to better quantify tonnage based consolidation influence and mechanics

US Data on Ballast Consolidation

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What buckling safety after maintenance and after consolidation?

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US Data on Ballast Consolidation

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Volpe/Amtrak Test Summary

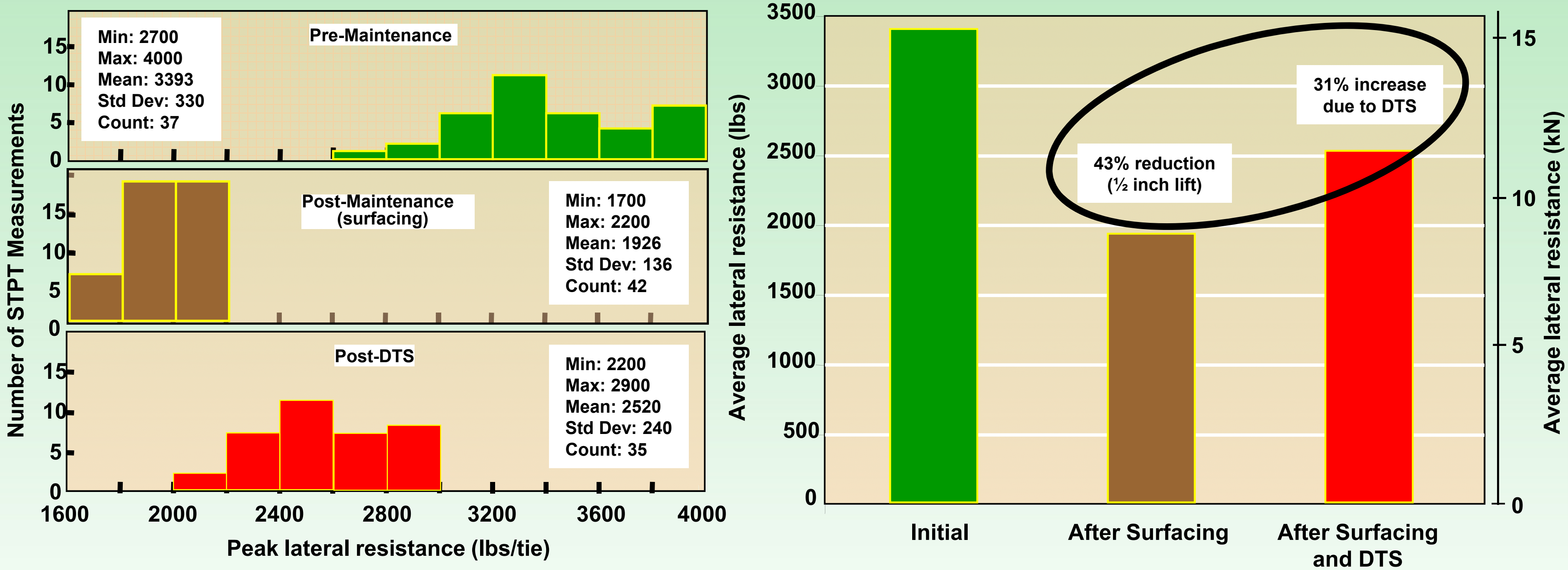
Concrete Tie Track

STPT Measurement

Plasser DTS

US Data on Ballast Consolidation

Volpe/Amtrak Test Summary



- Maintenance influence: TLR reduction of 43%
- Dynamic Track Stabilization influence: TLR increase of 31%

Data was used to evaluate minimum TLR for buckling stability!

Track Lateral Resistance and Buckling Safety

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What is the minimum TLR required for buckling safety?

❑ **ANSWER:** depends on track type/condition, buckling loads and on buckling safety criteria

- Track neutral temperature
- Track alignment/curvature
- Rail temperature
- Vehicle loads/parameters
- Buckling safety criteria*
  [US: T_{Bmin}]

+

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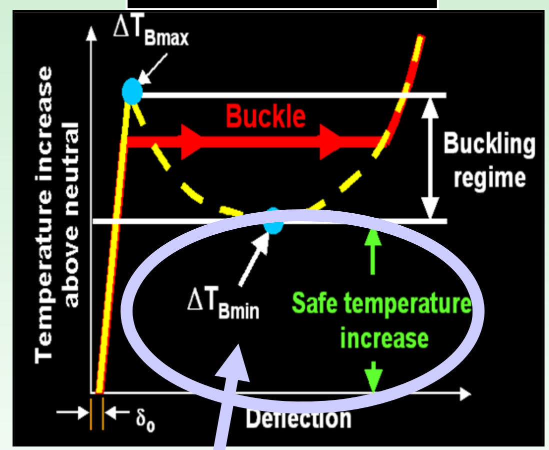
Buckling Safety Criteria



Max. Allowable Temperature Increase Above Neutral

*UIC Leaflet # 720 (ERRI/D202):
- Level 1: T_{Bmin}
- Level 2: $T_{Bmin} + \Delta$
  [$\Delta = 0.25(T_{Bmax} - T_{Bmin})$]

Minimum Resistance for Buckling Safety

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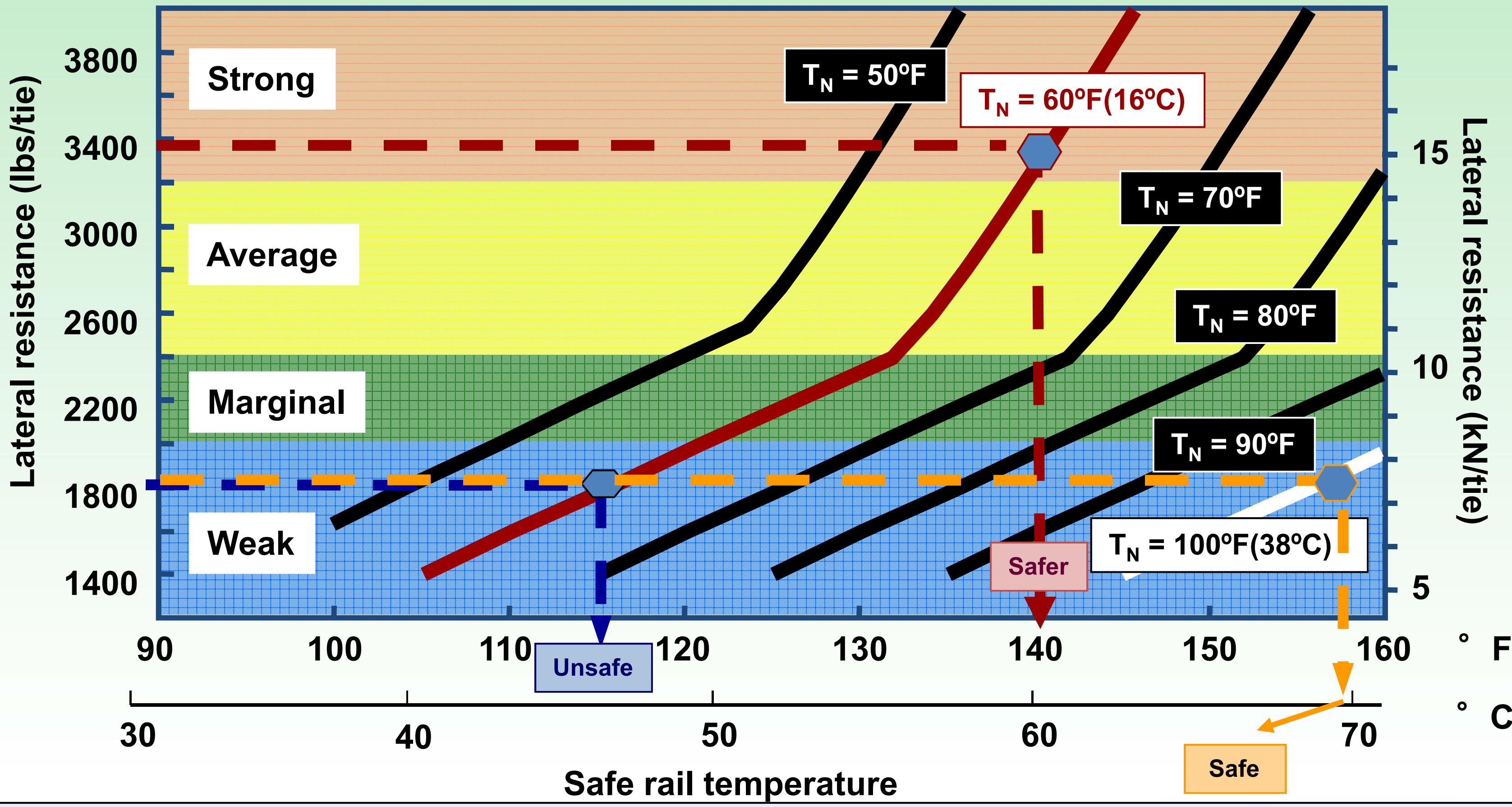
Buckling Safety Criteria Based "Safe" Temperature Limits

Parameters: *5° (350m radius) curve; concrete tie track with Class 4 (25mm/10m) line defect; US-136# CWR; variable lateral resistances* → *CWR-SAFE*



❑ **Note:** for more details, refer to Kish & Samavedam: *"Track Buckling Prevention: Theory, Safety Concepts, and Applications"* [DOT/FRA/ORD-13/16, March 2013]

Influence of Track Stabilization on Buckling Safety

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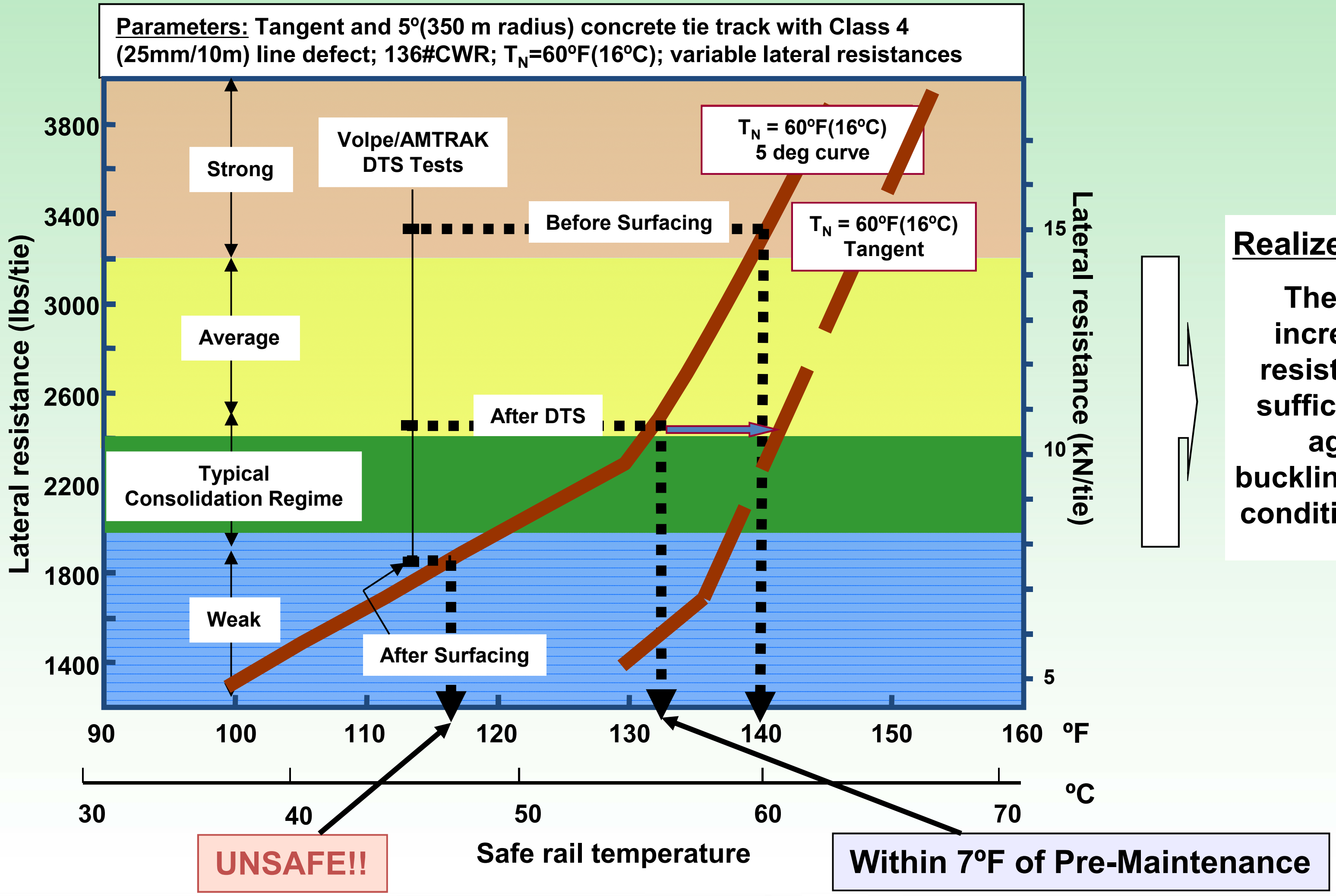

Realized DTS Benefits

The 30-40% DTS increase in lateral resistance provides sufficient protection against track buckling for most track conditions/parameters

DTS and Speed Restrictions

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Added Benefit of DTS: Increased Safety During Speed Restrictions

After track maintenance (weakened ballast)

- If dynamic track stabilization (DTS): no or limited slow orders.
- If no dynamic track stabilization: slow order traffic for 0.1 MGTs or more.

?

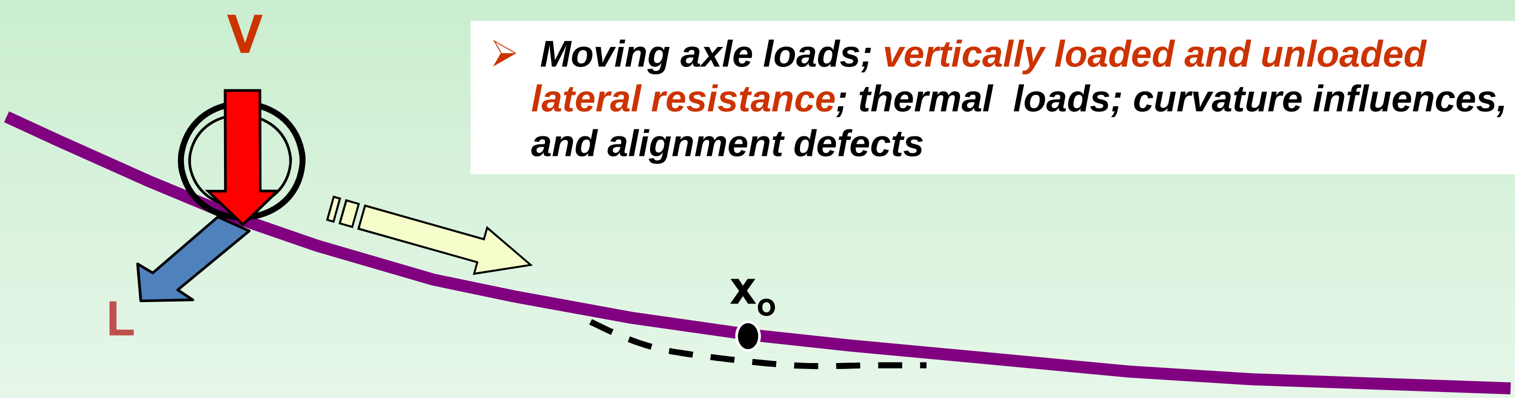
At elevated temps (high thermal force conditions)

- Apply at temperatures as required by RR's CWR policies and speed restriction criterion.

- If apply DTS: more immediate safety and allows for higher slow order temperatures
- If apply slow order traffic: less safety and requires lower slow order temperatures

The High Axle Load (L/V) Problem - Track Shift

- **Track Shift:** incurrence of cumulative lateral residual deflections under many axle L/V passes (HSR issue, but with potential freight rail applications)



- *Moving axle loads; vertically loaded and unloaded lateral resistance; thermal loads; curvature influences, and alignment defects*

- **Key Issue:**
  - what is the permissible net axle L/V to limit lateral deflections to “allowable” values

    or

  - for a prescribed L/V, what is the minimum ballast resistance required to limit lateral deflections to “allowable” values

Lateral Resistance Influence on Track Shift

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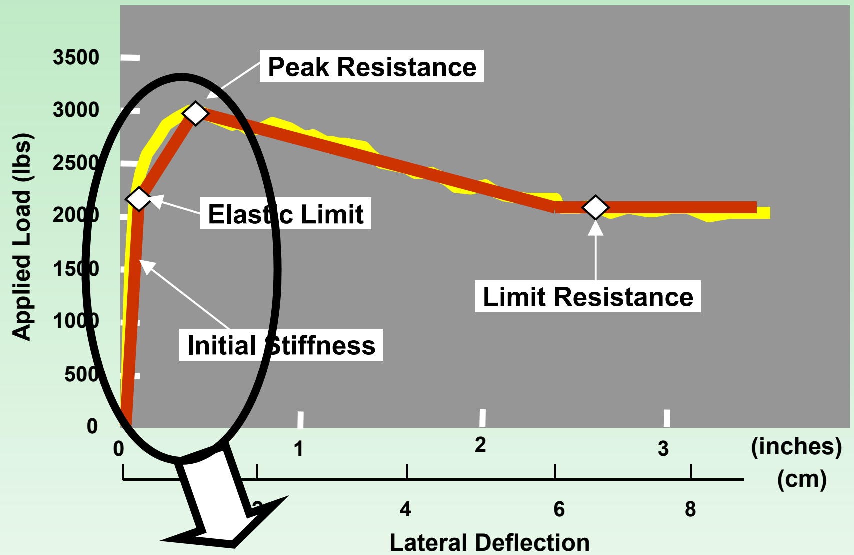
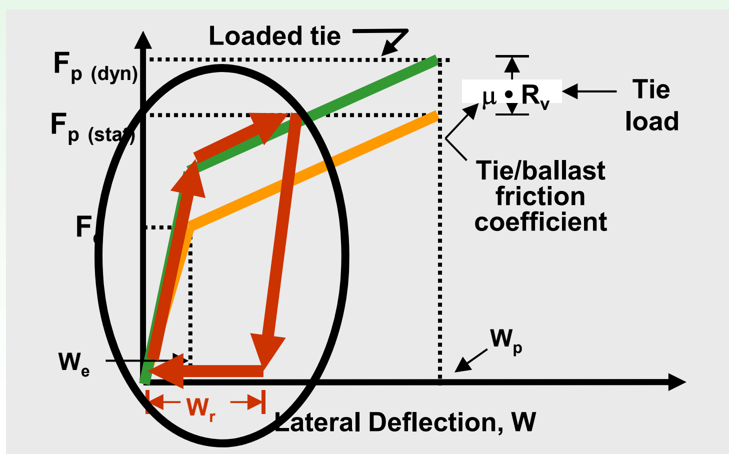
Elastic Limit, Peak Resistances, and Moving Load Issues





Hysteresis loop (loading/unloading cycle) is a key part of the track shift mechanism

Track Lateral Shift and Moving Loads

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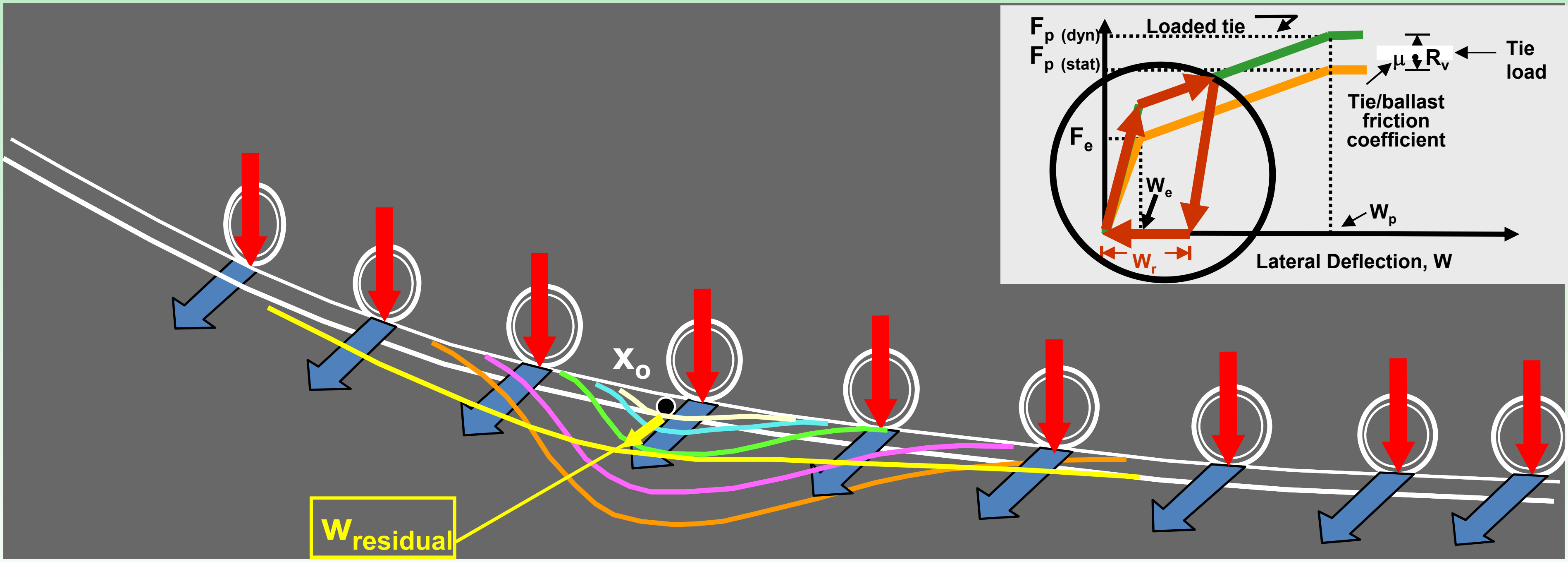
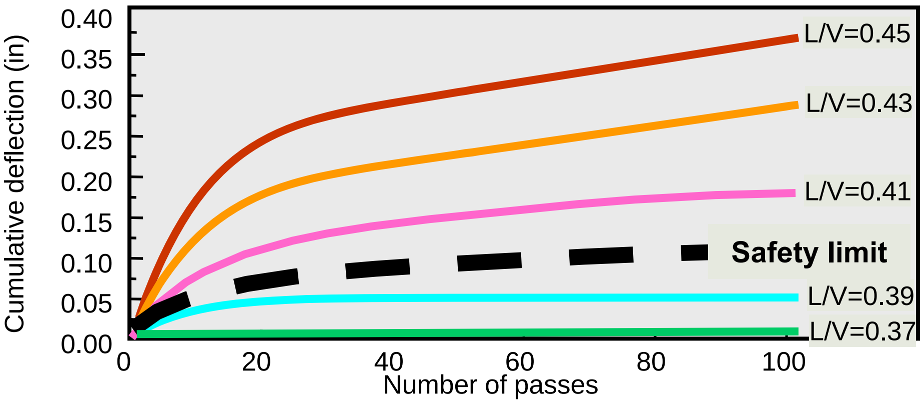
Tack Shift Residual Deflection Mechanism: Moving L/V Loads



For different L/Vs sum up all the w_r's from many axle passes



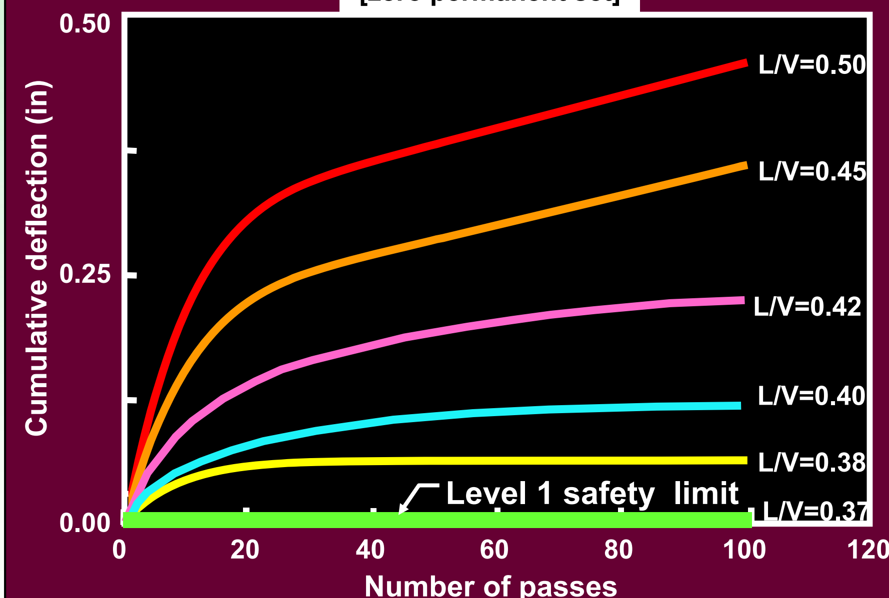
Track Shift Safety Concepts

Consulting Services

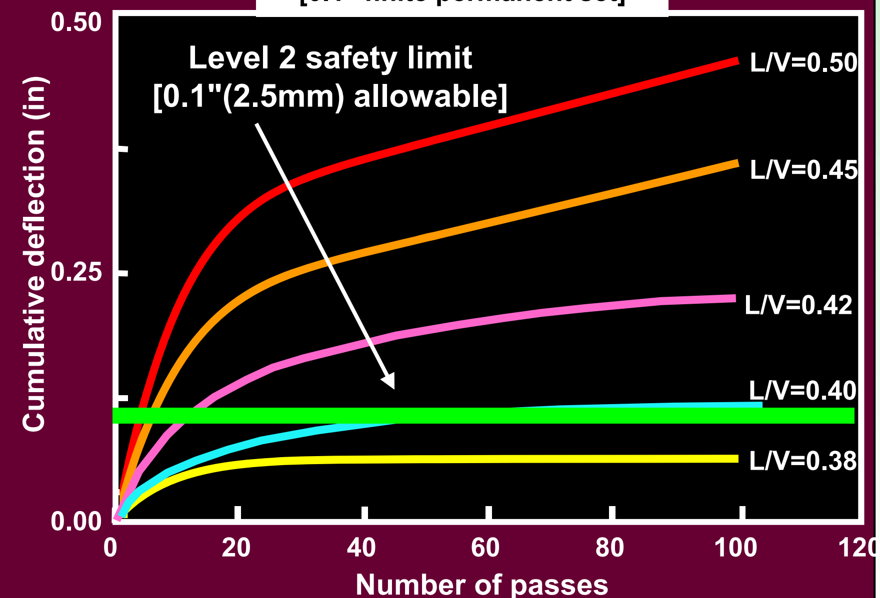
Track Shift Safety Criteria

"Lateral loads generated by high-speed vehicles operating under maximum speed, cant deficiency, thermal load, and initial line defect conditions should not produce permanent lateral track displacements exceeding X inches"

Level 1 Safety:
elastic limit criteria
[zero permanent set]



Level 2 Safety:
allowable deflection criteria
[0.1" finite permanent set]



RSAC/FRA (March/2013)

FRA/VTI High Speed Rail Track Safety Standards
(Level 2 Safety)

US Safety Limits

$L = 0.4V + 5$

(L,V in kips; V = axle load)

Track Shift Safety Limits

US Safety Limits [Level 2 Criterion]

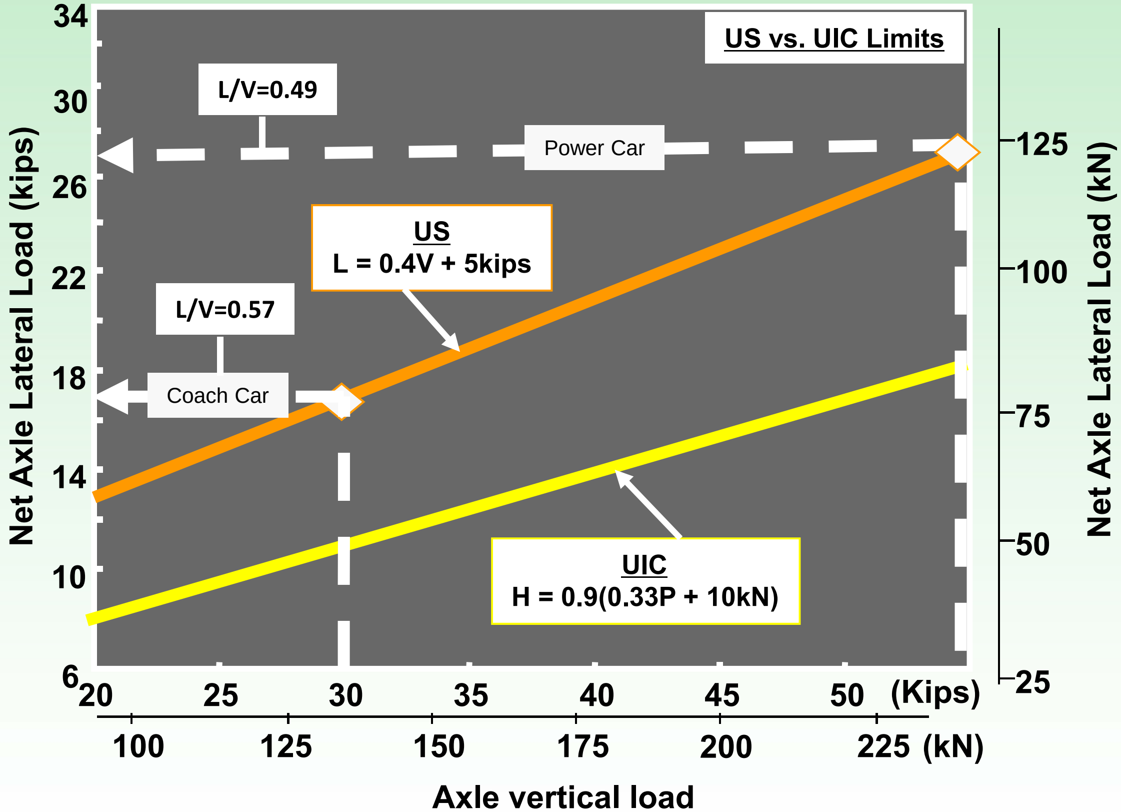
$L = 0.4V + 5$

(L,V in kips; V = axle load)

UIC Safety Limits [Level 1 Criterion]

$H = k(0.33P + 10)$

(H,P in kN; P=axle load; k=0.9 for HSR)



Question: what minimum track lateral resistance is required for compliance with track shift safety limits?

Lateral Resistance Influence on Track Shift

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What lateral resistance is required to comply with safety limits?

High Speed Passenger

US Limits

$L = 0.4V + 5$

(L,V in kips, V=axle load)

UIC Limits

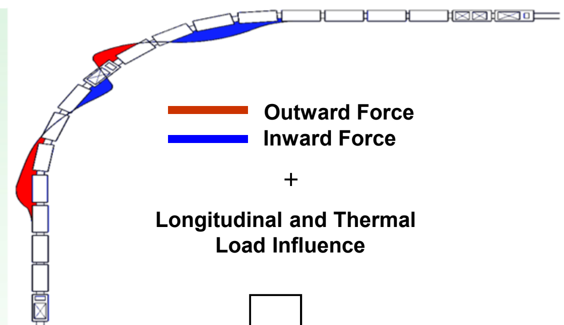
$H = k(0.33P + 10)$

(H,P in kN, k=0.9 for HSR)

Have L/V (H/P) criteria, but don't have limiting ballast resistance

High Tonnage Freight

140 Car Train (36 ton axle loads)



Don't have either L/V criteria or limiting ballast resistance

Requires R&D

Ballast Strength and Lateral Stability

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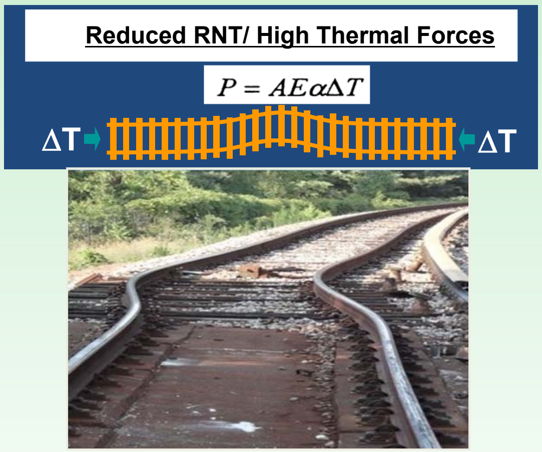
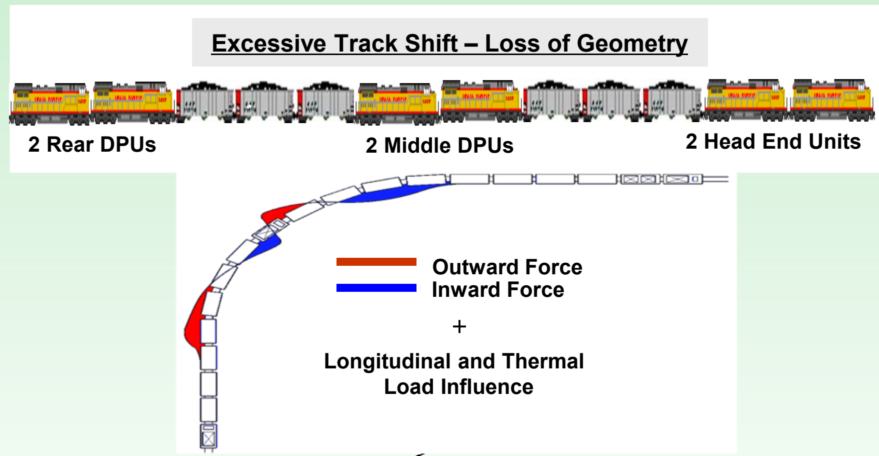
Have we reached the limit of lateral ballast strength capacity under freight operation?

YES: with reduced RNTs



YES: with high L/V's



How to Improve?

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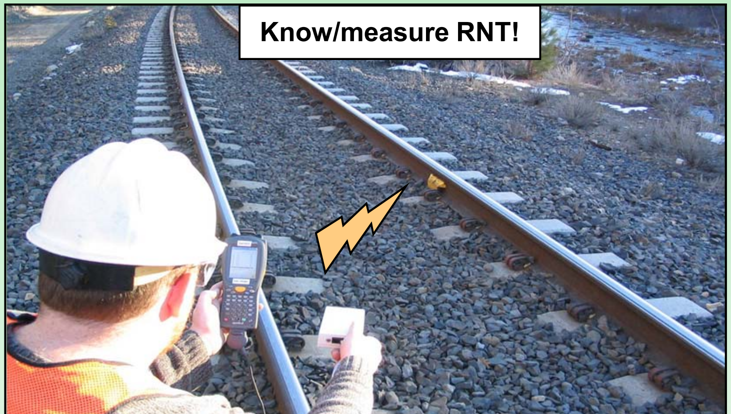
Ballast Strength and Lateral Stability

How to Improve?

Know/measure RNT!



Promotes all aspects of stress management
and CWR safety

Promote improved ballast maintenance practices
for more effective lateral resistance management

DTS provides a quick,
efficient and effective
restoration of TLR

Develop/apply "best practice" guidelines
for CWR/RNT management

- ensure effective anchors/fasteners
- promote more effective CWR installs
(especially in cold weather)
- limit/monitor curve movement
- conduct hot and cold weather inspections
- develop more effective rail break/defect
repair RNT readjustments practices
- improve hot-weather speed restrictions

Consider alternative track designs aimed at
"High Lateral Strength Track"

HDS–SSL Ties
@ FAST

❑ **Require/conduct more R&D on improving track stability management**

Conclusions

- Ballast lateral resistance is an important parameter for track geometry retention and track stability management.

- It is a complex parameter: non-linear, variable, difficult to measure, has both static and dynamic components where the tie/ballast friction coefficient plays a key role.

- It is a key parameter for both track buckling and track shift evaluations, but each requires different components of the lateral resistance function.

- Ballast maintenance (surfacing, lifting, tamping) reduces lateral resistance by 40-60% requiring quick and efficient restoration.

Conclusions

- Dynamic track stabilization (DTS) has proven to be a quick, efficient and effective means to restore lateral resistance requiring no speed restrictions. The 30-60% resistance restoration promotes:
  - lateral stability for track buckling prevention for most conditions
  - improved hot weather speed restrictions
  - improved ballast longitudinal resistance
  - “smoothening” of neutral temperature along the rail
- Based on US data, traffic (tonnage) consolidation may require more than the currently accepted 0.1MGTs to achieve a minimum 30% DTS equivalent. (MORE R&D IS REQUIRED FOR EVALUATION!)

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Challenges/Research Needs

1 - evaluation of train tonnage (MGT) influence on consolidation

- **What is the mechanics of ballast compaction under traffic loads?**
  - What is the influence of axle loads?
  - What is the influence of train speeds?
  - What is the influence of track types? (concrete/wood/tangent/curved)
  - What is the influence of maintenance?

BOTTOM LINE: what tonnage is required for adequate consolidation?

2 - what ballast strength is required for maximum net axle L/Vs under HSR operations?

3 - development of L/V criteria and ballast resistance requirements for heavy, long freight trains with distributed power to prevent excessive track shift ➡ **New concern: ballast fouling/liquifaction**

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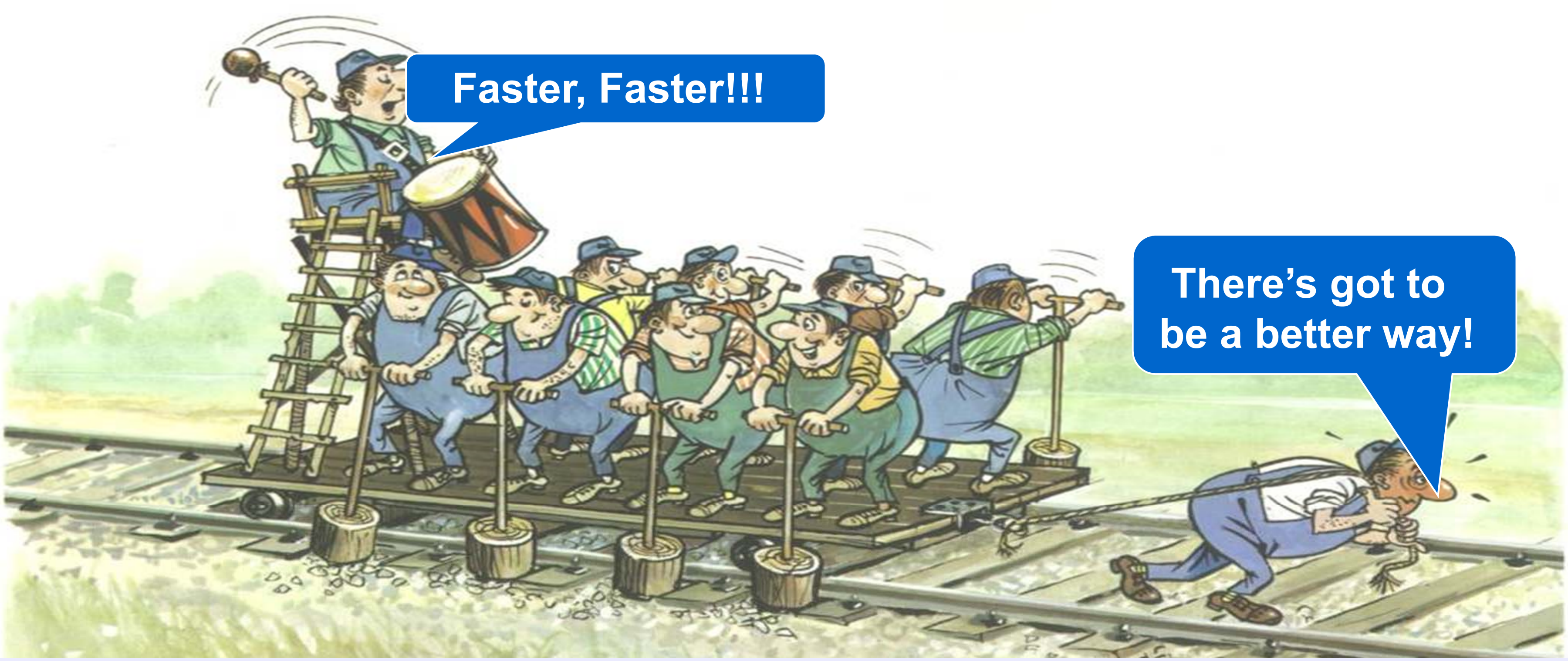
Ballast Strength and Track Lateral Stability



THANK YOU AND QUESTIONS?

Relevant References to Presentation

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Presenter's CV

ANDREW KISH, Ph.D.
Railway Technology Consultant
Kandrew Inc. Consulting Services
E-mail: kandrewinc@aol.com
Web: www.kandrewinc.com

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Dr. Kish received his Ph.D. from New York University in Applied Mechanics and Mathematics in 1974. He has been at the US DOT's Volpe Research Center for over 30 years where as a senior technical expert on track structures and mechanics managed a multitude of research programs in the field of track mechanics including track stability, CWR maintenance, track buckling prevention, and high speed rail safety.

On the international front, from 1992–1998 he served as the US DOT's representative to the European Rail Research Institute's (ERRI) Committee on track stability where he was instrumental in developing new CWR safety codes for the Union of International Railways (UIC).

His work has resulted in over 120 publications on CWR safety, stability, and related track mechanics topics. Over the years he has conducted many Track Buckling Workshops and Seminars, has developed Training Courses for the industry, and is a recognized international expert in the field of track stability, CWR maintenance, and track buckling prevention. Dr. Kish retired from the Volpe Center in 2004 to form his consulting company Kandrew Inc. Consulting Services, and remains active in providing rail technology consulting services to the industry and the research community.