TRACK BUCKLING RESEARCH

1.0 INTRODUCTION

This research is intended to improve railroad safety by developing means to prevent derailments due to lateral buckling of the track under a moving train.

1.1 PROBLEM DEFINITION

Track buckling is formation of large lateral misalignments in continuous welded rail (CWR) track, often resulting in catastrophic derailments. Both curved and tangent tracks are susceptible to buckling with typical curve buckle amplitudes ranging from 6"-14" and tangent buckles from 12"-28". Buckles are typically caused by a combination of three major factors: high compressive forces, weakened track conditions, and vehicle loads (train dynamics).

Compressive forces result from stresses induced in a constrained rail by temperature above its "stress free" state, and from mechanical sources such as braking, rolling friction and wheel flanging on curves. The temperature of the rail at the "stress-free" state is known as the rail neutral temperature (i.e. the temperature at which the rail experiences zero longitudinal force). Initially, the rail's installation temperature or "anchoring temperature" is the rail's neutral temperature. Hence, at rail temperatures above the neutral, compressive forces are generated, and at temperatures below the neutral, tensile forces are developed. Track maintenance practices address the high thermal load problem by anchoring the rail at (neutral) temperature of 95 -110 °F. This high neutral temperature range prevents the generation of excessively high buckling forces even when the rail temperatures reach 130 -150 °F.

Weakened track conditions impacting the tracks buckling potential include: reduced track Resistance, lateral alignment defects, and lowered rail neutral temperature. Track resistance is the ability of the ballast, ties and fasteners to provide lateral and longitudinal strength to maintain track stability. Resistance is lowered if ballast is missing from under the ties, in the crib or from the shoulder. A full ballast section is important, especially on curves. Adequate ballast in the high side in curves should be on the order of 12"-18" to provide adequate lateral strength. Ballast on the low side is important because inward (pulling-in) movement in cold weather could lead to line defects and lowering of neutral temperature which could lead to a buckle when higher temperature rises occur in early spring. Track resistance is also lowered when ballast is disturbed. Surfacing, tie renewal and undercutting operations will weaken ballast resistance by as much as 40%-60% of undisturbed track. It is a usual industry practice to restrict train speed to minimize train forces while ballast strength is being restored either by traffic or by mechanical consolidation means. Longitudinal resistance offered to the rail/tie structure by adequate rail anchoring is important to prevent rail running and hence the decrease of rail neutral temperature.

Lateral alignment defects also reduce the track's buckling strength because buckles tend to initiate at alignment deviations. The larger the line defect, the more buckling prone the track will be. Alignment errors must be corrected in hot weather and in early spring when curves tend to realign themselves from a winter "pull-in" condition. Buckles can also initiate at bad, crooked welds.

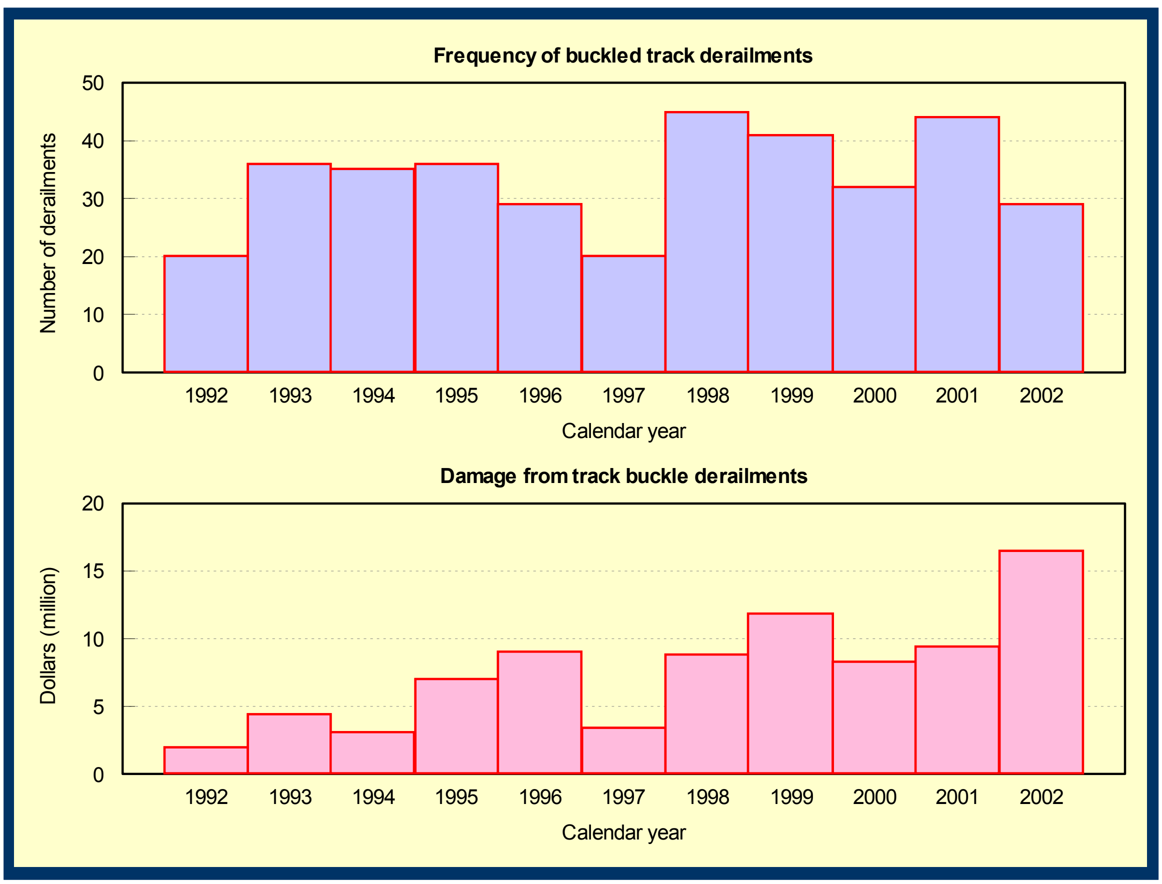
Maintaining a stable and high rail neutral temperature is critical for buckling prevention. Neutral or force-free temperature of CWR is usually different from initial installation or anchoring temperature. This difference is attributed to several factors, including rail longitudinal movement, track lateral shift/radial breathing in curves, track vertical settlement, and maintenance activities. Rail longitudinal movement (creep) is due to train braking and traction forces, or to differential thermal forces (sun and shade). Track lateral shift can be caused by excessive truck hunting, and by lateral forces generated by curving or by lateral misalignments. Compressive and tensile forces can cause radial breathing of curves especially in weak ballast conditions. Vertical differential settlement of rails can occur on new or recently surfaced track, or in areas of weak subgrade conditions. Maintenance operations influencing neutral temperature changes include: lifting, lining, and tamping, replacing broken rail, destressing, and installing CWR in cold weather. Research to date has shown that typical CWR rail installation (stress-free) temperatures of 100°F can reduce in service to 50 - 60°F due to these effects.

Track buckles usually initiate at small alignment deviations. Wheel loads and train action (dynamic uplift wave) tend to increase its size to levels which trigger the buckling process. Most buckling derailments tend occur deep in a train. Vehicles contribute to buckling by exerting lateral wheel forces in a curve. Lateral forces can also occur in tangent track from car movement caused by line or surface deviations or track hunting. The track must absorb this energy. Slack action, heavy dynamic braking and emergency brake applications can trigger a buckle. It is important to inspect track after a train passage in hot weather, especially if the track has recently been disturbed.

The above is a brief summary of the track buckling problem in terms of the three major causal factors: high compressive forces, weakened track conditions, and vehicle loads (train dynamics).

1.2 PROBLEM SEVERITY

Illustrations of track buckles are shown below together with the number of buckled track derailments/damage over the past ten years. As can be seen, the past five years' statistics indicate an average of 38 derailments a year with an increasing yearly damage level to as high as $17 million in 2002.



Track buckling illustrations and accident statistics

Currently there are no FRA safety performance standards in place addressing CWR buckling safety, the development of which is the principal objective of this research program. In its most recent Track Safety Standard promulgated under CFR 49/213.119 and 343 in 1998, FRA does however require railroads to have procedures in place for the safe installation, adjustment, maintenance and inspection of CWR. Key parts of these procedures address the adequacy of slow-order applications at high ambient temperatures and after track maintenance, and in providing adequate neutral temperature control when repairing/destressing CWR. The development of new data and information on these elements to support FRA standards and industry practices are also key parts of this research program.

1.3 RESEARCH TO DATE

The FRA and Volpe Center has been conducting research to better predict risk of catastrophic derailments due to sudden lateral buckling of track. This research has developed the rationale and approach to buckling prevention which consists of:

(a) the prediction of critical forces and conditions leading to buckles, and
(b) using a diagnostic tool to measure the in-situ forces against an "allowable" value.

Specific research activities geared toward this included developing predictive tools for evaluating the likelihood of track buckling in CWR tracks, applying these tools for buckling safety assessments i.e. toward determining the "allowable" values, evaluating the effectiveness of industry maintenance practices and procedures for the safe management of CWR, and developing techniques to measure longitudinal forces in CWR. This research has also identified the many parameters/conditions influencing CWR track buckling safety, the three most important ones of which are summarized below:

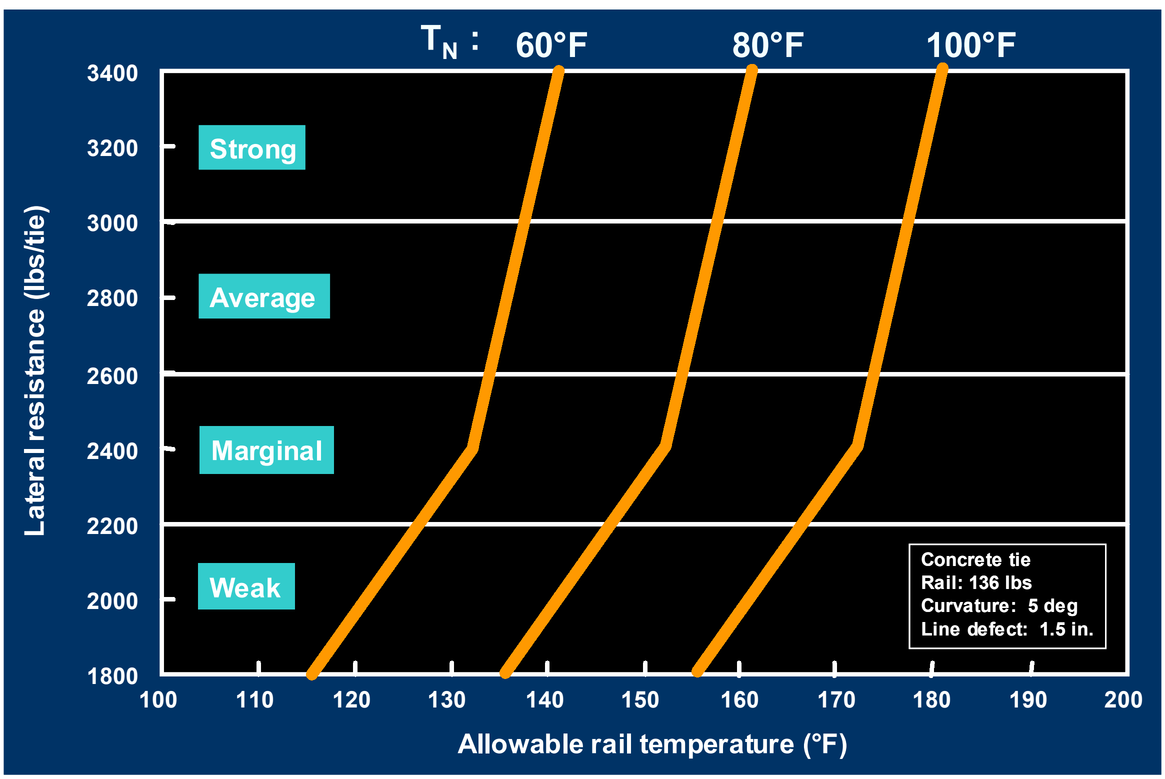
Parameter/Condition	Impact on Buckling Safety	Ability to Predict/Measure
Rail Longitudinal Force (RLF)/Neutral Temperature	Very high, since the compressive force in the rail is a direct cause of buckling. Variation in these force levels due to changes in the rail's "stress-free" (or neutral temperature) is a key agent in elevating the force levels to unsafe (buckling) values.	Analytic prediction of critical RLF values is available ("CWR-SAFE"), however in-situ non-destructive measurement capability of RLF is lacking to date. Hence detection of buckling prone conditions is not possible. The prediction and detection of incipient buckles remains a key research goal for this R&D program.
Track Lateral Resistance (TLR)	High, since it is the reaction the ballast offers to the rail/tie structure that offers the primary restraint against buckling. TLR is also highly variable, influenced by many track construction and maintenance parameters. Thus when TLR becomes "weak", buckling can result when accompanied by high RLF values. Additionally TLR is a highly non-linear function, has static and dynamic components, and requires complex characterizations hence a detailed knowledge of this parameter is essential for analytic buckling predictions and subsequent safety limit determination and verification.	TLR measurement capability exists (STPT). However, TLR's high decrease value with maintenance remains a main buckling prevention and R&D concern. Industry practice currently utilizes mechanical/traffic consolidation means to quickly restore to "safe" values, however, effectiveness of these processes are still under investigation. For the prediction of the critical or "safe" RLF values, a "dynamic" (i.e. vertically loaded) TLR value is required which is analytically handled through an experimentally determined "tie/ballast friction" factor. The key unknowns on TLR are the "maintenance decrease" values, the "stabilization increase" values, and the variation of these values on typical line segments.
Track Lateral Alignment (TLA)	High, since buckling parametric studies have shown that lateral alignment defects increase the track's buckling potential, i.e. a track with "large" (Class 3) alignment defect has a lower buckling safety than one with a "small" (Class 6) line defect. TLA's also act as "triggers" for buckles.	TLA is a key input parameter to buckling analyses in terms of a prescribed amplitude and wavelength. It is typically a track geometry (TG) car measured parameter. For buckling analysis and model input, the TG data has to be provided the correct "amplitude-frequency" statistics.

The determination and application of these key parameters/measurements to buckling safety evaluations predictions remain the key driving factors of the track stability research program referred to as TSRP.

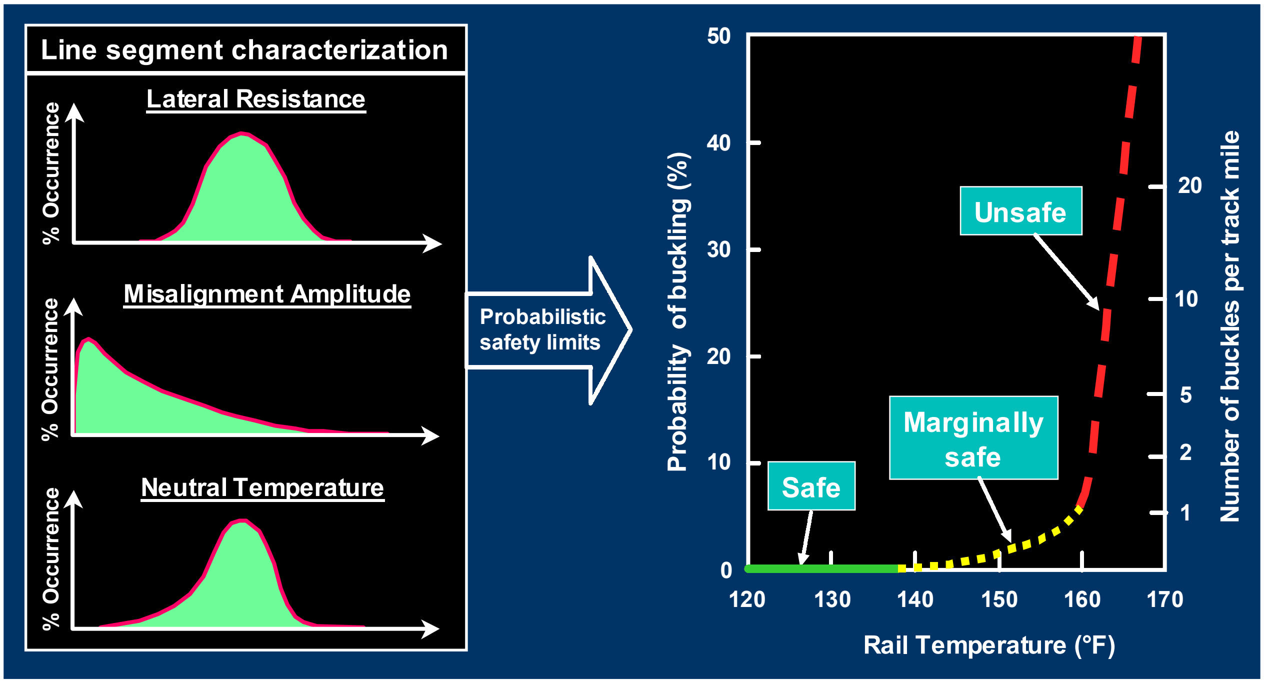
1.4 ADDITIONAL RESEARCH NEEDS

Consistent with FRA's mission of developing "performance" based safety standards, the global research objective of the TSRP is to develop "performance" based guidelines and specifications for the prevention of derailments due to buckled track, and to develop supportive industry maintenance and inspection guidelines for the safe management of CWR.

It is expected that the performance based guidelines will specify either deterministic "safety limits" in terms of minimum track lateral strength capacity (lateral resistance) as a function of allowable rail force or rail temperature increase values, or "risk" based performance limits in terms of acceptable buckling probabilities versus rail temperature as illustrated by the figures below. Either option depends on R&D's ability to develop the key component elements for its practical application.



Example of deterministic CWR safety limits



Example of probabilistic CWR safety limits

Research to date has developed the analytic capability to predict critical buckling forces and temperatures, developed safety concepts and criteria, and established a buckling safety evaluation methodology (all incorporated in the analysis program "CWR-SAFE"), and has exercised this predictive tool for the development of prototype safety limits illustrated above. Both types of limits are strongly track parameter/condition (neutral temperature, lateral resistance, and lateral geometry alignment) dependent which are highly variable and generally not known in terms of specific values. Hence the direct application of the first set of limits, which require knowledge of the specific neutral temperature and lateral resistance values, is limited by these unknowns. Consequently, more research is required on their quantification, specifically the determination of the applicable neutral temperatures (including the measurement technique development), and "weak, recently maintained" track resistance characterization (i.e. to know or be able to measure the "weak" resistance values). This latter is also aimed at determining effectiveness of track lateral resistance consolidation after maintenance.

Since this FRA goal has recently been augmented to develop "risk based performance standards", further research is also required to enable the development of "risk based" performance measures (in line with the second figure above). The probabilistic (risk) approach has the advantage of offering substantially more flexibility to safe CWR management by allowing for a "risk acceptance" in terms of "number of buckles permitted", which fosters the ability to extend the operating rail temperature range. This extended rail temperature range also offers the option of defining slow orders in that range for risk mitigation. However, for this approach to work, statistical variation descriptors on the three key parameters (see left hand box above) per applicable line segment or territory are required, as well as the ability to relate the "probability of buckling" to a meaningful equivalent, such as "number of buckles/track mile (see the right vertical axis in the figure above).

The supportive maintenance and inspection guidelines are expected to be based on establishing requirements for:

1. Ballast lateral strength
2. CWR laying temperatures and effective adjustment of CWR through destressing
3. Appropriate ballast consolidation for recently maintained track
4. Speed restrictions
5. Measurements of neutral temperature, lateral resistance, and track movements

These maintenance and inspection guidelines are also to be employed by the FRA's Office of Safety to evaluate current industry procedures and safety specifications in response to the requirements of the FRA Track Safety Standards.

1.5 ADDITIONAL RESEARCH REQUIRED

In line with the above, efforts will be continued to finalize the predictive tools ("CWR-SAFE") for buckling safety evaluations and documenting its theory and applications, and exercising the model for the development of "risk" based safety limits. Studies will also address the continued development of a risk-based buckling safety evaluation methodology, particularly the development of means define and predict "buckling risk" i.e. the transition from the "probability of buckling" to its equivalent "number of buckles/track mile" (see right vertical axis of risk figure above), and the definition and acquisition of the statistical data required for the risk evaluations, notably the representative distributions of track lateral resistance, rail neutral temperature, and lateral alignment defects.

Assessments of the effectiveness of current industry practices in CWR installation, maintenance, repair, and neutral temperature readjustments will be continued, with special emphasis on evaluating the adequacy of mechanical track stabilization's means of restoring track lateral strength for buckling safety assurance. Additionally, efforts will be continued in the evaluation of neutral temperature readjustment practices in conjunction with the continued development and validation of the FRA/Volpe tool (RDFI-Rail Destress Force Indicator) for CWR destressing. RDFI is a novel prototype technique for performing a more effective rail repair and adjustment of CWR through prescriptions on fastener/anchor removals and rail weld "gap" size requirements so that the target neutral temperature and its uniformity is achieved with better success.

The program's output will also be applied to the establishment of a track stability database to be utilized by the FRA, the railroads and the research community to help buckling prevention. It is also expected to provide technical support to the FRA's Office of Safety in developing information needed to establish compliance guidelines for the new track safety standards in CWR and track lateral strength. This support may include generating prototype CWR safety requirements, developing technical support documents, data, and information required for reviewing industry standards and practices; conducting new analyses and tests to establish new safety limits; and developing improved maintenance and inspection strategies.

The overall work under TSRP is structured along four subtask elements: ***Buckling Safety Assessment Studies, Track Resistance Characterization, CWR Inspection and Maintenance Technology, and Track Safety Standards Support***. The first provides the analytic capability (predictive tools/models), the buckling safety criteria, and the CWR performance standards. The second provides the measurement techniques and quantification of the track resistance parameters required for the models and for industry practice/guideline evaluation/development. The third addresses the development of the measurement capability for rail force determination, and improved maintenance/inspection procedures for better control of CWR neutral temperature variation. The last program element provides the required safety standards support/material to the FRA's Office of Safety. These subtask elements are described in detail under Section 6.0 - Work Plan.

As the use of continuous welded rail (CWR) tracks in the United States increases, coupled with the trends towards increasing axle loads, speeds, and traffic volumes, the number of buckled track induced train derailments can increase unless adequate preventive measures such as describe above are in place. To develop these preventive measures, and thus reduce the number of catastrophic buckling incidents, the FRA/Volpe Center plans to conduct continued experimental and analytic investigations in line with the overall safety mission of the Federal Railroad Administration (FRA).

2.0 OBJECTIVES

The principal objectives of the TSRP are:

1. To develop safety performance requirements for the track to account for the environmentally and operationally imposed loads so that the track can be adequately maintained to a desired operational level of safety

2. To develop techniques to measure the longitudinal force of the rail and the lateral resistance of the track which can be "indicators" of impending loss of track lateral stability

3. To evaluate the effectiveness of remedial actions (including slow-orders), and develop appropriate inspection strategies and maintenance guidelines for the prevention of catastrophic failures due to buckling

3.0 SCOPE

The work required to fulfill the above objectives encompasses a multi-year research effort ranging from analytical modeling studies and full scale tests on both wood and concrete tie CWR tracks, to the development of innovative diagnostic measurement concepts and techniques for providing the inspection capability and required safety assurance for buckling prevention.

4.0 INTERFACES

This work directly supports the FRA Track Systems Research Program objectives, and builds upon the Volpe Center's engineering capabilities in rail/track/vehicle safety research projects developed over the past 25 years for the FRA. The research and test activities delineated in this plan is expected to be coordinated with the FRA's Office of Safety, the Research and Test Departments of the individual railroads, the Association of American Railroad's (AAR) subsidiary TTCI, the American Railway Engineering and Maintenance of Way Association (AREMA), and the railroad supply industry.

5.0 APPROACH

The Volpe Center's approach to researching the solution to the CWR buckling problem consists of:

- Developing rigorous analytic models and tools for the prediction of critical buckling forces and temperatures
- Conducting controlled full-scale field tests for the determination of the mechanics of track stability, for the evaluation of critical parameters, and for the validation of analytic predictive tools
- Developing rational safety criteria for use by the industry which encompass safe operating limits as well as the required inspection/diagnostic tools for detection and prevention of buckles
- Extending the developed safety criteria to performance based safety specifications and to optimized maintenance strategies

6.0 WORK PLAN

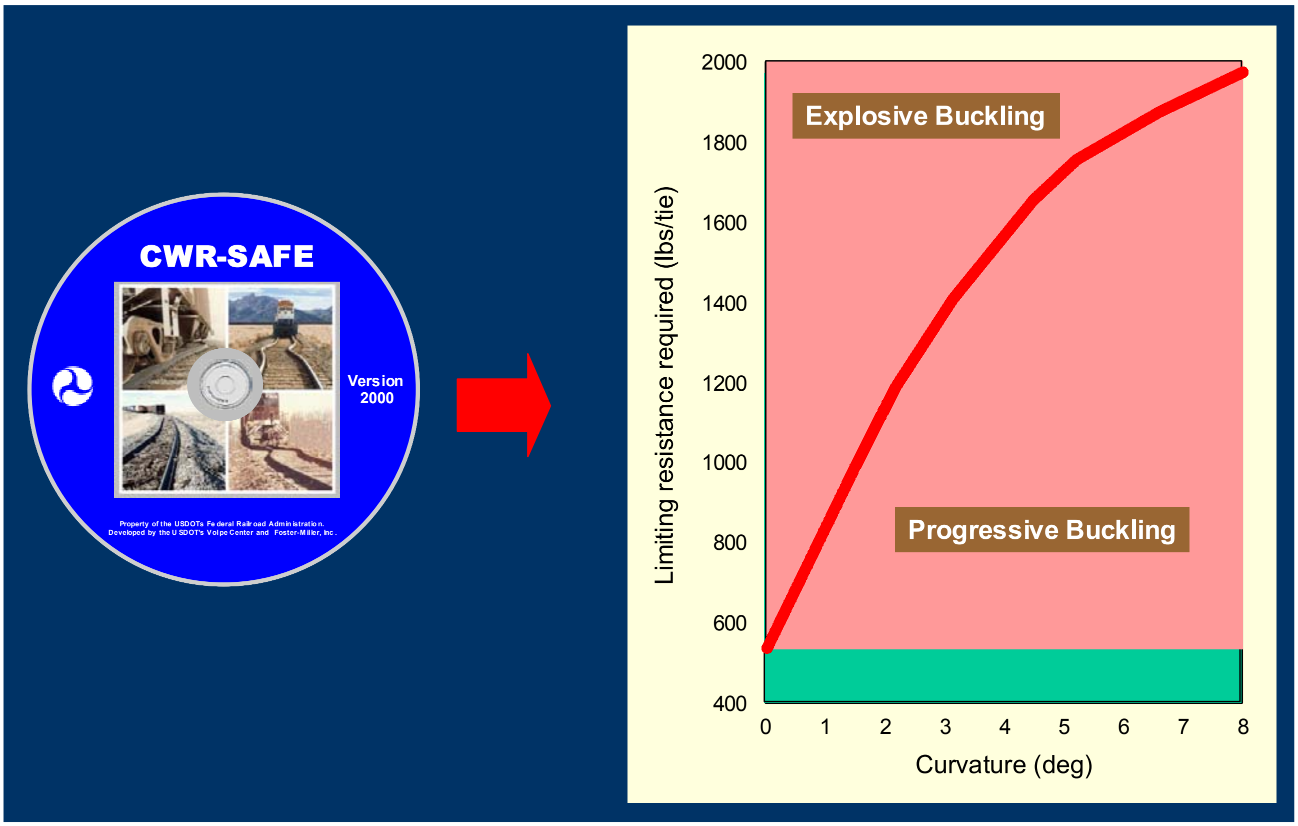
The research program consists of the following four project elements:

1. Buckling Safety Assessment Studies
2. Track Resistance Characterization
3. CWR Inspection/Maintenance Technology
4. Track Safety Standards Support

The following briefly describes these four project elements (subtasks).

6.1 Buckling Safety Assessment Studies

Work under this subtask is aimed at developing and documenting the analysis capability for dynamic buckling response evaluation (CWR-SAFE), conducting the relevant verification studies and tests as required, performing parametric assessments of track buckling behavior, developing new risk based approaches for the prediction derailment potential due to buckled track, and ultimately developing the safety performance requirements for buckling prevention. Some illustrative examples are shown below:



Example of CWR-SAFE application to determine of limiting lateral resistance condition for buckling prevention

Buckling Advisory									
Critical Buckling Temperatures	Rail Neutral Temperature (RNT)	Pre - surfacing				Post - surfacing			
		Tan		5°		Tan		5°	
		Class 4	Class 6	Class 4	Class 6	Class 4	Class 6	Class 4	Class 6
	Weak *(RNT_{min} = 60°F)*	142	150	132	142	134	142	110	133
	Strong *(RNT_{min} = 85°F)*	162	170	152	162	158	166	136	158

Example of CWR-SAFE application to determine critical buckling temperatures for recently maintained concrete tie track

6.2 Track Resistance Characterization

Work under this subtask is directed toward quantifying the key parameters necessary for providing the required "buckling restraint" to the track structure. Elements of this work include developing a methodology to measure the track resistance parameters, conducting studies to quantify the parametric influences on ballast resistance (including the effects of mechanical and traffic induced consolidation), and evaluating track longitudinal and torsional resistance as required.

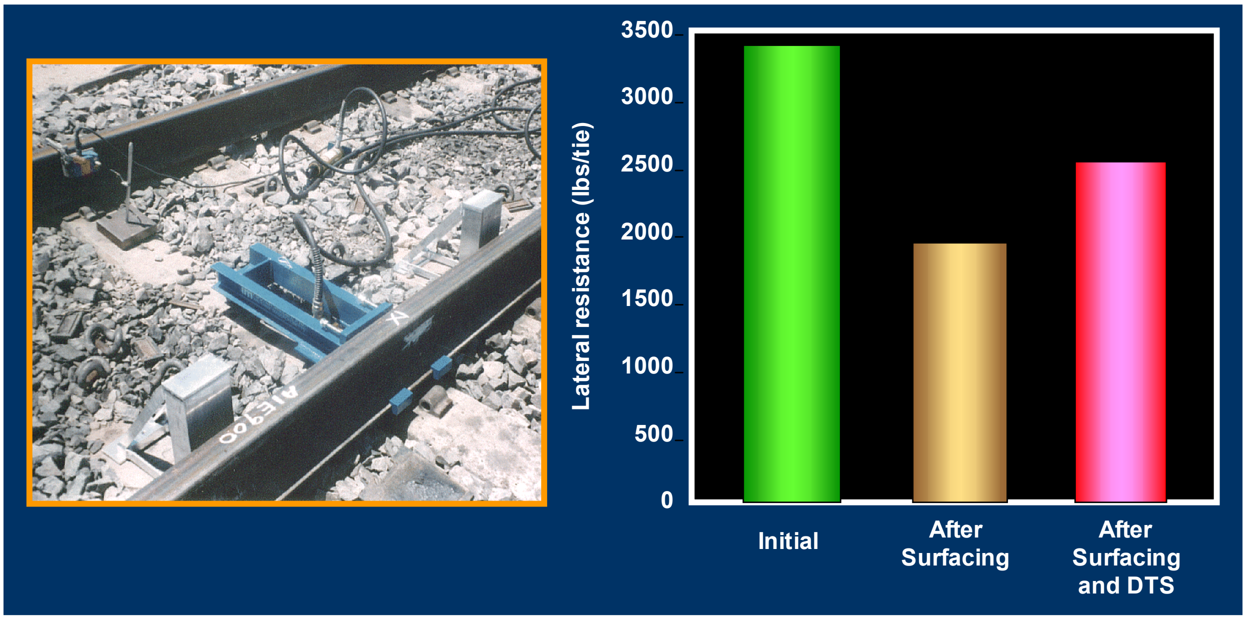
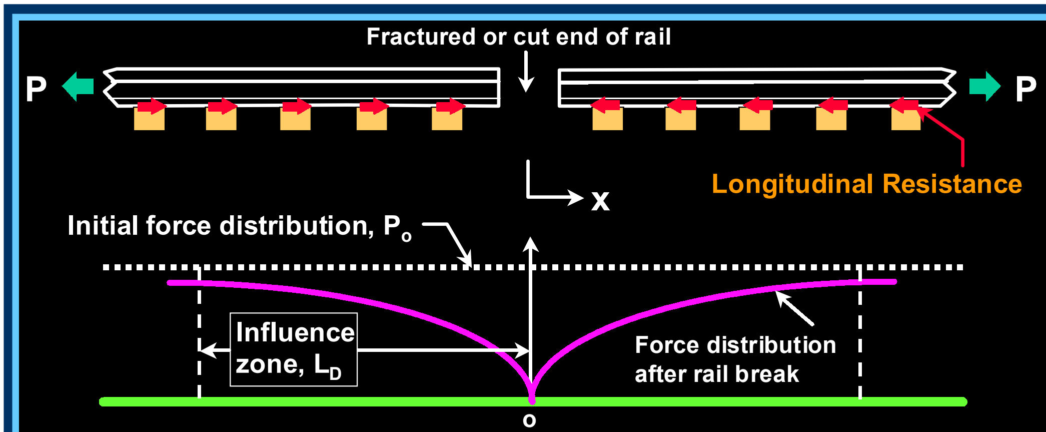


Illustration of lateral resistance measurement (STPT) and its application to maintenance influence evaluation

6.3 CWR Inspection/Maintenance Technology

The objective of this task is to quantify rail neutral temperature/longitudinal force characteristics through measurements, analyses, and field tests. A part of the effort will be focused on the rail longitudinal force (RLF) measurement capability development which has been highly elusive and technically challenging throughout the previous research endeavors. In the absence of a viable nondestructive measurement technique for longitudinal force determination, however, this subtask also attempts to develop the database on rail neutral temperature variation as a means to determine "a neutral temperature safety factor (NTSF)" for buckling safety evaluations. The NTSF is important in setting a reference condition for the safe temperature increase values as part of the buckling safety evaluations. A second objective of this subtask is the development of improved CWR maintenance practices and strategies to better control the rails' neutral temperature condition.

Rail longitudinal force determination via strain gages



ISSUE:

How to effectively repair CWR after a tensile failure during winter, and how to readjust *("cut-rail out")* in summer

PROBLEM:

How to achieve desired target neutral temperature:

i) How many fasteners to remove (what is the influence zone, L_D)

ii) How much rail to cut-out (what is the correct gap size)

Illustration of rail neutral temperature readjustment after rail break

6.4 Track Safety Standards Support

Under this subtask, technical support shall be provided to the FRA's Office of Safety in developing and evaluating track safety standards for CWR stability assurance and maintenance. This support will include the generation of prototype specification addressing CWR track buckling safety for both freight and passenger service tracks, the development of supportive data and technical information, and the conduct of additional tests and analyses as required to establish/evaluate the specifics of the standard. Work will be conducted on an interactive basis with the Office of Safety and the Office of Research and Development. Evaluation studies on current safety standards feasibility are also planned, including applications to both Short Line railroads and high-speed passenger service.

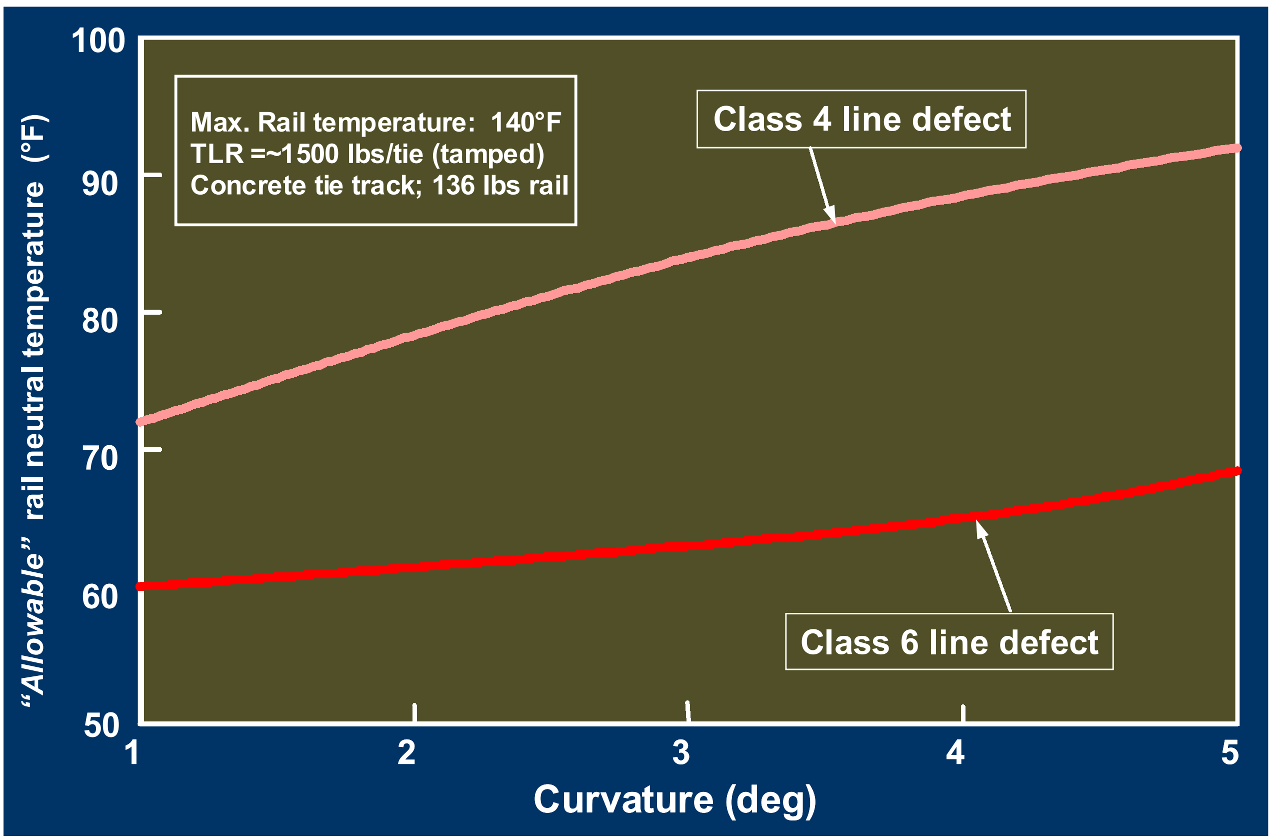


Illustration of safety requirement for minimum rail neutral temperature

7.0 IMPLEMENTATION

The results of the four subtask activities will be applied to the development of guidelines and recommendations for buckling prevention of CWR tracks. The guidelines are expected to encompass "performance" based instructions, as well as maintenance/design requirements which can be utilized by the FRA and the railroad industry for buckling prevention.

The "performance" based guidelines will specify either:

- Safety limits in terms of minimum track strength capacity (lateral resistance) as a function of allowable rail force or rail temperature increase values for a fixed (deterministic) parameters, or

- Safety limits in terms of probability of buckling versus rail temperatures values (when governing parameters are statistically defined for a specific line segment).

The former requires knowledge of in-situ rail force, lateral resistance and geometry alignment condition for application, while the latter requires "pedigreeing" track line segments/conditions in terms of characteristic variation of these parameters.

The maintenance/design guidelines will be based on establishing requirements for:

1. Ballast lateral strength
2. CWR laying temperatures and effective adjustment of CWR through destressing
3. Appropriate ballast consolidation for recently maintained track
4. Speed restrictions
5. Measurements/monitoring of neutral temperature, lateral resistance, and track movements

The project's output will also result in the establishment of a database on key track buckling parameters to be utilized by the railroads and the research community for the overall improvement of the safety and performance of CWR tracks.

8.0 POTENTIAL BENEFITS

It is expected that the results of TSRP will have a substantial influence on the reduction of the number catastrophic accidents due to track buckling. According to AAR and industry sources, TSRP results have already played a significant role in reducing the number of derailments of 174 1980 to the 42 in 1999. One major carrier reported "that the successful reduction of track buckling induced derailments and the resultant cost saving, to a large extent, was attributable to TSRP research results to date and its buckling prevention recommendations". It is anticipated that as TSRP research culminates into final guidelines, recommendations, and safety practices, further benefits will be realized by the railroad industry.

9.0 RECENT LITERATURE ON TRACK BUCKLING RESEARCH

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