RISK ANALYSIS BASED CWR TRACK BUCKLING SAFETY EVALUATIONS

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ABSTRACT

As part of the Federal Railroad Administration's (FRA) track systems research program, the US DOT'S Volpe Center is conducting analytic and experimental investigations to evaluate track lateral strength and stability limits for improved safety and performance. This paper deals with a part of this research addressing the development of a comprehensive CWR buckling safety analysis which includes a risk analysis based approach for prediction of probable number of buckles on a given track. These risk based buckling evaluations are particularly useful for dealing with statistical variability in the track parameters. The risk approach can provide economic options for track maintenance to achieve the desirable buckling strength. The buckling risk methodology and the statistical parametric descriptors are discussed and a buckling risk analysis model is presented with illustrative examples. The model also provides a computational scheme for the determination of buckling probability as a function of maximum rail temperature when the key influencing parameters of track lateral resistance, lateral alignment defect and rail neutral temperature are given as statistical variables. The risk based approach as well as the previously developed deterministic approaches in CWR-BUCKLE and CWR-INDY are all being integrated in a single new computer program called CWR-SAFE. CWR-SAFE is a Windows based software analysis package for a comprehensive buckling safety evaluation for use by both the railroad industry and the research community.

KEY WORDS: Track buckling models, CWR stability analysis, buckling risk assessment, buckling safety

1. INTRODUCTION

Continuous welded rail (CWR) is replacing jointed track for the advantages of better economics of maintenance and enhanced ride comfort. A well-known risk with CWR, however, is its potential for buckling due to high thermally induced compressive loads, with possible train derailment consequences. In the U.S. where CWR is typically installed in the range of 90° to 110°F, the stress-free temperature can come down to 50° to 70°F due to a variety of causes including rail movement through fasteners. Every 1°F increase in the rail temperature increases the compressive force in the rail by about 2500 lbs (2.5 kips), depending on the rail cross sectional area. On a hot summer day, the rail temperature can exceed the ambient air temperature by about 30°F, and can reach values in the range of 140° to 160°F, depending on the geographic location. The resulting compressive loads can be on the order of 250 kips/rail which can cause a track buckling failure in the lateral plane. The buckle size depends on the track curvature, rail force level, and the track lateral resistance, and can vary from a few inches to a few feet. The possibility of track buckling is greatly accentuated by vehicle loads, which induce track uplift between the trucks, thus reducing the local lateral resistance. The presence of line defects can also contribute to the initiation of buckling. All these elements are important in buckling safety evaluations and in buckling prevention practices.

The buckling safety assessments to date are performed using the computer programs CWR-BUCKLE and CWR-INDY. The safety methodology in current use in the U.S. requires deterministic input parameters, i.e. each parameter is assigned a definite value. In actual field conditions however, the track parameters vary and can be more appropriately represented by statistical descriptors such as the mean value, standard deviation and a distribution function. Use of such descriptors enables the determination of the *probability of buckling* as a safety estimator. The purpose of this paper is to present a risk based methodology for buckling probability evaluations. Examples will be presented to illustrate the methodology and its practical applications.

2. RISK BASED APPROACH

The buckling safety analyses performed in CWR-BUCKLE and CWR-INDY can be considered as "deterministic analyses" in the sense that all the input parameters have definite values and therefore the track *either buckles or does not.* A track safety/maintenance strategy based on such deterministic analyses can be expensive since it has to be based on the worst case scenario of the parameters. It is expedient, therefore, to use a probabilistic methodology which can account for the statistical variations in input parameters. Such methodology will also provide improved flexibility in determining maintenance options and performing safety evaluations/inspections. For example, with a risk based approach one can choose a range of values between the ballast condition (shoulder, crib) and the CWR neutral temperature to achieve the same degree of safety. Such a choice would also permit better allocation of maintenance resources. It is also shown that maintenance schedules will also impact the probability of buckling.

Each maintenance operation at a given location is considered as a single event that changes the important parameters (lateral resistance and neutral temperature) giving rise to a probable buckling event. The location determines the type of track construction (concrete vs. wood, curved vs. tangent). The probability of buckling at each of the critical locations (affected by maintenance) will be calculated, based on the probabilistic distributions of the lateral resistance, misalignment and the loss of CWR rail neutral temperature. The peak rail temperature at these locations, which will depend on the time of year, is assumed to be known. Attention is focussed on maintenance scheduled at different locations and times of the year. The total annual probability for all these locations and hence for a track mile can be estimated from the analysis.

The probabilistic method is the current trend in other modes of structural failure evaluations and safety assessments. The nuclear, aircraft, and naval industries have long benefited from such methods, which are easily extendable to railroad applications, specifically to developing probabilistic estimates of buckling failure. The risk methodology for such purpose requires not only the *failure probability*, but also the *severity or the consequence* of the failure. For example, if buckling is predicted, does it cause a derailment and with what damage level? In the military specifications for safety methodology, the severity is expressed into four broad categories:

- Catastrophic.
- Critical.
- Marginal.
- Negligible.

As applied to a track buckling induced derailments, for example, a slow speed coal freight train operating in a high degree curve may not result in the same level of damage as a high-speed corridor passenger train on a tangent track. It is known that a tangent track tends to buckle explosively with a large deflection, whereas the curved track may buckle progressively with comparatively smaller buckle amplitudes. Hence even if the parameters of the tangent and the curved track are such that to give equal probability of buckling, the severity of the passenger vehicle on the tangent can be catastrophic compared to the one for the freight car on the curve. Therefore, the overall risk of buckling has to be measured by the probability of the event occurring, weighted by the severity of the consequence or damage caused by that event.

In the subsequent developments, attention will be focused on buckling probability. The severity aspects of the risk methodology will be examined in subsequent studies.

3. BUCKLING PROBABILITY DEFINITION

The fundamental parameters in the evaluation of failure probability of a structure are “load” and “strength.” Both of these parameters vary probabilistically in the service life of the structure. The load and strength can be represented along the x-axis, and their probabilities along the y-axis. The buckling “load” will be expressed in terms of the rail temperature increase over the neutral, and the "strength" is expressed in terms of the allowable temperature increase, ΔT_{All}, Reference [1]. Thus,

$$(\Delta T)_{Load} = T_R - T_N \tag{1}$$

$$(\Delta T)_{Strength} = (\Delta T)_{All} \tag{2}$$

The intersecting or "interference" zone in this type of graph represents the situations in which the load equals or exceeds the strength. The probability of this load exceeding the strength is the "*failure probability of the structure*" schematically shown in Figure 1. It can be evaluated on the basis of the so-called "convolution" integral [2] given below.

$$P(\Delta T) = \int_A^B \Psi_1 \left[\int \Psi_2 d\Delta T \right] d\Delta T \tag{3}$$

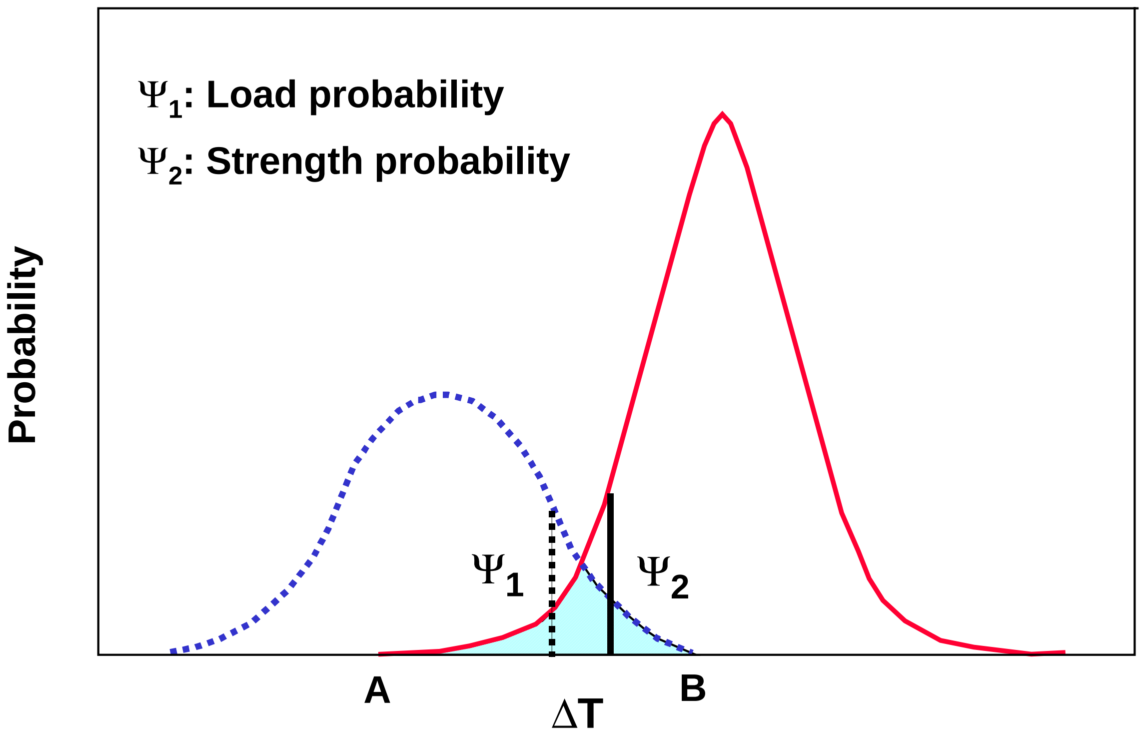

Figure 1. Schematic of Interference Principle

The allowable temperature increase, $(\Delta T)_{All}$ is determined for the following primary track parameters:

- Lateral resistance, F
- Lateral misalignment, δ

Other parameters such as the torsional and the longitudinal resistance, vehicle loads, etc., are also important in the buckling strength assessment. Their influence is generally small when compared with that of the two primary parameters; hence, their variations in the field conditions are not accounted for in this work for simplicity. Rail cross-section is also an important parameter. In the analysis developed here, the rail section is kept constant to that of a standard AREA 136. The overall approach adopted here is shown in Figure 2.

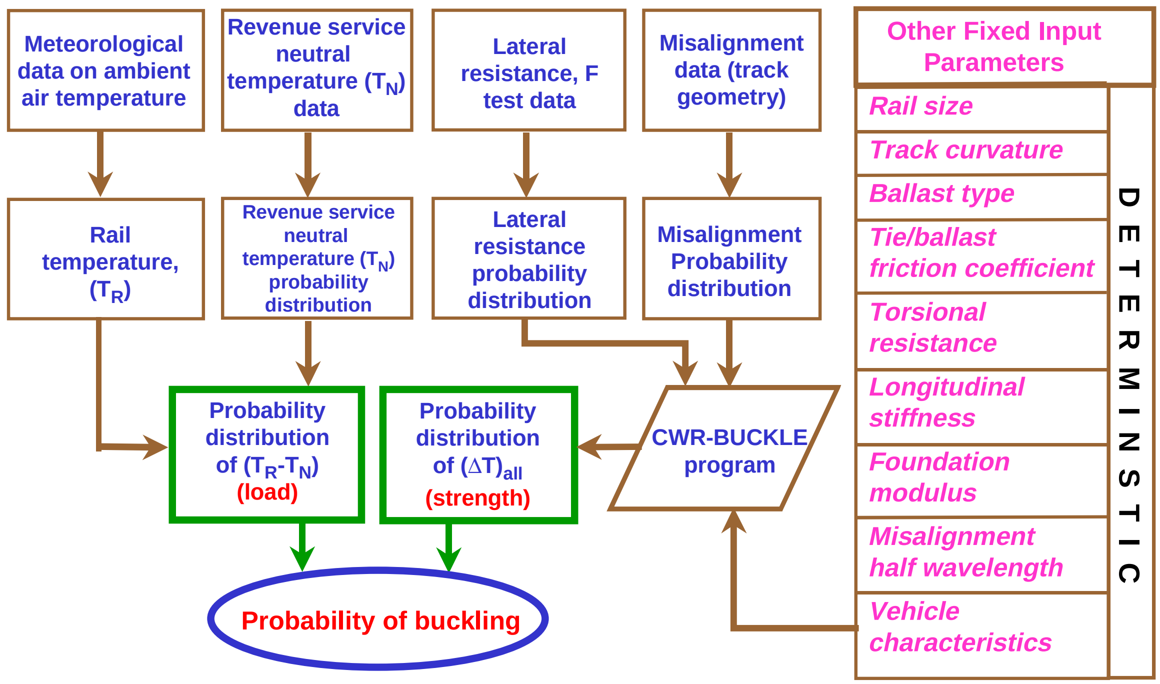

Figure 2. Buckling Risk Evaluation Methodology

The CWR-BUCKLE program calculates the buckling strength for given input parameters which are considered to be deterministic. The criterion for buckling safety is $(\Delta T)_{Load} \leq (\Delta T)_{All}$

This is the classical deterministic approach in which the above criterion is satisfied or not. Hence, the track will either buckle out or not. The "probability" of buckling is either 100 percent or 0. Safety criteria and limits for the ΔT_{All} determination are as first shown in Reference [3] which were recently incorporated into UIC Leaflet #720 through ERRI D202 [4]. The present probabilistic method involves evaluation of:

- Buckling Probability at critical locations, and
- Annual buckling probability per mile on a given segment.

Critical locations are defined as those experiencing maintenance and other activities which can contribute to track buckling. The maximum rail temperature is an important parameter in the "load" quantification. From a practical point of view, this represents a critical factor for the railroads on their timing decisions for CWR track maintenance, slow orders, and heat patrols. The maximum rail temperature is assumed to be known for all the days in the calendar year. Assuming that the other variables (lateral resistance, misalignment, and the rail neutral temperature) are probabilistic, the probability of buckling at a given rail temperature can be calculated.

The annual buckling probability is the sum total of all the probabilities for all events (maintenance activities) at all the critical locations in the track segment under consideration. It is assumed that the peak rail temperature at the locations at the time of activity is known. The sum of probabilities for all the events is the annual probability from which the probability per mile can be evaluated.

Table 1 gives a summary of methods which are available for the CWR safety evaluation.

Table 1. Summary of CWR Safety Evaluations Methods

Method	Deterministic Parameters	Statistical Parameters	Probability
1. Deterministic Approach	Rail Temperature, T_R Neutral Temperature, T_N Lateral Resistance, F_P Misalignment, δ	None	0 or 1
2. Probabilistic Method			
• Buckling at a critical location due to an event	Rail Temperature, T_R	Lateral Resistance, F_P Misalignment, δ Neutral Temperature, T_N	Probability of buckling as a function of rail temperature
• Annual buckling probability per track mile on a given segment	Rail temperature, T_R at scheduled maintenance times; Maintenance schedules, locations and time of year	Rail temperature, T_R Neutral Temperature, T_N Lateral resistance, F_P Misalignment, δ	Annual number of incidents per mile

4. INPUT PARAMETERS FOR BUCKLING PROBABILITY EVALUATION

4.1 Rail Neutral Temperature Frequency

The installation temperature is typically set in the US in accordance with the CWR procedures of each railroad and is usually within the range recommended by the American Railway Engineering and Maintenance-of-Way Association (AREMA). The values are typically in the range of 90°- 110°F depending on the climate. However, as research has shown [5], the neutral temperature does not stay at the rail installation temperature and can reduce to lower values, as low as 50°F in some cases. This is generally due to rail/track movements (creep, curve "breathing," track settlement) and track maintenance activities. Field tests have shown that the CWR neutral temperature can vary in the range of 50° to 110°F [6]. The distribution in this range is not expected to be normal, although this has not been evaluated. For the purpose of numerical illustrations, distributions are assumed as shown in Figure 3 based on limited US testing.

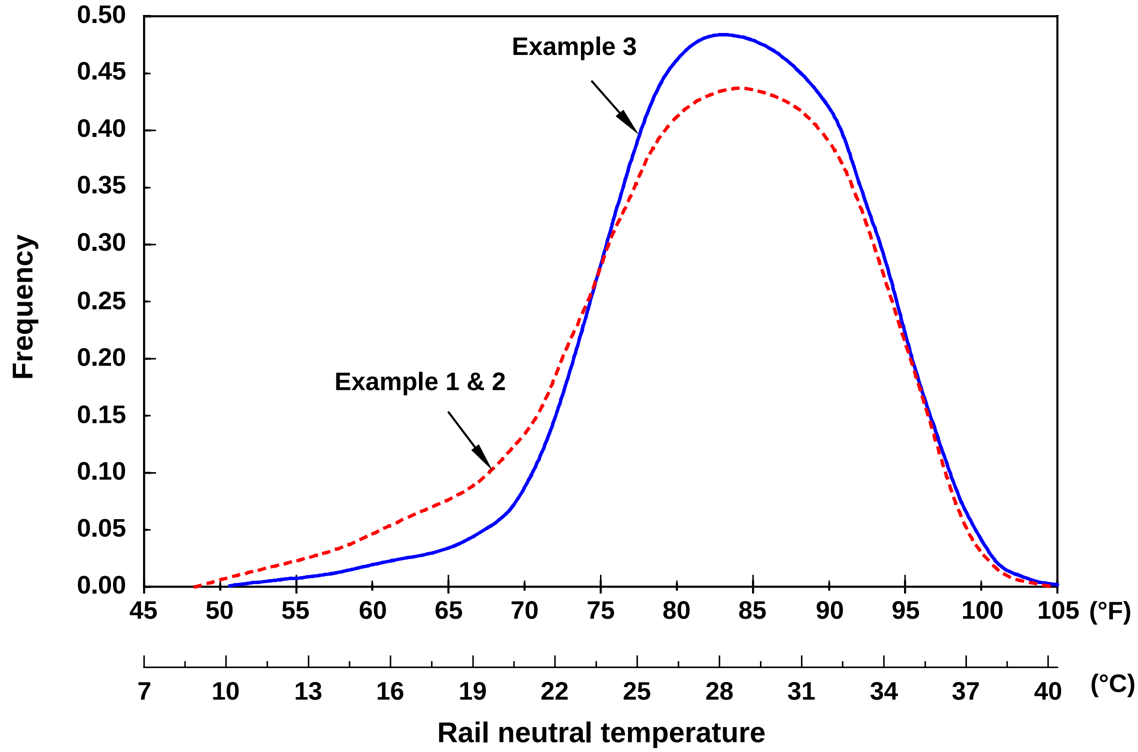

Figure 3. Typical Rail Neutral Temperature Distribution

The neutral temperature considered here is the average of the two rails. It should be noted that the distributions in Figure 3 are spatial distributions. Although the neutral temperature can vary with time after CWR installation or rewelding and trafficking, it is assumed that a "steady-state value" exists at a given location. Figure 3 can be constructed on the basis of one time testing at a number of locations spread over the territory. Methods are available to determine the neutral temperature before and after destressing, or just after rail installation. It is possible to develop a database of the neutral temperatures at different locations to determine the frequency distribution such as in Figure 3.

4.2 Lateral Resistance Frequency

Lateral resistance varies along the track even for a given type of construction (concrete ties, wood ties, tracks with different ballast materials, tamping history, etc.). Scatter in lateral resistance values along the track is inherent in the nature of the railroad environment. Differing tie and ballast types, local soft spots in the ballast, and non-uniformity in ballast consolidation levels all contribute to the variations in lateral resistance. Extensive testing presented in Reference [7] has shown that it is possible to determine a probability distribution of the resistance for a given type of track and level of consolidation. Some of the distributions found in the field tests approximate the "normal" (Gaussian) distributions. In this work, it is not necessary to assume normal distribution. Figure 4 represents typical distributions of the resistance for a timber-tie the track. The resistance can be determined at a number of locations using test fixtures developed in the U.S. and Europe. The Single Tie Push Test (STPT) technique has been used to quantify lateral resistance for U.S. tracks [7,8].

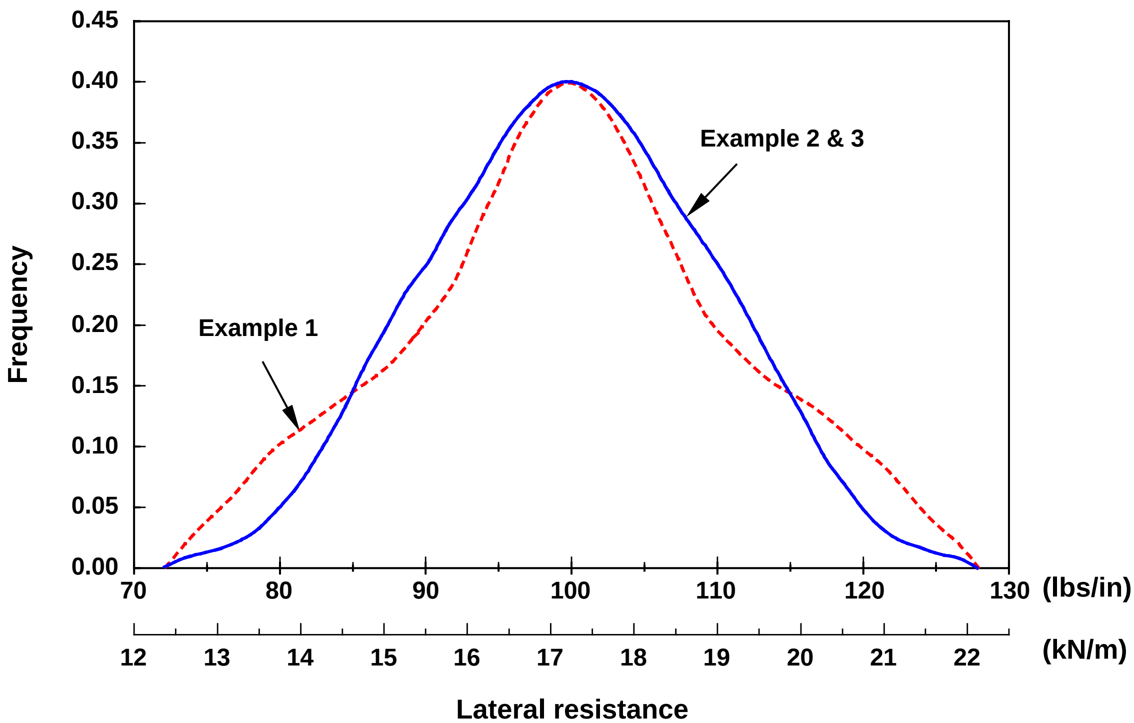

Figure 4. Typical Lateral Resistance Distribution

4.3 Lateral Misalignment Frequency

The allowable lateral misalignment depends on the classification of track, as per the FRA definitions. The current allowable misalignment amplitudes for the U.S. track classes 4 to 9 are usually given as maximum deviations from the ideal shape over a given chord length. For tangent track , the permissible deviations are 1.5 in. for Class 4, 0.75 in. for Classes 5 and 6, and 0.5 in. for high-speed track Classes 7, 8 and 9 for a 62 ft chord length.

Track geometry records can be used to evaluate the probability distributions of the misalignment amplitudes and wavelengths. Although the wavelengths are important, independent distributions for the wavelengths are not considered here. For a given misalignment amplitude, the wavelength is computed automatically in the computer program. The program also allows wavelength to be an input parameter in the analysis. The misalignment distribution depends on the track maintenance practices and the class of the track. Figure 5 shows possible distributions for the FRA Class 4 track.

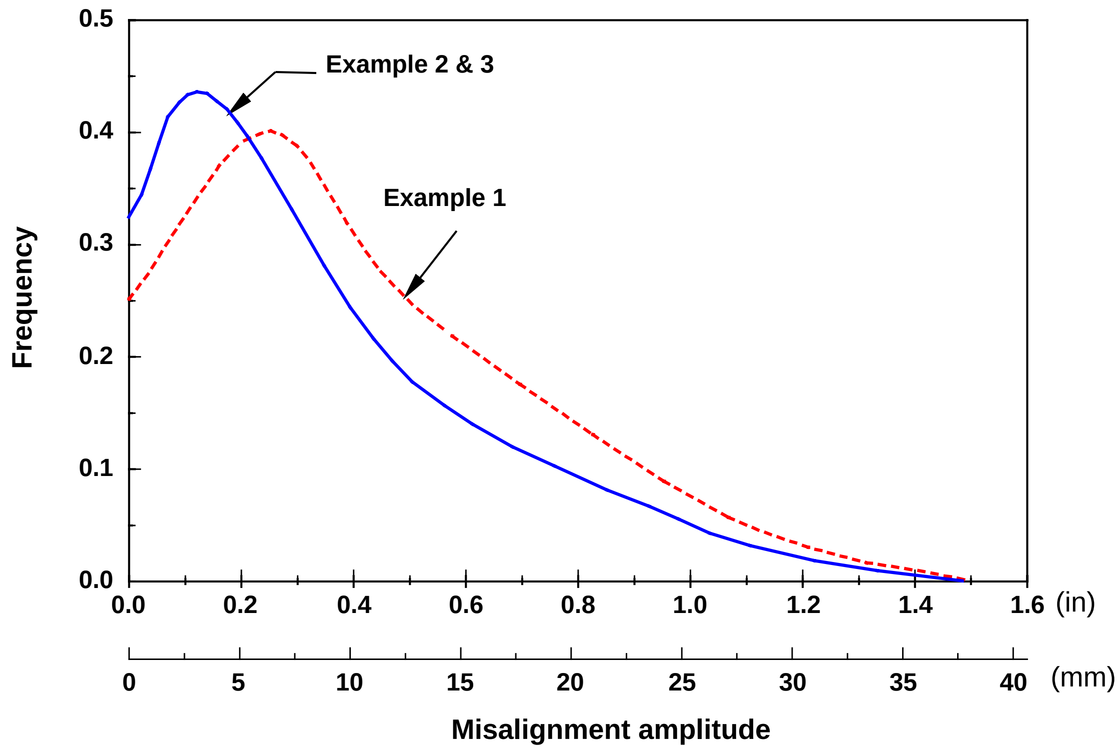

Figure 5. Typical Misalignment Amplitude Distribution

5. CWR-SAFE

The safety analysis package *CWR-SAFE* incorporates the four analysis modules into one comprehensive Windows program. The modules developed previously include *CWR-BUCKLE* and *CWR-INDY*. Two new modules *CWR-RISK(GAU)* and *CWR-RISK(GEN)* are currently being developed on the basis of the methodology indicated in Figure 2.

- *CWR-BUCKLE is* a user-friendly PC-based analysis program which calculates the buckling response of continuous welded rail (CWR) tangent and curved tracks due to thermal and vehicle loads. The calculated buckling response can be used in conjunction with safety criteria to develop "allowable" operating temperature regimes for CWR track, as well as "margins of safety" determinations for buckling prevention, Reference [9]. The program has been validated through the conduct of full-scale buckling tests and is currently used by researchers within the USDOT, the US railroad industry, as well as other worldwide railroad and research organizations, including the UIC and ERRI.
- *CWR-INDY* evaluates the CWR track buckling strength and buckling safety based on a number of relevant structural (track design) parameters. This "industry version" of the program has been derived from CWR-BUCKLE by changing to simpler input parameters. This enables the US railroad personnel to conduct a more direct and "easier" buckling safety analysis.

- *CWR-RISK(GAU)* evaluates the buckling probability as a function of the parameters: track lateral resistance, misalignment amplitude and temperature increase over neutral. The parameter inputs to the program are mean values and standard deviations. All other input parameters such as rail size, track curvature, longitudinal stiffness, and vehicle type are input as in the program "CWR-BUCKLE." The output of the program is a table of rail temperature and corresponding buckling probability. The user can also get a screen plot of buckling probability vs. rail temperature.
- *CWR-RISK(GEN)* program is similar to *CWR-RISK(GAU)* except that the parameters: track lateral resistance, misalignment amplitude and temperature increase over neutral can be more general statistical distributions, i.e., they do not have to follow a normal (Gaussian) distribution. These inputs (frequencies vs. the variables) are specified in a numerical format as shown in Tables 2 to 4. All other input parameters such as rail size, track curvature, longitudinal stiffness, etc. are input as in the program "CWR-BUCKLE." The output of the program is a table of rail temperature and corresponding buckling probability. The user can also get a screen plot of buckling probability vs. rail temperature. The program works as follows: the inputs to the program (refer to Figure 2) are the frequency distributions of the primary variables, and the deterministic values of other parameters. The lateral resistance and the misalignment distributions are numerical inputs at discrete intervals of the variables. From this and the fixed parameter data, the *CWR-BUCKLE* module will calculate the probability distribution of strength through calculations of the allowable rail temperature increase for each discrete case of lateral resistance and misalignment. A subroutine in *CWR-RISK(GAU)* or *CWR-RISK(GEN)* will calculate the probability distribution of load at a given rail temperature, using the neutral temperature frequency distribution. The probability of buckling is determined through the convolution integration of Load and Strength distributions, as schematically illustrated in Figure 1. The rail temperature is then varied and the buckling probability as a function the rail temperature as in Figure 6 is derived.

These four program modules are now contained within one program which allows the user to do preprocessing, analysis, and postprocessing. The preprocessors allow the user to enter/edit the input data using a graphical user interface (GUI) dialog form. They check all data for correctness and automatically "fill in" any pre-defined data values. The postprocessors display the graph or output data from the output files the four programs generate. The user may run any of the four programs to obtain the output data file or chose to use an existing output data file. The following is a summary of the CWR-SAFE program features:

1. It supports the dual-unit system (FPS and Metric, the program *CWR-INDY* has at present only FPS units) and on-the-fly switching of the current unit during data entry with automatic unit conversion of data values.
2. The data entry form facilitates interactive data entry by loading the default data values for all items (for editing

numerical data or for multiple choice list data) except for the project/title strings. This default data loading is done not only for a new form but also for resetting the current data with the DEFAULT button.

3. It validates all user data entered by checking their conformance to the legitimate data value ranges and other inter-data relational rules. It prompts the user for corrections of invalid data and will not save invalid data.
4. It exploits the multi-tasking capability of Windows to allow concurrent running of the three processes: preprocessor, analysis engine (*CWR-BUCKLE, CWR-INDY, CWR-RISK(GAU),* and *CWR-RISK(GEN)*), and postprocessor (with multiple windows) for multiple files (in batch mode).
5. The postprocessor allows the user to send the output graphs to the printer for a hardcopy.

6. NUMERICAL EXAMPLES

Three numerical examples are presented to illustrate the probabilistic approach for general distributions. The examples demonstrate the benefits of improved resistance, alignment and neutral temperature control. The neutral temperature distributions for Examples 1, 2 and 3 are shown in Figure 3. Examples 1 and 2 have the same baseline distribution, whereas Example 3 has an improved distribution with higher frequencies for temperatures greater than 75°F. The frequencies are smaller at lower temperatures, which is an advantage from buckling strength point of view. The lateral resistance distributions for the three examples are shown in Figure 4. Example 1 represents a baseline case, whereas Examples 2 and 3 have better distributions with higher frequencies in the central region of resistance values (85 - 115 lbs/in). The misalignment amplitude distributions are shown in Figure 5. Examples 2 and 3 have smaller levels of misalignments than Example 1, which are beneficial from the buckling point of view. The probability of buckling is calculated using the program CWR-SAFE for a range of maximum rail temperature.

Numerical Example 1

This represents a baseline range of input parameters for a weak tangent track. Table 2 shows the assumed values of input parameters, their mean values and standard deviations. The assumed probabilities of the rail temperature, rail neutral temperature, lateral resistance, and misalignment amplitude are derived from Figures 3 through 5. A plot of the probability of buckling versus rail temperature is shown in Figure 6. When the rail temperature exceeds 145°F, the buckling probability increases very fast.

Table 2. Input Parameters for Numerical Example 1

RAIL NEUTRAL TEMPERATURE PROBABILITY DISTRIBUTION							
T (neutral) (°F)	50	60	70	80	90	100	110
Probability	0.004	0.047	0.135	0.411	0.392	0.011	0
LATERAL RESISTANCE (Fp) PROBABILITY DISTRIBUTION							
Fp (lbs/in.)	72	80	90	100	110	120	128
Probability	0	0.1	0.2	0.4	0.2	0.1	0
MISALIGNMENT AMPLITUDE PROBABILIITY DISTRIBUTION							
Misalignment (in.)	0	0.25	0.5	1	1.25	1.5	
Probability	0.25	0.4	0.25	0.075	0.025	0	

Numerical Example 2

This example compares the reduction in buckling probability by improving the track to have "more uniformity" in resistance and alignment. The input parameters are shown in Table 3. The neutral temperature remains the same as numerical Example 1. A plot of the probability of buckling versus rail temperature is shown in Figure 6. When the rail temperature is 140°F the buckling probability is found to be 0.0035, reduced by about 50% of the value for Example 1.

Table 3. Input Parameters for Numerical Example 2

RAIL NEUTRAL TEMPERATURE PROBABILITY DISTRIBUTION							
T (neutral) (°F)	50	60	70	80	90	100	110
	0.004	0.047	0.135	0.411	0.392	0.011	0
LATERAL RESISTANCE (Fp) PROBABILITY DISTRIBUTION							
Fp (lbs/in.)	72	80	90	100	110	120	128
Probability	0	0.05	0.25	0.4	0.25	0.05	0
MISALIGNMENT AMPLITUDE PROBABILIITY DISTRIBUTION							
Misalignment (in.)	0	0.15	0.5	1	1.25	1.5	
Probability	0.323	0.432	0.18	0.05	0.015	0	

Numerical Example 3

This shows further reduction in buckling probability by improved neutral temperature control, achievable through de-stressing and good fasteners. The input parameters for this example are shown in Table 4. A plot of the probability of buckling versus rail temperature is shown in Figure 6. When the rail temperature is 140°F the buckling probability is found to be 0.00145, reduced by about 80% of the value for Example 1.

Table 4. Input Parameters for Numerical Example 3

RAIL NEUTRAL TEMPERATURE PROBABILITY DISTRIBUTION							
T (neutral) (°F)	50	60	70	80	90	100	110
Probability	0	0.019	0.088	0.461	0.421	0.011	0
LATERAL RESISTANCE (Fp) PROBABILITY DISTRIBUTION							
Fp (lbs/in.)	72	80	90	100	110	120	128
Probability	0	0.05	0.25	0.4	0.25	0.05	0
MISALIGNMENT AMPLITUDE PROBABILITY DISTRIBUTION							
Misalignment (in.)	0	0.15	0.5	1	1.25	1.5	
Probability	0.323	0.432	0.18	0.05	0.015	0	

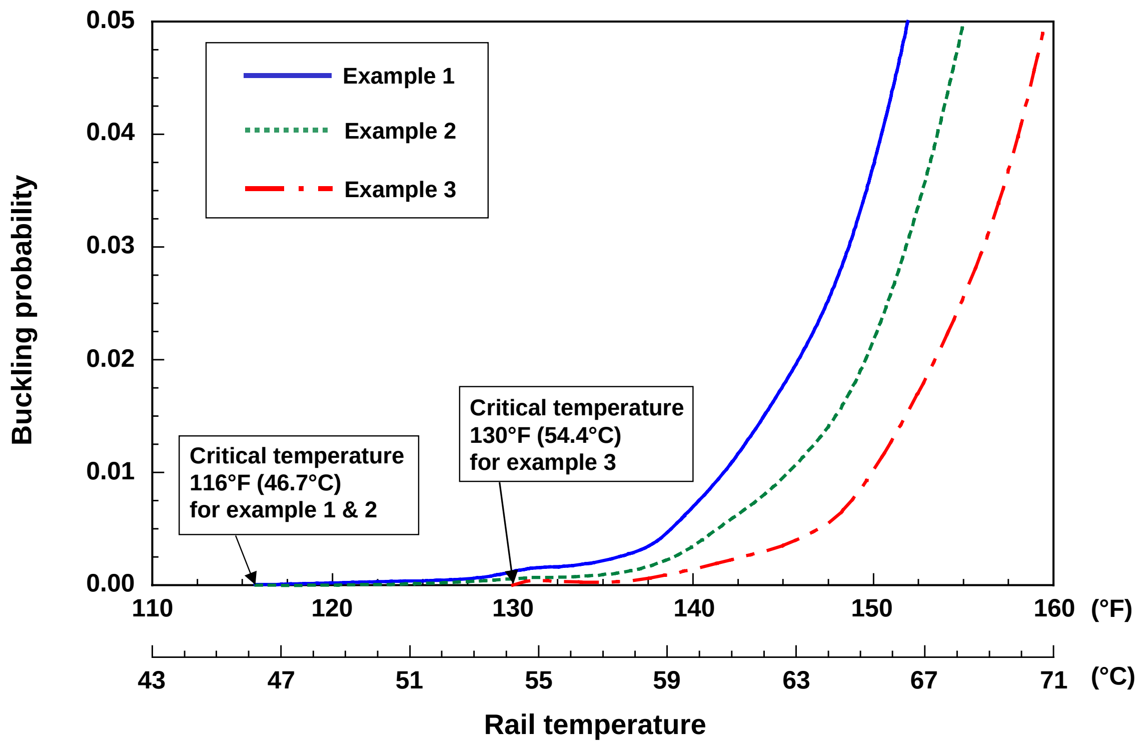

Figure 6. Buckling Probability vs. Rail Temperature

The foregoing examples illustrate that the buckling probability can be evaluated if the probability of individual parameters are known or can be estimated. The buckling probability can be reduced to a desired level by controlling the distribution of lateral resistance, misalignment amplitude, and the neutral temperature. These distributions can be improved (higher “mean” values and lower “deviations” for the rail neutral temperature and the track lateral resistance; lower “mean” values and “deviations” for the misalignment) by specific track maintenance as indicated in Table 5. As seen from the table, alternate methods exist to reduce the probability of CWR buckling potential. These methods can be considered by the railroads to arrive at a cost efficient method of maintenance for a target level of buckling risk.

Table 5. Maintenance Activities for Improved Parameters

Parameter	Methods for Improvement
Rail Neutral Temperature	
Average Value	Achieve high values through hydraulic tensors or improved rail heating
Deviation from Average	Achieve uniformity through optimized destressing over longer CWR lengths; ensure effective rail fastening; limit curve movement
Lateral Resistance	
Average Value	Achieve high values through maintaining good ballast section and adequate consolidation after maintenance
Deviation from Average	Avoid local weak spots contributing to non-uniformity in lateral resistance
Misalignment	
Average Value	Control alignment deviation through frequent inspections, and realignment as necessary
Deviation from Average	Reduce track shifting forces by improved vehicle characteristics and reduced speeds; limit curve movement with temperature

7. ANNUAL PROBABILITY OF BUCKLING

To estimate the total probability of buckling on a given revenue line, the following procedure has been developed. Buckling is usually due to tamping and other maintenance operations particularly in warm weather conditions and due to inadequate neutral temperature readjustment after repairing broken rail. The locations and the frequency of tamping in a year and the corresponding anticipated maximum rail temperatures are important. The rail temperatures at the maintenance operations can be estimated from previous annual data and by using meteorological data on ambient air temperatures, the relevant rail temperatures can be determined. Figure 7 shows a schematic representation of maximum rail temperature. Table 6 shows schematically the day and location of maintenance activities on a given territory in a year, using Examples 1 –3 as illustrations for track characteristics.

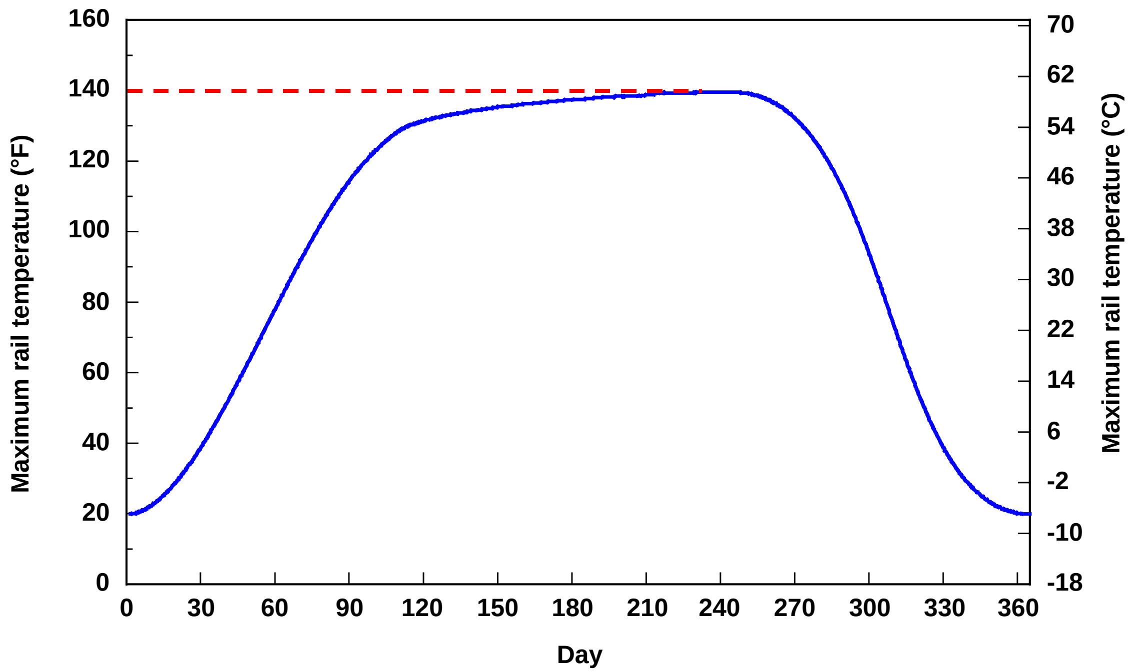

Figure 7. Hypothetical Daily Peak Temperatures

Table 6. Probability of Buckling Due to Each Maintenance Activity

Location	Track Characteristics	Activity	Day	Max Rail Temp (Figure 7)	Buckling Probability (Figure 6)
1	Table 2	Tamping	1 April 2000	120°F	0.00019
2	Table 3	Realignment	1 May 2000	130°F	0.00055
3	Table 4	Destressing	1 August 2000	140°F	0.00145
			Annual Probability		Σ

The annual probability of buckling per track mile can be used to evaluate the anticipated annual number of buckles in a given territory. For example, if the sum of annual probability of buckling in Table 6 works out to be 0.01/mile, then over a 5000 mile territory, the number of anticipated buckles is about 50 in a year. If the annual probability can be reduced to 0.001/mile, then the number of buckles can be reduced to five in a year over the territory. The benefits of such a reduction in the number of buckling incidents can be important to the railroads. The reduction in annual buckling probability can be achieved with the following means:

- The maintenance activities (Table 6) can be optimally scheduled to give low probabilities of buckling. Less maintenance at high temperatures will be beneficial. Perform maintenance on "stronger" tracks at higher temperatures and on "weaker" tracks at lower temperatures.
- Use maintenance methods of Table 5 for improving track strength parameters to reduce buckling probability.
- Apply speed restrictions when there is a finite probability of buckling on "hot" days. This will potentially reduce the damage if buckle induced derailment should occur. The probabilistic method presented here can help answer the following speed reduction relevant questions:
  - i. At what maximum rail temperature (critical temperature) should the speed restrictions be applied?
  - ii. What is the percent reduction in speed over the maximum permissible at the location when the rail temperature is above the critical temperature as determined in (i).

The relationship between the rail temperature and the probability of buckling (Figure 6) is fundamental to determine the rail critical temperature above which speed restrictions should be imposed. According to the current US practice on aircraft structures, the probability of failure should be less than 10^{-6}. Invoking the same kind of number for railroad considerations, speed restrictions may be considered above the threshold probability whenever $P(T) \geq 10^{-6}$. The temperature corresponding to $P(T) = 10^{-6}$ will be called the critical temperature, T_C. In the numerical examples presented, this value is 116°F for Examples 1 and 2, and 130°F for Example 3. Up to this temperature, maximum line speed is permitted. When the rail temperature exceeds the critical temperature, imposition of speed reductions are required. A "risk based" formula for the speed restriction can be postulated along the following lines. *Since the square of the speed is proportional to the external energy available for buckling, the speed should be reduced in a square root proportion to the increase in buckling probability.* We can also stipulate (in line with current railroad practice) that traffic speed should be "low" when the buckling probability equals or exceeds a certain preset value. The rail temperature corresponding to this probability level will be defined as the limiting temperature, T_L. For rail temperatures between T_C and T_L the following speed reduction formula is proposed:

$$\frac{V}{V_{\max}} = \alpha - \beta \sqrt{\frac{P(T)}{P(T_L)}} \tag{4}$$

where α and β are numerical factors to be determined, V_{max} is the maximum line speed, P(T) is the probability of buckling at the rail temperature T, and $P(T_L)$ is the limiting probability beyond which only very low speed traffic is permissible. The above formula is valid for $T_C < T_R < T_L$.

Since the speed is reduced with the increase in the buckling probability, the "damage" levels are also reduced. At low speeds (such as 5% V_{max}, for example) we assume that the damage, hence, the risk is negligible, so for

$T_R > T_L$, this low speed is recommended.

As an illustration, consider Example 2. Let us assume that the threshold probability for speed restriction is 10^{-6} (T_c = 116 °F from Figure 6) and the limiting probability, $P(T_L) = 10^{-3}$ (T_L = 136 °F from Figure 6). At $T = T_C$:

$$1 = \alpha - \beta\sqrt{10^{-3}} \tag{5}$$

and at $T = T_L$:

$$0.05 = \alpha - \beta \tag{6}$$

which gives α = 1.031 and β = 0.9810. The relationship between the maximum speed and the temperature for the Example 2 track is shown in Figure 8, using Eq. 4.

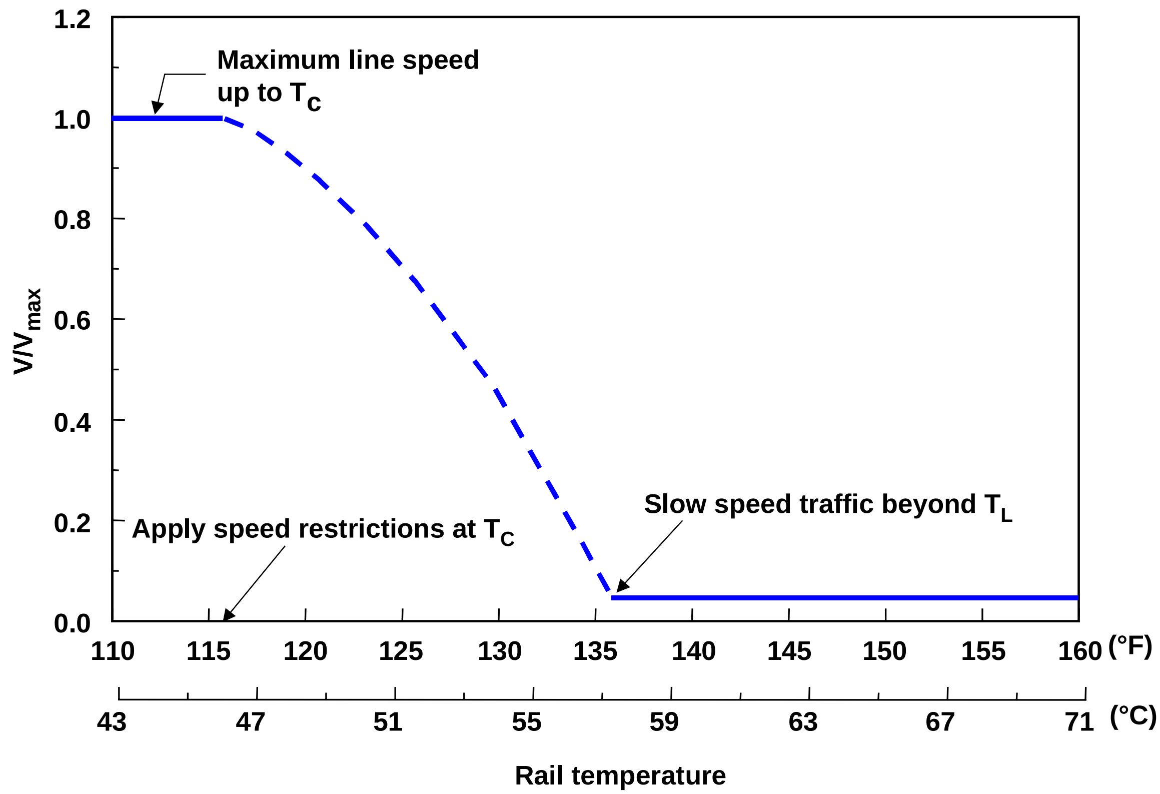

Figure 8. Speed Reduction as a Function of Rail Temperature

7. CONCLUSIONS

- CWR buckling under vehicle and thermal loads can be predicted using deterministic and probabilistic approaches. The deterministic approach will decide whether the CWR track with given parameters, will buckle out or not. If it does not buckle, the "safety assurance" in terms of a buckling margin of safety can also be evaluated. The probabilistic approach recognizes the statistical variability in the input parameters. For given statistical distributions of these parameters, the probabilistic approach gives the probability of buckling as a function of anticipated maximum rail temperature.
- The probabilistic approach developed for CWR track buckling evaluations provides more flexibility in the maintenance of CWR tracks. Tradeoffs are possible between ballast lateral resistance, CWR neutral temperature and other parameters for more cost-effective maintenance for the same level of buckling risk.
- A computational procedure for the determination of buckling probabilities has been formalized into a comprehensive buckling safety analysis program called CWR-SAFE. The program incorporates both the deterministic and probabilistic analysis modules of CWR-BUCKLE, CWR-INDY, CWR-RISK(GAU) and CWR-RISK(GEN) into one Windows based buckling safety analysis package.
- The overall annual buckling probability over a given territory is dependent on the maintenance schedule, rail temperature and track parameters including neutral temperature, lateral resistance and misalignment distributions. Segments requiring maintenance can be prioritized to minimize the annual buckling probability on the basis of track conditions and the anticipated maximum rail temperatures at the segments during maintenance activities.
- The CWR-SAFE probabilistic method presented here can provide a rational basis for speed reductions for buckling risk mitigation when the rail temperature is above a "critical temperature". Allowable speed levels can also be determined using the method.

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