Track Buckling Derailment Prevention Through Risk-Based Train Speed Reductions

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ABSTRACT

This paper presents a “science-based” approach to mitigating track buckling induced train derailments through a risk based train speed reduction rationale. At present the railroad practices on speed reduction at elevated temperatures vary and are based on limited knowledge on buckling temperatures and on the effects of speed influences on track buckling. This paper presents a science based rationale and approach for identifying rail temperatures at which speed restrictions should be applied, and suggests a “risk-index” based temperature at which trains should be curtailed to lower speeds. The approach is based on a probabilistic method for predicting the probability of buckling with increase in rail temperature. Then based on an “accepted buckling probability” index, the rail temperature limits for the imposition of slow orders are determined. Numerical examples are presented to demonstrate the method on a 5° curved (350 m radius) track for a set of typical distributions of lateral resistance, misalignments and rail neutral temperatures. A specific application of the method is demonstrated for a high tonnage line segment on the Union Pacific Railroad’s North Platte/Kearney Subdivision. Based on measured track parameters on this line segment, the probabilistic method is applied for the determination of the maximum rail temperatures permissible before imposing slow orders.

Key Words: CWR, track buckling, risk based maintenance, train speed restrictions, heat orders, probabilistic buckling analyses, derailment prevention

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1. INTRODUCTION

Railroads impose slow order operations on continuous welded rail (CWR) tracks to prevent track buckling induced derailments when the tracks have undergone maintenance operations such as tamping, lining, and surfacing. General “blanket” speed restrictions are also applied whenever the ambient temperature exceeds the rail’s installation temperature. Maintenance operations are also typically restricted whenever this limit is reached, unless such operations are followed by track consolidation using a Dynamic Track Stabilizer (DTS). The application of DTS has been shown to increase the track lateral strength rapidly, thereby eliminating the need to depend on slow ordered train traffic to achieve the required consolidation.

The train speeds under slow orders after maintenance vary with railroad practices and policies. For some railroads, the initial speed after maintenance may range from 10 to 30 mph, and the required minimum consolidation is typically 100,000 tons of traffic. Alternate policies are in place when employing dynamic track stabilization (DTS). The initial speeds may remain at 10 to 30 mph, but the required traffic consolidation is substantially reduced to as low as one to three tonnage trains, after which normal operating speeds are resumed. This is due to DTS’s ability to restore lateral resistance consolidation equal to a 0.1MGT equivalent level [1, 2, 3]. Studies have shown [3] that this level of consolidation is adequate to offer the minimum lateral resistance against track buckling under most cases as long as the track’s neutral (stress-free) temperature is maintained to a reasonably high value.

Most railroad policies also call for train speed restrictions referred to as “blanket heat orders” to reduce the track’s buckling potential at elevated temperatures. Such slow orders are typically imposed at temperatures 10–20°F above the territory’s designated laying temperature, however, such slow-order temperatures may be conservative in most cases.
Speed reduction is an attempt to mitigate derailments and their consequences. The track failure mode with CWR at elevated temperatures can be either track buckling or progressive track shift. Track shift is typically the result of high net axle lateral to vertical load (L/V) ratios causing progressive growth of lateral misalignments. This progressive growth can be further accentuated by high thermal forces. The track shift problem is more prevalent to high speed-high L/V conditions, and is treated in another study.

Because of the many varying slow-order policies, their effectiveness in reducing buckling induced derailments needs to be evaluated on a science basis. This paper is confined to addressing the track buckling aspects only, specifically as applied to the development of a rationale for slow orders to minimize track buckling induced derailments at elevated temperatures.

1.1 Track Buckling

Track buckling occurs due to the compressive longitudinal thermal force in the rails. Research has shown that buckling strength in terms of compressive load $P_s$ is determined by:

$$P_s = AE\alpha \Delta T_{all}$$

where:

- $A =$ cross sectional area of the two rails
- $E =$ Young's modulus of rail steel
- $\alpha =$ coefficient of thermal expansion of rail steel
- $\Delta T_{all} =$ allowable temperature increase for buckling prevention in line with the criteria in [1].

$\Delta T_{all}$ is an output of analysis programs such as CWR-SAFE [4] and is determined through the application of a track quality based safety criterion. For the safety criterion details and for
parametric studies on $\Delta T_{all}$, refer to [5, 6]. The track will buckle whenever the thermal load $P_t$ exceeds the strength $P_s$. The thermal load $P_t$ is expressed through the relationship,

$$P_t = AE\alpha(T_R - T_N)$$

where $T_R$ is the rail temperature and $T_N$ is the rail neutral temperature. It should be noted that in practice track buckling is a “dynamic” event i.e. needing the wheel/rail loads to induce a buckle. One key aspect of this “dynamic trigger” is the vehicle induced reduction of lateral resistance caused by track uplift, and another is the train dynamics influence on the buckling potential i.e. on the buckling regime as indicated in Figure 1 below. CWR-SAFE determines $\Delta T_{all}$ (shown as $T_{bmin}$ in Figure 1) incorporating these dynamic aspects, as well as other key parameter influences, including the effects of lateral alignment defects and track curvature.

![Figure 1. Buckling Stability Fundamentals](image)

The implication of the $\Delta T_{all}$ limit is that the railroads can run trains at full speed if the rail temperature increase over the neutral is at or below $\Delta T_{all}$. A practical constraint to this is that some of the key parameters influencing $\Delta T_{all}$ are not easily measurable or known, or if they are known, they are highly variable. Because of this variability, the deterministic way of evaluating the allowable temperature $\Delta T_{all}$ may not be sufficient. These key highly variable parameters include track lateral resistance, lateral alignment condition, and the rail neutral temperature. Because of
the variability of these parameters, the maximum allowable rail temperature to prevent track buckling i.e. $\Delta T_{\text{all}}$ is not precisely determinable, hence poses a difficulty of establishing and setting slow order temperatures.

Speed reductions, however, are important for the following reasons:

1. Reduced speeds can increase the track's buckling temperature when operating above the track's safe temperature increase, $\Delta T_{\text{all}}$. This is due to the fact that reduced speeds will diminish the train energy transmitted to the track. Since this energy is relatable to the track’s buckling energy [6], the reduced energy input into the track reduces the track’s buckling potential. It should be noted, however, that the extent of this reduction as a function of train speed is not known, and is the subject of current research.

2. Reduced speed will generally reduce the damage in the event of a buckle induced derailment i.e. the consequence of a derailment is diminished.

3. Reduced speed may prevent train derailments at buckles in some instances since at lower speeds the buckled amplitudes may be negotiable by the train without derailing.

In view of the above, it is clear that a new rationale for slow orders at elevated temperatures is required which accounts for the variations and unknowns in the key parameters. Such new rationale should provide for a science based method of determining the temperature limits for imposing speed reductions. The key issues for the development of this rationale are:

- At what temperatures should speed reductions be imposed?
- What should be the required speed reduction?
The aim of this paper is an attempt to answer these questions by providing the framework, rationale, and methodology based on a “risk acceptance” criterion which can be used for speed restrictions development.

2. TECHNICAL APPROACHES TO SLOW ORDERS

There are three science-based approaches to provide a rationale to slow orders:

1. Deterministic Buckling Analysis Basis
2. Buckling Energy Basis
3. Probabilistic Buckling Analysis – Risk Index Basis

All of these approaches to a large extent depend on a determination of track’s buckling potential, and are discussed in detail [7] where it’s shown that the most promising approach is the third one dealing with the probabilistic approach. This probabilistic-risk index approach is summarized below.

2.1 Probabilistic Buckling Analysis – Risk Index Approach

In this approach, the track’s buckling potential with rail temperature is expressed in probabilistic terms as the probability of buckling versus rail temperature. Once the probability of buckling is known, then it could be used to determine the temperatures at which speed reductions should be imposed. The speeds then can be reduced in some proportion to offset the increase in the buckling probability.

The fundamental principle used here is consistent with failure analysis of structures in that the buckling load has to be less than the buckling strength, and its application requires the evaluation of buckling probability as a function of the rail temperature as schematically shown in Figure 2.
Once the buckling probability is known, a speed reduction temperatures can be established based on a risk acceptance criterion i.e. on an accepted bucking probability. This is the risk index approach.

2.1.1 Determination of the Buckling Probability versus Rail Temperature

The buckling strength is determined by $\Delta T_{\text{all}}$, with the key parameters of lateral resistance and misalignments. Their variability expressed in terms of a statistical histogram based on the frequency of occurrence of its values over a chosen length of track segment, as indicated in Figure 2(a,c). These $\Delta T_{\text{all}}$ values are calculated for all combinations of the parameter values together with their probabilities as indicated in Figure 2(b).

The buckling load is represented by the difference of the rail temperature and the neutral temperature. The neutral temperature distribution is measured or assumed [Figure 2(c)]. At a given rail temperature, $T_R$, the load probability is determined by the difference of $(T_R - T_N)$, Figure 2(e).

Knowing the probabilities of strength and load, the buckling probability is evaluated using the convolution integral over the interference zone, Figure 2(g). This integral represents the probability of load exceeding the strength and is discussed in [7, 9]. Using this, the relationship between the rail temperature and the probability of buckling can be calculated and presented as in Figure 2(h).
The relationship between the buckling probability and the temperature (Figure 2h) provides a basis for the determination of the allowable speed. Up to a rail temperature where the probability of buckling is "very small" i.e. "close to zero", normal posted line speeds can be permitted. This close to zero probability temperature is called the critical temperature, $T_c$, and is usually taken as the $10^{-6}$ value on the probability curve. Above this temperature speed restrictions should be imposed because a more rapidly increasing probability of buckling exists. When the probability increases with rail temperature to a certain "limit value", the speed should be slow (i.e. on the order of 10–20 mph). This limiting value can be determined based on a "risk index" in terms of a probability of buckling being accepted. The temperature corresponding to this limiting probability is called the limiting temperature, $T_L$. Figure 3 illustrates the concept for a risk index of $10^{-3}$ i.e. for an accepted probability of buckling of 1 in 1000.
If the damage due to buckled track derailment can be assumed to be proportional to the vehicle kinetic energy, and hence to the square of the speed, as shown in [7, 8] the suggested speed formula for the same level of damage at all speeds can be expressed as:

\[ \frac{V}{V_{\text{max}}} = \left[1 - \frac{P_b(T)}{P_b(T_L)}\right]^5 \]  

(2)

where:

- \( V \) = Reduced speed
- \( V_{\text{max}} \) = Permissible maximum authorized line speed
- \( P_b(T) \) = Buckling probability at rail temperature, \( T \)
- \( P_b(T_L) \) = Limiting probability of buckling at the limiting temperature, \( T_L \)
The resultant speed reduction is as schematically shown in Figure 4. In cases where Figure 4’s complex behavior makes practical application difficult, one can simplify the above through linear approximations as shown in Figure 5.

Figure 4. Probabilistic Speed Reduction with Rail Temperature

Figure 5. Linear Approach to Speed Reductions with Rail Temperature

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The rationale for the linearized approach shown in Figure 5 is currently under investigation by several agencies through vehicle/dynamics interaction modeling to determine “allowable speeds” based on the ability to negotiate certain size buckled amplitudes without derailing.

In summary, the advantages of the probabilistic based speed restrictions are:

- Computer software CWR-SAFE is available to determine the buckling probability versus temperature.

- The method has a rational extension to a “risk-index” based slow order policies

- The method, being probabilistic, accounts for the variability of track conditions in the field, and offers a “risk” based approach.

- At a minimum, the approach provides the temperature, \( T_c \), at which slow orders should be imposed

The disadvantages of the method are:

- The method requires the knowledge/measurement of the three key parameters of lateral resistance, alignment defect, and rail neutral temperature for the applicable line segment to enable the determination of their statistical frequency distributions needed for the probabilistic evaluations.

3.0 ILLUSTRATIVE EXAMPLE OF PROBABILISTIC BUCKLING ANALYSIS

The first step in the approach requires the statistical distributions of the three parameters of lateral resistance, lateral misalignments, and rail neutral temperature as indicated in Figure 6.
From these inputs, the strength and the load probabilities are computed (see Figure 2b,e) via the CWR-SAFE program. The program then computes the convolution integral in the interference zone, Figure 2g, which is the buckling probability as a function of the rail temperature. To illustrate the procedure, input distributions on lateral resistance, misalignments, and neutral temperature (RNT) are chosen as in Table 1. Two types of inputs are chosen for the neutral temperatures, Case 1 and Case 2. Although both exhibit the same low end value, Case 2 is a “stronger” neutral temperature distribution because of the higher mean value.

Table 1. Input Distributions

<table>
<thead>
<tr>
<th>Lateral resistance</th>
<th>Misalignment amplitude</th>
<th>Rail RNT (Case 1)</th>
<th>Rail RNT (Case 2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fp (lb/in)</td>
<td>Freq</td>
<td>RNT (°F)</td>
<td>Freq</td>
</tr>
<tr>
<td>70</td>
<td>0.00</td>
<td>50</td>
<td>0.00</td>
</tr>
<tr>
<td>85</td>
<td>0.05</td>
<td>60</td>
<td>0.04</td>
</tr>
<tr>
<td>100</td>
<td>0.25</td>
<td>70</td>
<td>0.21</td>
</tr>
<tr>
<td>115</td>
<td>0.40</td>
<td>80</td>
<td>0.50</td>
</tr>
<tr>
<td>130</td>
<td>0.25</td>
<td>90</td>
<td>0.21</td>
</tr>
<tr>
<td>145</td>
<td>0.05</td>
<td>100</td>
<td>0.04</td>
</tr>
<tr>
<td>160</td>
<td>0.00</td>
<td>110</td>
<td>0.00</td>
</tr>
</tbody>
</table>

Figures 6 shows the distributions of lateral resistance, misalignment, and the two neutral temperature cases graphically. CWR-SAFE takes the input misalignment and lateral resistance data and formulates the strength distribution.
Figures 6a,b,c. Lateral Resistance, Misalignment and Neutral Temperature Frequency Distributions

Next, CWR-SAFE calculates the load curve. This is the rail neutral temperature minus the rail temperature, and corresponds to the force in the rail a given rail temperature. CWR-SAFE then compares the load curve to the strength curve by using the convolution integral. The probability of buckling versus rail temperature range is the output from the program. A 5° curve with the track characteristics as presented in Table 2 is provided as an example.
Table 2. Assumed Track Parameters

<table>
<thead>
<tr>
<th>DATA INPUT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dual rail size (lb/yd)</td>
</tr>
<tr>
<td>Tie type</td>
</tr>
<tr>
<td>Tie weight (lbs)</td>
</tr>
<tr>
<td>Tie spacing (in)</td>
</tr>
<tr>
<td>Track curvature (deg)</td>
</tr>
<tr>
<td>Ballast type</td>
</tr>
<tr>
<td>Tie/ballast friction coeff</td>
</tr>
<tr>
<td>Torsional resistance</td>
</tr>
<tr>
<td>(in-kips/rad/in)</td>
</tr>
<tr>
<td>Longitudinal stiffness</td>
</tr>
<tr>
<td>(psi)</td>
</tr>
<tr>
<td>Foundation modulus/rail</td>
</tr>
<tr>
<td>(psi)</td>
</tr>
<tr>
<td>Vehicle type</td>
</tr>
</tbody>
</table>

Figure 7a presents the output in terms of the relationship between the buckling probability and the rail temperature for the two cases. These graphs also show the critical rail temperatures, $T_c$, at which the buckling probability just begins to exceed $10^{-6}$. This is the critical temperature ($T_c$) at which the speed restrictions should be imposed, since the probability of buckling will increase with rail temperature beyond $T_c$ at a more rapid rate. The critical temperature is 114°F for both cases (due to both having the same lowest neutral temperature value of 60°F). Figure 7b shows the $T_c$'s based on a 0.001 accepted probability of buckling to be 128°F for Case 1, and 135°F for Case 2.
4.0 CASE STUDY ON PROBABILISTIC BUCKLING ANALYSIS APPROACH TO HEAT SPEED RESTRICTIONS ON THE UNION PACIFIC'S KEARNEY SUBDIVISION

The Union Pacific Railroad (UP) is running heavy freight tonnage through most of its territory; some lines such as the Kearney Sub experiences over 400 MGTs per year. This line, because its high tonnage and put-through capacity, requires specialized maintenance requirements and detailed attention to maintaining optimal speeds. For this reason the imposition of hot weather speed restrictions i.e. blanket heat orders during hot summer temperatures requires special attention. UP sought to apply the aforementioned “risk” based approach to help evaluate its
current heat order policy and establish a more science based approach to blanket heat order requirements.

In line with the methodology described above, the UP collected the data on the Kearney Sub’s rail neutral temperature (RNT) distribution and on its lateral alignment geometry as shown in Figure 8. Since the UP was not able to conduct the required lateral resistance measurements on the Kearney Sub, it was willing to accept as a baseline a set of lateral resistance test results from a recent Amtrak concrete tie test program. The detailed results are provided in [3], and the relevant data to this application is shown in Figure 9. The UP test site particulars used in the analysis are summarized in the Figure 10.
Figure 9. Track Lateral Resistance Data for Concrete Ties from [3]

Figure 10. UP’s Kearney Sub Site Description

• 133 lbs CWR; concrete (scalloped) ties
• Neutral temp (RNT): 28 VERSE measurements
• Tangent - 2° deg curves
• Alignment: 1 mile EC-4 data @ each RNT site
• Class 5, 70 mph, 135 MGTs (on #2)
• Lateral resistance: use Volpe/AMTRAK data

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With the data shown in Figures 8-10, the CWR-SAFE program was exercised to evaluate the probability of buckling versus rail temperature for the four conditions relevant to the Kearney Sub, namely tangent versus 2° (873 m radius) curve, and “weak” versus “strong” lateral resistances. The results of the analysis for the weak lateral resistance cases are shown in Figure 11 below.

Figure 11. Probability of Buckling versus Rail Temperature for the UP’s Kearney Sub

With the UP’s desire to limit the buckling probability to “zero” or “very small”, there was no need to develop a probability of buckling index such as $10^{-3}$ shown in the example of Figure 3 or 7b. i.e. for the UP, $T_C$'s would define the limiting temperatures. Examination of Figure 11 shows that the critical temperature, $T_C=160^\circ F$ (71°C) (corresponding to the “weakest” condition on the Kearney Sub) is the limiting temperature, i.e. $T_C=160^\circ F=T_L$. What this suggests is that up to a rail temperature of $160^\circ F$ the track’s buckling potential is very small, and if the track is maintained to the conditions on which these analyses are based, full line speeds may be permissible up to this temperature. For an actual heat restriction temperature an additional margin of safety of 10 to 20°F can be applied for added conservatism. It should be noted that UP’s current Level 1 and Level 2 heat orders are typically below these numbers providing even more conservatism. As a cautionary note however, it should be remarked that Figure 11 results were based on 28 RNT
measurements over the 100 mile (160 km) segment where the lowest value obtained was 81°F (27°C). From a more complete and statistically valid perspective, additional RNT measurements would have been useful. Additionally, the RNT data was obtained on a “one time VERSE measurement” basis so that its variability with time could not be factored into the analysis. For a more correct RNT profile a continuous RNT measurement is recommended which not only provides for a more accurate heat restriction temperature determination but also for the management of the heat order imposition with changing RNT conditions as well. Such tests with continuous RNT measurement employing Salient System’s Rail Stress Module (RSM) technology are currently in planning stages.

5. CONCLUSIONS

1. The train speeds under slow orders vary with railroad practices and policies, and tend to be empirical. Their effectiveness in reducing buckling induced derailments needs to be evaluated on a rational basis. Approaches are presented here based on which “science based” slow order procedures can be developed.

2. The probabilistic buckling approach proposed here requires statistical inputs on the lateral resistance, misalignments, and the rail neutral temperature. The output of the method is the buckling probability versus temperature relationship. The approach identifies the critical temperatures above which the speed restrictions should be imposed. These critical temperature values are highly track parameter dependent, the most important being the track’s neutral temperature.

3. If some risk is permitted, trains may be operated at higher temperatures than the critical. A risk-based approach is presented here where if some finite “risk” in terms of probability of buckling is accepted then higher operating rail temperatures are possible. This added risk may be mitigated, however, by an appropriate speed reduction in this temperature regime.

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4. A speed reduction formula is proposed for the vehicle speeds when in the range of the rail temperature between the critical and the limiting temperature. The speed formula is devised to maintain equal levels of risk (product of probability and damage assumed proportional to the square of the speed) within the critical temperature regime. Other speed reduction formulas such as linear or step function type can also be developed for more practical railroad implementation.

5. The Union Pacific’s application of the probabilistic approach to its heavy tonnage Kearney Sub showed that for the measured parameters the critical temperature up to which the probability of buckling is very small (10^-6) was in the range of 160-172°F. Since the maximum rail temperatures are not expected to be greater than 140°F (60°C) on this territory, track buckling is not likely if the track is maintained to the level of the measured parameters. The apparent conservatism of current UP heat order policies for blanket heat orders could be revisited in view of these findings.

REFERENCES


