ADDIS ABABA UNIVERSITY
ADDIS ABABA INSTITUTE OF TECHNOLOGY
SCHOOL OF CIVIL AND ENVIRONMENTAL ENGINEERING

CONTINUOUS WELDED RAIL TRACK BUCKLING SAFETY EVALUATION

A thesis submitted to the school of Graduate Studies of Addis Ababa University in Partial fulfillment of the degree of Master of Science in railway engineering

By

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October, 2015

The undersigned have examined the thesis entitled ‘CONTINUOUS WELDED RAIL TRACK BUCKLING SAFETY EVALUATION’ presented by Gezu Mengistu, a candidate for the Degree of Masters of Science in Civil Engineering with Railway Engineering. And hereby certify that it is worthy of acceptance.

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ABSTRACT

Continuous welded rails (CWR) are rails that are welded together to become long continuous members. With the introduction of CWR several problems caused by traditional tracks have been solved, but the stability of the track is highly affected by change of temperatures and vehicle load.

Since expansion of the rails is hardly possible in CWR-track, a temperature increase and vehcle load will result in high compressive stresses and track buckling may occur. Therefore the Volpe Center, Foster-Miller, Inc. (FMI), research over the past 20 year develops versatile computer analysis software called CWR-SAFE for solving track buckling. The program incorporates both the deterministic and probabilistic analysis modules of CWR-BUCKLE, CWR-INDY, and CWR-RISK into one Windows based buckling safety evaluation package. This paper presents results of the application of CWR-BUCKLE software model for evaluation of CWR track buckling safety. Buckling can be explosive or progressive. Explosive buckling is characterized by equilibrium jumps between the two critical temperatures (identified as Tbmax and Tbmin) on the buckling response curve. In progressive buckling no distinct critical temperatures maximum and minimum exist, this usually occurs for weak track conditions. 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.

A sensitivity study has been performed showing the significance of the different parameters in buckling safety of the CWR track with respect to the detail effect of each parameter. Notably, the model accounts for all the important parameters influencing track buckling researched up to date by railway companies. Buckling safety graph is prepared by choosing lateral resistance as a primary variable in the determination of the safe allowable temperature increase with the other (secondary) parameters set at their average or nominal values.

As a conclusion of the investigations, several parameters have a significant impact on the buckling temperatures, Tbmax and Tbmin. The most important parameters are the temperature values and the lateral track resistance. When maximum rail temperature rise and Peak Lateral Resistance reduced, buckling will occur. It is important to note that the results presented represent trends and sensitivity influences for a set of fixed parameters. For a specific track type or condition, actual representative parameters should be used for buckling safety evaluation.

Key Words: - CWR-track, Buckling Safety, sensitivity Analysis, and Buckling Temperature.

ACKNOWLEDGEMENT

Firstly, I would like to express deepest gratitude to my advisor Matias Kabtamu (MSc), for his constant motivation, guidance, support, supervision and constructive suggestion throughout this thesis work. I want also to thank Dr.Wesley Mui for his Providing CWR-SAFE model and suggesting valuable comments to keep the research on track.

I gratefully acknowledge the staff of Ethiopian Railway Corporation and National meteorological Agency of Ethiopia for providing me the necessary information for the input of this thesis work.

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LIST ACRONYMS AND ABBREVIATIONS

AAR	Association of American Railroads
BMS	Buckling Margin of Safety
VNTSC	Volpe National Transportation System Center
USDOT	US, Department Of Transportation
CWR	Continuous Welded Rail
PRLT	Preferred Rail Laying Temperature
RNT	Rail Neutral Temperature
ERRI	European Rail Research Institute
FRA	Federal Railroad Administration
NAL	Net Axle Lateral Load
RDFI	Rail Distress Force Indicator
RUD	Rail Uplift Device
SF	Safety Factor
STPT	Single Tie Push Test
TCS	Truck Center Spacing
TTC	Transportation Technology Center
UIC	Union of International Railways

LIST OF SYMBOLS

Ω	Energy Required Buckling the Track
Ψ	Load Frequency
α	Rail Steel Coefficient of Thermal Expansion
μf	Tie-Ballast Friction Coefficient
Δo	Initial Misalignment Amplitude
Tbmax	Upper Buckling Temperature Increase
Tbmin	Lower Buckling Temperature Increase
T_R	Rail Temperature Increase
T_{pprog}	Progressive Buckling
2L	Buckling Wavelength
2Lo	Misalignment Wavelength
Z	The apparent shortening of rail
A	Rail Cross Sectional Area
E	Rail Steel Modulus
F	Longitudinal Resistance
Fb	Resistance from Tie Bottom
Fe	Resistance from Shoulder
FL	Limiting Lateral Resistance
FP	Peak Lateral Resistance
Iyy	Rail Section Moment Of Inertia about the Lateral Axis through Centroid
Izz	Rail Section Moment Of Inertia about the Vertical Axis through Centroid
Kf	Longitudinal Stiffness
Kv	Track Vertical Stiffness
L/V	Lateral to Vertical Force Ratio
P	Longitudinal Rail Force
R	Radius of Curved Track
Rv	Vehicle Contributes An Additional Load
S	Tie Spacing
Tall	Allowable Rail Temperature Increase
TBMAX	TM Maximum Rail Temperature

TN	Rail Neutral Temperature
TM	Maximum Rail Temperature
To	linear torsional stiffness
U	Rail Longitudinal Displacement in Adjoining Section
u	Rail Longitudinal Displacement In Buckled Zone
V	Axle Vertical Load
W	Lateral Deflection
Wb	Pre-Buckling Deflection
Wc	Post Buckling Displacement
Wo	Initial Misalignment Function
Wp	Peak Lateral Displacement

1 INTRODUCTION

1.1 Background

Railways are one of the prime modes of transportation in many countries. It closely associated with passenger and cargo transportation; there is a high risk in terms of the potential loss of human lives life and assets. New technologies and better safety standards are constantly being introduced, but accidents still occur. There will always be some risk associated with derailments and collisions, but it can be reduced by detailed research into the root causes. Some of the causes require improvement in skill and efficiency, for example In the USA, according to the Volpe National Transportation Systems Centre between 1998 and 2002 there was an average of 38 derailments per year, and the annual value of the damages incurred went up to 17 million US dollars. In the UK there were 445 accidents of track buckling between 2000 and 2009, six of which resulted in derailment, according to the data provided by the Rail Accident Investigation Branch (Derby 2010).

The numbers of accidents presented above may be somewhat discouraging, but if the track is well designed, safety evaluation and maintenance operations are properly executed, this type of accidents can actually be avoided, which highlights the importance of studies on this thesis.

Most of the jointed track has been replaced by continuous welded rail (CWR) track over the last four decade in most countries. Continuous welded rails (CWR) are rails that are welded together to become long continuous members. As compared to jointed track, the CWR track reduces maintenance costs, increases the service life of track and vehicle component, increases passenger comfort, and decrease traction energy consumption as well as noise emission (Tzepushelov and Troyitzky, 1974). Using CWR will ensure a smooth ride and reduce unneeded abrasion.

The main issue with using CWR is the temperature induced stress. Unconstrained rail steel expands in hot weather and shrinks in cold weather. Due to fixed ends, the rails are restrained from expanding and shrinking. Hence, the rails will experience a compressive stress in hot weather and they will undergo a tensile stress in cold conditions. The stability of the track is highly affected by Track buckling is formation of large lateral misalignments in continuous welded rail (CWR) track, often resulting in catastrophic derailments, Buckles are typically caused by a combination of three major factors: high compressive forces, weakened track conditions, and vehicle loads (train dynamics).

Figure 1-1:-Rail buckling (Telegraph Media Group, 2010)

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. Initially, the rail's installation temperature or "anchoring temperature" is the rail's neutral temperature (also called "stress free temperature" – denoted SFT). Hence, at rail temperatures above the neutral, compressive forces are generated, and at temperatures below the neutral, tensile forces are developed. Figure 1.1 shows how the rails could buckle due to a large difference between RNT and ambient temperature. To prevent this problem, the rails are installed at the temperature between hot and cold conditions; thus, setting up the RNT to be in between the buckling and fracturing region.

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. 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 (Volpe National Transportation). 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 cold "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 due to train braking and traction forces, or to differential thermal forces (sun and shade).Track lateral shift/radial breathing in curves that 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. Track vertical settlement which can occur on new or recently surfaced track, or in areas of weak sub grade conditions. Maintenance activities that can influence neutral temperature changes including: lifting, lining, and tamping, replacing broken rail, de-stressing, and installing CWR in cold weather. Research to date has shown that typical CWR rail installation (stress-free) temperatures of can reduce in service to 10ºC - 15ºC due to these effects (Samavedam G. and Kish A.1999).

Moreover, the maximum temperature of the rail can exceed the ambient temperature by around 20^{o}C in hot weather(chine's code 2005), causing the rail steel to reach temperatures of 55^{o}C when the ambient temperature is 30^{o}C. This result causes a greater chance of rail buckling. For example, a CWR is installed at 25^{o}C (RNT = 25^{o}C). Consider that rail buckling happens at a temperature difference of 20^{o}C. Thus, the rail will buckle when the temperature reaches to 45^{o}C. Due to the rail movement through the fastener, the RNT drops to 15^{o}C. This change in RNT causes the rail to buckle when the temperature reaches 35^{o}C.

The example above shows how important it is to keep inspecting the rail neutral temperature of CWR. Installing CWR at a “safe” region between buckling and fracturing temperatures does not guarantee that the rail will not buckle in the future. Hence, in order to prevent the rails from fracturing or buckling safety evaluation to be needed.

Vehicle loads 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 (Kish and Samavedam 2005).

Recently, the rise of the rail temperature is accelerating further due to the global warning and the track stability (buckling) problems that results from the axial force in the CWR have become the most important issue. In order to prevent the track buckling in the hot summer and ensure the safety of the running train CWR track buckling analysis continuous engineering research over the last 20 years.

Climate change is predicted at different scenario according to these predictions extreme high temperatures will become a more frequent occurrence. The result is that the number of buckles expected per year could increase if the track is maintained to the current standard (K. Dobney).

There is now widespread scientific consensus (IPCC 2007) that the global annual average temperature is likely to be 2^oC above pre-industrial levels by 2050. A 2^oC warmer world will experience more intense rainfall and more frequent and more intense droughts, floods, heat waves, and other extreme weather events. Climate change is already taking place now, thus past and present changes help to indicate possible future changes. Also those Climate models suggest a future warming in Ethiopia increased at about 0.2° C- 0.4° C per decade.

All US mainline track(2010-2013) track buckling caused derailments rank first from accident Caused both in number of derailment and cost of damage per derailment so it need a high priority industry goal to improve. Accidents in descending frequency by cause all us mainline shown below

Table 1-1 Accidents in descending frequency by cause all us mainline track 2010-2013(Kish 2014)

Accident cause(T-Codes:65 Total)	No.of Accs.	% Total	2010	2011	2012	2013
T109 track alignment irreg.(buckled/sun kink)	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
T108 track alignment irreg.(not buckled/sunkink)	19	2.7	4	3	5	7
T111 Wide gage (spikes/other rail fasteners0	15	2.1	1	9	2	3
T299 other rail and joint bar defects	15	2.1	2	5	3	5
T002washout/rain/slide/etc.dmg-track	14	2	5	6		3

To keep the derailments and the dollar damage down, FRA and the industry continue to work toward improved buckling prevention practices. This includes a better understanding of the track buckling mechanics and parameters, developing better techniques for improved maintenance, detecting incipient buckling prone conditions, and butter managing the risk associated with buckled track .This thesis aimed at furthering this knowledge toward a better understanding of track buckle safety evaluation

A typical response of the track structure subjected to a temperature rise can be described by three different temperatures: neutral temperature (T0), buckling temperature (T_B;max) and the safe temperature (T_B;min), Temperature T_0 corresponds to the temperature at which the axial stress installed on the rails is zero, coinciding with the origin of the graph in Figure 1-2

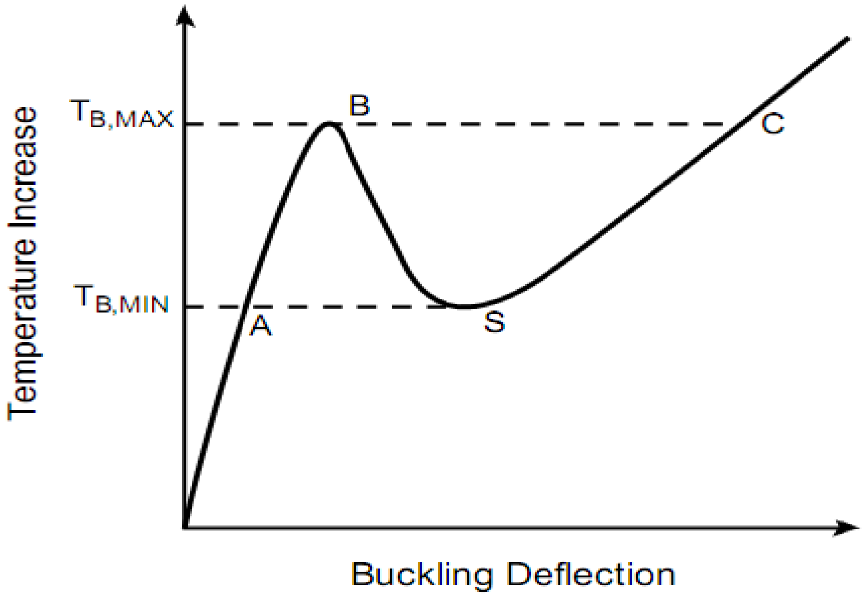


Figure 1-2:- Lateral displacement of the track due to the increase of temperature (Esveld 2001).

The curve in Figure 1-2 can be divided into three branches: AB and SC correspond to stable equilibrium configurations, while BS reflects an unstable equilibrium configuration. Point B represents the limit for the temperature rise above the neutral temperature, when the track structure is no longer stable and a snap-through phenomenon occur, corresponding to a sudden increase of the lateral displacements until a new stable configuration is reached. For a temperature increase between TB,min and Tb,max, buckling is likely to occur, provided that there is enough energy, such as forces due to passing trains. For this reason it is common to consider, conservatively, TB,min as the safe temperature(Esveld 2001).

The actual buckling of the railroad track structure is suspected to be a complex interaction between the vertical, lateral and torsion modes. To make the analysis tractable, however, most studies restricted themselves to either the vertical or the horizontal plane. This is because the buckling behavior of actual track structures shows that only one mode of failure, either vertical or horizontal mode, is dominant in the final buckled form.

The present study is to determine the value of Tbmin using a set of analytical methods developed by other researchers or CWR-SAFE 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 (Kish and Samavedam). 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.

The prevention of track buckling is related to the determination of rail allowable temperature. This thesis will investigate the buckling response of CWR tangent and curved tracks due to thermal and vehicle loads by safety criteria of buckling at a given rail temperature developed by FRA and UIC .

1.2 Purpose of the Study

The purpose of the study is to present an approach for CWR track safety based on the factor influencing track buckling parameter with CWR-SAFE program.

This will help to better estimate the CWR tracks buckling effect due to thermal and vehicles, to prevent the occurrence of rail failures by taking the required action at the right time and extending rail life expectancy by predicting allowable temperature of a given track.

1.3 Objectives

The objectives of the thesis are:

- One of the objectives is a sensitivity study has been performed to evaluate the effects of the individual parameters on the upper and lower critical buckling temperatures of the CWR track with respect to the detail effect of each parameters varying one parameter at time, and fixing other parameters at their nominal values.
- To evaluate 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. CWR-SAFE model is one of the tools vital to the achievement of these objectives. Continuous welded rail (CWR) tangent and curved tracks buckling allowable temperature under vehicle and thermal loads can be predicted using these model deterministic approaches. This 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.

1.4 Research Questions

In order to fulfill the purpose of the study and the objectives, the following research questions need to be answered:

- How can each track parameter influencing the track buckling process?
- What is the minimum track lateral resistance required for buckling safety for a specific track type or condition?

1.5 Methodology

The computer program CWR-SAFE, which consists of three modules, CWR-BUCKLE, CWR-INDY, and CWR-RISK, developed under Volpe National Transportation Systems Centre's Track Stability Research Program for the Federal Railroad to evaluate buckling strength and perform safety analysis of CWR track is used.

This comprehensive predictive model encompasses several different modules designed to perform both deterministic and probabilistic buckling analyses, based on the dynamic buckling theory validated by tests, and predicts safe limits for buckling prevention. The model accounts for all the important parameters influencing track buckling, such as rail size, curvature, lateral resistance, tie-ballast friction, fastener torsional and longitudinal resistances, track vertical stiffness, misalignment amplitude and wavelength, and vehicle parameters. Applications of the model are demonstrated through analyses of parametric sensitivity, development of buckling safety limits in terms of safe and critical temperatures, and evaluation of annual probability of buckling occurrences for typical CWR line segments.

CWR-SAFE a comprehensive CWR buckling program includes three basic modules for safety analyses.

- The CWR-BUCKLE module is a fundamental buckling analysis program using a deterministic approach. The output includes the buckling response curve, critical temperatures, safe allowable temperatures, energy required to buckle the track, margin of safety, and methods to increase the margin of safety if it is inadequate.
- The CWR-INDY uses simple track inputs, such as ballast type, shoulder and crib level, and tie type. Like CWR-BUCKLE, this program provides deterministic values for the buckling temperature, safe allowable temperature, and margin of safety.

- CWR-RISK is the third module in CWR-SAFE for which three key inputs, lateral resistance, misalignment, and neutral temperature, require statistical descriptors. All other parameters remain deterministic the output of the CWR-RISK program is the probability of buckling versus rail temperature.

A computational procedure for the determination of buckling allowable temperature 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, and CWR-RISK into one Windows based buckling safety analysis package. The limitation of this study is it consider only the deterministic part CWR-BUCKLE

The probabilistic approach limits need further evaluation because of lack of data on parameter variation for required statistical representations. The deterministic methodology presented below

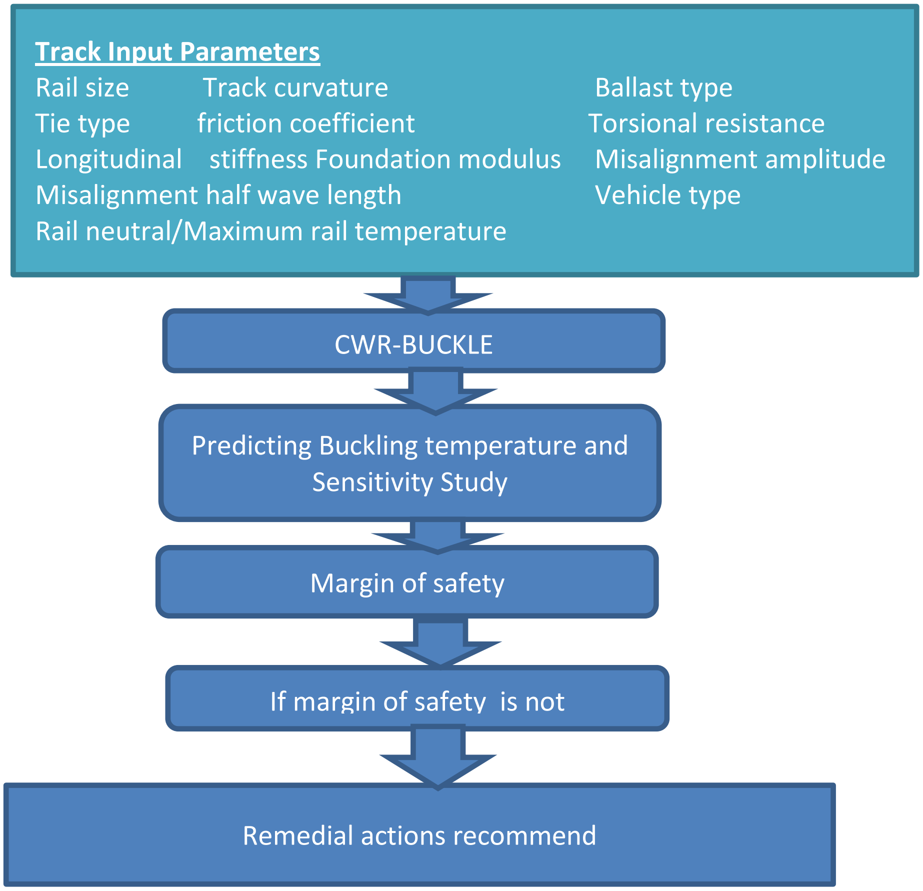


Figure 1-3:-CWR Safety Evaluation Methodology

The computer program requires several input parameters to perform the track buckling and safety analyses. These parameters are summarized below.

Table 1-2 Input parameter

	Parameters	Range	Used
1	Rail Size (AREA)Kg/m	43,45,50,60,75	50KN/m
	a. Area of Two Rails (cm^2)		131.6
	b.Iyy(horizontal axis) for 2 Rails (cm^4)		4074
	c. Izz (vertical axis) for 2 Rails (cm^4)		754
2	Track Tie Type	wood/concrete	Concrete
	a. Tie & Fastener Weight (kN)	0.67 -4.45	3.34
	b. Tie Spacing (mm)	304.8 -914.4	600
3	Track Radius of Curvature (m)	115 to ∞	350
4	Ballast Type	Granite or slag	Granite
	Peak Lateral Resistance (kN/m)	8.76 -52.54	20
5	Tie-Ballast Friction Coefficient	0.65 -2.30	0.86
6	Torsional Résistance (m-kN/radper track-m)	0 - 2224	112
7	Longitudinal Stiffness (kPa)	172 - 3447	3000
8	Foundation Modulus (MPa)	13.79 -69	68
9	Misalignment Amplitude (mm)	2.54 -76.2	38.1
10	Misalignment Half-Wavelength (m)	3 -20	5
11	Vehicle Type		
	a. Number of Axles		4
	b. Axle Load (kN) 293	0 - 333.6	293
	c. Truck Center Spacing (cm)	889 -2032	1046
	d. Axle Spacing (cm)	101.6 - 304.8	1900
12	Rail Neutral Temperature (deg C)	Depend on Geographic location	25
13	Maximum Rail Temperature (deg C)	1.5*ambient Tbmax	70

The value range of Track geometry, rail-sleeper-ballast interaction has taken from data used in CWR track buckling analysis model by Samavedam (1993) and Van (1996). The most important rail properties in case of stability of CWR are the cross-sectional area A and the moment of inertia in lateral I_y and vertical I_z direction. Three other material constants for steel are used to denote the rail in track models, namely the Young's modulus E, the coefficient of thermal expansion α and the Poisons ratio ν. The value of the young's modulus varies between $2.05*10^{11}$ and $2.10*10^{11}$ N/m2 and α has a value in the range of $1.0*10^{-5}$ to $1.2*10^{-5o}c^{1}$, Poisons ratio for steel is 0.3 (Samavedam 1995).Rail size currently under construction in Ethiopia used for analysis.

Measurements show that the maximum rail temperature is higher than the maximum air temperature (samavedam, 1995) differences of 15 to 20^{o}C.For this study a simplified correlation Trail is equal to 1.5Tair (Hunt, G.A. 1994) is assumed. As data from national meteorological Agency shows on a hot day in Ethiopia low land the extreme maximum air temperature may reach values up to 25 to 46^{o}C, hence the maximum rail temperature will be in the range of 38 to 69 ^{o}C, includes design values maximum rail temperature may rise above 70 ^{o}C.

In most railway companies the appropriate neutral rail temperature (RNT) is usually chosen by the track engineer and is about 5^{o}C above the midpoint between the highest and lowest temperature of the rail temperature range in that specific region

2 LITERATURE REVIEW

2.1 Introduction to track buckling

It is impossible to talk about high-speed railway at the present day without taking into account the necessity of joints elimination. Impacts occur when a railway wheel encounters discontinuities generated by gaps of the rail joints. These large impact forces may cause damages to wheel, track and vehicle. A modern solution to solve this problem is to make CWR track (Ungureanu, 2010).

The welding of rail should be realized only into prescribed temperature range for decrease the risk of rail track buckling in a hot season and the risk of rail breaking in cold season Nevertheless during hot season several hundreds of track buckling occurs worldwide and they cause major damage. The number of CWR buckling and the costs of damages and repairs are increasing each year (van, 1997).

Track buckling became a critical track safety concern with the installation of continuous welded rail on many miles of mainline track in high speed and heavy tonnage corridors since the 1960’s. Because of this concern, an investigation was conducted to improve the understanding of the influence of maintenance practices on track buckling potential and to ensure maintenance practices provide an adequate margin of safety against track buckling. Railroad maintenance practices that help mitigate the development of buckling prone conditions include rail laying, welding, and repair practices that help to maintain a high rail neutral temperature (the temperature at which the net longitudinal force in the rail is zero). Track stabilization following ballast disturbance such as surfacing or ballast renewal helps to ensure track stability against buckling. Railroads typically employ various means of track stabilization to compact and stiffen the ballast bed to ensure that the track is stable.

Lateral buckling in rails is a very common defect in which the rail bulges out on either side due to expansion. As the temperature rises, longitudinal expansion in the rail takes place (Zarembski, et al., 2005).It is the lateral misalignment or even derailment of continuous welded rail (CWR) .A narrower definition is used by (Kish et al. 2003) which describes track buckling as a “suddenly occurring large deflection type instability phenomenon.” .

Railway track is subject to vertical, lateral, and longitudinal forces from the environment, traffic, and maintenance, which the track structure must safely resist. When the longitudinal rail force is not adequately constrained by the lateral resistance of the track, a track buckle can occur. The main factors influencing track buckling are:

- The rail longitudinal force (neutral temperature),
- Track lateral resistance,
- The magnitude of dynamic uplift occurring between the trucks of a rail vehicle, and
- The magnitude of track geometry lateral alignment deviations.

Longitudinal rail force is the driving factor for track buckling. When ambient temperature is high, rail temperature raises more than ambient temperature and the thermal expansion of the rail is constrained, causing a large compressive force in the rail. The large compressive force can cause the track to buckle in the lateral plane in various mode shapes and amplitudes. Curves, especially in the presence of initial lateral alignment defects, tend to be more vulnerable than tangent track (Kish 1997).

The lateral resistance can be divided into three components: tie bottom friction, tie side friction, and tie end or shoulder restraint. All three vary with tie material, ballast type, ballast gradation, and strength, which is partly a function of ballast compaction. The bottom friction component is most influenced by tie type, weight, and vertical load, which affects the friction developed at the tie bottom-ballast interface. Side friction is most influenced by crib content due to interlocking of the ballast and friction of the ballast against the side of the tie. End restraint is mostly dependent upon the shoulder geometry since the shoulder ballast resists tie movement mainly through ballast shearing resistance (i.e., an increase in shoulder width generally results in an increase in shoulder restraint). Track maintenance such as ballast cleaning, tamping for surface/alignment, and subsequent compaction of the ballast layer under traffic or using mechanical stabilization influences the bottom and side restraint by changing the ballast characteristics (Kish 2002).

Dynamic rail uplift, the uplift between two trucks of a car also influences track buckling behavior. In the uplift zone, in extreme cases, the tie bottom can lose contact with the ballast, reducing or eliminating that component of lateral resistance to buckling. The applied vehicle loading, vehicle dimensions, track weight, and track vertical modulus (stiffness of track support) define the magnitude and extent of dynamic uplift.

Another factor contributing to buckling is track alignment. Track alignment deviations are a concern for track buckling since any deviation from straight reduces the load needed to induce buckling. In addition, alignment deviations have been shown to grow under thermal load and vehicle passage (i.e. the lateral load from the vehicle traversing the misalignment can increase its size under multiple passes), which can cause the track to suddenly snap into a buckled configuration when the misalignment amplitudes and thermal loads are high.

Track buckling is a serious problem for rail industries. This problem occurs because of the high longitudinal compressive force of the rail. It is because of high rail temperature over stress free temperature (SFT) of the rail. The high rail stress contributes many problems such as track buckling, rail joint failure, rail break and failure of turnouts. The direct and indirect costs of track buckling problems are very high. To solve this problem, it is necessary to study different causes of track buckling, safety and their preventive actions. The influences of rail temperature, SFT and lateral misalignment of track on track buckling need proper investigation.

Continuous welded rail (CWR) though reduces the maintenance cost and improve ride quality, it suffers the risk of track buckling and pull apart due to constrained thermal stress. If not properly managed, track buckle and pull apart problems occur which contradict the cost minimizing objective of the use of CWR. Buckle occurrences can cause derailments, traffic delays, increase maintenance costs, reduce safety margin and negatively affect a customer's perception of rail safety (Howie, 2005).

Prevention of track buckling by routine maintenance and inspection is desirable for the cost effective management of track stability as the costs related to derailments and delays in traffic are greater than that of regular maintenance and inspection.

Several theoretical and experimental investigations have been carried out over the last 30-40 years to manage the track stability, and to sort out preventive practices to reduce the risk of buckling. It has been identified that track near the fixed structure, downhill and braking zones are more vulnerable to buckle (Esvled 2001). A reasonable number of buckles can be occurred within a few days of any maintenance work if proper precaution is not taken. A curved track is more susceptible to buckling.

2.2 Buckling Mechanism

Buckling is the sudden lateral shift in the track alignment to release the built up compressive forces in the rail. Consider a long CWR track, Figure 2-1, which is straight but for a small initial lateral sinusoidal type misalignment described by amplitude δo and a wavelength 2L0. With increase in rail temperature, the compressive force P will increase, which may produce some growth in the initial misalignment. FRA Experiments and field observations have shown that as temperature increase to a maximum level will increase the initial misalignments to w_B, an unstable equilibrium state. At this state, the track can buckle out suddenly into a new lateral position, w_c, spanning a length of 2L. The magnitude of w_c is typically large, on the order of 6–30 in (0.15-0.73m), while its wavelength can be on the order of 40–80 ft. (12.2-24.4m). The displacement W_B is referred to as the pre-buckling displacement, the temperature increase at W_B when buckling takes place is the buckling temperature, and w_c is the post buckling

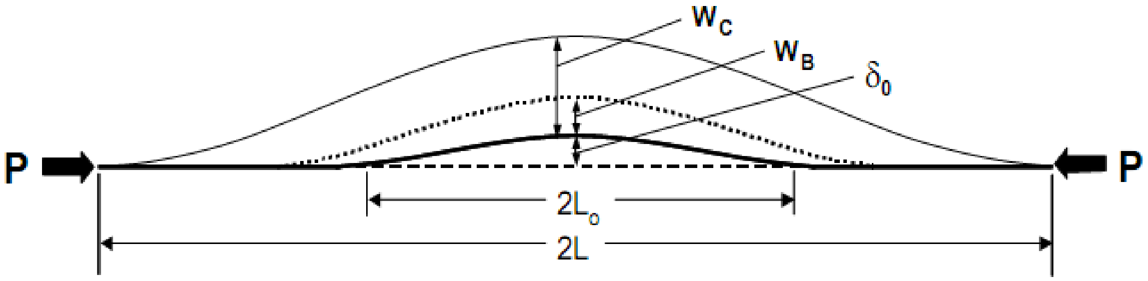


Figure 2-1:-Buckling mechanism (FRA 2013)

2.3 Buckle Influence Zone

A feature of the sudden explosive buckles is the accompanying rail force drop (energy release) in the buckled zone compared with that of the pre-buckling force value. This is due to the large lateral displacement contributing to the rail extension that releases some of the compressive load. The lateral displacement in the buckling zone is accompanied by the longitudinal motion in the outside zones, which feeds the rail into the buckling zone. The longitudinal motion will be felt through a substantially long section of CWR track. Thus, the rail force distribution in the buckled and adjoining zones is significantly altered, as indicated in Figure 2-2. This means that the CWR neutral temperature will be significantly altered after the buckling incident, and long sections of track have to be repaired and re-stressed. It also means that the theory of track buckling has to appropriately predict this energy release and force drop to correctly model buckling mechanism.

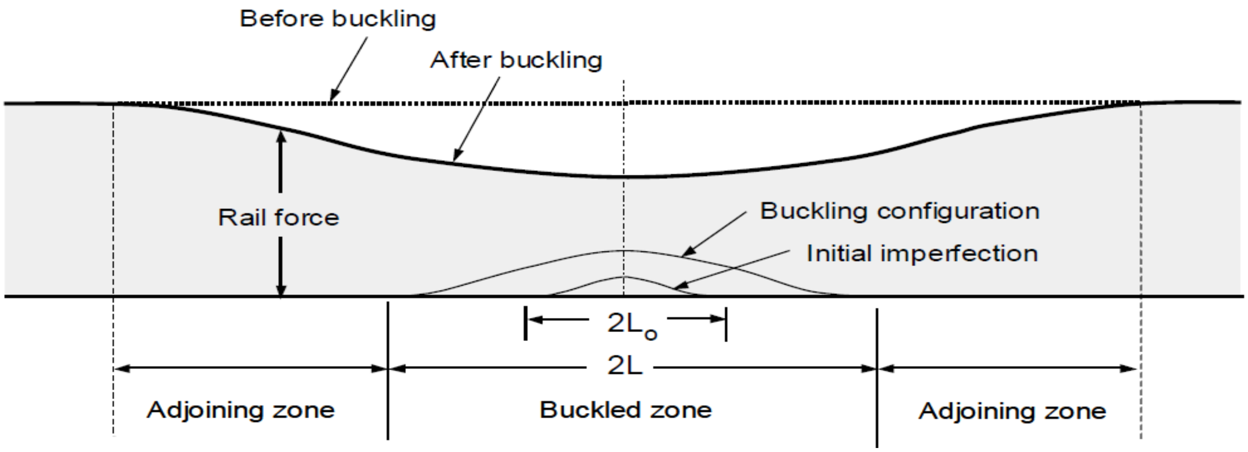


Figure 2-2:-Rail Force Distribution after Buckling (FRA 2013)

2.4 Buckling Theory

Buckling theories are based on mechanistic track model shown in Figure 2-3. The buckling force is the combined compressive load in the two rails, which depends on the rail cross-sectional area and the temperature rise. In general, the rail is fixed to the sleepers by elastic fastenings, which apply a predetermined clamping force to secure the rail to the sleepers. This clamping force is normally of the magnitude such that all the longitudinal movement of the rail is transmitted to the sleepers, the resistance to rail/sleeper sliding being greater than the resistance to longitudinal movement offered by the ballast. A well constrained track prevents the longitudinal and lateral movements of the rail caused by thermal force and train load. Track condition can be weakened by initial misalignment, lack of consolidation of ballast, inappropriate rail to sleeper fastening, track works, sleeper types, sleeper spacing, maintenance activities etc. A weak track cannot provide the required resistance to the loads that cause buckling.

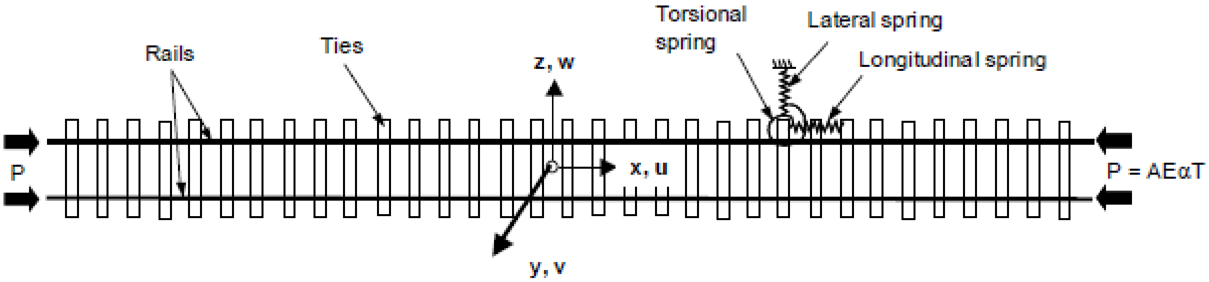


Figure 2-3: Rail Track Model (FRA 2013)

The lateral resistance generated between the ties and the ballast, as well as the longitudinal and torsional resistances generated in the rail fasteners, offers the resistive forces to the buckling force. The lateral resistance depends on nonlinear tie-ballast spring characteristic because the tie displaces laterally through the ballast. The longitudinal resistance depends on longitudinal spring characteristic of the rail/tie/fastener/ballast. In other cases, the rail creeps through the fasteners with no or negligible longitudinal movement of the ties. The rail-to-tie fastenings also offer rotational rigidity (modeled by torsional springs), which reacts against the rail's tendency to rotate during the buckling deformations.

Different buckling theories developed over the last four decade are mostly based on the following principles: Track beam (Kerr, 1978), Beam on elastic foundation, Finite element (SO and Martin, 1976; Esveld and van Hengstum, 1988; Van Hengstum, 1987), Three- dimensional model (Lim and Sung, 2004), Finite Difference Method (Wen-pei et al., 2005)

The theories developed under FRA research are divided into two basic categories, deterministic and probabilistic. The deterministic method requires parameters to be specified with certainty as in classical mechanics. The buckling strength of the CWR track is evaluated using classical formulations and expressed in terms of the temperature increase over the neutral temperature .The method indicates that either track will buckle or not at a given temperature for a set of input parameters. A later subsection presents the required parameters and their characterization.

2.5 Buckling Mode Shapes

A buckled track could have several shapes with buckling taking place in several wave forms. (Fig 2-7) Buckling in the form of a 'C' could occur a on sharp curve shape I while buckled track resembling an 'S' shaped curve is generally evidenced on straight tracks II,whereas higher modes, such as symmetric Shape III, can also occur. Figure 2-7 shows these schematically. The actual buckled mode shape occurring in track is largely influenced by the shape of the initial misalignment. Tangent track typically buckles out in Shape III, whereas curved track buckles in Shape I, and the theory has to properly account for them in terms of appropriate boundary conditions, as discussed below.

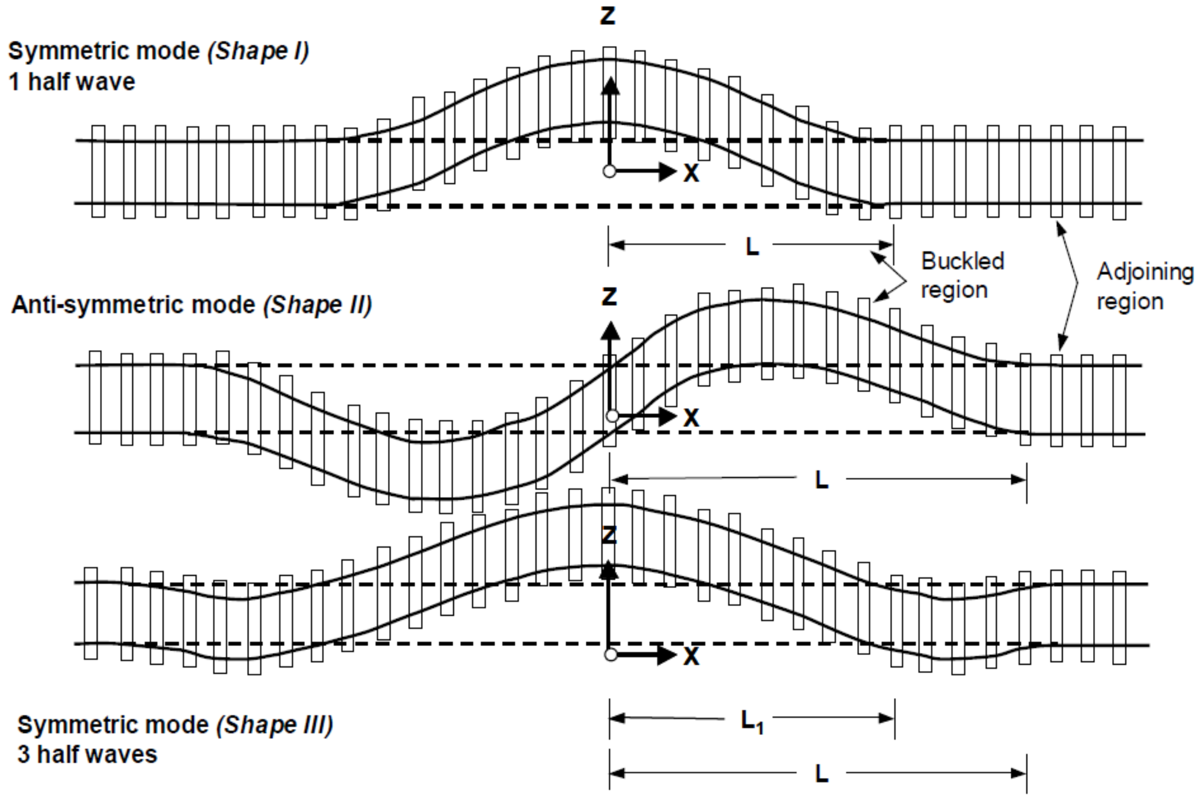


Figure 2-4:- CWR Track Lateral Buckling Modes (FRA 2013)

Vertical buckling is uncommon in practice in the field (Kerr, 1975) because vertical movement is mostly restricted by track self-weight. The moment of inertia of rail is designed such that it would buckle in the lateral direction. The post buckling equilibrium states the track-beam constituting different buckling shapes (shape I – III, Figure 2-7) have been used to determine the effect of constraints on the lateral displacements in (Kerr, 1978). Shape II has been found to be adequate for buckling analysis and a relationship between temperature increase and axial force with lateral displacements has been established considering constant lateral resistance.

2.6 Buckling Response Computation

Figure 2-8 shows the buckling response characteristic which shows two critical buckling temperatures in general. At the upper buckling temperature Tb,max, the track will buckle out with zero disturbance or energy input. The lower buckling temperature Tb,min means that the track will buckle out only with sufficient external energy input. Obviously, the difference between two critical temperatures and the energy required to buckle track need to be included in evaluating the stability for CWR track buckling (Samavedam et al., 1993). Sometimes, the buckling response, so called progressive buckling, shows that two critical temperatures coalesce into one, as shown in Figure 2-8.

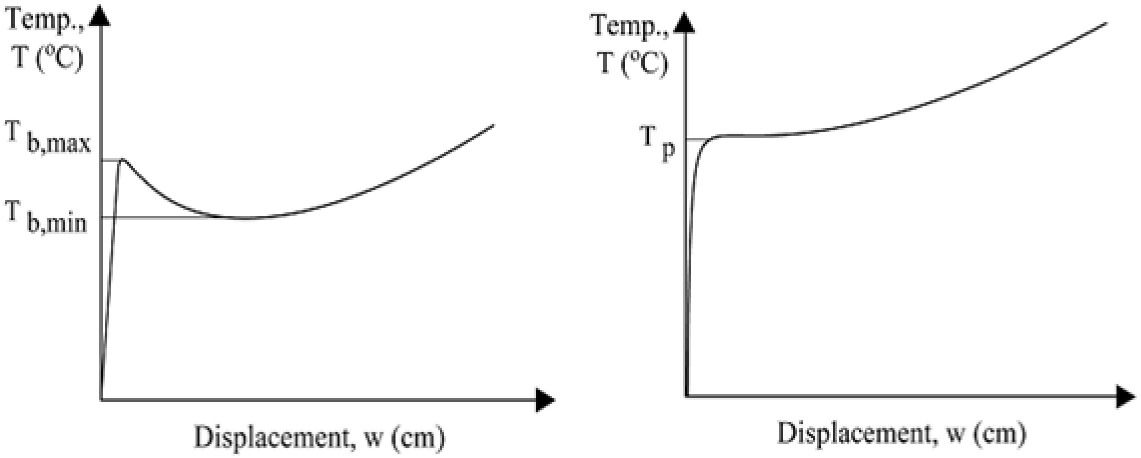


Figure 2-5:- Explosive and progressive Buckling Response curve

2.7 Mathematical Formulation of CWR-Buckle

Nonlinearity of axial, lateral and torsional resistances was incorporated in the formulation of track buckling in (Samavedam, 1993). Potential energy expression has been used to derive two fundamental non-linear differential equations through the use of variational calculus that govern the buckling phenomenon.

Figures 2-9 show the geometric shapes of simplified straight and curved CWR track model before and after the buckling. The track domain is separated into two regions (a buckling zone and an adjoining zone), which are formulated by corresponding differential equations, respectively; A buckled zone where longitudinal displacement is neglected; An adjoining zone that extends to infinity where lateral displacement is neglected.

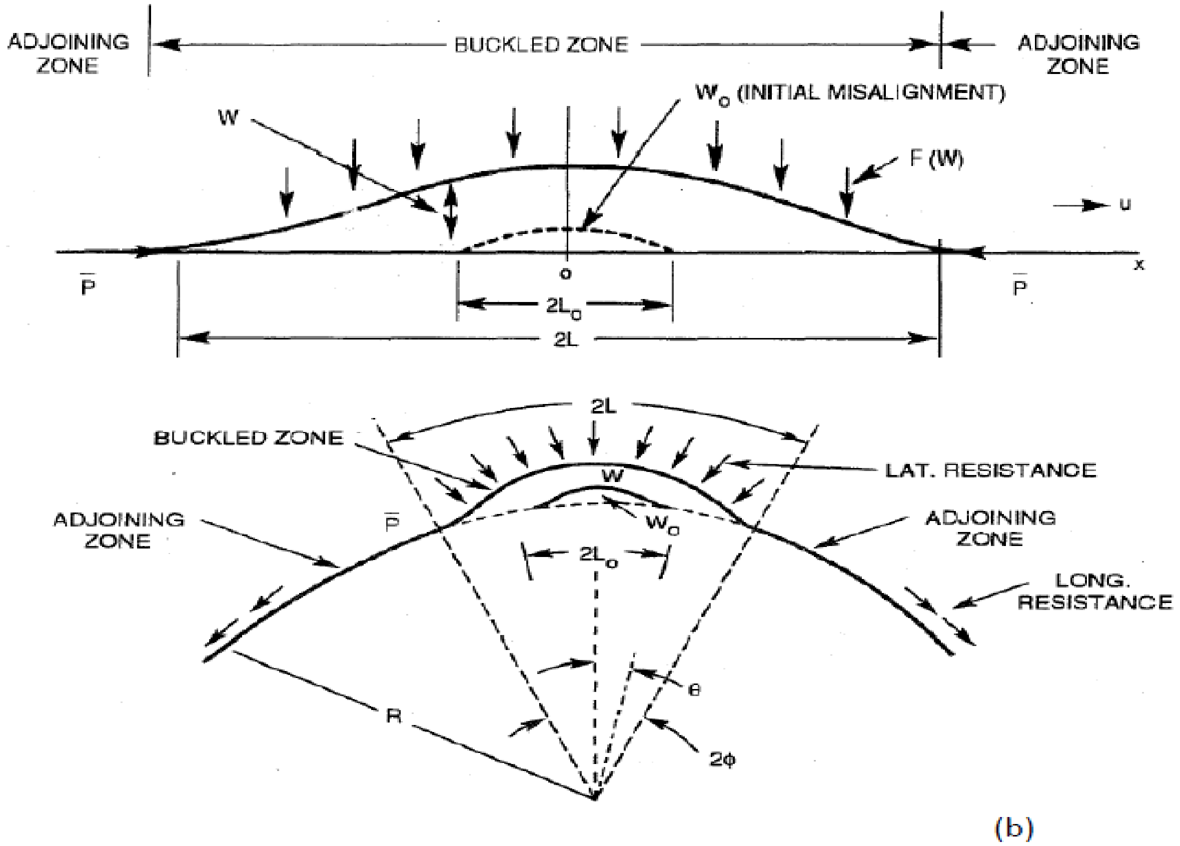


Figure 2-6:- Buckling Mechanism (Samavedam et al., 1993): a: Tangent Track, b: Curved Track

Summarized the derived equations of Samavedam (1993) for the buckled zone which are as follow:

For tangent track:

$$P = EI_{zz}\frac{d^4w}{d\theta^4} + (p-\tau)\frac{d^2w}{dx^2})=-F\ (w(x))-p\frac{d^2wo}{dx^2}) \qquad 2.1$$

For Curved track

$$P = \frac{EI_{zz}}{R^4}\frac{d^4w}{d\theta^4} + \frac{(p-\tau)}{R^2}\frac{d^2w}{dx^2})=-F\ (w\ (\theta)) + \frac{p}{R} - \frac{p}{R^2}\frac{d^2wo}{d\theta^2}) \qquad 2.2$$

Where, E= Modulus of elasticity (N/m2),Izz = Rail area moment of inertia about vertical axis (m4), w= Lateral deflection (mm), x= Longitudinal distance from centre of track (m),P = force in rails (kN), τ = Torsional stiffness of track, F[W(x)]= Lateral resistance distribution function (kNm),w_o = initial imperfection distribution, R= radius of curvature (m), θ= rotation angle (rad). By solving equations 2-1 and 2-2, lateral deflection (w) and lateral resistance functions (F [w (x)]) for tangent and curved track have been derived discussed in the following sections:-

Solving equation 2.1 & 2.2

- **Lateral Deflection**

The infinite trigonometric series for lateral deflections of tangent (Equation 2-3) and curved track (Equation 2-4) in the buckled region as derived are as follows:

$$w(x) = \sum_{n=1,3,5\ldots}^{\alpha} \left(A_m \cos\frac{m\pi x}{2L}\right) \qquad 2.3$$

$$w(\theta) = \sum_{n=1,3,5\ldots}^{\alpha} \left(A_m \cos\frac{m\pi\theta}{2\phi}\right) \qquad 2.4$$

Where, Am = the factor that take accounts for the Fourier coefficients effecting lateral resistance on the track and initial imperfection in the track. It differs for tangent and curved track, 2L = buckling length (m).

- **Lateral resistance Distribution**

The lateral resistance distribution functions for tangent (Equation 2.5) and curved track (Equation 2.6) derived are as follow:

$$F\,(w(x)) = \sum_{m=1,3,5\ldots}^{\infty} \left(a_m \cos(\frac{m\pi x}{2L})\right) \qquad 2.5$$

$$F\,(w(\theta)) = \sum_{m=1,3,5\ldots}^{\infty} \left(a_m \cos(\frac{m\pi\theta}{2\phi})\right) \qquad 2.6$$

Where, a_m is the Fourier coefficient that accounts for the effect of lateral resistance.

- **Vertical deflection**

To determine loss and addition of lateral resistance due to the vertical track deformation under wheel loads. The Differential equation based on the Winkler model for vertical deflection υ can be written as

$$EIyyv''' + Kvv = \sum \delta_i\,(x - x_i\,)V_i + Q \qquad 2.7$$

where EIyy is the flexural rigidity for two rails in the vertical plane, kυ is the track foundation stiffness(assumed constant),vi are the vertical wheel loads ,v is vertical deflection, δi are the dirac delta functions, Q is the track weight per unit length, x is longitudinal distance from center of track .

The distributed foundation (sleeper-ballast) Rv(x) can obtained by solving equation 2.7 and applying boundary condition v=v' to 0 at infinity

$$Rv = Kv.V(x) \qquad 2.8$$

Where Kv track modulus (Mpa), Rv distributed foundation reaction (N/m), V(x) vertical deflection

- **Temperature Calculations**

The required temperature rise (T) above RNT to buckle the track is derived by using continuity requirements on the longitudinal displacement between the buckled and adjoining zones, and expressed as following equation.

$$\mathrm{T} = \frac{\mathrm{p}}{\mathrm{AE}\alpha} + \frac{\mathrm{Z}\Psi}{\alpha(1+\Psi\mathrm{L})} \qquad 2.9$$

$$\Psi 2 = \frac{\mathrm{K_f}}{\mathrm{AE}}$$

Where, Kf =longitudinal stiffness (N/m2), E= Modulus of elasticity (N/m2), P=force in rails, α=coefficient of thermal expansion (oC/m), A=Cross sectional area of rail (m2), Ψ=a constant indicates longitudinal stiffness per rigidity of rail, Z=a function that accounts for the lateral deflection and lateral imperfection along the length, and it varies for tangent and curved track. In the limit, when R approaches infinity the expression for Z of curved track reduces to that of the tangent track.

2.7.1 Energy Required for Lateral Deflection and Buckling

To analyses the lateral stability of CWR track by applying the principle of minimum potential energy derived the equations (2.43- 2.50) (Samavedam et al. 1993). Track buckling potential is characterized by upper (TB, MAX) and lower (TB, MIN) buckling temperatures. It can be noted from Figure 2-10 that, if the track is subjected to a temperature of TB, MAX, the energy required to cause track buckling will be zero, i.e., the track will buckle spontaneously. After buckling, the track reaches a stable state where buckling temperature is TB, MIN. Van, (1997) states that buckling is not only based on maximum temperature at which buckling starts, but also on minimum temperature after buckling, which can be found with a post-buckling computation. Also shows that buckling energy requirement at TB, MIN is much higher than that at TB, MAX. The energy required to cause buckling can be used as a measure of the degree of stability.

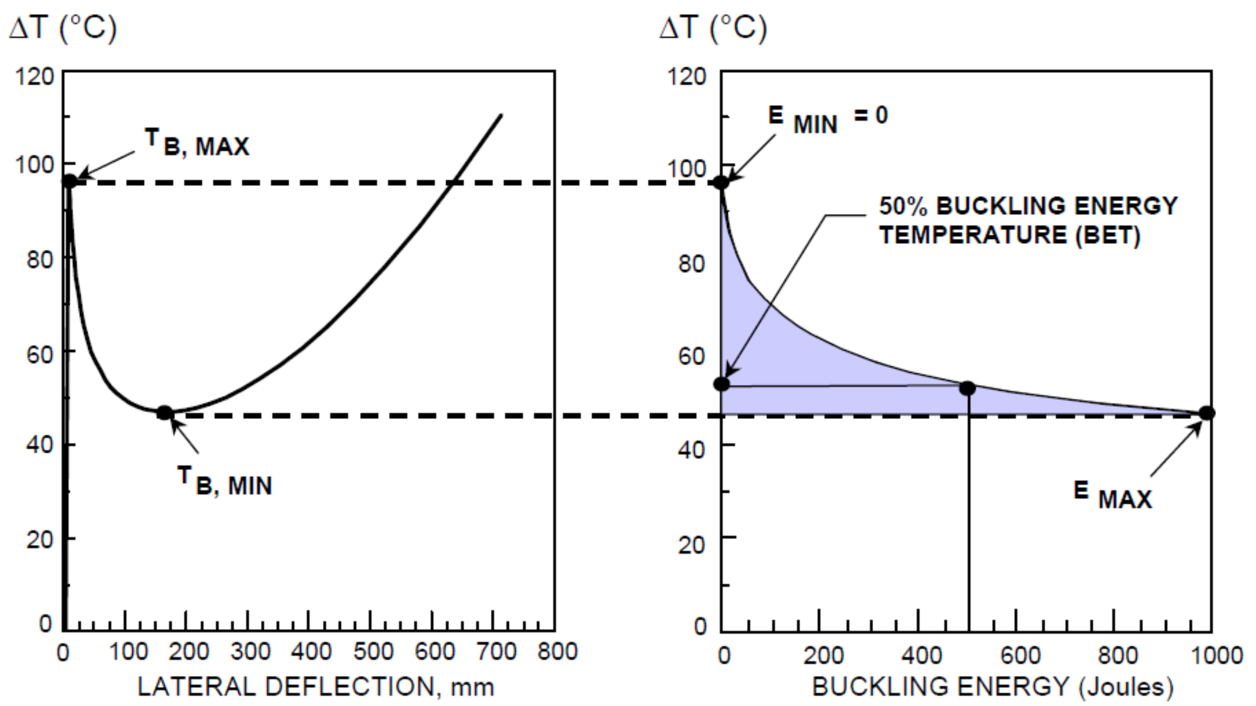


Figure 2-7:-Buckling temperature and energy (Esveld, 2001)

The pre-buckling state has been represented by position 1, while past buckling unstable state by position 2, and it will be automatically move to position (3) in Figure 2-10. Energy required to shift the track from position 1 to position 2 can be obtained by using the following equations (Samavedam et al., 1993):

$$\Omega= (V2-V1) +W \qquad 2.10$$

$$V1=\frac{1}{2}\int_0^\infty \frac{p_\infty{}^2}{AE}dx \qquad 2.11$$

$$V2=\frac{1}{2}\int_0^\infty \frac{p_\infty{}^2}{AE}dx + \frac{EI_{zz}}{2}\int_0^\infty \left(\frac{d^2w}{dx^2}\right)^2 dx \qquad 2.12$$

$$V2 - V1 =\frac{1}{2}\int_0^\infty \frac{p^2-p_\infty{}^2}{AE}dx+\frac{EI_{zz}}{2}\int_0^\infty \left(\frac{d^2w}{dx^2}\right)^2 dx \qquad 2.13$$

$$W=W1+W2 \qquad 2.14$$

$$W1=\iint_0^{w(x)} F\big(W(x)\big)dwdx \qquad 2.15$$

$$W2=\iint_0^{u(x)} F\big(u(x)\big)dudx \qquad 2.16$$

The work done against a linear longitudinal resistance $f=k_f u$ is given by

$$W_2=\frac{K_f}{4\Psi^3}\left(\left(\frac{P}{AE}-\alpha T\right)^2\right. \qquad 2.17$$

where, Ω =Energy required to move track (from position 1 to 2) or to buckle the track, V1, V2 = strain energies, W= work done against resistance forces, P_∞= AE α (TN - TR),P = longitudinal force (N), longitudinal force in the rail (N), W1= work done against lateral resistance (Nm), W2= work done against longitudinal resistance (Nm), u = axial displacement in the buckled zone (m), w= lateral deflection, F[w(x)] = lateral resistance distribution function, f[u(x)]= longitudinal resistance distribution function

Equation 2-13 shows that the total strain energy is the sum of the effects of compressive axial force and the force due to beam bending. Equations 2-15 and 2-16 show the work done against lateral and longitudinal resistances. The total energy requirement is the sum of potential energy and work done (Equation 2-10).

2.8 Static versus Dynamic Buckling Model

Track buckling caused by longitudinal compressive force buildup due to rise of temperature above the stress-free temperature due to thermal loads alone is called static buckling. The industry today is more concerned with buckling caused by the movement of a train on the track in the presence of thermal loads. Such a buckling is called dynamic buckling. The effects of a moving train which could contribute to dynamic buckling are as given below: Loaded axles, tractive and braking forces applied, hunting motion and Vibrations induced by the moving train

If vertical axle loads are applied on the rails, the sleeper will move vertically in the ballast. The simplest way to model this are vertical linear-elastic springs, known as a Winkler foundation. The static vertical deformations due to four axle loads on a Winkler foundation are shown in Figure 2-11 the static buckling model ignores the effects of vehicle loads and considers the buckling of track resulting from longitudinal compressive loads only. In the buckling region, the resistance to lateral buckling is offered by a tie-ballast structure with no vehicle vertical load influence. The correct modeling requires the inclusion of the vehicle vertical loads and their influence on lateral resistance. The vertical loads are distributed along the track depending on the axle and truck center spacing of the vehicle. Although the lateral resistance directly under the wheels increases, the resistance of the track segment between the trucks can decrease because of the uplift wave of the section. This uplift wave is referred to as the central wave and shown schematically in Figure 2-11. Recession and precession waves exist (or occur) behind and in front of a train (as shown for two cars in the figure) where the lateral resistance can reduce. The central wave generally has maximum reduction in the lateral resistance and is therefore critical for buckling. This suggests that the track section under the vehicle can be most vulnerable to buckling due to loss of lateral resistance; in fact, buckling under the train is a frequent occurrence.

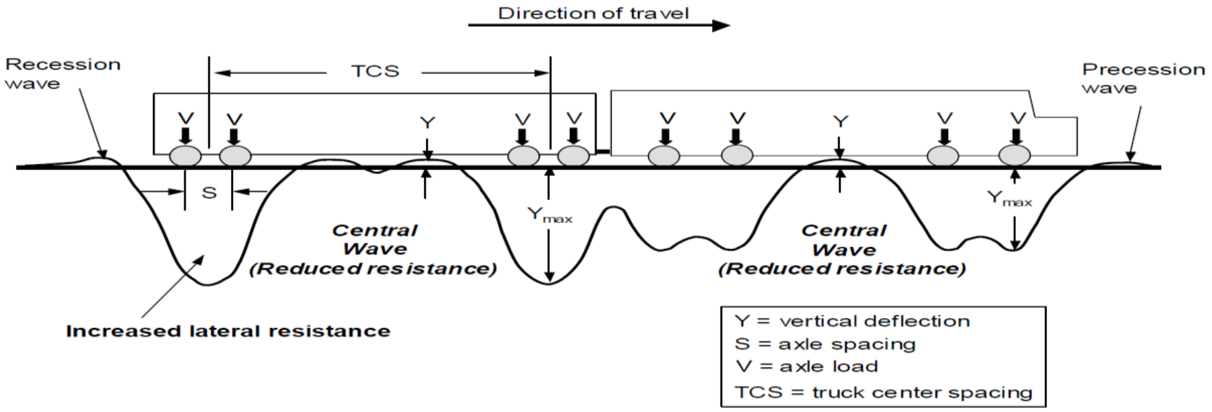


Figure 2-8:-Definition of Uplift Waves (FRA 2013)

Buckling under the central wave uplift should be distinguished from the potential track shift that could occur if the wheels carry high lateral loads during negotiation of curves and lateral misalignments. The force that tends to move the curve laterally is the net axle force (the sum of the lateral forces at the two wheels of an axle). The net axle force is expressed in terms of the lateral to vertical force ratio (L/V). Unless this L/V ratio exceeds a threshold limit, no track shift or lateral movement will occur under the wheels [Samavedam1997]. Track shift occurs gradually under a wheel passage, whereas lateral buckling between the two trucks of a car can occur rather suddenly. Track buckling due to central wave uplift is generally not dependent on the NAL force because the lateral deflection, if any, from the net axle load (NAL) load is confined to a small region under the wheel where the lateral resistance is the highest.

In summary, dynamic buckling theory is required for the more accurate buckling predictions. This means that the influence of the vehicle loads in producing the dynamic uplift is essential in the model, specifically, to account for the reduced resistance and the subsequent reduction in buckling strength.

2.9 Tangent versus Curved Tracks

FRA field tests and observations of actual buckles show that the buckling behavior of curved tracks can be different from that of tangent tracks. Tangent track is generally a sudden explosive type of buckle and can displace to either side depending on the direction of the initial misalignments or the weaker side of lateral resistance. Track buckles with Shape III on tangent track typically have the amplitude of the middle wave relatively large compared with the two end waves.

Curved tracks generally buckle outward in Shape I as seen in figure 2-7. Because of the initial curvature, it would require significant energy to bend the rail in the opposite direction of its curvature (i.e., inward to produce the tail ends of Shape III). Another important feature of curved track buckling is the tendency toward progressive buckling, especially for curves with weak lateral resistance and with high curvatures.

Curved tracks also exhibit radial movement (breathing), especially under weak lateral resistance condition when in the presence of large diurnal and seasonal rail temperature changes. Temperature increase over the neutral can produce radially outward movement; temperature decrease from the neutral can produce radially inward movement. This radial breathing can be detrimental to the track because it reduces the lateral resistance further and may generate local lateral misalignments, which can precipitate buckling. Radial movement can be on the order of a few inches or more and can create buckling prone conditions by reducing neutral temperature, weakening lateral resistance, and producing local alignment defects.

2.10 Main parameters Influencing buckling

In order to reduce the risk of track buckling it is important to identify the causes of buckling. The thermal buckling analysis of tangent and curved continuous welded rail (CWR) are studied for the lateral buckling prevention. The parameters include rail size, track lateral resistance, track longitudinal and torsional stiffness’s, initial misalignment amplitude and wavelength, track curvature, tie-ballast friction coefficient and truck center spacing. Parametric studies are performed to evaluate the effects of the individual parameters on the upper and lower critical buckling temperature

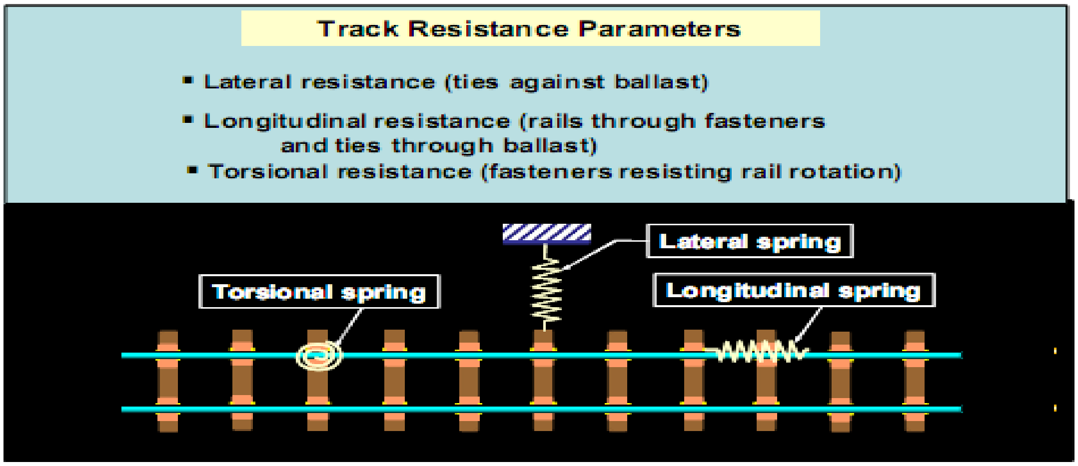
2.10.1 Foundation Modulus (Vertical)

The track foundation modulus is a measure of the vertical stiffness of the track foundation. This is used to determine the vertical load distribution on the ties, from which the dynamic lateral resistance is evaluated.

Samavedam et al. [1993] show the effect of track foundation vertical stiffness on track buckling potential, and it has been observed that upper buckling temperature increases with the increase of vertical stiffness. Lower buckling temperature also increases with the increase of stiffness, but this increase is less sensitive to that of upper buckling temperature. However an initial downward slope is visible in both the temperatures due to the complex relationship between the vehicles induced uplift wave and buckling lengths.

2.10.2 Track resistance

Track resistance is one of the most important parameters influencing track performance and safety. Through its three in-plane components of lateral, longitudinal, and torsional, and one out-of-plane of vertical, it influences most track lateral stability aspects including geometry retention and buckling prevention. The three in-plane components are schematically shown in Figure 2-13 with their typical "spring" analogy representations.



Track Resistance Parameters

- Lateral resistance (ties against ballast)
- Longitudinal resistance (rails through fasteners and ties through ballast)
- Torsional resistance (fasteners resisting rail rotation)

Figure 2-9:- Track resistance Parameter (Samavedam et al. 2003)

Longitudinal resistance provided to the rail/tie structure by fasteners and anchors is important to prevent rail running (and thus limit rail neutral temperature variation), and to limit tensile break gap sizes in the event of rail breaks.

Torsional resistance provided by the spiked tie plates, anchors and fasteners against rail rotation (in-plane-bending) also offers "rigidity" to the track structure, especially against buckling.

Lateral resistance is the reaction offered by the ballast against lateral movement, often referred to as the "lateral strength". It is a tie-ballast interaction parameter which is influenced by several factors such as ballast section, condition, consolidation, maintenance, tie type and condition, and train loads.

Buckling analyses embodying the non-linear aspects of the lateral resistance and its tie/ballast friction coefficient based dynamic effects are available through the US DOT/Volpe center developed CWR-SAFE model (User's Guide 2000).

2.10.3 Misalignment Amplitude

The misalignment amplitude (δ0) is the size of the track misalignment prior to the occurrence of buckling, as shown in Figure 2-14.

2.10.4 Initial Misalignments

Misalignments present in the track play an important role in triggering track buckling. It is considered that rail is manufactured to an initial straightness, which typically permits maximum defect amplitudes of 0.5 mm over 2 m of rail length [Samavedam, G., Blader, F. & Thomson, D., 1996].

Straight tracks with smaller lateral imperfections buckled at much higher temperature increases than those tracks with noticeable lateral imperfections. Again, one train can create a small amplitude line defect which can increase the buckle proneness for the next train coming (F. Brimann and F. Raab).Negative deflection occurs under locomotive axles while the central bending wave under the hopper car increases the potential for lateral deflection (Samavedam et al. 1993). This is more severe for larger bogie center spacing's. The upper buckling temperature condition has been found to be more sensitive to misalignment than lower buckling temperature. It has been found that both upper and lower buckling temperatures increase with the increase of half wavelength and decrease with the increase of amplitude. Investigation shows similar trends considering the fixed relationship between amplitude and half wavelength (Esveld's 1998).

2.10.5 Misalignment Wavelength

The misalignment wavelength (2L0) is the total length of the track misalignment before the occurrence of buckling, as shown in Figure 2-14. The misalignment shape can be mathematically approximated by a simple polynomial.

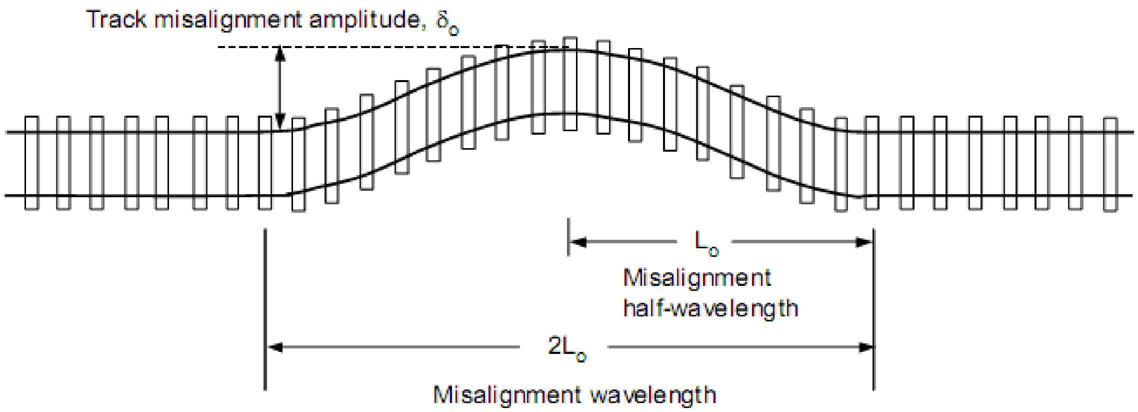


Figure 2-10:-Track Misalignment (FRA 2013)

2.10.6 Temperature

Currently empirical relations have been used to determine rail temperature from the ambient temperature. F. Birmann and F. Raab concluded that there is an accumulation of permanent lateral track deformations due to reversal of temperature over a period of time, which increases buckle potential. Van [1997] states that buckling is not only based on maximum temperature at which buckling starts, but also on minimum temperature after buckling, which can be found with a post-buckling computation. In all cases rail neutral temperature affects the result most significantly. However a potential difficulty is the variable nature of neutral temperature. RNT tends to shift downward over time due to the effects of traffic, rail movement and track maintenance. Longitudinal stiffness plays an important role in controlling neutral temperature variations. Pandit describes the theoretical formula of neutral temperature using longitudinal strain in rail

The neutral temperature is the rail temperature at which zero longitudinal force exists in the rail. The temperature increases in the buckling analysis are measured with respect to the neutral temperature. Although this parameter is required only in the safety analysis part of the deterministic model, a statistical distribution of this parameter is a key input in the probabilistic buckling strength evaluations.

The rail temperature is the maximum anticipated temperature of the rail found in the segment of track being analyzed. This is required together with the rail neutral temperature in the safety assessment parts of the analysis.

2.10.7 Tie-Ballast Friction Coefficient

The tie-ballast friction coefficient is a measure of the tie bottom surface influence in lateral resistance when the track is vertically loaded. It is required in the evaluation of the track dynamic lateral resistance and the uplift computation.

Sleeper ballast friction is the main contributor to lateral and longitudinal resistance. Friction coefficients between the ballast and sleeper end, sleeper bottom and sleeper side provide the resistance to track movement (Samavedam et al. 1993).

Uplift of track occurs when the sum of vertical deflection forces caused by vehicle loads and the self-weight of the track is less than zero. It has been found that increasing the coefficient of roughness increases both upper and lower buckling temperature.

2.10.8 Torsional Resistance

Experimental test have been performed to measure the torsional moment in the fastener versus the rotation angle. In such a test the rail is clamped by fasteners on a fixed sleeper and loaded with a torsional moment (Samavedam et al.1993).The rail fasteners (which can include cut spikes/anchors or elastic fasteners) also provide rotational restraint against the lateral bending of the rails. The resistance is linearized with respect to the rail rotation, and the torsional stiffness is specified per fastener. Concrete and timber sleepers with different fastener systems (McKay Safelok and Pandrol fastener) showing that the timber sleeper fastening systems are much stiffer than concrete Pandrol and McKay systems (Samavedamet al.1993). It has been shown that sleeper type or condition has no significant influence on torsional resistance, while fastener type is a significant parameter. Again, lower buckling temperature is more sensitive to torsional resistance increase compared to the negligible change of upper buckling temperature. Hence buckling strength of the track is not consistently affected by this phenomenon.

2.10.9 Rail Properties

The most important rail properties in case of stability of CWR are the cross-sectional area A and the moment of inertial in lateral Iy and the vertical Iz direction.

Analysis by Tew et al. (1991) shows the result of Miyai and concludes that lateral stability of any track section decreases with the increase of rail size. However they found one anomaly with the 53 kg/m rail which has higher horizontal moment of inertia compared to that of other larger rail sizes. This property helps to resist lateral bending. This effect was also verified by Railways of Australia (1988) by using Association of American Railroads (AAR) track buckling model.

Track buckling temperature decreases with the increase of rail size more rapidly than the lower buckling temperature (Samavedamet al.1993). This is because of the fact that increased area contributes to more thermal force and thereby reduces the effect of increasing bending stiffness. Again, though smaller rail section shows better buckling strength that does not allow for lower bending stiffness and hence maximum axle load of smaller rail. Hence an optimization between wheel load and fatigue is necessary to select an appropriate rail size.

2.10.10 Longitudinal resistance

In longitudinal direction the fastener has to be able to transfer longitudinal forces to the sleeper, to limit gaps in case of rail breakage and to prevent longitudinal track creep. Thermal gradient, dynamic braking and rail creep generate longitudinal forces in the rail. Track must provide adequate longitudinal resistance to restrict longitudinal movement. Ballast mass between the sleepers and rail to sleeper connection friction (from toe load grip on the rail foot and the use of rail anchor devices) provide longitudinal resistance.

Lower buckling temperature increases with the increase of longitudinal resistance, while upper buckling temperature remains almost constant (Samavedam et al. 1993). The same trend of longitudinal resistance characteristic using CWERRI software, track has no/little misalignment, longitudinal resistance will have little effect on buckling (Esveld 1998).

2.10.11 Curvature

Samavedam et al. [1993] show that upper buckling temperature decreases more rapidly than lower buckling temperature with the increase of curvature. Strong, weak and medium track have been considered for the test. It has been found that progressive buckling can occur at 7 degree or higher curvature for weak track. However the model does not consider effects of non-uniformly distributed ballast resistance along the track, missing sleepers and fasteners, variation of track gauge and differing neutral temperatures between two sites. Esveld [1998] study uses CWERRI model to observe curvature effect on track buckling and it has been found that, although the characteristics are similar to the study of Samavedam et al. [1993].

2.10.12 Vehicle parameters

Axle load, Net Axle L/V ratio, bogie or truck centre spacing (TCS) and number of passes contribute to the static track buckling parameters. Samavedam et al. [1993] show that upper buckling temperature decreases with the increase in axle load, while lower buckling temperature remains almost constant. It has been found [Samavedam et al. 1993] that longer TCS provide higher safety margins against possible explosive buckling.

Kish et al. [1997] show that deflections over 5 mm are likely to be unstable after 20 passes. Samavedam et al. [1996] observed that track tends to stabilize after several passes of a constant load. But after reaching a critical value of load, residual deflection tends to increase.

Lateral load does not remain constant when a train passes over any misalignment in the track Kish et al. (1997).

3 SENSITIVITY STUDY

The next part of this paper discusses the sensitivity of upper (Tb,max) and lower (Tb,min) critical temperature to the parameter variations shown in table1.2 Each parameter was varied over a practical range while keeping all other parameters constant at the “fixed value”. The calculated results for upper (Tb, max) and lower (Tb, min) critical temperature used in safety evaluation. It can be noted from Figure 2-11 that, if the track is subjected to a temperature of Tb,max, the energy required to buckle the track will be zero, the track will buckle spontaneously. After buckling, the track reaches a stable state where buckling temperature is Tb,min. It also shows that buckling energy requirement at Tb,min is much higher than that at Tb,max.

3.1 Track parameter to be used in analysis

A parameter analysis is performed to investigate the important parameters in curved and tangent track buckling. The track model is shown in Figure 3-1.

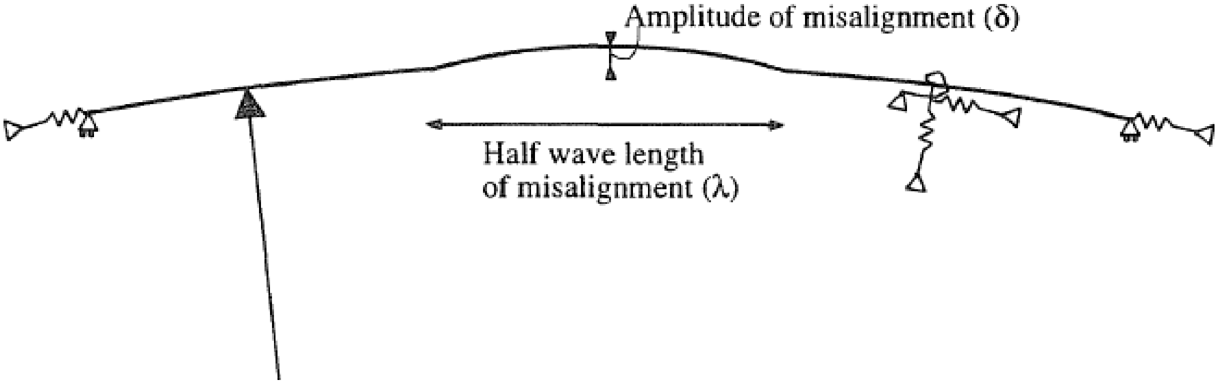


Figure 3-1:- Top view of CWR track model (van 1996)

The track length curvature has a radius of 350 m. In the middle of the track a horizontal misalignment is present, characterized by a half-sine wave with a length of 5m and amplitude of 0.0381m. The rails are modeled by geometrically non-linear beam elements with the parameters of two 50Kg/m rails. The sleeper distance is 0.61 m. The fasteners are modeled by linear-elastic torsional springs with spring stiffness 112 m-kN/rad per meter track.

In vertical direction (out of plane in Figure 3-1) the track is supported by linear-elastic ballast elements with a stiffness of 68MPa. Fixed values E = 2.1×106kg/cm2, μ=0.86, α = 1.15×10-5 $1/^{o}C$. Van 1996 and CWR-SAFE 2000 model suggestion.

The lateral resistance F=20KN/m the model is vertically loaded by two boogies represented by four vertical axle loads F_v equal to 293 KN each, see Figure 3-2. The center spacing between the boogies is 10.46 meter. The spacing between the axles in a boogie is 1.9 meter. The center of the half-sine misalignment is located in the middle between the boogies. For detail input Parameters of Model for the Analysis see table 1.2

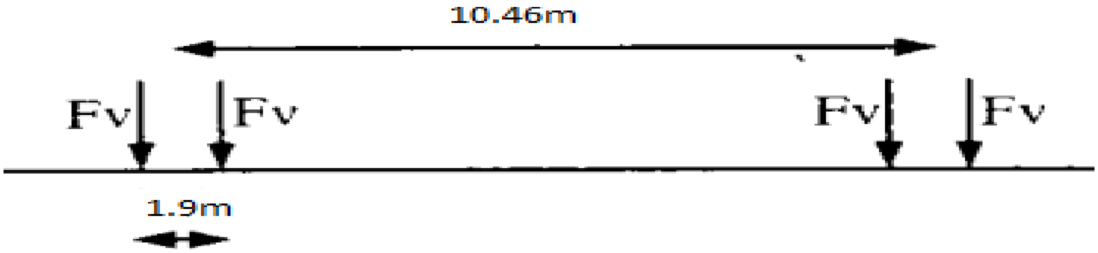


Figure 3-2:- Vertical axle loads on track

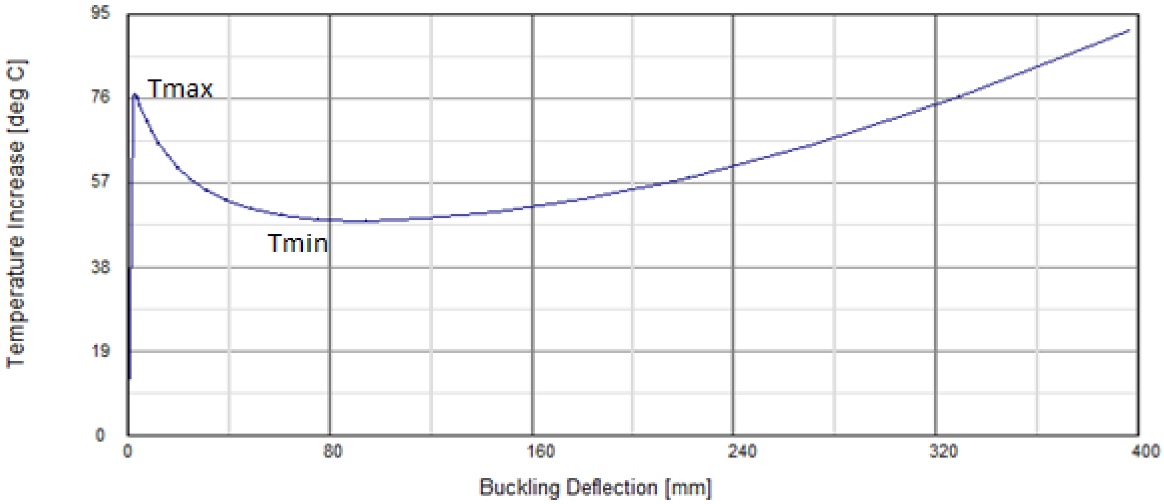


Figure 3-3:- Lateral displacement at the middle of CWR model versus temperature increasing

The plot of Figure 3-3 can be characterized by 2 points. The first characteristic point is the temperature Tbmax at which buckling starts, which is the highest point in the figure after which the temperature will drop and deformations grow rapidly. A special developed option in CWR-BUCKLE based on an arc-length controlled solver technique can follow the temperature decrease. The second characteristic point is the minimum temperature Tbmin that occurs after buckling has started.

3.2 Numerical analysis

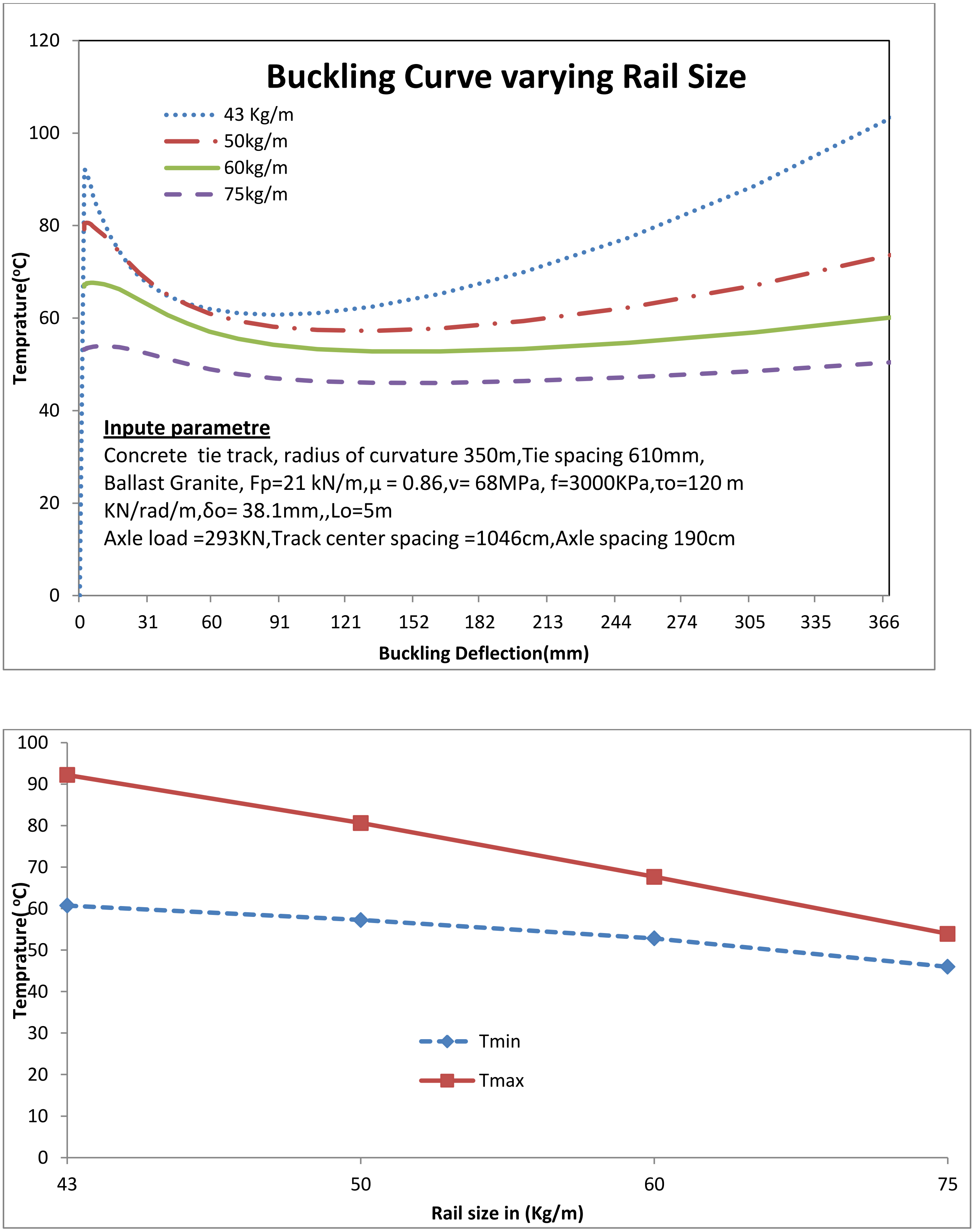
In this study, analytic thermal buckling analysis of CWR tracks under vehicle loads are performed based on static thermal buckling approach. The parameters used in this study include rail size, track lateral resistance, track longitudinal and torsional stiffnesses, initial misalignment amplitude and wavelength, track curvature, tie-ballast friction coefficient and truck center spacing. Sensitivity studies for the evaluation of quantitative effects of parameters and critical buckling temperatures have been changing one parameter at a time fixing others on their nominal value, is selected to investigate the effect of the individual parameter.

3.2.1 Effects of rail size

Table 3-1 shows the size of rails that are presently used in Ethiopia. The results for effect of rail size on buckling are shown in Fig. 3-4 for rail sizes in Table 3-1.The results show that buckling temperature decrease with increasing in rail size. The bending moment of inertia and cross-sectional area increase with increasing rail size. The increase in area increases the thermal force, which offsets the corresponding increase in bending stiffness, thus reducing the overall buckling strength. The upper buckling temperature is more sensitive to the rail size

Table 3-1 Typical Rail Properties

Size	Area	Weight	Area moment	
	(cm^2)	(Kg/m)	I_x(cm^4)	I_x(cm^4)
43	57	44.6	1489	260
50	65.8	51.5	2037	377
60	77.5	60.6	3217	1048
75	95.1	74.6	4490	1330



Inpute parametre

Concrete tie track, radius of curvature 350m,Tie spacing 610mm, Ballast Granite, Fp=21 kN/m,μ = 0.86,v= 68MPa, f=3000KPa,τo=120 m KN/rad/m,δo= 38.1mm,,Lo=5m

Axle load =293KN,Track center spacing =1046cm,Axle spacing 190cm

Figure 3-4:- Buckling curve varying Rail size

3.2.2 Effects of lateral resistance

The effects of lateral resistance are shown in Figure 3-5 above. The values of lateral resistance 10 to 60KN/m are used. As lateral resistance increases, both the upper and the lower buckling temperatures increase, and the upper buckling temperature Tb,max is more sensitive than the lower buckling temperature to the changes in lateral resistance.

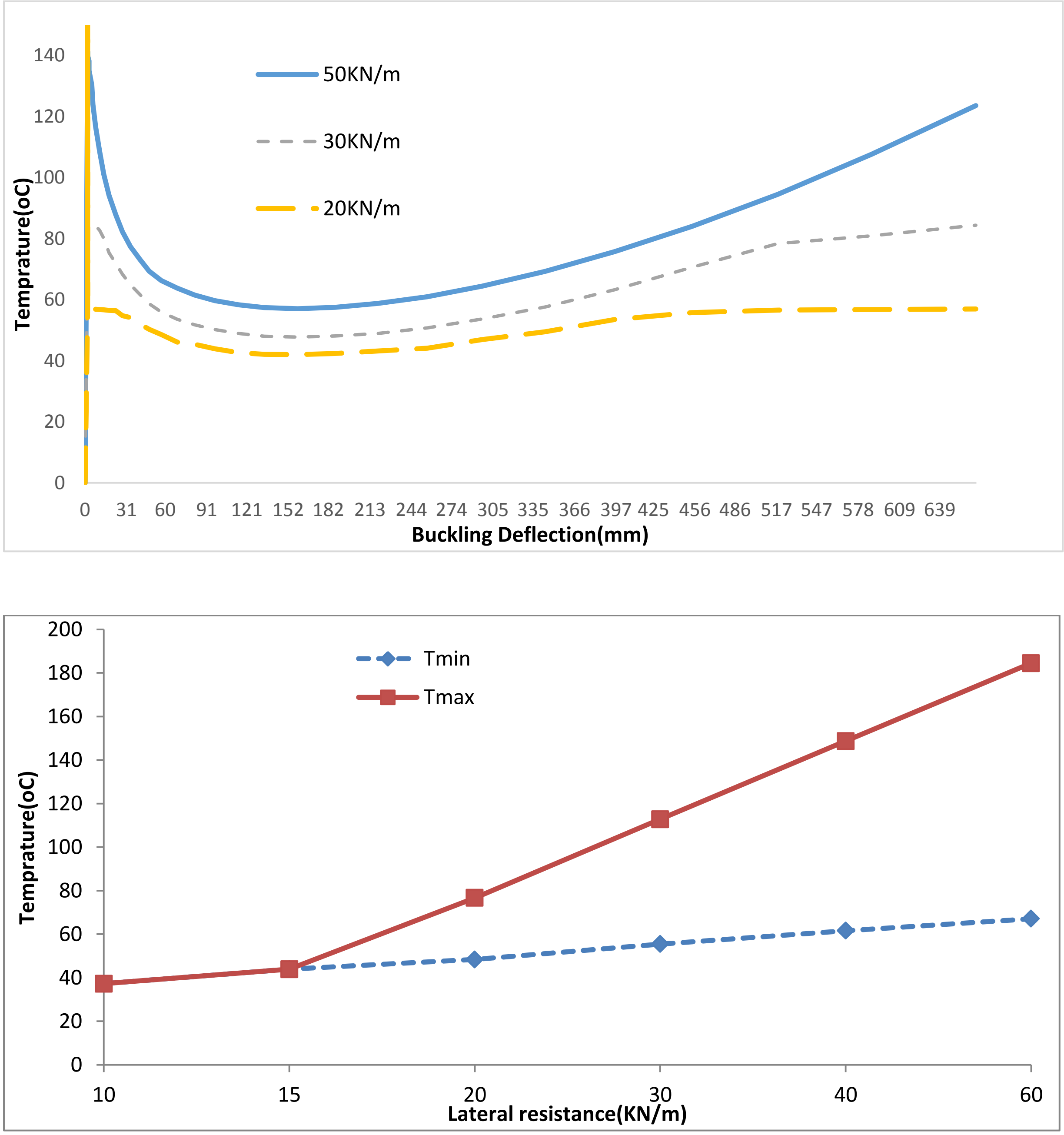


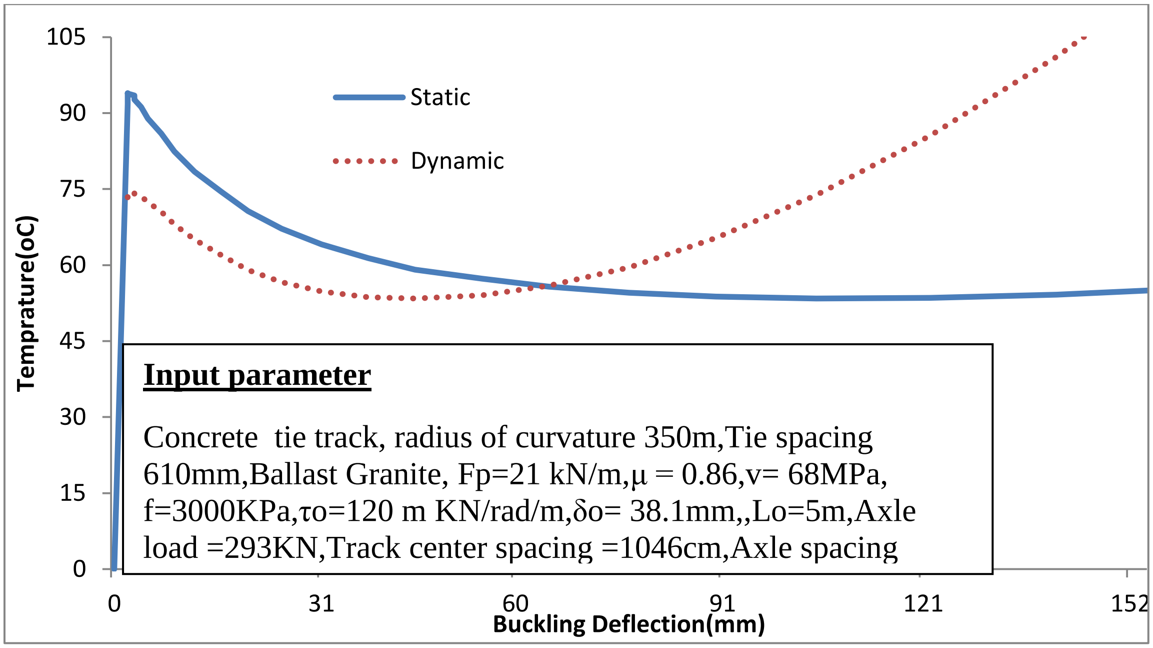
Figure 3-5:- Buckling Curve varying lateral resistance

3.2.3 Effects of Static versus Dynamic Buckling

As this example illustrates, static considerations provide unconservative numbers hence inadmissible for buckling safety evaluations, and therefore dynamic theory applications are required. Consequently, the use of the dynamic theory is implicit in all the subsequent parametric studies presented here.

Recalling that static buckling refers to a purely thermal load induced buckling (i.e., without the influence of vehicle loads, dynamic uplift, and train energy inputs), Figure 3-6 shows the buckling response curve for the input parameters noted in the figure.

The track is expected to buckle out statically at its Tbmax= 93.91 C °c since the track is in a state of unstable equilibriums. The corresponding dynamic case is also shown in the figure, indicating a small buckling regime between ΔTbmin and ΔTbmax of 53.42°C and 74.27°C. From a safety point of view (and in accordance with the safety criterion), the permissible temperature increase value should be below Tbmin value of 53.42 °C. As this example illustrates, static considerations provide un conservative numbers hence inadmissible for buckling safety evaluations, and therefore dynamic theory applications are required. The results show that the upper critical buckling temperature is highly affected by the uplift due to vehicle loads



Input parameter

Concrete tie track, radius of curvature 350m,Tie spacing 610mm,Ballast Granite, Fp=21 kN/m,μ = 0.86,v= 68MPa, f=3000KPa,τo=120 m KN/rad/m,δo= 38.1mm,,Lo=5m,Axle load =293KN,Track center spacing =1046cm,Axle spacing

Figure 3-6:-Static versus Dynamic Buckling Behaviors

Buckling safety summery

Table 3-1:-The upper and lower critical buckling temperature increases, deflections, wavelengths, forces and energies for Dynamic case are as follows:

At the LOWER CRITICAL TEMPERATURE INCREASE		
Temperature increase above neutral	= Tb,min =	53.42 C
Max buckling deflection	= Wmax =	80.14 mm
Buckled half-wavelength	= L =	3810.00 mm
Force in rail at time of buckle	= P =	837.51 kN/rail
Energy required to buckle	= E =	.22 kJ
At the upper critical temperature increase		
Temperature increase above neutral	= Tb,max =	74.27 C
Max buckling deflection	= Wmax =	263.76 mm
Buckled half-wavelength	= L =	4450.03 mm
Force in rail at time of buckle	= P =	1157.69 kN/rail
Energy required to buckle	= E =	.00 kJ

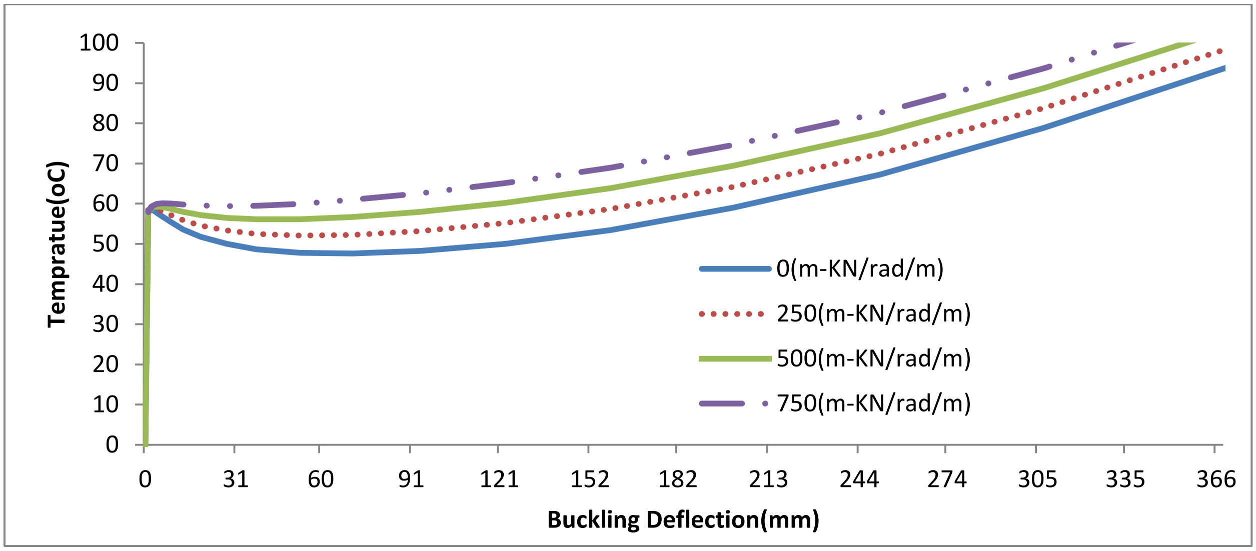
Buckling safety summary

Table 3-2:-The upper and lower critical buckling temperature increases, deflections, wavelengths, forces and energies for static case are as follows:

At the LOWER CRITICAL TEMPERATURE INCREASE		
Temperature increase above neutral	= Tb,min =	53.43 C
Max buckling deflection	= Wmax =	105.65 mm
Buckled half-wavelength	= L =	4445.00 mm
Force in rail at time of buckle	= P =	837.47 kN/rail
Energy required to buckle	= E =	.55 kJ
At the upper critical temperature increase		
Temperature increase above neutral	= Tb,max =	93.91 C
Max buckling deflection	= Wmax =	412.13 mm
Buckled half-wavelength	= L =	5843.08 mm
Force in rail at time of buckle	= P =	1463.98 kN/rail
Energy required to buckle	= E =	.00 kJ

3.2.4 Torsional Resistance

The effects of fastener torsional resistance on the CWR track buckling are examined using ranging from 0 to 1000 m-KN/rad/m. The results are shown in Figure 3-7. Both buckling temperatures increase with increasing torsional stiffness. The lower buckling temperature is more sensitive to the stiffness change, resulting in a significant increase.



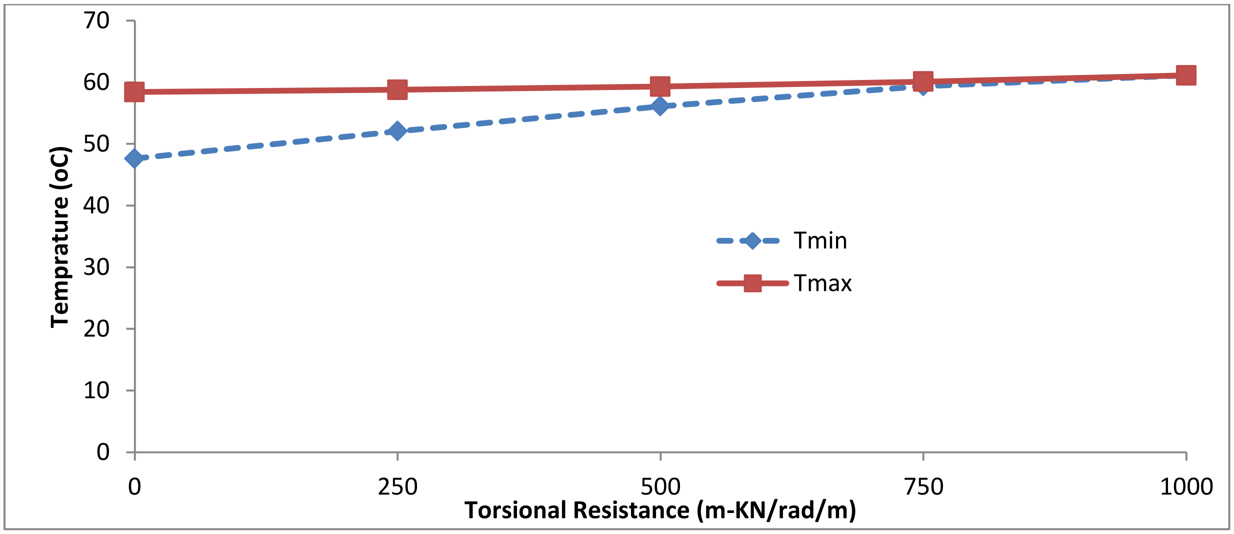


Figure 3-7:-Buckling curve varying torsional stiffness

3.2.5 Effects of track curvature

The effects of track curvature are studied using curves radius ranging from tangent to 130m. The buckling results are shown in Figure 3-8. The results show that increasing curvature reduces both the upper and the lower buckling temperatures Tb,max and the upper buckling is more sensitive to the changes in curvature. For high curved tracks, the buckling temperatures are drastically reduced in comparison to low curved tracks.

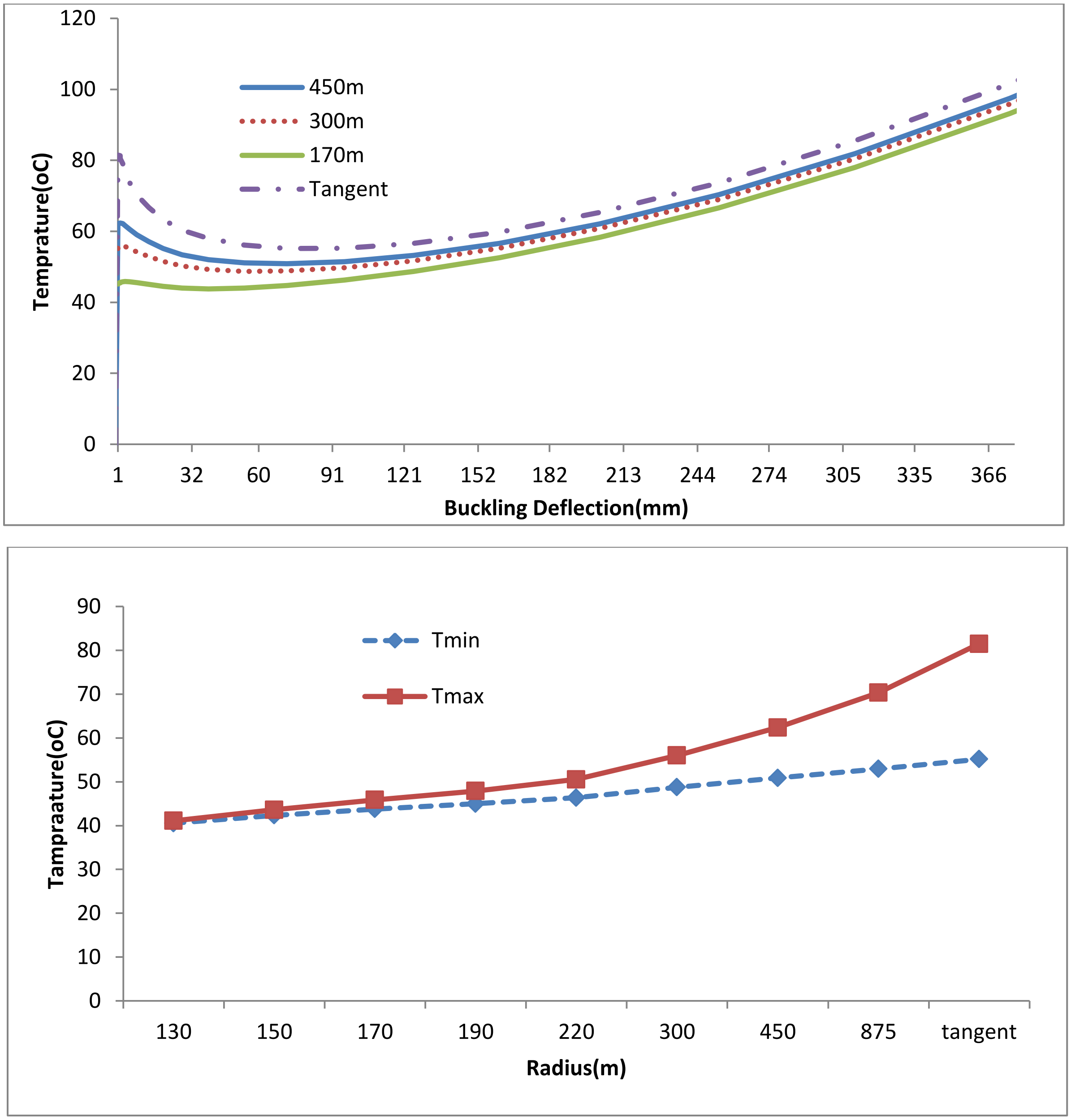


Figure 3-8:-Buckling curve varying curvature

3.2.6 Effects of initial misalignment amplitude

Misalignment effects are examined first by using typical misalignment amplitudes ranging from 15 to 75mm. The results are shown in Figure 3-9. Both temperature quantities decrease as the misalignment amplitude increase, with the upper critical temperature being more sensitive to these changes. A progressive buckling condition appears at amplitude of approximately 45mm.

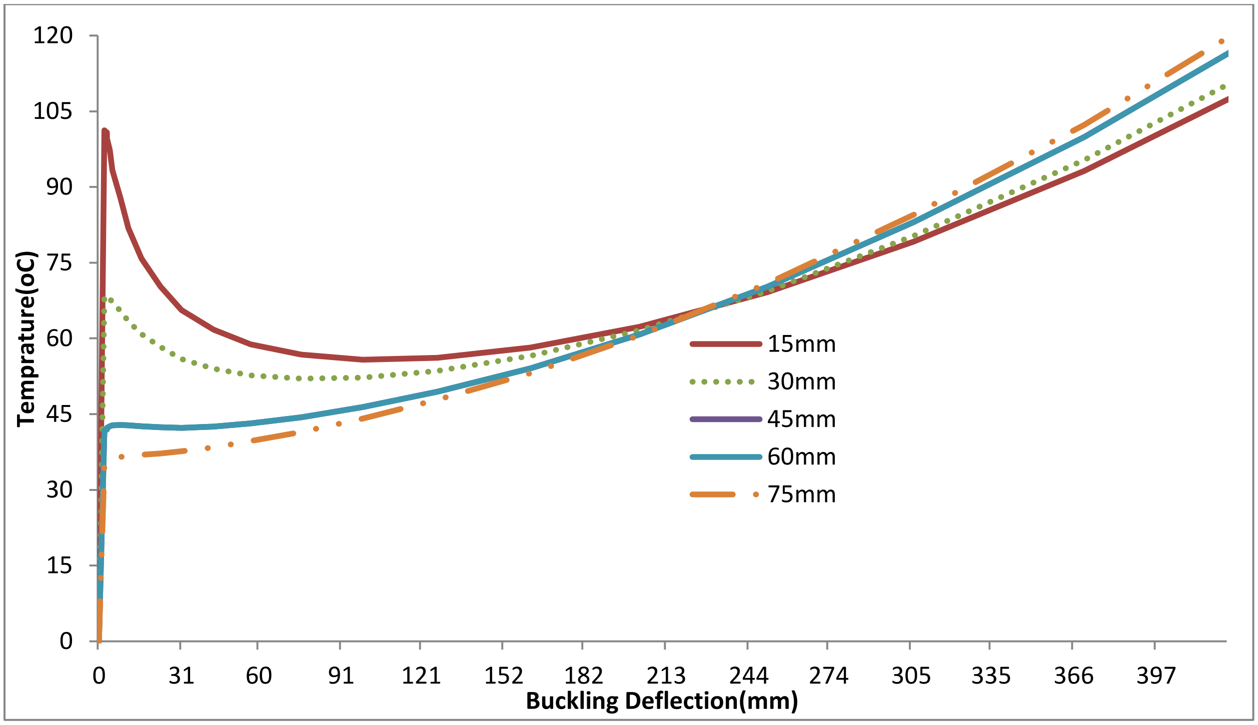
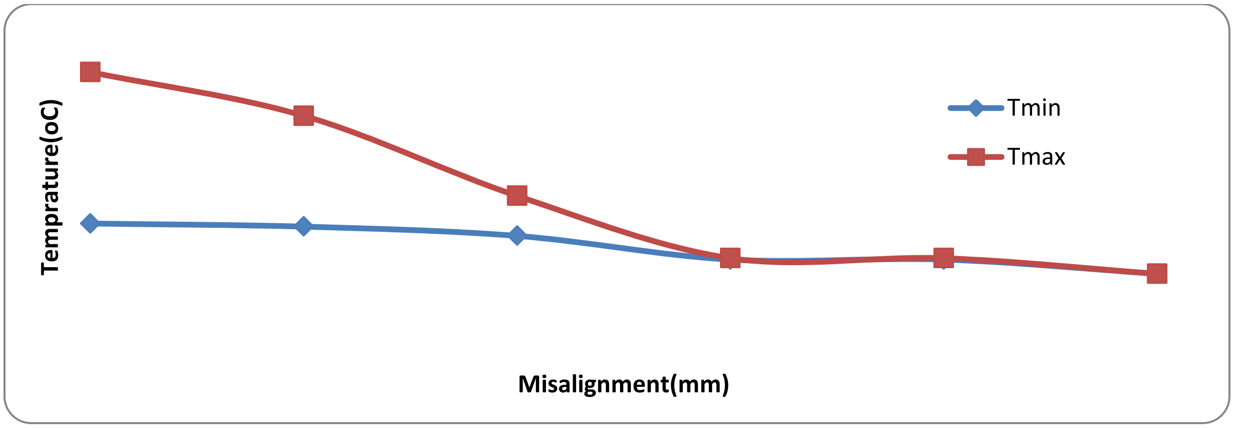
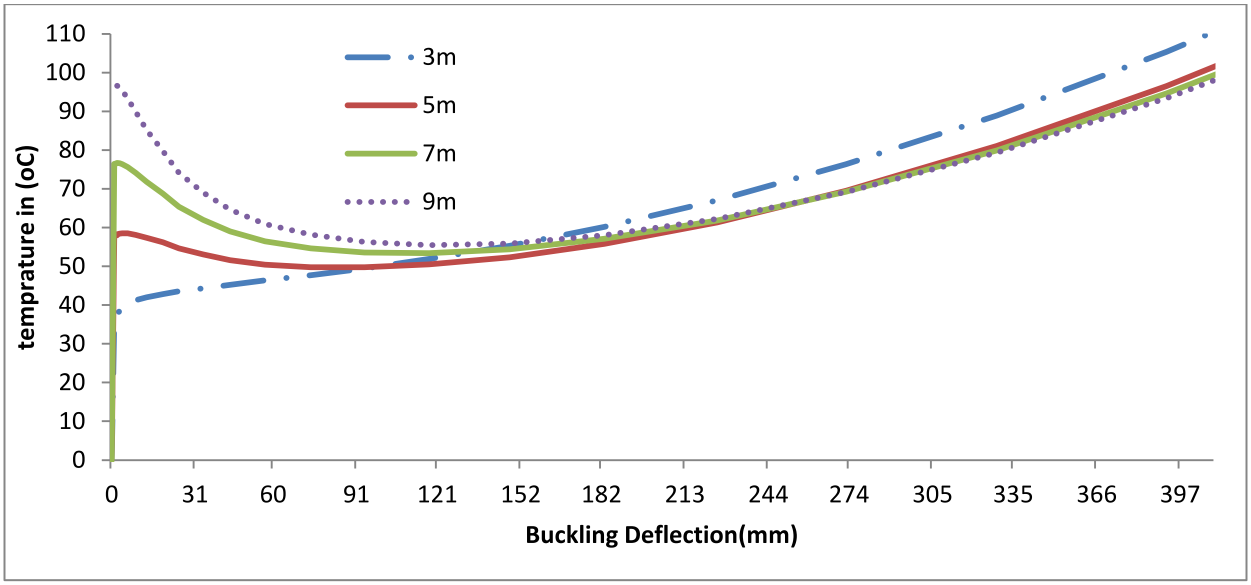


Figure 3-9:- Buckling curve varying misalignment



3.2.7 Effects of Initial Misalignment Wave-Length

The misalignment effects are studied using constant misalignment amplitude of 5m, but with changing misalignment wave length ranging from 3m to 9m. The results are shown in Figure 3-10. The lower critical temperature is relatively insensitive to the effects of wave-length. A progressive buckling condition is reached at a wave length of 3m. The difference between upper and lower temperature is getting larger when the wave length increases.



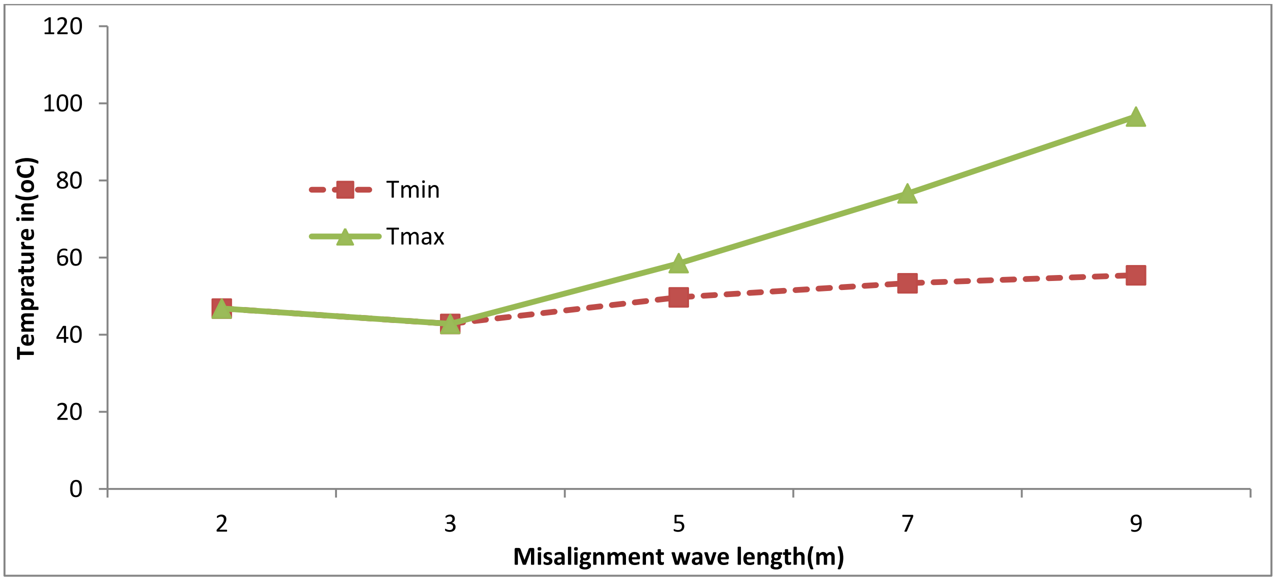


Figure 3-10:- Buckling curve varying misalignment wave length

3.2.8 Effects of tie-ballast friction

The lateral resistance can be expressed as the sum of the base, side, and end shoulder resistance components of the tie:

F_p = Fb+Fs+Fe

Defining the coefficient μf in terms of weight of tie, Q (including the weight of rail and fasteners):

Fb = μf Q

μf can be considered an index of tie bottom roughness, Q =9.3Kn/m

Table 3-3:- Three Components of Resistance and Their Assumed Variations with μf (FRA, 2013)

μf	Fs (KN/m)	Fe (KN/M)	Fb (KN/m)	Fp (KN/)
0.8	8	4	7	19
0.86	8	4	8	20
1.2	8	4	11	23
1.6	8	4	15	27
2	8	4	19	31
2.2	8	4	20	32

The tie bottom surface roughness is an important parameter as it determines the component of the base resistance Fb. The roughness factor is artificially expressed as friction coefficient, which is influenced by the type of ties and ballast, the age of tie, and amount of consolidation. The effects of friction coefficient on buckling are examined using ranging 0.8 to 2.2. The results are shown in Figure 3-11. An increasing surface roughness of the tie bottom (increasing μ) increases both the upper and the lower buckling temperatures.

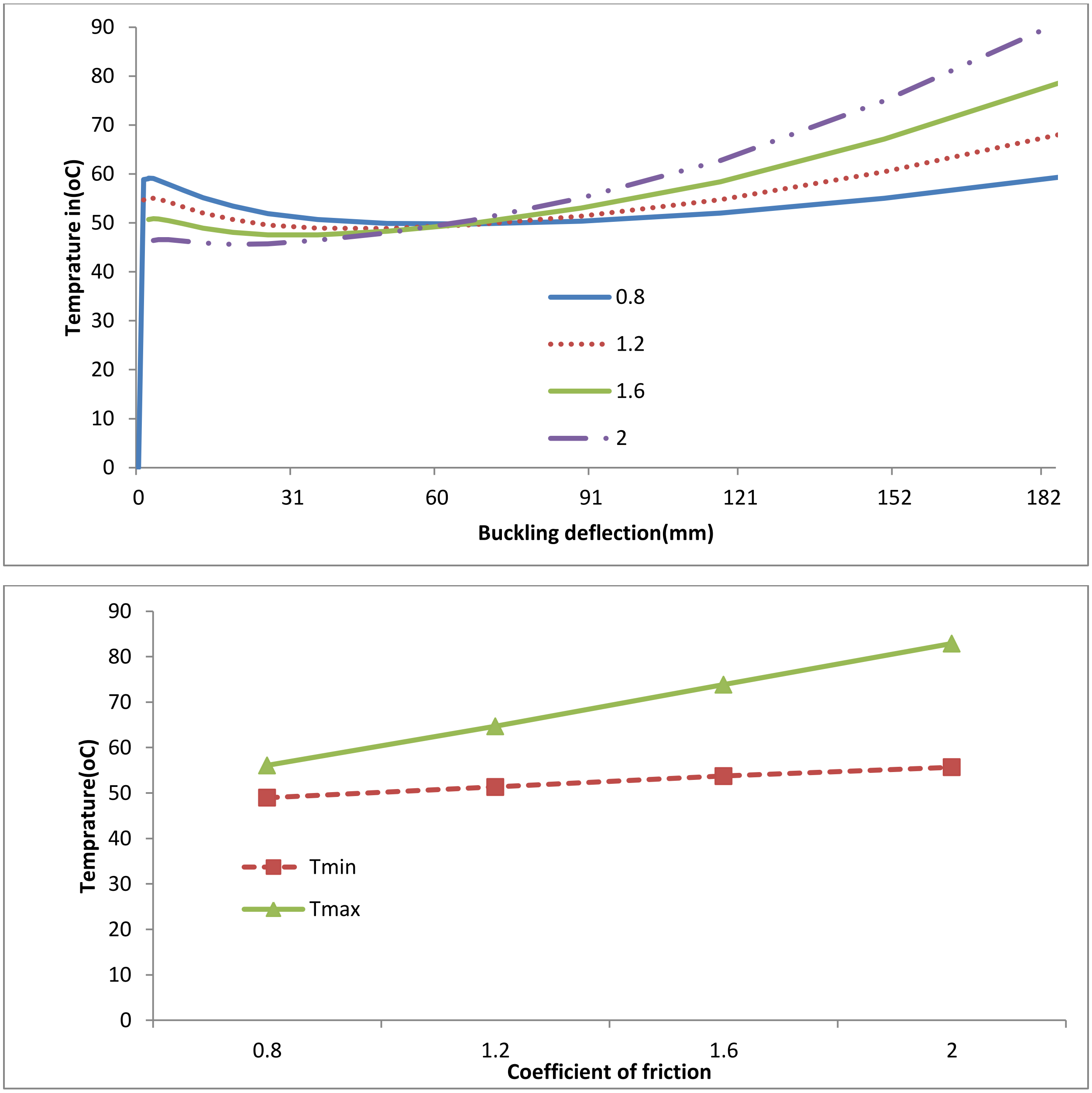
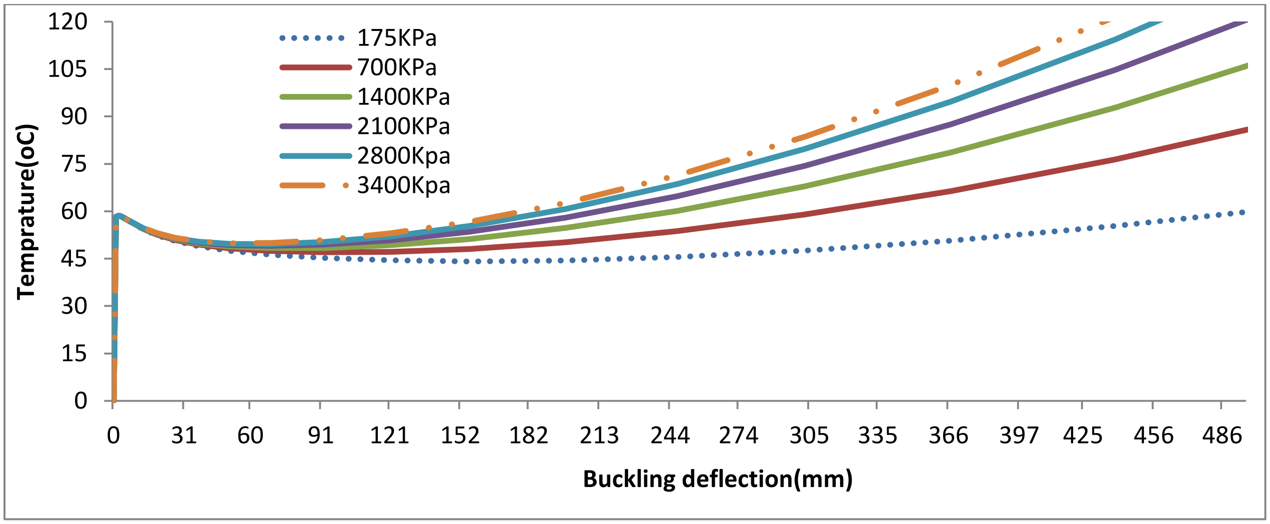


Figure 3-11:- Buckling curve varying coefficient of friction

Care must be exercised in attempting to evaluate µf influence without making the direct adjustments in FP along the lines of Table 3-3 (i.e., if one assumes a fixed FP and runs the variations on µf, results opposite in trend to Figure 3-11 will be obtained).

3.2.9 Effects of longitudinal stiffness

Track longitudinal resistance is the resistance offered by ties and ballast to the rails as they tend to move in the longitudinal direction in the event of buckling, thermal force gradients, or in response to braking and acceleration train action. For this sensitivity study, a typical range of stiffness values (175 to 3400KPa) is used. The buckling results are shown in Figure 3-12. The lower buckling temperature shows a slight increase with the increase of longitudinal stiffness, whereas the upper buckling temperature is essentially in dependent of changing stiffness. Since longitudinal stiffness influence on Tbmin is relatively small, the need to determine or know longitudinal stiffness exactly is not as important as some of the other parameters.



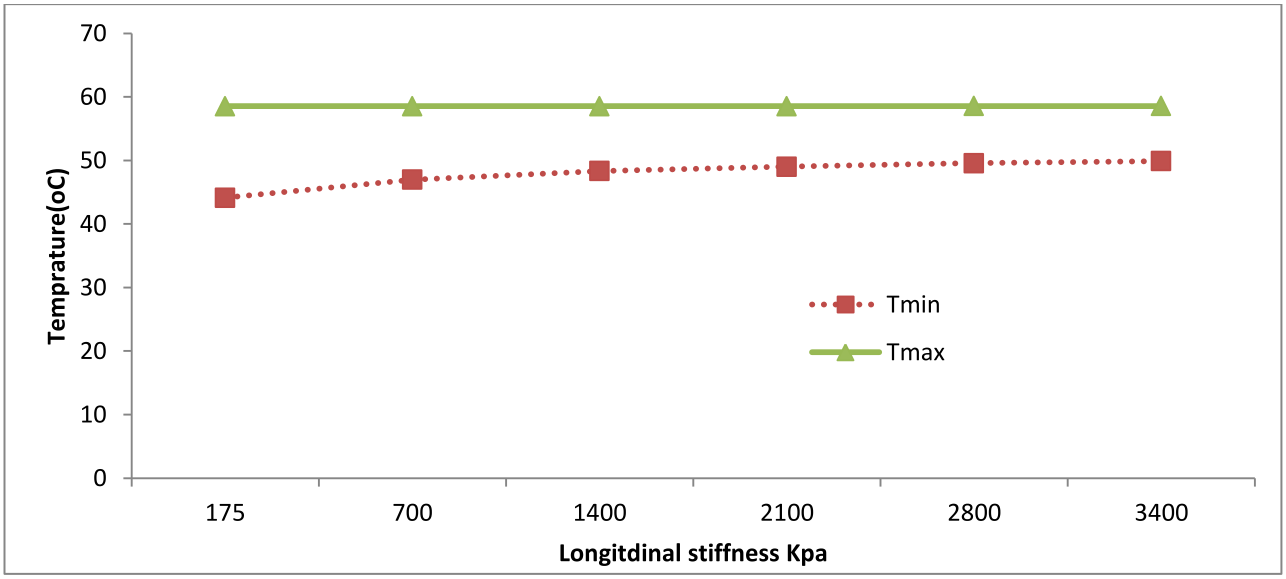
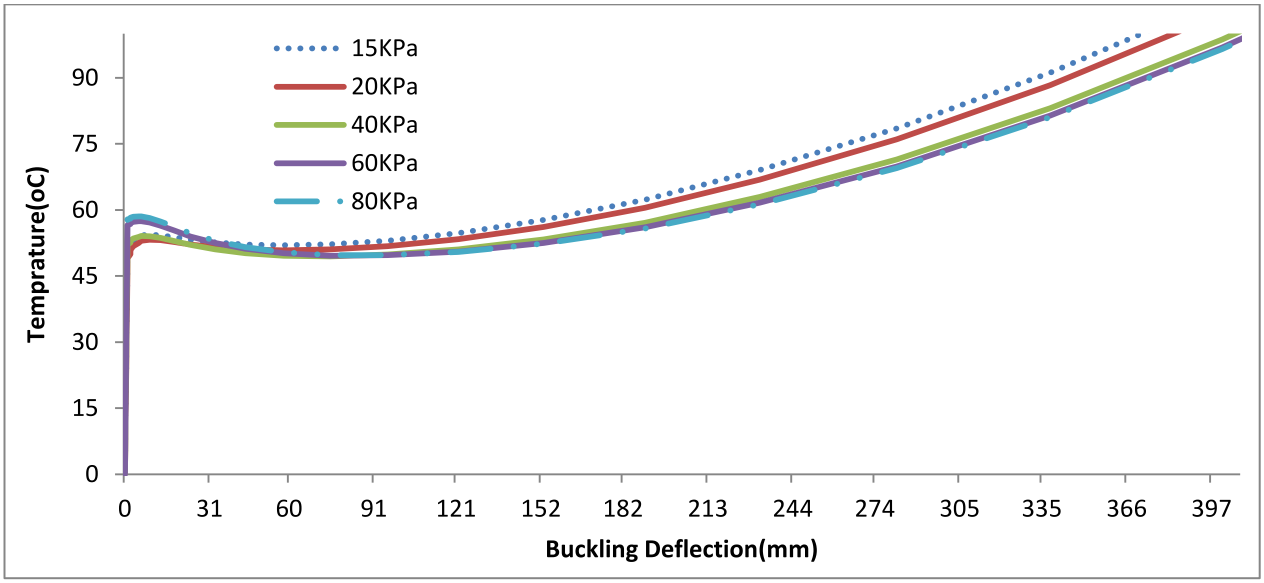


Figure 3-12:- Buckling curve varying longitudinal stiffness of track

3.2.10 Effects of Track Foundation Vertical Stiffness

The presence of vehicle loads causes uplift in the track, which is partially dependent upon the track foundation stiffness. The effects of foundation stiffness are examined using a typical range of 15 to 80KPa is used the results are shown in Figure 3-13. Tbmax is more sensitive to stiffness variations than Tbmin,



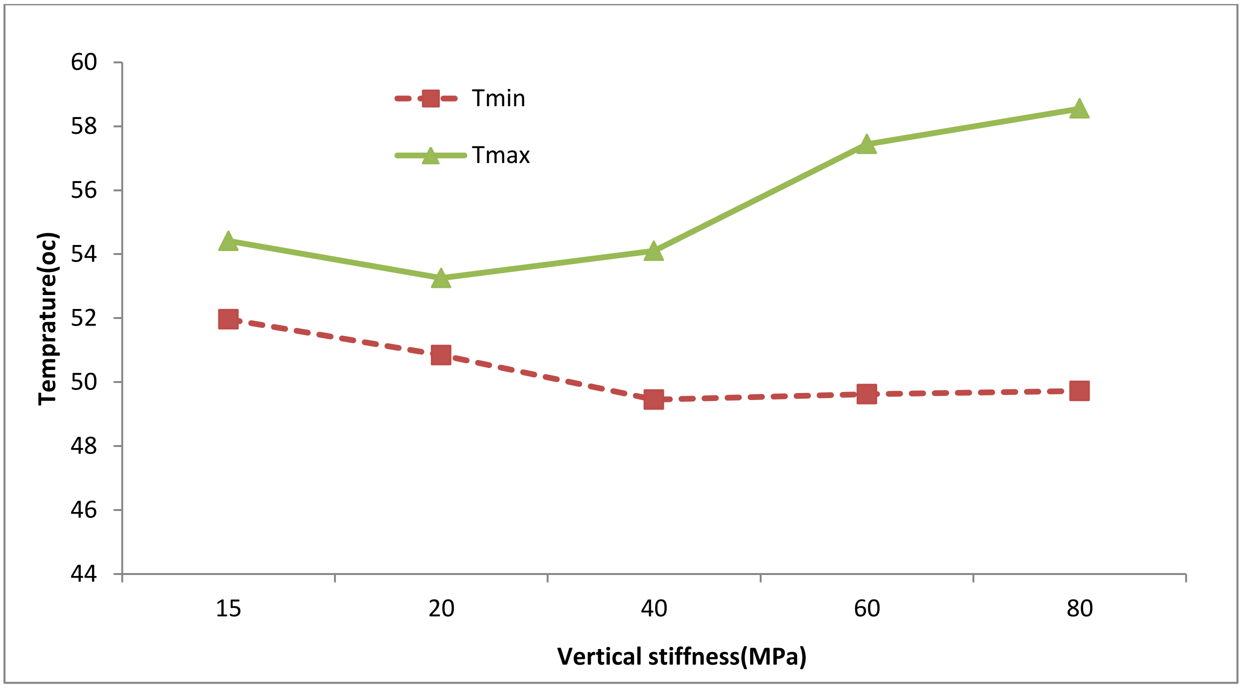


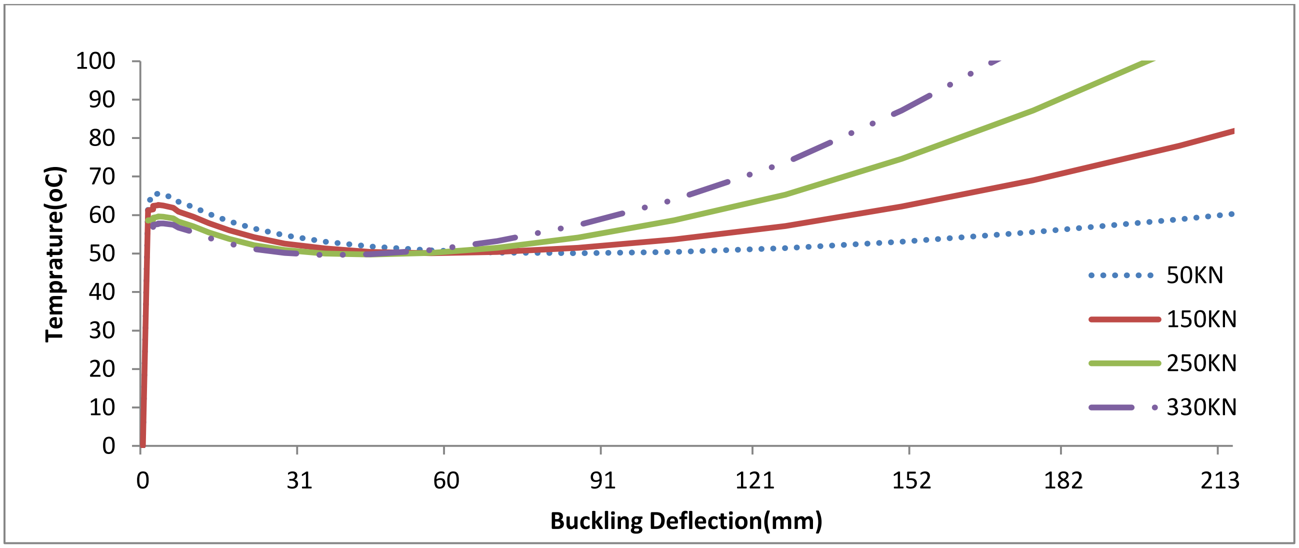
Figure 3-13:- Buckling curve varying vertical stiffness

3.2.11 Effects of Vehicle Parameters

The effect of vehicle loads is to cause rail uplift and thus reduction of buckling strength in comparison with the static buckling case. The primary vehicle parameters controlling the uplift are the axle loads and the truck center spacing (TCS), which vary with vehicle size and type.

3.2.12 Influence of Axle Loads

To examine the effects of these vehicle parameters on buckling, the axle load is varied 50KN (5ton) to 330KN (33ton). The axle spacing and truck center spacing for this car are 900cm and 2000cm, respectively. All other parameters are set at the nominal values. As shown in figure 3-14 increased axle loads tend to reduce the upper buckling temperatures but with very little influence on Tbmin. The lower critical temperature is relatively insensitive to the effects of axle load and is essentially constant. However, the upper critical temperature decreases with the increasing axle load. This is an important aspect of dynamic buckling since the rapid decrease in the upper critical temperature quickly reduces the energy barrier for buckling. The practical implication is that lighter cars tend to have larger buckling margins of safety than heavier cars.



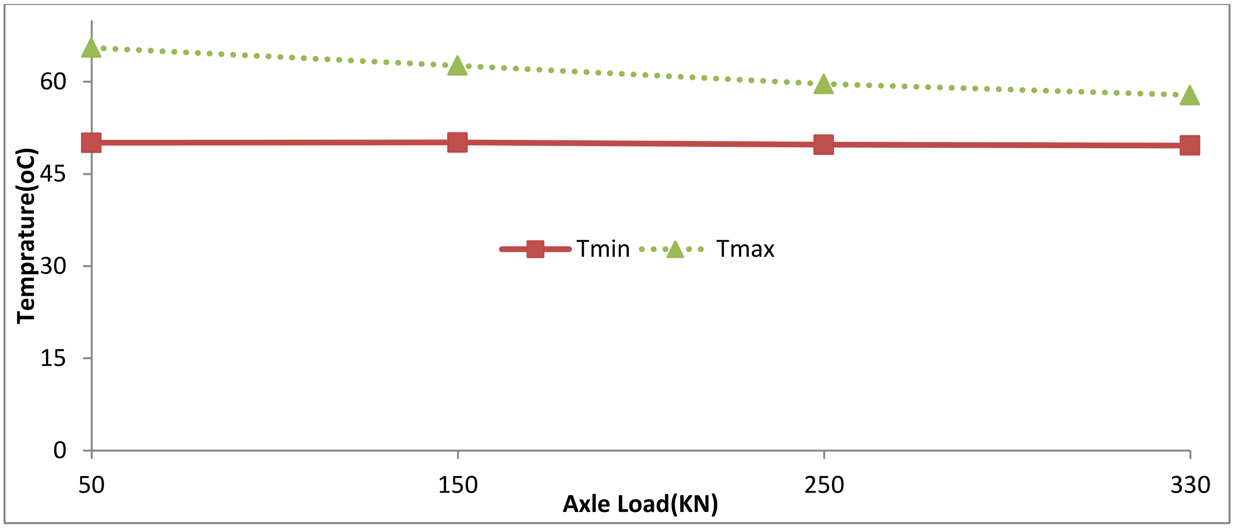
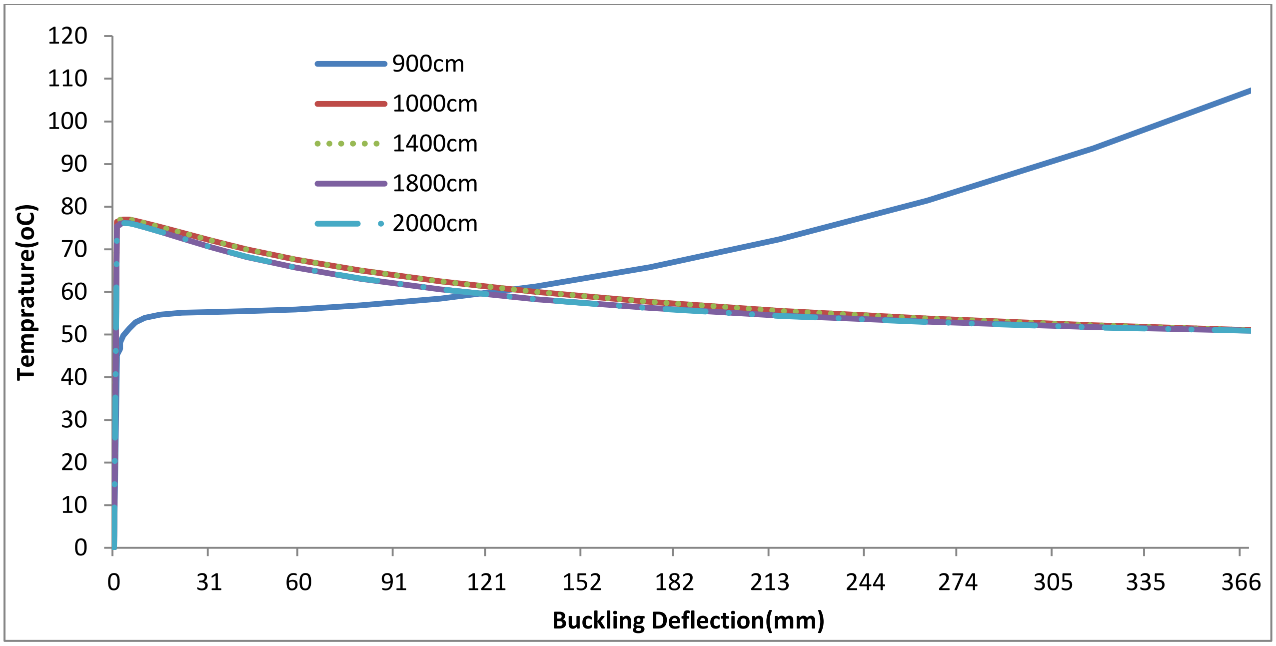


Figure 3-14:- Buckling curve varying Axle Load

3.2.13 Effects of the track center spacing

The effects of vehicle truck center spacing as shown figure 3-2 are examined using a range of 900 to 2000 cm. Each of these cars has four axles with an axle spacing of 190 cm. The results are shown Figure 3-15. The buckling temperatures do not follow the same trends with increasing truck center spacing. The upper buckling temperature is more sensitive to truck center spacing change, first decreases, but then increases slightly. Also, it can be seen that critical truck center spacing is about 10 m. This spacing is considered to be critical because the difference between upper buckling temperature and lower buckling temperature is small. Therefore, the buckling can occur with a little energy.



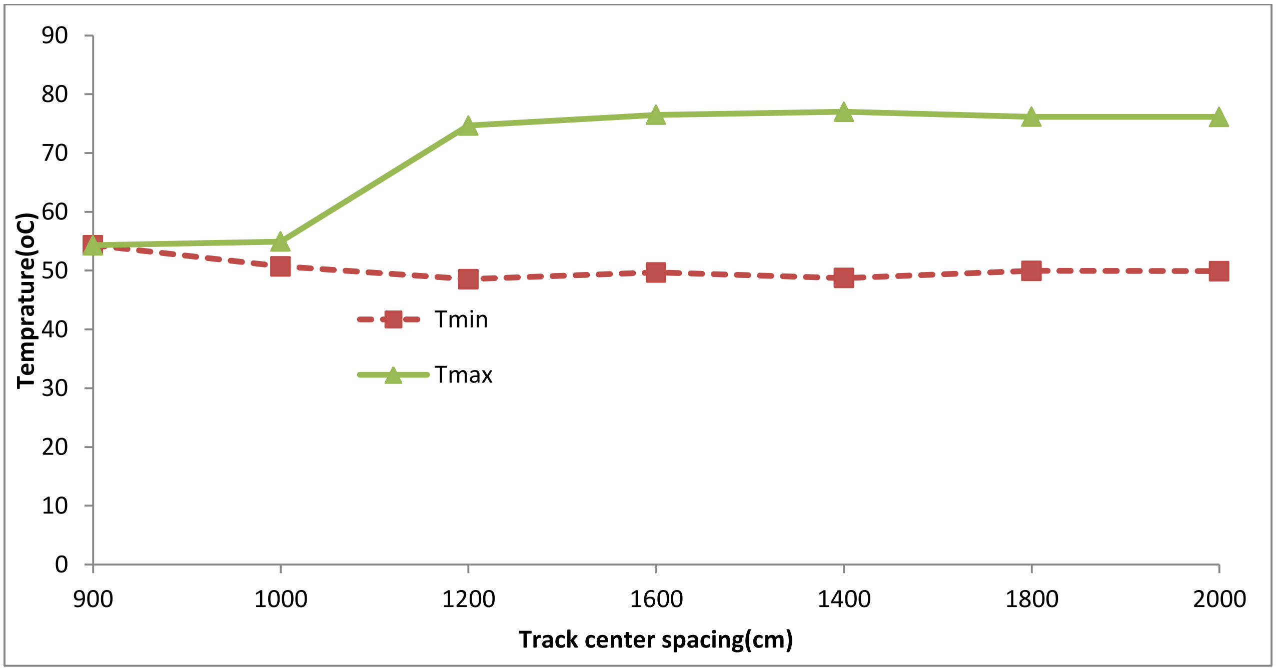


Figure 3-15:- Influence of TCS on Buckling Temperatures

4 SAFETY EVALUATION

4.1 Buckling Response

When buckling of CWR track occurs, the track experiences a large movement to a laterally deformed shape. A typical buckled shape of CWR track is shown in Figure 4-1. The buckling of track occur either "explosively" or gradually increasing "progressive" buckling displacement. These two different types of track buckling response are described below.

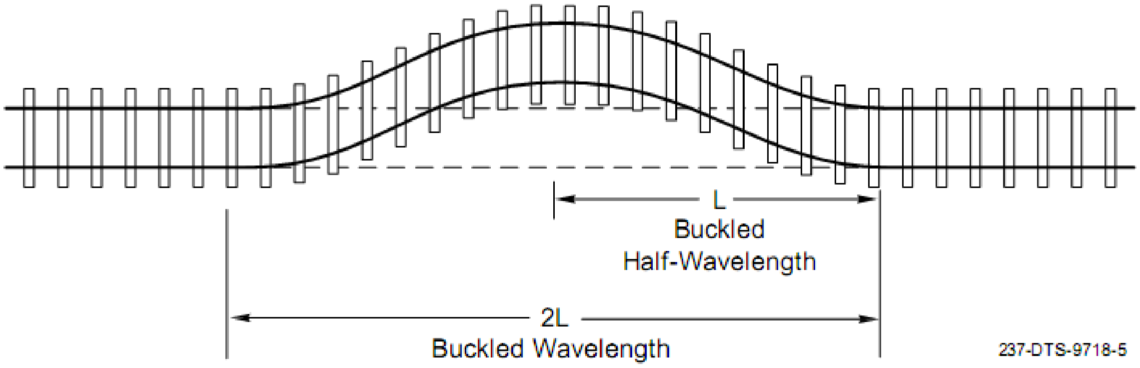


Figure 4-1:-Typical buckled mode shape (FRA, 2013)

4.1.1 Explosive Buckling

A typical buckling response characteristic is shown in Figure 4-2. In general, the curve shows two critical temperatures. The upper critical temperature, TB,MAX, represents a track position that is unstable in the infinitesimal sense, i.e., with zero disturbance or energy input, the track will "explosively" buckle out from position, B, to stable position, C.

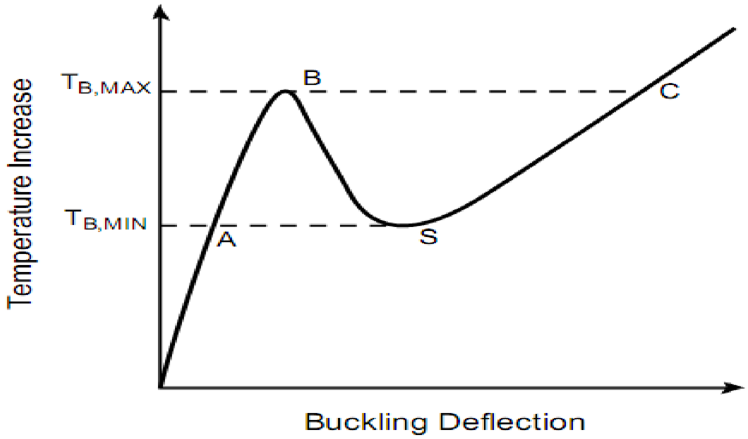


Figure 4-2:-Typical buckling response characteristic (CWR-SAFE 2000)

On the other hand, the track can also explosively buckle from position A into position S with sufficient finite external energy input. Hence the minimum possible buckling temperature increase is TB, MIN. The absolute temperatures are determined by the sum of the critical temperature increase and the rail neutral temperature (TN). The upper and lower critical temperature increases play an important role in the assessment of buckling safety. In the CWR-SAFE, the buckling response characteristic and the upper and lower critical temperature increases are calculated based on the input parameters.

4.1.2 Progressive Buckling

In some extreme cases the buckling response can degenerate into the form shown in Figure 4-3.In this case the buckling temperature increase corresponds to the "knee" of the response curve, and is denoted TP, or TPROG. The track response to increasing rail temperature will be a progressive growth in lateral displacement, in contrast to the "explosive" response characteristic shown in Figure 4-2. Progressive buckling is normally associated with "weak" tracks such as those with extremely low lateral resistance, large line defects or very sharp curves

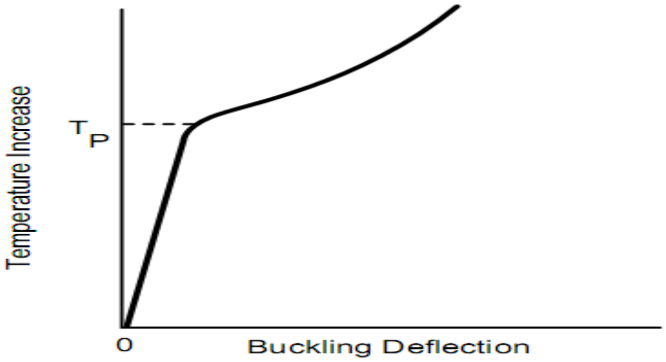


Figure 4-3:-Typical progressive buckling response characteristic (CWR-SAFE 2000)

If the model determines that progressive buckling has occurred based on the input parameters, the program calculates the progressive buckling temperature increase, TP, which is denoted in the program output by Tprog.

4.2 Buckling Safety

Buckling starts at a temperature Tbmax after which in most cases the temperature decreases in the post buckling path (Figure 4-2). Only for weak tracks the shift is more gradual Figure 4-3. Since Tbmax is strongly depended on the misalignment; it can be considered as an upper bound for which buckling will occur. Following the post buckling behavior, a minimum temperature T min is found below which buckling cannot occur, which is a lower bound. Therefore, as (Samavedam, 1993) proposes, a safety criteria based on both temperatures Tbmax and Tbmin could be formulated. In case of a low ballast resistance (tamped ballast) or in case of a small track radius (curve breathing) progressive track shifting is found without a snap-through behavior. Then Tbmax and T min are not found and criteria should be based on a limited track shifting. Different software's has been developed to predict the Tbmax and Tbmin temperatures for given track and rolling stock parameters. In the USA, the program developed is called CWR-SAFE. The inputs to these programs are: Rail section, Track curvature, Rolling stock characteristics, Lateral ballast resistance and the misalignment in the track.

Using these programs the Tbmin and Tbmax of the given track for a given set of parameters are determined. The policies regarding CWR maintenance can then be decided.

These could include:

- Allowable Temperature rise above t_n for maintenance activities
- Temperature at which track enter the danger zone, and necessitates hot weather patrolling.

The CWR-SAFE can be used to determine allowable operating temperature regimes for CWR track, as well as "margins of safety" against buckling occurrence based on buckling safety criteria.

The basic premise for CWR buckling safety assurance lies in the performance-based requirement that CWR track should have the buckling strength required to withstand the environmentally and operationally imposed loads for the range of expected operating condition. The translation of this statement into viable and usable safety specifications requires a rational CWR buckling safety management Methodology. This methodology consists of the application of the following four key elements:

- CWR track system/component characterization
- Conduct buckling buckling/stability analysis
- Establish and apply safety criteria
- Perform safety evaluation

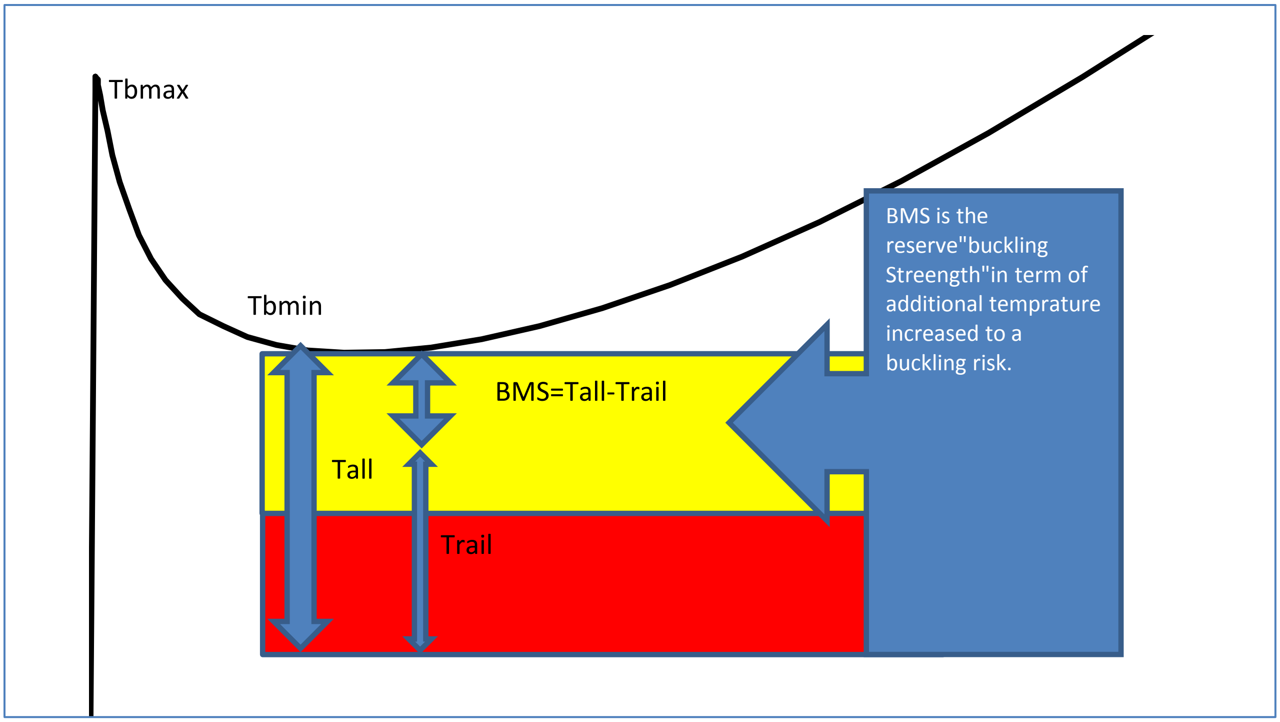
Which requires the application of a dynamic or quasi-dynamic buckling analysis/model, such as for instance the U.S. Department of transportation (DOT) CWR-BUCKLE program or the

CWERRI model, With respect to safety evaluation, this requires either the application of safety criteria to directly perform a buckling safety evaluation and determine reserve buckling strength, or to develop safety guidelines/specifications in terms of allowable temperature increase limits as functions of track parameters/conditions, apply these specifications for safety assessments

4.2.1 Buckling Safety Criteria

The fundamental approach for the buckling safety criteria is to define, for a given set of track and vehicle parameters, an allowable increase in the rail temperature (TALL) for safe operations. Buckling will not occur till the rail temperature (TR) exceeds the rail neutral temperature plus the allowable temperature increase (TN + TALL). Hence knowledge of TN is also required in the safety evaluation.

For every set of data which contain the physical and geometrical parameters of the CWR track introduced in the CWR-BUCKLE model it will result (Figure 4-4) a buckling response curve of track



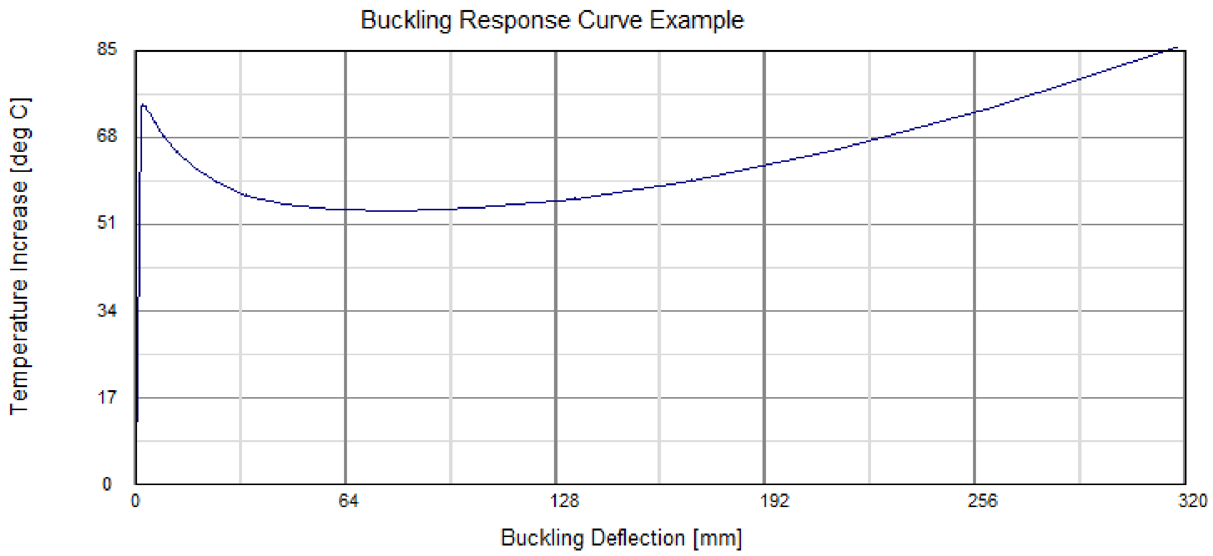


Figure 4-4:- buckling response curve of track

This curve is characterized by two points (Van, 1997):

[Tb, max]:-the maximum increase of temperature for which the buckling certainly starts, and

[Tb, min]:-the minimum increase of temperature occurs in the post-buckling domain.

For a railway track safety conditions, [Tall] is the maximum allowable temperature above the neutral temperature of the rail that is considered safe as far as track buckling is concerned.

The allowable temperature increase is automatically calculated in the safety analysis part of the program. This calculation is based on the upper and lower critical temperatures (Tb,max and Tb,min) or the progressive temperature (Tprog).The allowable temperature increase is calculated as follows:

The safety concepts and criteria proposed by researchers are based on one of the following situations:-

- Evaluation of [Tb, max];
- Evaluating of [Tb, min];
- Simultaneous quantification of [[Tb, max];] and [Tb, min].

Since the first situation leads to imprudent results in terms of safety, and the second method leads to too conservative results, it appears that the third method is the most rational, and therefore it is based on safety criteria developed by UIC and FRA.

For this reason the criterion of safety implemented in CWR-BUCKLE program is provided by

For Non-Progressive Buckling

- TALL = TB, MIN, If (TB, MAX - TB, MIN) > 10°F [5.6°C]
- TALL = TB, MAX - 10°F [5.6°C], If (TB, MAX - TB, MIN) < 10°F [5.6°C]

For Progressive Buckling

- TALL = TP - 10°F [5.6°C]

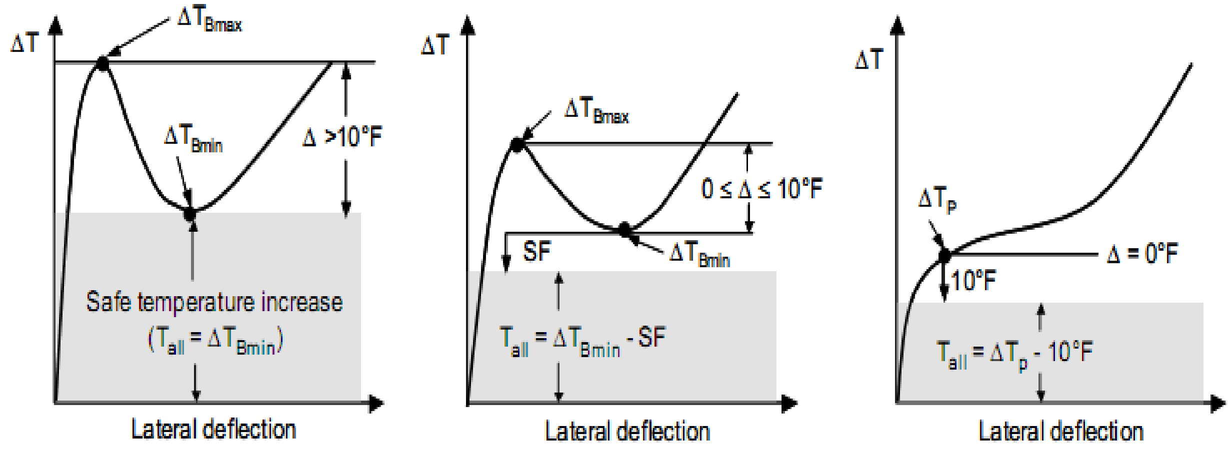


Figure 4-5:- Illustration of Safety Criterion (FRA)

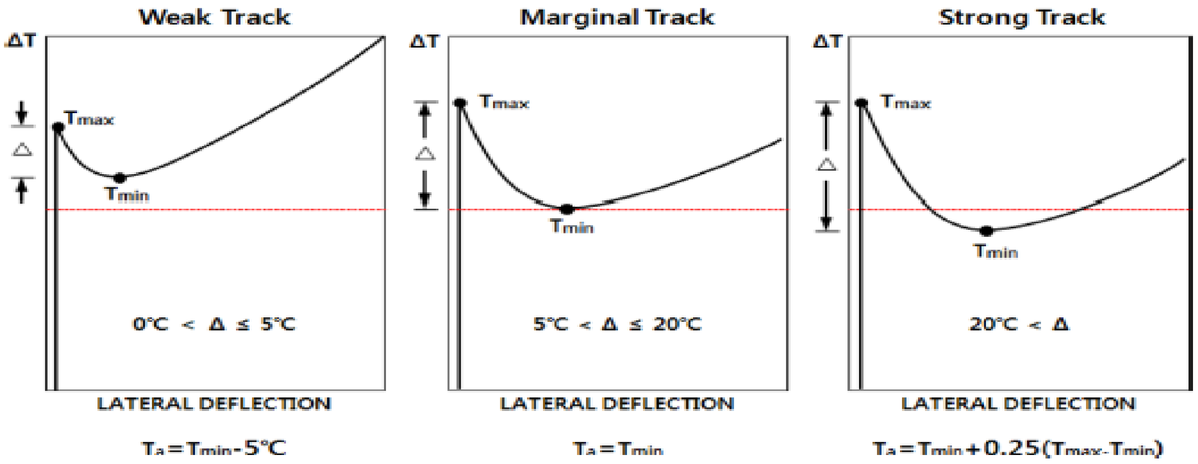


Figure 4-6:- Allowable Buckling Temperature (UIC720R)

4.2.2 Buckling Safety Margin (BSM)

The Buckling Safety Margin (BSM) is a measure of the relative buckling safety for a given set of track and vehicle parameters. The BSM is based on the allowable temperature increase (TALL) calculated by the program, and the rail temperature (TR) and rail neutral temperature (TN); this is input during the safety analysis phase of the program.

There are four ranges for the BSM, which are based on the formula

BSM = TALL - (TR - TN) which is proposed by FRA and UIC720R

Ideally the BSM should be as large as possible (>40°F [22°C]) to provide the greatest margin of buckling safety. The BSM is automatically calculated during the safety analysis phase of the program.

The four ranges for the BSM are as follows:-

- **No Margin:** - In this case, the BSM, as calculated by the formula above, is less than zero. This implies that there is no margin of safety for the given set of parameters, rail temperature and neutral temperature, and that buckling potential is high.
- **Minimum Required Range:** - In this case the BSM is between 0 and 20°F [0 and 11°C].This implies that there is only a small margin of safety for the track in question.
- **Adequate Range:** - In this case the BSM is between 20 and 40°F [11 and 22°C], implying that there is an adequate margin of safety for the track in question.
- **Desired Range:** - In this case the BSM is greater than 40°F [22°C]. This is considered the ideal range, as it provides the largest margin of safety for the given track.

4.3 Buckling Energy

Buckling energy is the energy input from external sources, required to buckle the CWR track at a given temperature above TALL. This energy may originate from several sources, including the dynamic loads imparted to the track by vehicle passage. The computer program automatically calculates the energy required to buckle the track at each temperature increase. Note that when the track is at the upper critical temperature increase (TB, MAX), zero external energy is required to buckle the track, whereas at the lower critical temperature increase (TB, MIN) a finite amount of external energy is required.

4.4 Buckling Strength Evaluation

The buckling strength is defined as the capacity of the track to resist forces causing sudden loss of lateral stability resulting in large misalignments. Analytically, it is quantified in terms of an allowable rail temperature increase above neutral, Tall that the track structure can withstand before buckling. The buckling margin of safety (BMS) often used in buckling safety evaluations is the difference between the actual buckling strength, Tall , and the buckling strength required which is based on the difference of the maximum rail temperature and the rail neutral temperature. For buckling safety, BMS>0, and the larger the BMS, the larger is the .buckling safety. For additional discussion on buckling safety concepts, parametric behavior, and CWR-BUCKLE field test validation studies refer to (Kish, A. and G. Samavedam 1998, 1993&1990)

The tracks buckling strength was calculated using the CWR-BUCKLE program using the parameters shown in Table 4-1.

Numerical example is presented to illustrate application of CWR-BUCKLE utilizing certain input parameters of track and vehicle, to predict the following:

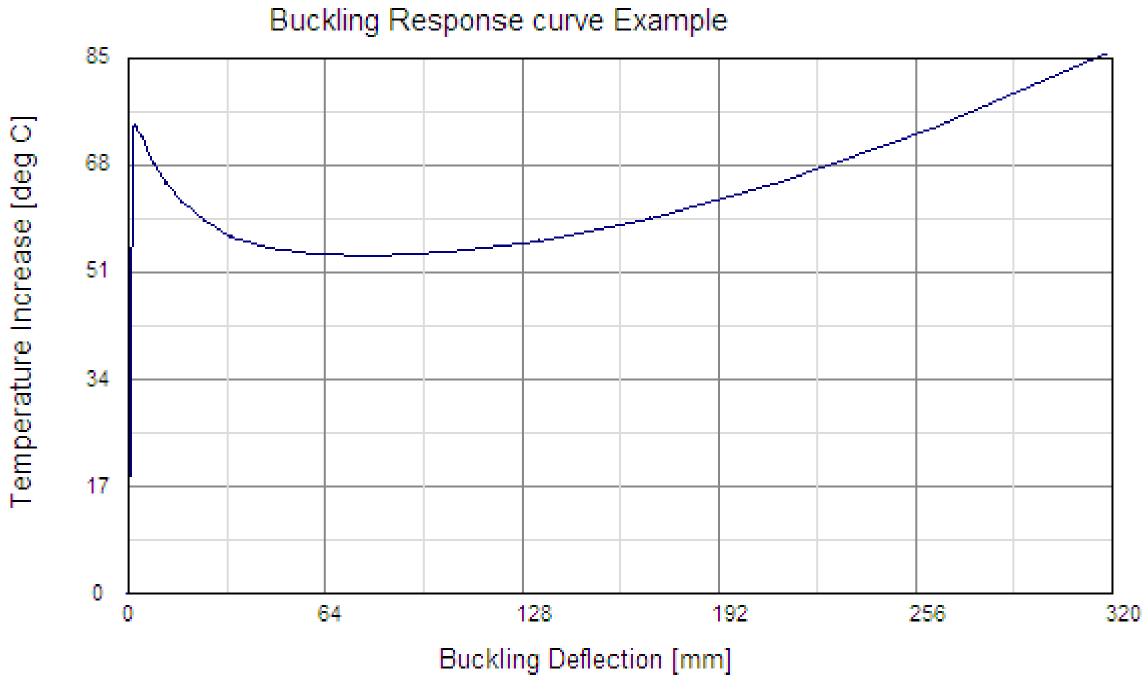
- The buckling strength, expressible in terms of the two critical temperatures, Tbmax and Tbmin, or the TP as defined in previously section. It can predict the entire pre-and Post-buckling response curve of the temperature versus lateral deflection.
- It can compute the buckling energy of the track at a given rail temperature.
- It predicts the rail forces before and after buckling.
- It predicts the allowable rail temperature increase for buckling safety and the track's BMS. The BMS is indicative of the reserve buckling strength in terms of additional acceptable temperature increase before buckling. If the margin of safety is not adequate, the program provides recommendations on how to improve BMS.

Table 4-1:-Input Parameters for CWR-BUCKLE model

NO.	Parameter	Input Value
1	Rail Size (AREA)	50Kg/m
	a. Area of Two Rails (cm^2)	131.6
	b. Iyy (about horizontal axis) for 2 Rails (cm^4)	4074
	c. Izz (about vertical axis) for 2 Rails (cm^4)	754
2	Track Tie Type	Concrete
	a. Tie & Fastener Weight (kN)	3.34
	b. Tie Spacing(mm)	610
3	Track Radius of Curvature (m)	350
4	Ballast Type	Granite
	Peak Lateral Resistance (kN/m)	20
5	Tie-Ballast Friction Coefficient	0.86
6	Torsional Resistance (m-kN/rad per track-m)	112
7	Longitudinal Stiffness (kPa)	3000
8	Foundation Modulus (MPa)	68
9	Misalignment Amplitude (mm)	38.1
10	Misalignment Half-Wavelength (m)	5
11	Vehicle Type	
	a. Number of Axles	4
	b. Axle Load (kN	293
	c. Truck Center Spacing (cm)	1046
	d. Axle Spacing (cm)	1900
12	Rail Neutral Temperature (deg C)	25
13	Maximum Rail Temperature (deg C)	70

The following example illustrates a typical CWR-BUCKLE run with the input parameters shown In Table 4-1

With the above inputs, CWR-BUCKLE provides a graph displaying buckling temperature and deflection as shown in Figure 4-6. The figure shows the two salient temperatures, namely the Tb,max = 58.55^{o}C and Tb,min = 49.72 ^{o}C. In addition to the graph, the output includes a buckling results summary and a safety analysis, as shown in Table 4-2 and Table 4-3.



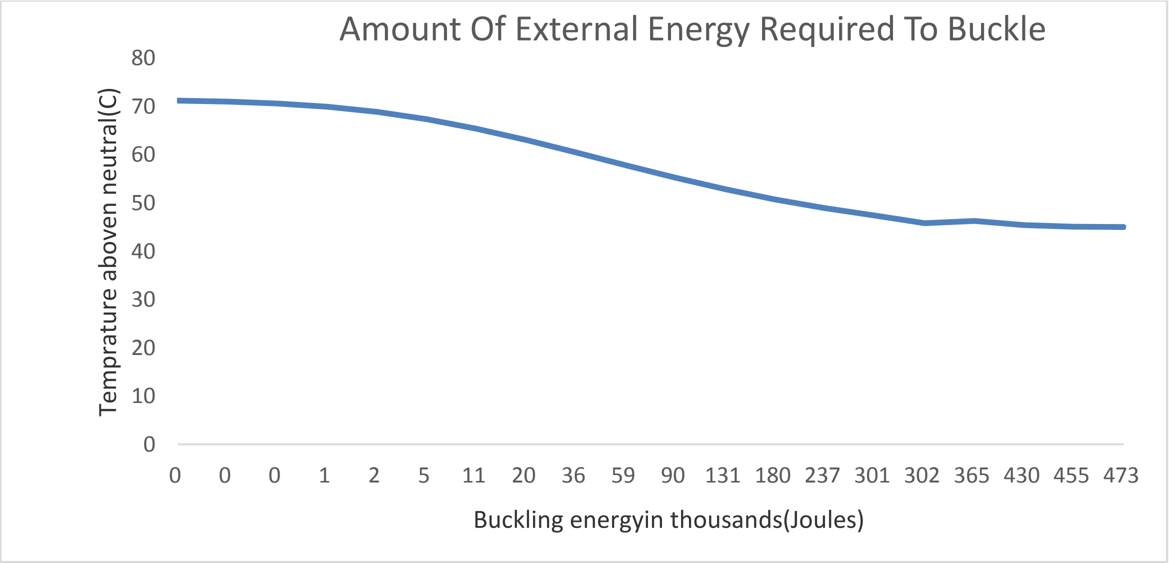


Figure 4-7:- Buckling Deflection versus Temperature

Table 4-2 shows if the track were to buckle out at the lower critical temperature of 49.72 °C the corresponding amplitude would be 69.87 mm, with the half wavelength of 3810.00mm. The force in the rail to cause the buckle is 779.55 kN/rail, and at the Tb,max of 58.55°C, the required energy to buckle the track is zero (as opposed to the energy required to buckle the track at the lower critical temperature Tb,min = 49.72 °C, which is .08 kJ).

The upper and lower critical buckling temperature increases, deflections, wavelengths, forces and energies for this case are as follows

Table 4-2:-CWR-BUCKLE Output Buckling Results Summary

AT THE LOWER CRITICAL TEMPERATURE INCREASE

Temperature increase above neutral	Tb,min	49.72 C
Max buckling deflection	Wmax	69.87 mm
Buckled half-wavelength	L	3810.00 mm
Force in rail at time of buckle	P	779.55 kN/rail
Energy required to buckle	E	.08 kJ

AT THE UPPER CRITICAL TEMPERATURE INCREASE

Temperature increase above neutral	Tb,max	58.55 C
Max buckling deflection	Wmax	177.74 mm
Buckled half-wavelength	L	4254.42 mm
Force in rail at time of buckle	P	911.03 kN/rail
Energy required to buckle	E	.00 kJ

Table 4-3 shows the safety analysis that gives the safe allowable temperature increase, Tall = Tbmin = 49.72 °C, and, if the neutral temperature for this case is 25 °C, then the track should not buckle until Tr = 49.72 + 25 = 74.72°C. Because the maximum rail temperature in this example was set at 70 °C, the BSM is approximately 4.42 °C.

Table 4-3:-CWR-BUCKLE Output – Buckling Safety Analysis

```
For this case, the difference between the upper and lower critical buckling temperature increases
is greater than 5.56 deg C.  The maximum allowable rail temperature for this case is thus given
by:

            Tall   =   allowable rail temperature increase above neutral

                   =   Tb,min

                   =   49.72 deg C

      The results of the buckling safety analysis are as follows:

            Tall   =   allowable rail temperature increase above neutral (49.72 deg C)

            Tn     =   rail neutral temperature (25.00 deg C)

            Tr     =   maximum rail temperature (70.00 deg C)

                       Buckling will occur if:

                       (Tr  -  Tn)  > Tall

                           For this case,

                     (Tr  -  Tn)  = 45.00 < Tall

        Based on the above, BUCKLING SHOULD NOT OCCUR FOR THIS CASE.

       The Buckling Safety Margin for this case is:    4.72 deg C. This Safety Margin is within the
MINIMUM REQUIRED range for buckling safety.
```

Neutral temperature and track lateral resistance are the two primary Parameters which determine the lateral buckling potential of continuous welded rail (CWR) track at a given maximum rail temperature. These parameters can change due to maintenance and service operations (Kish 2003).When maximum rail temperature rise to $75^{o}C$ buckling will occur. To reduce buckling potential the remedial actions should be taken when rail temperature rise above $75^{o}C$ for this case.

By rerun BUCKLE-SAFE with lower values of Peak Lateral Resistance (15kN/m) to determine the decreased resistance required to increase buckling potential. The result as follow

BUCKLING RESULTS SUMMARY

This case resulted in progressive buckling. The progressive buckling temperature increase, deflection, wavelength, force and energy are as follows:

```
      Temperature increase above neutral = Tprog   =     43.90 C

      Max buckling deflection            = Wmax    =      6.15 mm

      Buckled half-wavelength             = L       =   3020.69 mm

      Force in rail at time of buckle    = P       =    679.25 kN/rail

      Energy required to buckle          = E       =       .00 kJ
```

Since this case has resulted in progressive buckling, the maximum allowable rail temperature increase is determined from the progressive buckling temperature increase, as shown below:

```
             Tall   =   allowable rail temperature increase above neutral

                   =   Tprog - 5.56 deg C

                   =   38.34 deg C

            The results of the buckling safety analysis are as follows:

             Tall   =   allowable rail temperature increase above neutral (38.34 deg C)

Tn     =   rail neutral temperature (25.00 deg C)

Tr     =   maximum rail temperature (70.00 deg C)

                        Buckling will occur if:

                        (Tr  -Tn)  > Tall

                            For this case,

                      (Tr  -Tn)  = 45.00 > Tall

   Based on the above, BUCKLING WILL OCCUR FOR THIS CASE.

   To reduce buckling potential, the following remedial actions should be taken:

             -  Increase the rail neutral temperature (Tn);

             -  Increase the track lateral resistance (Fp)*; and/or

             -  Restrict operation to lower rail temperatures and   lower vehicle speeds.
```

* Note: the User should rerun this program with higher values of lateral resistance to determine the increased resistance required to reduce buckling potential.

4.5 Buckling Safety Based Temperature Limits Graphs

The graph is prepared giving the maximum permissible temperature (75^{o}C) for buckling safety in terms of two primary parameters: lateral resistance and CWR neutral temperature. Lateral resistance is chosen as a primary variable in the determination of the safe allowable temperature increase with the other (secondary) parameters set at their average or nominal values. For an assumed line defect and track curvature, the maximum allowable rail temperature plotted against the lateral resistance over a given neutral temperature (25^{o}C).

The examples of safety limit charts for 50kg/m rail CWR concrete tie track with, 5°curvature for line defect of 38.1mm. The assumed fixed parameters for the track conditions are as shown in the Figure 4-8.

A convenient method to determine the lateral ballast resistance per sleeper has been developed in the USA. It is called the single tie push test (STPT). Once the lateral ballast resistance value is obtained graph could be given to the field maintenance engineer to enable him to predict the allowable temperature rise TALL over the neutral temperature

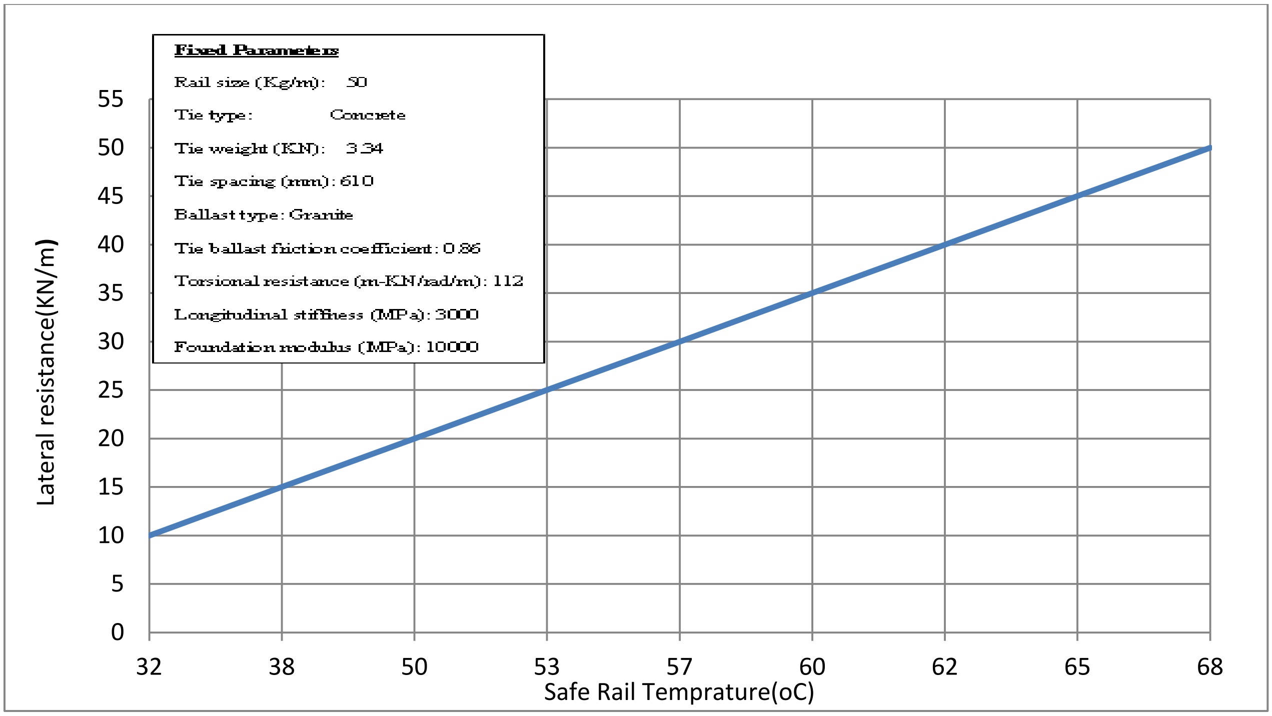


Figure 4-8:-Safety limits in terms of minimum track strength capacity (lateral resistance) as a function of allowable rail force or rail temperature increase values for a fixed parameters

5 CONCLUSION AND RECOMMENDATION

5.1 Conclusions

In this study, the sensitivities of the track parameter about the buckling of the CWR track are investigated using CWR-BUCKLE program developed by Foster-Miller, Inc. (2000).

A comparative study on track buckling parameters has been carried out. It is necessary to consider different track construction standards and vehicle parameters over a specific track to determine safe operating practice. The study includes a thermal buckling theory which accounts for both thermal and vehicle loading effects in the evaluation of track buckling. Parametric studies are performed to evaluate the effects of the individual parameters on the upper and lower critical buckling temperatures.

Each track buckling parameter has its own individual effect on track buckling; each parameter often depends on other parameters. Comparatives among different parameters attempted to study a thermal and vehicle buckling theory for the evaluation of curved and tangent CWR track buckling, and the relationship between the critical temperatures and the required buckling energy used as a measure of the degree of stability using CWR-BUCKLE model. Parametric studies are performed to evaluate the effects of rail size, track curvature, track lateral resistance track longitudinal and torsional stiffness's, initial misalignment amplitude and wavelength, tie-ballast friction coefficient and truck center spacing. Some of the important findings based on the parameter study are listed below.

- The result shows that the upper and lower critical temperatures both decrease with increasing curvature, and the upper buckling temperature is more sensitive.
- The lateral resistance is an important parameter, which influences buckling temperatures. The buckling temperatures increase as the lateral resistance increases. A progressive buckling condition appears at approximately 15KN/m.
- The lower buckling temperature shows a slight increase with the increase of longitudinal stiffness, whereas the upper buckling temperature is essentially in dependent of changing stiffness.
- As rail size increases, both the upper and lower buckling temperatures decrease. The increase in area increases the thermal force, which offsets the corresponding increase in bending stiffness, thus reducing the overall buckling strength

- The results show that the upper and lower critical temperatures both increase with increasing tie ballast friction coefficient.
- Both buckling temperatures increase with increasing torsional stiffness. The lower buckling temperature is more sensitive to the stiffness change, resulting in a significant increase. A progressive buckling condition appears at 750m-KN/rad/m.
- Tbmax is more sensitive to track foundation vertical stiffness variations than Tbmin
- A progressive buckling condition appears at amplitude of approximately 60mm. Misalignment significantly influences the both lower and upper critical temperature. Therefore, good alignment is very important to prevent the CWR track buckling.
- The lower critical temperature is relatively insensitive to the effects of wave-length. A progressive buckling condition is reached at a wave length of 3m. The difference between upper and lower temperature is getting larger when the wave length increases.
- The buckling temperatures do not follow the same trends with increasing truck center spacing. Results show that a critical truck center spacing is about 11 m. truck center spacing most strongly influences the upper buckling temperature, with the lower buckling temperature being relatively unaffected.
- Bogie or truck centre spacing (TCS) and number of passes contribute to the static track buckling parameters. The analysis show that upper buckling temperature decreases with the increase in axle load, while lower buckling temperature remains almost constant. The practical implication is that lighter cars tend to have larger buckling margins of safety than heavier cars.

The CWR-BUCKLE program was used to estimate the safety of the track against buckling using track parameters.CWR buckling under vehicle and thermal loads can be predicted using this model. The model 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 methodology presented herein is capable of determining the safe and buckling temperatures. It is, therefore, a useful tool for predicting the risk of lateral buckling in any CWR track.

5.2 Recommendations for future work

The work present has attempted to study continuous welded rail (CWR) track buckling sensitivity as influenced by the range of all key parameters (rail size, track curvature, track lateral resistance track longitudinal and torsional stiffness's, initial misalignment amplitude and wavelength, tie-ballast friction coefficient and truck center spacing) and safety evaluation, However, due to financial constraints and time limitations the present research work did not cover detail information on Safety evaluation.

In view of this work, it would be desirable to consider the following recommendations for the future work for the development safe CWR track lateral stability due to thermal and vehicles load railway system in Ethiopia.

- Full scale experiments should be set up and carried out to determine the continuous welded rail (CWR) track buckling strength as influenced by the range of all key parameters such as the lateral, torsional and longitudinal resistance, vehicle loads, and etc. validation of model on base of test according to track standard and geographic locations.
- Unlike the case of the deterministic approach, which gives the margin of safety that could vary from location to location; the probabilistic approach can need to be study in the future. The probability of buckling at a given rail temperature can be expressed by the number of expected buckles over a given track section. Knowing the annual rail temperature over the region, one can compute the probable number of buckles in a year.
- The safety issues related to thermal buckling problems due to climate change should be taken as a critical issue in future studies. And in addition such as signaling failure, equipment failure, train control failure and track structure failures to safety problem in railway system needs a detail investigation.
- The literature review a comprehensive study of Railways all over the world be ill with track buckles caused by variations in thermal stresses arising from temperature fluctuations due to climate change, Notable series research carried by Kerr, Samavedam and Kish from the Volpe Centre in the United States, Esveld from the European Railway Research Institute, and Hagaman and Kathage for the Railways of Australia (ROA). Buckling and track parameters which contribute to track instabilities have been studied and characterized comprehensively using CWR-SAFE and CWERRI. So Ethiopian also

needs the institute that gives a special concern and detailed study to track instability due to variation in thermal stresses arising from temperature fluctuation due to climate change.

- In general when hot season onset. Need to remind operators to be aware of the risks to safety associated with operating railways in hot weather conditions related with track buckling. Rail operators should manage the risk of track buckling by: Monitoring the stresses and movement of the rails, and adjusting the rail stress if required. Monitoring locations of reduced lateral resistance, such as areas of poor ballast or track condition, Monitoring locations that have been recently disturbed through track maintenance, putting in place speed restrictions on very hot days to reduce the severity of any effects of track buckling and dynamic loads.

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7 APPENDIXES

Appendix A: Safety margin within the minimum required

```
########################################################################
#           CWR SAFE: BUCKLE MODULE     VERSION 2000                   #
########################################################################
                            ******************
                            *     RUN LOG    *
                            ******************
CWR Track Buckling Safety Evaluation

Input Filename:                                        AAIT2015.inb

Output Filename:                                       AAIT2015.oub

Run Date:                                              07-27-2015

Run Time:                                              20:15:47

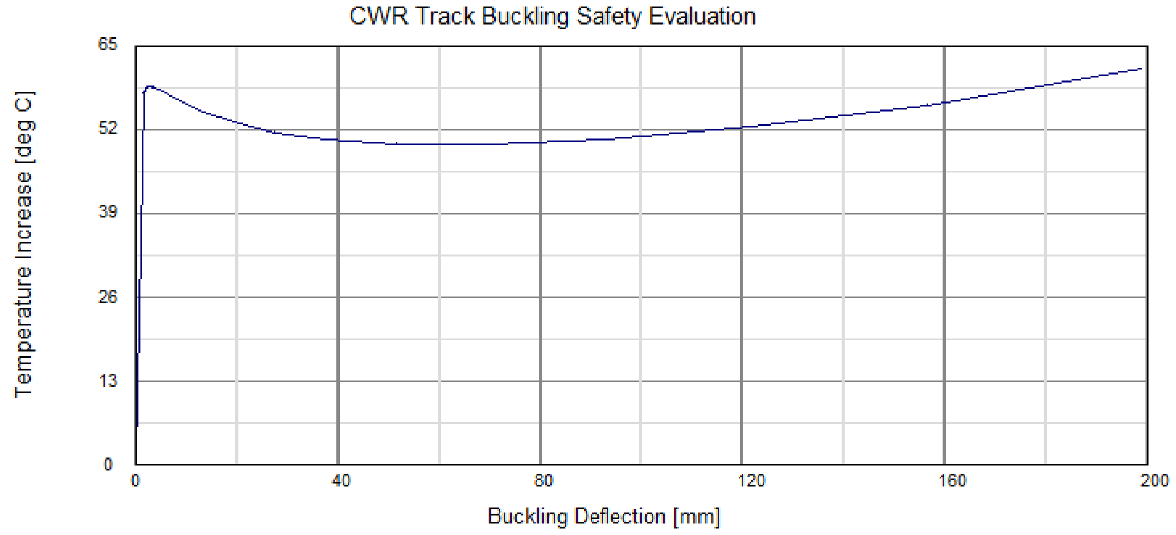
########################################################################
                            ******************
                            *   INPUT DATA   *
                            ******************
1. Rail Size                                                  50Kg/m
 a. Area of Two Rails (cm^2)                                  131.60
 b. Iyy (about horizontal axis) for 2 Rails (cm^4)            4074
 c. Izz (about vertical axis) for 2 Rails (cm^4)              754
2. Track Tie Type                                            Concrete
 a. Tie & Fastener Weight (kN) 3.34    b. Tie Spacing (mm)    610.0
3. Track Radius of Curvature (m)                              350.00
4. Ballast Type                                              Granite
 a. Peak Lateral Resistance (kN/m)                             20.00
 b. Limiting Lateral Resistance (kN/m)                         14.53
 c. Peak Lateral Displacement (mm)                             6.35
 d. Limiting Lateral Displacement (mm)                         57.15
5. Tie-Ballast Friction Coefficient                            0.86
6. Torsional Resistance (m-kN/rad per track-m)                 112
7. Longitudinal Stiffness (kPa)                                3000
8. Foundation Modulus (MPa)                                    68.00
9. Misalignment Amplitude (mm)                                 38.10
10. Misalignment Half-Wavelength (m)                           5.000
11. Vehicle Type
 a. Number of Axles                                            4
 b. Axle Load (kN)                                             293.0
 c. Truck Center Spacing (cm)                                  1046
 d. Axle Spacing (cm)                                          190.0
12. Rail Neutral Temperature (deg C)                           25.00
13. Maximum Rail Temperature (deg C)                           70.00
########################################################################
```

```
########################################################################

                 ****************************************
                 *       BUCKLING RESULTS SUMMARY       *
                 ****************************************

The upper and lower critical buckling temperature increases, deflections,
wavelengths, forces and energies for this case are as follows:
At the LOWER CRITICAL TEMPERATURE INCREASE,
        Temperature increase above neutral = Tb, min =     49.72 C
        Max buckling deflection             = Wmax    =     69.87 mm
        Buckled half-wavelength             = L       =   3810.00 mm
        Force in rail at time of buckle     = P       =    779.55 kN/rail
        Energy required to buckle           = E       =       .08 kJ
At the UPPER CRITICAL TEMPERATURE INCREASE,
Temperature increase above neutral         = Tb, max =     58.55 C
Max buckling deflection                    = Wmax    =    177.74 mm
Buckled half-wavelength                    = L       =   4254.42 mm
Force in rail at time of buckle            = P       =    911.03 kN/rail
Energy required to buckle                  = E       =       .00 kJ

########################################################################
```



```
########################################################################

                     ********************************
                     *   BUCKLING SAFETY ANALYSIS   *
                     ********************************
For this case, the difference between the upper and lower critical
buckling temperature increases is greater than 5.56 deg C.  The maximum
allowable rail temperature for this case is thus given by:
Tall   =   allowable rail temperature increase above neutral
       =   Tb,min =   49.72 deg C
The results of the buckling safety analysis are as follows:
Tall   = allowable rail temperature increase above neutral (49.72 deg C)
Tn     =   rail neutral temperature (25.00 deg C)
Tr     =   maximum rail temperature (70.00 deg C)
Buckling will occur if:
(Tr - Tn)  > Tall
For this case,
(Tr - Tn)  = 45.00 < Tall
Based on the above, BUCKLING SHOULD NOT OCCUR FOR THIS CASE.
The Buckling Safety Margin for this case is: 4.72 deg C.
This Safety Margin is within the MINIMUM REQUIRED range for buckling
safety.

########################################################################
```

```
#######################################################################
                      ******************************
                      *   BUCKLING RESPONSE DATA   *
                      ******************************
                  L         =   Buckled Half-Wavelength
                  P         =   Force per Rail in Buckled Zone
                  w         =   Lateral Deflection
                  T         =    Temperature Increase above Neutral
                 Energy     =   Energy Required to Buckle
L         P            w          T            Energy
(mm)      (kN)          (mm)     (deg C)          (kJ)
------------------------------------------------------------
6858.0     307.30     3270.522    2558.24           .0000
6731.0     315.36     2971.014    2174.62           .0000
6604.0     323.91     2689.051    1837.31           .0000
6477.0     332.96     2425.079    1543.33           .0000
6350.0     342.52     2179.287    1289.30           .0000
6223.0     352.61     1951.743    1071.72           .0000
6096.0     363.23     1742.257     886.94           .0000
5969.0     374.39     1550.278     731.16           .0000
5842.0     386.10     1374.942     600.65           .0000
5715.0     398.41     1215.202     491.89           .0000
5588.0     411.36     1069.916     401.69           .0000
5461.0     425.01      937.923     327.23           .0000
5334.0     439.44      818.090     266.05           .0000
5207.0     454.76      709.352     216.04           .0000
5080.0     471.06      610.768     175.44           .0000
4953.0     488.47      521.548     142.77           .0000
4826.0     507.12      441.071     116.81           .0000
4699.0     527.11      368.879      96.52           .0000
4572.0     548.54      304.633      81.02           .0000
4445.0     571.45      248.051      69.53           .0000
4318.0     595.79      198.824      61.32           .0000
4191.0     621.37      156.712      55.78           .0000
4064.0     647.58      121.615      52.34           .0000
3937.0     674.02       92.901      50.47           .0238
3810.0     700.46       69.868      49.72           .0814
3683.0     726.33       51.620      49.73           .0833
3556.0     753.64       37.699      50.39           .0641
3429.0     782.69       27.155      51.54           .0424
3302.0     813.16       19.291      53.03           .0244
3175.0     843.26       13.518      54.66           .0120
3048.0     869.94        9.386      56.18           .0049
2921.0     890.46        6.524      57.37           .0016
2794.0     903.54        4.619      58.14           .0003
2667.0     909.89        3.397      58.50           .0000
2540.0     911.03        2.642      58.55           .0000
2413.0     909.56        2.188      58.44           .0000
2286.0     906.65        1.924      58.24           .0000
2159.0     903.49        1.772      58.03           .0000
2032.0     900.61        1.687      57.85           .0000
1905.0     898.26        1.642      57.70           .0000
#######################################################################
END OF FILE
```

Appendix B:-Buckling with decreasing rail neutral temperature

```
#######################################################################
#               CWR SAFE: BUCKLE MODULE     VERSION 2000              #

#######################################################################
                                ******************
                                *     RUN LOG    *
                                ******************
       CWR Track Buckling Safety Evaluation
       Input Filename:                                        AAIT2015.inb
       Output Filename:                                       AAIT2015.oub
       Run Date:                                                07-26-2015
       Run Time:                                                  21:15:41

######################################################################
                                ******************
                                *   INPUT DATA   *
                                ******************
      1. Rail Size                                            User-Defined
         a. Area of Two Rails (cm^2)                                131.60
         b. Iyy (about horizontal axis) for 2 Rails (cm^4)            4074
         c. Izz (about vertical axis) for 2 Rails (cm^4)               754
      2. Track Tie Type                                           Concrete
         a. Tie & Fastener Weight (kN)                                3.34
         b. Tie Spacing (mm)                                         610.0
      3. Track Radius of Curvature (m)                              350.00
      4. Ballast Type                                              Granite
        a. Peak Lateral Resistance (kN/m)                          20.00
        b. Limiting Lateral Resistance (kN/m)                      14.53
        c. Peak Lateral Displacement (mm)                           6.35
        d. Limiting Lateral Displacement (mm)                      57.15
     5. Tie-Ballast Friction Coefficient                             .86
     6. Torsional Resistance (m-kN/rad per track-m)                  112
     7. Longitudinal Stiffness (kPa)                                3000
     8. Foundation Modulus (MPa)                                   68.00
     9. Misalignment Amplitude (mm)                                38.10
    10. Misalignment Half-Wavelength (m)                           5.000
    11. Vehicle Type
      a. Number of Axles                                             4
      b. Axle Load (kN)                                            293.0
      c. Truck Center Spacing (cm)                                  1046
      d. Axle Spacing (cm)                                         190.0
    12. Rail Neutral Temperature (deg C)                           20.00
    13. Maximum Rail Temperature (deg C)                           75.00

#####################################################################
```

```
########################################################################

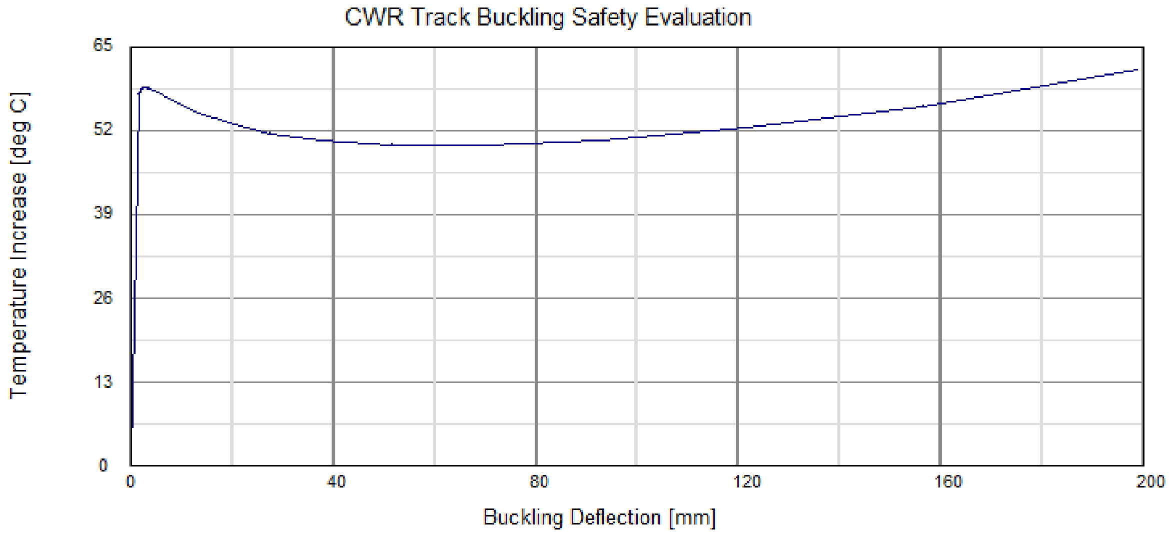
                     ****************************************
                     *       BUCKLING RESULTS SUMMARY       *
                     ****************************************

The upper and lower critical buckling temperature increases, deflections,
wavelengths, forces and energies for this case are as follows:

       At the LOWER CRITICAL TEMPERATURE INCREASE,
       Temperature increase above neutral  =  Tb,min  =     49.72 C
       Max buckling deflection             =  Wmax    =     69.87 mm
       Buckled half-wavelength             =  L       =   3810.00 mm
       Force in rail at time of buckle     =  P       =    779.55 kN/rail
       Energy required to buckle           =  E       =       .08 kJ

       At the UPPER CRITICAL TEMPERATURE INCREASE,
       Temperature increase above neutral  = Tb,max  =     58.55 C
       Max buckling deflection             = Wmax    =    177.74 mm
       Buckled half-wavelength             = L       =   4254.42 mm
       Force in rail at time of buckle     = P       =    911.03 kN/rail
       Energy required to buckle           = E       =       .00 kJ


########################################################################
```



```
#######################################################################
                          ********************************
                          *   BUCKLING SAFETY ANALYSIS   *
                          ********************************
For this case, the difference between the upper and lower critical
buckling temperature increases is greater than 5.56 deg C.  The maximum
allowable rail temperature for this case is thus given by:
             Tall   =   allowable rail temperature increase above neutral
                    =   Tb,min
                    =   49.72 deg C
The results of the buckling safety analysis are as follows:

              Tall   =   allowable rail temperature increase above
                          neutral ( 49.72 deg C)
              Tn     =   rail neutral temperature (20.00 deg C)
              Tr     =   maximum rail temperature (70.00 deg C)
                            Buckling will occur if:
                            (Tr - Tn)  > Tall
                                 For this case,
                         (Tr - Tn)  = 50.00 > Tall
Based on the above, BUCKLING WILL OCCUR FOR THIS CASE.
To reduce buckling potential, the following remedial actions should be
taken:
               -  Increase the rail neutral temperature (Tn);
               -  Increase the track lateral resistance (Fp)*; and/or
               -  Restrict operation to lower rail temperatures and
                  lower vehicle speeds.
* Note:  the User should rerun this program with higher values of lateral
resistance to determine the increased resistance required to reduce
buckling potential.

#######################################################################
```

```
########################################################################

                           ******************************
                           *   BUCKLING RESPONSE DATA   *
                           ******************************

                      L        =   Buckled Half-Wavelength
                      P        =   Force per Rail in Buckled Zone
                      w        =   Lateral Deflection
                      T        =   Temperature Increase Above Neutral
                      Energy   =   Energy Required to Buckle

              L          P            w          T             Energy
            (mm)       (kN)          (mm)      (deg C)          (kJ)
           -------------------------------------------------------------
            6223.0     352.61     1951.743    1071.72           .0000
            6096.0     363.23     1742.257     886.94           .0000
            5969.0     374.39     1550.278     731.16           .0000
            5842.0     386.10     1374.942     600.65           .0000
            5715.0     398.41     1215.202     491.89           .0000
            5588.0     411.36     1069.916     401.69           .0000
            5461.0     425.01      937.923     327.23           .0000
            5334.0     439.44      818.090     266.05           .0000
            5207.0     454.76      709.352     216.04           .0000
            5080.0     471.06      610.768     175.44           .0000
            4953.0     488.47      521.548     142.77           .0000
            4826.0     507.12      441.071     116.81           .0000
            4699.0     527.11      368.879      96.52           .0000
            4572.0     548.54      304.633      81.02           .0000
            4445.0     571.45      248.051      69.53           .0000
            4318.0     595.79      198.824      61.32           .0000
            4191.0     621.37      156.712      55.78           .0000
            4064.0     647.58      121.615      52.34           .0000
            3937.0     674.02       92.901      50.47           .0238
            3810.0     700.46       69.868      49.72           .0814
            3683.0     726.33       51.620      49.73           .0833
            3556.0     753.64       37.699      50.39           .0641
            3429.0     782.69       27.155      51.54           .0424
            3302.0     813.16       19.291      53.03           .0244
            3175.0     843.26       13.518      54.66           .0120
            3048.0     869.94        9.386      56.18           .0049
            2921.0     890.46        6.524      57.37           .0016
            2794.0     903.54        4.619      58.14           .0003
            2667.0     909.89        3.397      58.50           .0000
            2540.0     911.03        2.642      58.55           .0000
            2413.0     909.56        2.188      58.44           .0000
            2286.0     906.65        1.924      58.24           .0000
            2159.0     903.49        1.772      58.03           .0000
            2032.0     900.61        1.687      57.85           .0000
            1905.0     898.26        1.642      57.70           .0000

########################################################################
      END OF FILE
```

Appendix C: Progressive buckling with decreasing Lateral resistance

```
#######################################################################
#                CWR SAFE: BUCKLE MODULE     VERSION 2000             #
#######################################################################
                            ******************
                            *     RUN LOG    *
                            ******************
CWR Track Buckling Safety Evaluation

Input Filename:                                        AAIT2015.inb

Output Filename:                                       AAIT2015.oub

Run Date:                                                07-26-2015

Run Time:                                                  22:35:48

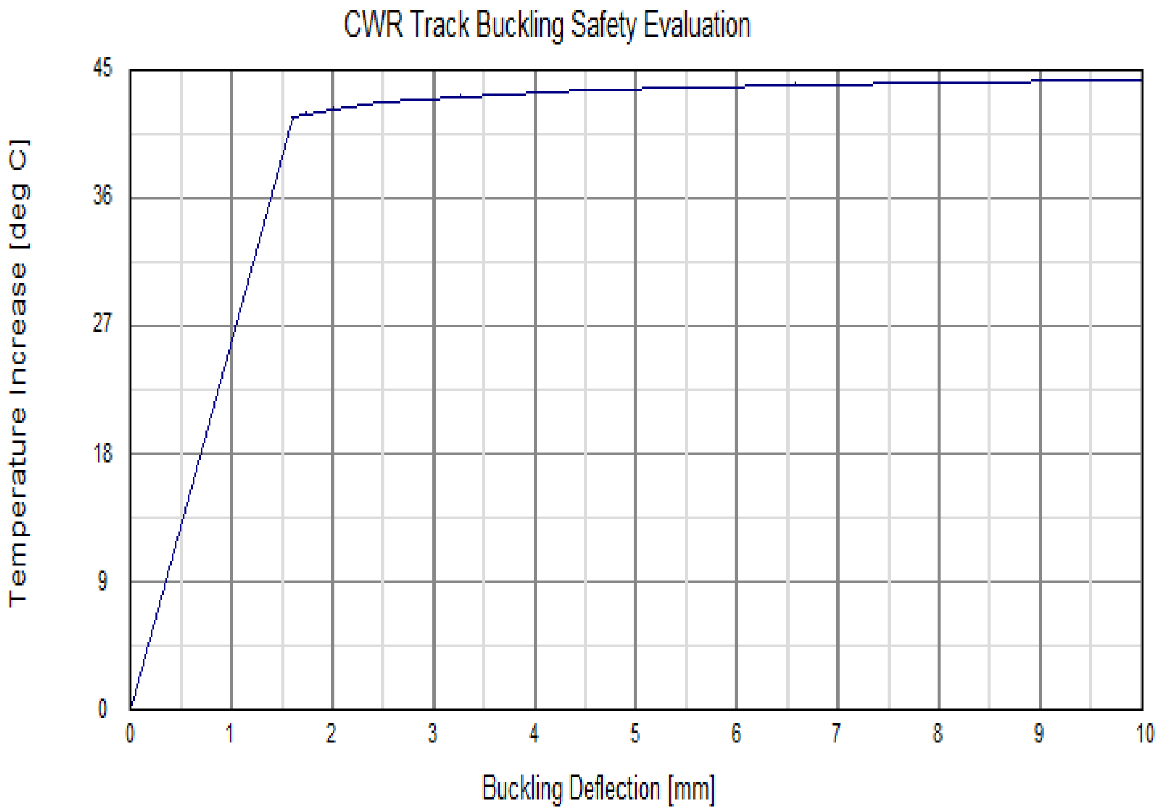
#######################################################################

                            ******************
                            *   INPUT DATA   *
                            ******************
1. Rail Size                                                 50Kg/m
 a. Area of Two Rails (cm^2)                                 131.60
 b. Iyy (about horizontal axis) for 2 Rails (cm^4)           4074
 c. Izz (about vertical axis) for 2 Rails (cm^4)             754
2. Track Tie Type                                            Concrete
 a. Tie & Fastener Weight (kN)                               3.34
 b. Tie Spacing (mm)                                         610.0
3. Track Radius of Curvature (m)                             350.00
4. Ballast Type                                              Granite
 a. Peak Lateral Resistance (kN/m)                            15.00
 b. Limiting Lateral Resistance (kN/m)                        12.63
 c. Peak Lateral Displacement (mm)                            6.35
 d. Limiting Lateral Displacement (mm)                        57.15
5. Tie-Ballast Friction Coefficient                          0.86
6. Torsional Resistance (m-kN/rad per track-m)               112
7. Longitudinal Stiffness (kPa)                              3000
8. Foundation Modulus (MPa)                                  68.00
9. Misalignment Amplitude (mm)                               38.10
10. Misalignment Half-Wavelength (m)                         5.000
11. Vehicle Type
 a. Number of Axles                                          4
 b. Axle Load (kN)                                           293.0
 c. Truck Center Spacing (cm)                                1046
 d. Axle Spacing (cm)                                        190.0
12. Rail Neutral Temperature (deg C)                         25.00
13. Maximum Rail Temperature (deg C)                         75.00

#######################################################################
```

```
#######################################################################
                 ****************************************
                 *       BUCKLING RESULTS SUMMARY       *
                 ****************************************
This case resulted in progressive buckling. The progressive buckling
temperature increase, deflection; wavelength, force and energy are as
follows:
Temperature increase above neutral = Tprog   =     43.90 C
Max buckling deflection            = Wmax    =      6.15 mm
Buckled half-wavelength            = L       =   3020.69 mm
Force in rail at time of buckle    = P       =    679.25 kN/rail
Energy required to buckle          = E       =       .00 kJ

#######################################################################
```



```
########################################################################

                     ********************************
                     *   BUCKLING SAFETY ANALYSIS   *
                     ********************************
Since this case has resulted in progressive buckling, the maximum
allowable rail temperature increase is determined from the progressive
buckling temperature increase, as shown below:
Tall   =   allowable rail temperature increase above neutral
       =   Tprog - 5.56 deg C
       =   38.34 deg C
The results of the buckling safety analysis are as follows:
    Tall = allowable rail temperature increase above neutral (38.34 deg C)
    Tn   =   rail neutral temperature (25.00 deg C)
    Tr   =   maximum rail temperature (75.00 deg C)
Buckling will occur if:
   (Tr - Tn)  > Tall
For this case,
   (Tr - Tn)  = 50.00 > Tall
Based on the above, BUCKLING WILL OCCUR FOR THIS CASE.
To reduce buckling potential, the following remedial actions should be
taken:
     -  Increase the rail neutral temperature (Tn);
     -  Increase the track lateral resistance (Fp)*; and/or
     -  Restrict operation to lower rail temperatures and lower vehicle
speeds.
* Note:  the User should rerun this program with higher values of lateral
resistance to determine the increased resistance required to reduce
buckling potential.

########################################################################
```

```
#######################################################################
                      ******************************
                      *   BUCKLING RESPONSE DATA   *
                      ******************************
              L        =   Buckled Half-Wavelength
              P        =   Force per Rail in Buckled Zone
              w        =   Lateral Deflection
              T        =   Temperature Increase above Neutral
              Energy   =   Energy Required to Buckle
L         P            w          T            Energy
(mm)      (kN)          (mm)     (deg C)          (kJ)
------------------------------------------------------------
6858.0     303.41     3571.206    2986.71           .0000
6731.0     311.20     3237.446    2530.55           .0000
6604.0     319.49     2921.630    2127.49           .0000
6477.0     328.24     2626.903    1777.72           .0000
6350.0     337.47     2353.323    1476.82           .0000
6223.0     347.18     2100.756    1220.19           .0000
6096.0     357.38     1868.757    1003.09           .0000
5969.0     368.07     1656.528     820.76           .0000
5842.0     379.28     1462.968     668.56           .0000
5715.0     391.03     1286.818     542.21           .0000
5588.0     403.37     1126.783     437.87           .0000
5461.0     416.34      981.586     352.20           .0000
5334.0     430.01      850.044     282.27           .0000
5207.0     444.44      731.074     225.62           .0000
5080.0     459.71      623.722     180.13           .0000
4953.0     475.89      527.190     144.01           .0000
4826.0     493.03      440.817     115.75           .0000
4699.0     511.15      364.072      94.05           .0000
4572.0     530.24      296.511      77.76           .0000
4445.0     550.17      237.708      65.90           .0000
4318.0     570.70      187.213      57.57           .0000
4191.0     591.34      144.634      51.98           .0000
4064.0     611.21      109.716      48.47           .0000
3937.0     629.44       81.669      46.41           .0000
3810.0     645.28       59.635      45.29           .0000
3683.0     658.39       42.737      44.74           .0000
3556.0     668.38       30.072      44.49           .0000
3429.0     676.07       20.841      44.42           .0000
3302.0     680.88       14.255      44.38           .0000
3175.0     682.32        9.676      44.25           .0000
3048.0     680.31        6.583      43.99           .0000
2921.0     675.40        4.557      43.59           .0000
2794.0     668.84        3.267      43.12           .0000
2667.0     661.81        2.475      42.64           .0000
2540.0     655.29        2.007      42.20           .0000
2413.0     649.92        1.740      41.85           .0000
2286.0     645.92        1.600      41.59           .0000
#######################################################################
END OF FILE
```

Appendix D: safety margin within the adequate range by increase lateral resistance and neutral temperature

```
########################################################################
#               CWR SAFE: BUCKLE MODULE     VERSION 2000               #
########################################################################

                             ******************
                             *     RUN LOG    *
                             ******************
CWR Track Buckling Safety Evaluation
Input Filename:                                           AAIT2015.inb
Output Filename:                                          AAIT2015.oub
Run Date:                                                   07-26-2015
Run Time:                                                     22:59:32

########################################################################

                             ******************
                             *   INPUT DATA   *
                             ******************
1. Rail Size                                                        50Kg/m
 a. Area of Two Rails (cm^2)                                        131.60
 b. Iyy (about horizontal axis) for 2 Rails (cm^4)                    4074
 c. Izz (about vertical axis) for 2 Rails (cm^4)                       754
2. Track Tie Type                                                 Concrete
 a. Tie & Fastener Weight (kN)                                        3.34
 b. Tie Spacing (mm)                                                 610.0
3. Track Radius of Curvature (m)                                    350.00
4. Ballast Type                                                    Granite
 a. Peak Lateral Resistance (kN/m)                                   50.00
 b. Limiting Lateral Resistance (kN/m)                               25.93
 c. Peak Lateral Displacement (mm)                                    6.35
 d. Limiting Lateral Displacement (mm)                               57.15
5. Tie-Ballast Friction Coefficient                                   0.86
6. Torsional Resistance (m-kN/rad per track-m)                         112
7. Longitudinal Stiffness (kPa)                                       3000
8. Foundation Modulus (MPa)                                          68.00
9. Misalignment Amplitude (mm)                                       38.10
10. Misalignment Half-Wavelength (m)                                 5.000
11. Vehicle Type
 a. Number of Axles                                                   4.00
 b. Axle Load (kN)                                                   293.0
 c. Truck Center Spacing (cm)                                        1046
 d. Axle Spacing (cm)                                                190.0
12. Rail Neutral Temperature (deg C)                                 30.00
13. Maximum Rail Temperature (deg C)                                 75.00

########################################################################
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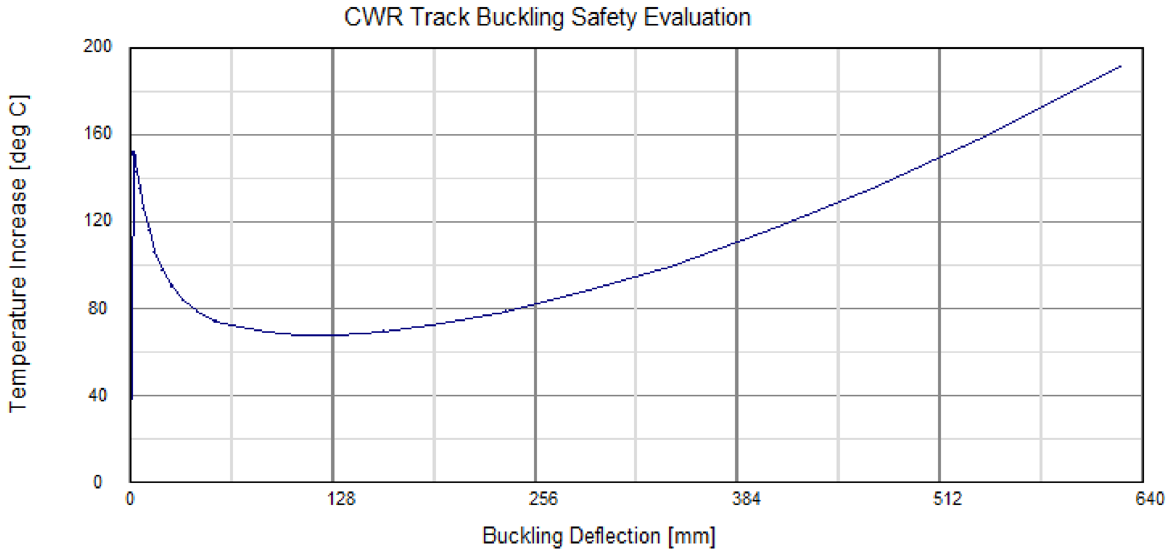
```
#######################################################################

                 ****************************************
                 *       BUCKLING RESULTS SUMMARY       *
                 ****************************************

The upper and lower critical buckling temperature increases, deflections,
wavelengths, forces and energies for this case are as follows:
At the LOWER CRITICAL TEMPERATURE INCREASE,
  Temperature increase above neutral        = Tb,min  =     67.66 C
  Max buckling deflection                   = Wmax    =    106.21 mm
  Buckled half-wavelength                   = L       =   3683.00 mm
  Force in rail at time of buckle           = P       =   1060.91 kN/rail
  Energy required to buckle                 = E       =      1.04 kJ

At the UPPER CRITICAL TEMPERATURE INCREASE,
  Temperature increase above neutral       = Tb, max =    151.96 C
  Max buckling deflection                  = Wmax    =    519.89 mm
  Buckled half-wavelength                  = L       =   4783.70 mm
  Force in rail at time of buckle          = P       =   2375.74 kN/rail
  Energy required to buckle                = E       =       .00 kJ


#######################################################################
```



```
########################################################################
                     ********************************
                     *   BUCKLING SAFETY ANALYSIS   *
                     ********************************
For this case, the difference between the upper and lower critical
buckling temperature increases is greater than 5.56 deg C.  The maximum
allowable rail temperature for this case is thus given by:
     Tall   =   allowable rail temperature increase above neutral
            =   Tb,min
            =   67.66 deg C
The results of the buckling safety analysis are as follows:
Tall   =   allowable rail temperature increase above neutral (67.66 deg C)
Tn     =   rail neutral temperature (30.00 deg C)
Tr     =   maximum rail temperature (75.00 deg C)

Buckling will occur if:
   (Tr - Tn)  > Tall

For this case,
    (Tr - Tn)  = 45.00 < Tall
Based on the above, BUCKLING SHOULD NOT OCCUR FOR THIS CASE.
The Buckling Safety Margin for this case is: 22.66 deg C. This Safety
Margin is within the ADEQUATE range for buckling safety.

########################################################################
```

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#######################################################################
                      ******************************
                      *   BUCKLING RESPONSE DATA   *
                      ******************************
                 L     =   Buckled Half-Wavelength
                 P     =   Force per Rail in Buckled Zone
                 w     =   Lateral Deflection
                 T     =   Temperature Increase above Neutral
                Energy =   Energy Required to Buckle
L         P            w          T            Energy
(mm)      (kN)          (mm)     (deg C)          (kJ)
------------------------------------------------------------
5842.0     417.98     1454.146     673.48           .0000
5715.0     432.72     1302.819     564.35           .0000
5588.0     448.52     1162.053     470.72           .0000
5461.0     465.13     1035.299     393.38           .0000
5334.0     482.83      919.340     328.52           .0000
5207.0     501.77      813.173     274.24           .0000
5080.0     522.16      715.850     228.96           .0000
4953.0     544.21      626.601     191.36           .0000
4826.0     568.19      544.795     160.36           .0000
4699.0     594.41      470.036     135.12           .0000
4572.0     623.17      402.077     114.92           .0000
4445.0     654.79      340.774      99.13           .0000
4318.0     689.60      285.993      87.17           .0000
4191.0     727.84      237.677      78.52           .0000
4064.0     769.38      195.924      72.72           .0000
3937.0     814.33      160.275      69.24           .7283
3810.0     862.55      131.324      67.78          1.0071
3683.0     915.26      106.209      67.66          1.0362
3556.0     972.90       85.526      68.82           .9385
3429.0    1037.06       68.666      71.09           .7944
3302.0    1103.95       53.815      73.95           .6620
3175.0    1185.66       42.972      78.25           .5156
3048.0    1278.84       33.981      83.52           .3877
2921.0    1386.61       26.611      89.91           .2778
2794.0    1510.08       20.536      97.43           .1874
2667.0    1649.28       15.524     106.06           .1166
2540.0    1801.58       11.430     115.59           .0650
2413.0    1959.18        8.173     125.53           .0313
2286.0    2107.19        5.730     134.90           .0125
2159.0    2225.65        4.064     142.42           .0041
2032.0    2304.74        3.037     147.45           .0011
1905.0    2349.06        2.447     150.26           .0002
1778.0    2368.81        2.119     151.52           .0000
1651.0    2375.74        1.937     151.96           .0000
1524.0    2375.10        1.836     151.91           .0000
1397.0    2370.93        1.779     151.65           .0000
1270.0    2364.99        1.746     151.27           .0000
1143.0    2358.65        1.726     150.86           .0000
1016.0    2352.41        1.714     150.46           .0000
#######################################################################
END OF FILE
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