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AFRICAN RAILWAY CENTER OF EXCELLENCE

DEPARTMENT OF RAILWAY ENGINEERING

(CIVIL INFRASTRUCTURE)

SLEEPER SPACING OPTIMIZATION ON BALLASTED TRACK STRUCTURE

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A Thesis Submitted in Partial Fulfillment of the Requirements for the Degree of Master of Science in Railway Engineering (Civil Infrastructure)

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APPROVAL

The undersigned have examined the thesis entitled **Sleeper Spacing Optimization on Ballasted Track Structure** presented by **Birhanu Asfaw**, a candidate for the degree of **Master of Science in Railway Engineering (Civil Infrastructure)** and hereby certify that it is worthy of acceptance.

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I, the undersigned, who is a post graduate student at Addis Ababa University, Addis Ababa Institute of Technology, declare that research work titled “**Sleeper Spacing Optimization on Ballasted Track Structure**” is my own original work and any content has not been presented elsewhere for assessment. All sources of materials used as a reference for the research have been properly acknowledged.

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ABSTRACT

Now days' transportation plays a great role for enhancing exchange or flow of row material, manpower, and information from place to place. Hence different means of transportations are emerged newly. For instance, railway is currently constructed with ballast or without ballast throughout the world to improve transportation of goods in general. However, railway structure needs huge investment designing it through optimum technique by improving serviceability and durability is a genuine question for professionals.

Ballasted track is the most commonly used railway structure in the world because of low construction cost and it has sufficient lateral load resistance capacity. For such tracks sleeper plays a great role in safely and smoothly transferring the axle load from the rail to the underneath ballast, sub ballast, and finally to the formation level. Beside to this sleeper affect the cost of construction, while providing sleepers at dense manner costs more even if safety is assured.

Currently, the provision of sleepers on ballasted track system is based on code recommendations which are different for different countries. This way of designing the track system greatly affect cost of construction even though strength criteria is attained. Therefore, providing sleepers in such away is expensive. So, numeric analysis on spacing of sleepers should be done using classic optimization techniques for newly constructed railways and to check the serviceability of constructed railroads.

Generally, this thesis deals about obtaining the optimum spacing of pre stressed concrete sleeper on the conventional track structure with various curvature values. The numeric analysis is done using the basic finite element methods and/or software i.e. ANSYS through considering train speed, axle load, and track curvature as design variables to obtain the optimum sleeper spacing.

Therefore, the finding of this research attempts to save extra cost through placing sleeper at optimum spacing obtained from analysis. For instance, sleepers provided at AALRT for tangent tracks with train speed less than 70 km/h is 600 mm but from analysis the spacing is 650 mm this leads to a conclusion of around 7.2 percentage of sleeper cost can be saved.

Key Words:

Ballasted Track, Pre Stressed Concrete Sleeper (PCS), Sleeper Spacing

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LIST OF SYMBOLS

Asb	Sleeper and Ballast effective contact area
b_t	Track Width
D_w	Wheel diameter
E	Modulus of Elasticity
E_b	Ballast modulus
EI	Flexural stiffness of Winkler beam
Es	Sub grade modulus
Esb	Sub-ballast modulus
f_c	Compressive strength of concrete
f_{ck}	Characteristic compressive strength of concert
g	Acceleration due to gravity
h	Thickness of ballast and sub ballast layer
I	Moment of inertia
l	Total length of sleeper
l_e	Effective length of sleeper supporting the maximum seat load in between rail
K_i	Stiffness values of i material
L_a	Distance between axle load
L_b	Distance between bogies
P	Static wheel load
P_d	Design wheel load
q_r	Maximum rail seat load
$Q_{centrifugal}$	Vertical wheel load due to centrifugal load on the outer rail
$Q_{dynamic}$	Dynamic wheel load component due to train speed
$Q_{quasi\text{-}static}$	Vertical quasi-static wheel load
Q_{static}	Vertical static wheel load
Q_{total}	Total vertical wheel load
Q_{wind}	Vertical wheel load due to wind force on the outer rail
R_c	Radius of the curved track
S	Ballast settlement
t	Time
w	Sleeper width

$Y_{centrifugal}$	Lateral load caused by centrifugal load on the outer rail
$Y_{dynamic}$	Dynamic lateral wheel load component
Y_{flange}	Lateral load in curve caused by flanging against the outer rail
$Y_{quasi\text{-}static}$	Quasi-static lateral wheel load
Y_{total}	Total lateral wheel load
Y_{wind}	Lateral load due to cross wind
β'	Speed coefficient
γ	Unit weight
δ	Impact factor depending on track condition
Δt	Time step
φ	Friction angle
σ_1	Major principal stress
σ_3	Confining pressure
σ_s	Sub grade stress
ε	Vertical strain due to loading
$\varepsilon_{p\text{-}b}$	Plastic strain on the ballast
ρ	Mass per unit volume or density
υ	Poisons ratio

ACRONYMS

AALRT –	Addis Ababa Light Rail Trains
ASTM –	American Standard for Testing of Materials
ARCE –	African Railway Center of Excellence
AREMA –	American Railway Engineering and Maintenance of Way Association
AS –	Australian Standard
BOEF –	Beam on Elastic Foundation
CWR –	Continuously welded rail
DAF –	Dynamic amplification factor
ERC –	Ethiopian Railway Corporation
ESC –	Engineering Standard Codes
FE –	Finite Element
FEA –	Finite Element Analysis
FEM –	Finite Element Method
ORE –	Office of Research and Experiments
PCSs –	Pre Stressed Concrete Sleepers
UCS –	Unconfined compressive strength
3D –	Three Dimensional

CHAPTER ONE

1 INTRODUCTION

1.1 Background

Railway is a means of transportation system where the train wheel moves over conically guided rail track system while the track is a fundamental part of the railway infrastructure and it represents the primary distinction between this form of land transportation and all others in which it provides a fixed guidance system.

In supporting and guiding railway vehicles, the track structure must restrain repeated lateral, vertical, and longitudinal forces, and other environmental loads. As elements of the track structure, individual cross ties receive loads from the rails or fastenings and in turn, transmit loads to the ballast and subgrade. Consequently, the design of a tie affects and the cross tie is affected by characteristics of other components of the track structure [1], [2]. Moreover, the vehicles on the track show dynamic movement. This dynamic behavior of railway tracks when trains are running is influenced by several factors, i.e. rolling stock, the components engineering property, and interaction of superstructure. Usually features like the sleeper spacing, rail pad stiffness, ballast damping and stiffness have an effect on the dynamic response of the track [4], [5], and [6].

Comparatively railway is more advantageous than highway transportation system with regard to cost, capacity, energy efficiency, and friendly with the environment. The most commonly used railway track system can be classified as rigid or slab track system and flexible or ballasted track system. In case of ballasted track sleeper are used in between the rail and the ballast to have a smooth load transfer but in slab track using sleepers is optional depends on the designer.

Further Sleepers can be classified based on the following criteria like construction materials, shape and type of construction. Those are wooden, steel, concrete, and composite sleepers that is based on construction materials used. Depending on their shape sleepers can be categorized as mono block or twin block sleepers. Moreover, on how they are constructed sleepers can be pre cast or in situ sleepers. According to [4], there are two types of concrete sleepers

a) Heavy Duty concrete sleeper: which is suitable for heavy freight tonnages and axle loads less than or equal to 30 tone or for providing greater lateral stability.
b) Medium Duty concrete sleeper: common for general use with axle loads less than or equal to 25 tone.

The functions of the sleepers are to transfer the vertical, lateral and longitudinal rail seat loads to the ballast and formation, and to maintain the track gauge and alignment by providing a reliable support for the rail fasteners. The vertical loads subject the sleeper to a bending moment which is dependent upon the condition of the ballast underneath the sleeper. The performance of a sleeper to withstand lateral and longitudinal loading is dependent upon the sleeper size, shape, surface geometry, weight and spacing [7], [8], and [9].

All the aforementioned sleeper types have their own advantages and dis advantage, but in common they provide the following functions in railway track system.

- To hold the rails to proper gauge in all situations i.e. exact gauge along straights and flat curves, slightly loose on sharp curves and slightly tight in diamond crossings.
- To support evenly throughout the rails firmly.
- To distribute the load transmitted through rails over large area of ballast underneath or to the bridge girders.
- To hold the rails to proper level in turnouts and crossovers, and at 1 in 20 in ward slope along straight tracks.
- To provide an elastic medium between the rails and ballast and also to absorb the vibrations caused due to moving axle loads.
- To maintain proper alignment of the track. On curves proper super elevation is provided by raising the outer rail and tamping the required quantity of ballast bellow the rails.
- To provide the insulation of track for the electrified for signaling and ease of maintenance.

Therefore, to attain those structural functions from sleepers; they should meet the following basic requirements:

- The initial cost and the maintenance cost of the sleepers should be low.
- The fittings required for fixing the rails on to the sleepers, should be simple which can be easily adjusted during maintenance.
- The crushing strength of the sleepers should be more with moderate weight.

- They should be able to maintain a perfect alignment, gauge and levels of the rails and should afford efficient adjustment and maintenance.
- They should provide sufficient bearing area to hold the rail seats and for the ballast to be supported on, to resist the crushing due to movement of heavy axle loads.
- They should be capable to resist the shocks and vibrations caused due to fast moving vehicles.
- They should provide insulation facilities for track circuiting in the electrified sections.
- The sleepers should be strong enough to withstand the pressure during packing process.
- The sleepers should be of such a design that they remain in their positions and do not get disturbed due to movement of trains.
- The material used for the sleeper doesn’t attract the sabotage and the theft qualities.

In Ethiopia as well some researchers have tried to investigate the optimum way of designing sleepers for ballasted track system. For instance, the numerical analysis on the behavior of prestressed concrete sleeper under different support conditions was studied by Haftom G/Michael but the sleeper spacing is considered as constant [10]. The other scholar Ndabamenye Theogene study the optimization of concrete sleepers subjected to static and impact loadings [11] similarly here also the spacing is considered as constant.

Generally, sleepers are the main structural components of ballasted track system where they support the rail at their ends to transfer and resist the axle load to the nearby track component i.e. ballast layer in such a way that both serviceability and strength requirements should be satisfied. But, nowadays sleepers are placed randomly or uniformly as per the standard values from codes. Therefore, providing sleepers at some recommended spacing may cause to invest extra cost which is over the required value or the serviceability period may be shortened. So, it is the best way to obtain the optimum sleeper spacing by using a classic approach for a particular sleeper type i.e. pre stressed concrete through investigating the essential parameters those are; axle load, train speed, various track curvature values.

1.2 Statement of the Problem

In the ballasted track system, sleeper is one of the main structural elements used to smoothly transfer load from the rail to the ballast. But, the provision of those elements at some spacing is from standard codes which is different for different countries.

Now day's different codes recommend different values for sleeper spacing in which it may bring those dis advantages as listed out earlier if it is provided inadequately. In Ethiopia as well in constructing railroad sleepers are placed at some spacing as per a code which is inadequate in saving cost and in providing serviceability with in its life span.

Since we don't have a general numeric formula for computing the corresponding spacing of sleepers is the case which enforces us to use codes in design. In addition to this, Sleeper spacing is a great factor which highly influence the cost of ballasted track construction. Therefore, in order to achieve economically efficient and structurally serviceable ballasted track system the spacing of sleepers should be designed and provided properly.

1.3 Research Objectives

1.3.1 General objective:

The main objective of this research work is to obtain the optimum spacing of pre stressed concrete sleepers on both tangent and curved ballasted track structural systems while strength, serviceability, and economy are satisfied.

1.3.2 Specific Objective:

Up on doing this research the following specific objectives are attained:

- To check the serviceability of currently provided sleepers at AALRT track sections.
- To know the effect of train speed, axle load, and track curvature on spacing of sleepers.
- To verify the recommended sleeper spacing of AREMA 2010 with the classic optimization analysis results obtained.
- To estimate the cost saved due to placing of sleepers per km according to the analysis output compared to codes recommendations.

1.4 Scopes and Limitations

This paper deals about the optimum spacing of pre stressed concrete sleepers on conventional track system for both tangent and curved tracks with standard track gauge width that commonly used in our country. The main constraints are axle load, train speed, and track curve radius through considering different curvature values to be applicable for both curved and tangent tracks and main constituents of ballasted track structure remains constant.

For this study a real optimization technique is not implemented due to complexity and erratic nature of the ground in depth and along track length. Instead a classic optimization method is used for obtaining the optimum spacing of sleepers on ballasted track system and commonly provided sleeper spacing i.e. 55cm, 60cm, 65cm, and 70cm are used to obtain economically optimum spacing. Even though several loads act on railroad for this study only vertical load which has significant effect on the structure is considered.

1.5 Organization of the Research

This research work is presented in five chapters as follows in brief explanation:

- Chapter One: Introduction part which gives a brief highlight on background and the problem statement of the research. The objective, the scope, and limitations to the research are found in this chapter.
- Chapter Two: Literature Review the behavior of prestressed concrete sleepers (PCSs) under vertical loading. Different standards on sleeper spacing recommendation. Factors affecting spacing of prestressed concrete sleeper is discussed in this chapter.
- Chapter Three: Study Methods and Methodology describes the classic optimization techniques and Finite Element Modelling for ANSYS as methodology used.
- Chapter Four: Analysis results and discussion: this part contains the numerical analysis result of prestressed concrete sleeper spacing and comparative study with code recommendation values is done.
- Chapter Five: Conclusion and recommendations. In the final chapter, the research thesis has been concluded and further research areas with some recommendations have been suggested.

Further, the following two appendices are included at the end of this document:

Appendix I: ANSYS analysis result for Tracks

Appendix II: Analysis comparisons

CHAPTER TWO

2 LITERATURE REVIEW

2.1 Introduction

The railway transportation system is the most commonly used means of transportation while the train wheel moves on steel rail through providing a fixed guided movement. It is efficient as being it is working friendly with the environment and it consumes a little energy; furthermore, railroad system enables to transport goods, human beings, and others.

The railroad system can be further classified as ballasted or conventional track and ballast less or slab track system depending on main constituents of the structural components. Ballasted track has the following main structural constituents: rail, sleeper, ballast, sub ballast, and sub base or formation soil as shown below in Fig.1. But slab or ballast less track has concrete slab instead of ballast which provides rigid structural system while other constituents remain the same for both railroad systems see Fig. 2 below a track without ballast.

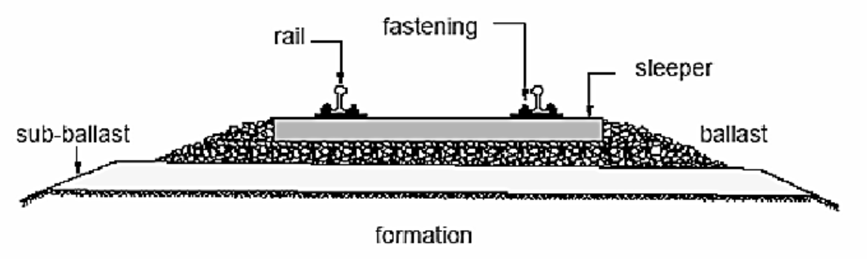


Fig 1 Schematic representation of ballasted track system

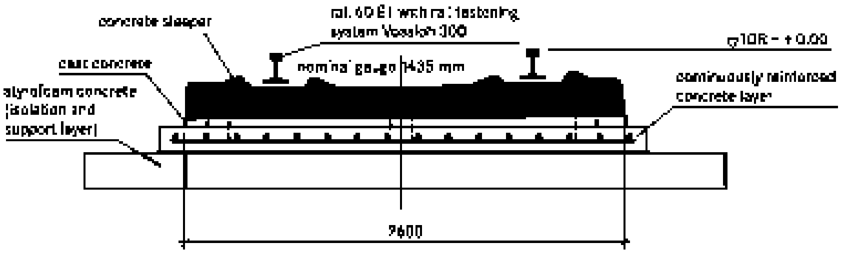


Fig 2 Schematic representation of slab track system

This research deals on optimizing spacing of sleepers on ballasted track system with and without curvature. So, slab track is not the concern of this paper therefore here below detail explanation is presented for constituents of conventional track system.

2.2 Ballasted Track System

It is the conventional rail track system which is most commonly used. The unique constituent of such track system is the ballast. Track ballast forms the track bed upon which railroad ties are laid. It is packed between, below, and around the ties. It is used to bear the load from the railroad sleepers, to facilitate drainage of water, and also to keep down vegetation that might interfere with the track structure.

Ballast also holds the track in place as the trains roll over it. It typically consists of crushed stone, although other, less suitable, materials have sometimes been used such as burnt clay. In such track structural systems, the load will distribute safely and smoothly in reduction order from rail to sleepers and then to ballast, sub ballast and finally to the formation level.

Its structural components are classified as super structure and substructure where sleeper ballast interface acts as classification boundary in which components above this interface are grouped under super structures whereas below it is sub structures as shown in figure below:

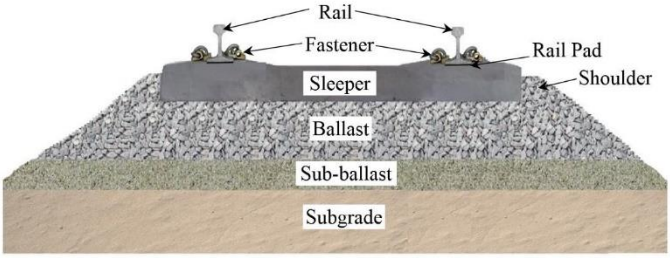


Fig 3 Cross section of Ballasted Track

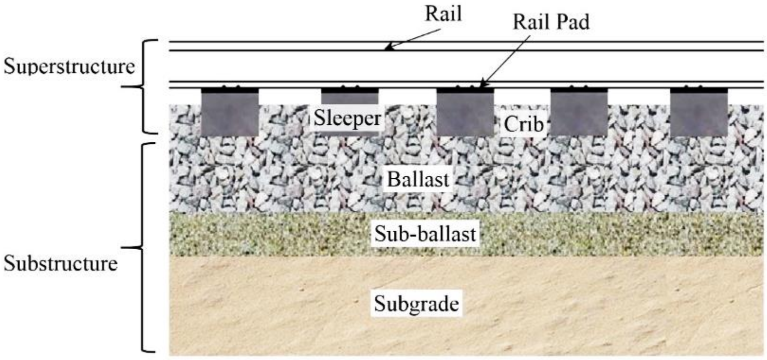


Fig 4 Longitudinal Ballasted track section

Each of the track components for ballasted track system i.e. rail, sleeper or cross tie, rail fastening, ballast, sub ballast, and sub grade or formation soil are briefly described as follows:

The Rail

Rails are the members of the track laid in two parallel lines to provide an unchanging, continuous, and level surface for the movement of trains. To be able to withstand stresses, they are made of high-carbon steel. Their main function in the track is:

a) To provide a continuous and level surface for the movement of trains.
b) To provide a pathway which is smooth and has very little friction. The friction between the steel wheel and the steel rail is about one-fifth of the friction between the pneumatic tyre and a metaled road.
c) To serve as a lateral guide for the wheels.
d) Rails bear the stresses developed due to vertical loads transmitted to them through axles and wheels of rolling stock as well as due to braking and thermal forces.
e) Rails carry out the function of transmitting the load to a large area of the formation through sleepers and the ballast.

The most commonly used rail cross section is flat footed rail also called vignole rail with an inverted T-type cross section which could be fixed directly to the sleepers with spikes. The main advantage of the flat-footed rail is that it is more economical in design, giving greater strength and lateral stability to the track as compared to other cross sections. The rail designation depends on its weight and the standard flat footed rail has a weight of 60 kg which is assigned as 60 kg (UIC) and the detailed dimensions are shown below. In this thesis the relation that exists in between the standard rail grade and sleeper spacing is derived in association with other variables.

The rail strength and its section has direct impact on bending stress and deformation resistance. Therefore, as rail strength increases the corresponding sleeper spacing will be wider because of having higher bending stresses and deformation resistance. For this case the rail grade of 60 kg has been used in AALRT in which it has the following geometric and engineering properties and dimensions shown below in figure and table.

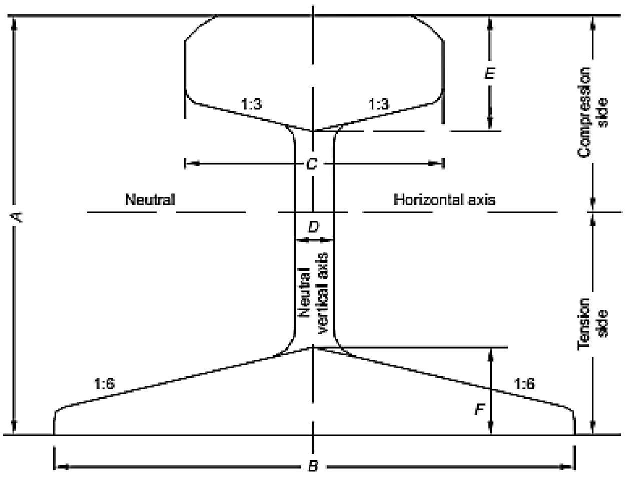


Fig 5 Standard flat-footed rail section

Rail section	Wt./m (kg)	Area of Section (mm^2)	Dimensions (mm)					
			A	B	C	D	E	F
50 R	24.80	3168	104.8	100.0	52.4	9.9	32.9	15.1
60 R	29.76	3800	114.3	109.5	57.2	11.1	35.7	16.7
75 R	37.13	4737	128.6	122.2	61.9	13.1	39.7	18.7
90 R	44.61	5895	142.9	136.5	66.7	13.9	43.7	20.6
52 kg(IRS)	51.89	6615	156.0	136.0	67.0	15.5	51.0	29.0
60 kg(UIC)	60.34	7686	172.0	150.0	74.3	16.5	51.0	31.5

Table 1 Details of standard rail sections

Rail fastening and pads

In ballasted railway tracks, the rails are discretely held by sleepers that are spaced along the longitudinal direction of the railroad. The rail and sleepers are usually secured by steel fasteners against vertical, lateral and longitudinal movement. Depending on the rail section and type of sleepers, different types of fasteners (e.g. e-clip, fast clip, tension clamp, bolt clamped, etc.) are used by railway designers throughout the world.

With the present railway technology, the rail is not placed just on top of the sleeper instead a rail pad of 10 to 15 mm thickness, which consists of an elastic material is used between the rail and sleeper. The major functions of the rail pad include providing resiliency in the rail-sleeper system, damping the train-induced vibration, and preventing or decreasing rail-sleeper contact attrition.

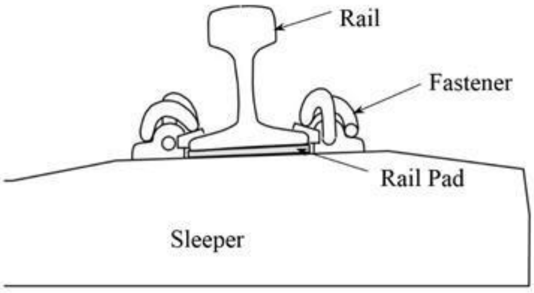


Fig 6 Typical Rail Fastening system

Sleepers or Cross ties

Sleepers are the transverse ties that are laid to support the rails. They have an important role in the track as they transmit the wheel load from the rails to the ballast. The main functions of sleepers are as follows.

a) Holding the rails in their correct gauge and alignment
b) Giving a firm and even support to the rails
c) Transferring the load evenly from the rails to a wider area of the ballast
d) Acting as an elastic medium between the rails and the ballast to absorb the blows and vibrations caused by moving loads
e) Providing longitudinal and lateral stability to the permanent way
f) Providing the means to rectify the track geometry during their service life.

Apart from performing these functions the ideal sleeper should normally fulfill the following requirements.

a. The initial as well as maintenance cost should be minimum.
b. The weight of the sleeper should be moderate so that it is convenient to handle.
c. The designs of the sleeper and the fastenings should be such that it is possible to fix and remove the rails easily.
d. The sleeper should have sufficient bearing area so that the ballast under it is not crushed.
e. The sleeper should be such that it is possible to maintain and adjust the gauge properly.
f. The material of the sleeper and its design should be such that it does not break or get damaged during packing.
g. The design of the sleeper should be such that it is possible to have track circuiting.

h. The sleeper should be capable of resisting vibrations and shocks caused by the passage of fast moving trains.
i. The sleeper should have anti-sabotage and anti-theft features.

Depending on the construction material used sleepers can be wooden, steel, cast iron, concrete sleepers. For this study we focus on concrete sleeper type which is prestressed concrete sleeper that is commonly used in the world due to economic consideration and durability of the structure.

According to [12], PCSs offers both technical and economic advantages. Sleeper cross-sections are kept fully in compression under design service loads to ensure that tension cracks do not occur. Pre stressed concrete members possess improved resistance to shearing forces due to the effect of compressive pre stress and are stiffer than reinforced concrete member of the same depth under working load. PCSs provide better load distribution to the underlying ballast bed, good longitudinal, lateral resistance, give stability to the track and maintain track gauge in a good manner due to their heavy weight.

The reported result [12], PCSs are difficult when handling, lying and maintaining due to their heavy weight. Transport, laying and maintenance of PCSs require superior technology which is not readily available in the manufacturing sectors of many developing countries. The main objective of this thesis is to obtain the optimum spacing of PCSs on the conventional or ballasted track system.

As per Indian rail standard, Sleeper density is the number of sleepers per rail length. It is specified as M + x or N + x, where M or N is the length of the rail in meters and x is a number that varies according to factors such as axle load and speed, type and section of rails, type and strength of the sleepers, type of ballast and ballast cushion, and nature of formation ground soil.

Ballast

The ballast is a layer of broken stones, gravel, moorum, or any other granular material placed and packed below and around sleepers for distributing load from the sleepers to the formation. It provides drainage as well as longitudinal and lateral stability to the track.

The ballast serves the following functions in a railway track system.

- Provides a level and hard bed for the sleepers to rest on.
- Holds the sleepers in position during the passage of trains.
- Transfers and distributes load from the sleepers to a large area of the formation.
- Provides elasticity and resilience to the track for proper riding comfort.
- Provides the necessary resistance to the track for longitudinal and lateral stability.
- Provides effective drainage to the track.
- Provides an effective means of maintaining the level and alignment of the track.

Now, to ensure uniformity, 50-mm (2") ballasts have been adopted universally for all type of sleepers. As far as points and crossings are concerned, these are subjected to heavy blows of moving loads and are maintained to a higher degree of precision. A small sized, 25-mm (1") ballast is, therefore, preferable because of its fineness for slight adjustments, better compaction, and increased frictional area of the ballast.

For the even distribution of load on the formation, the depth of the ballast is determined by the following formula: Sleeper spacing = width of the sleeper + 2 × depth of ballast. Further in this research we come up in detail how spacing of sleepers related with ballast stiffness and strength.

Sub-Ballast

Sub-ballast is a layer of aggregates usually comprised of locally available well graded crushed rock or sand-gravel mixtures, which is placed between the ballast and subgrade. They must be durable enough to bear the train-induced dynamic loads imposed via the rail-sleeper-ballast layer. Besides, it should have the proper filtering function. The sub-ballast layer can be used economically to fulfil the following key functions of ballast:

- Transfer and distribute the train-induced stress from the ballast layer to the underlying subgrade soil over a wider area to an acceptable level.
- Extend the subgrade frost protection by providing an insulation layer.

In addition, the sub-ballast layer has some other essential functions for satisfactory track performance that cannot be achieved by the ballast layer alone. These are as follows:

- Separate the ballast layer from the subgrade, and hence prevent penetration of the coarse ballast materials into the subgrade layer, and also prohibit upward migration of the fine subgrade materials into the ballast layer.
- Resist clay particles to mix with the infiltrated water, which may lead to slurry (mud) formation. This function prevents mud pumping, which is one of the major problems of ballast fouling and subgrade disgrace.
- Receive the rain water flowing through the ballast and drain it away to trenches at the sides of the track.
- Provide drainage of the underlying subgrade water that might flow upward

Subgrade and formation

Subgrade is the naturally occurring soil which is prepared to receive the ballast. The prepared flat surface, which is ready to receive the ballast, sleepers, and rails, is called the formation. The formation is an important constituent of the track, as it supports the entire track structure. It has the following functions.

a) To provide a smooth and uniform bed for laying the track.
b) To bear the load transmitted to it from the moving load through the ballast.
c) To facilitate drainage.
d) To provide stability to the track.

The formation can be in the shape of an embankment or a cutting. When the formation is in the shape of a raised bank constructed above the natural ground, it is called an embankment. The formation at a level below the natural ground is called a cutting. Normally a cutting or excavation is made through a hilly or natural ground for providing the railway line at the required level below the ground level. The ultimate bearing capacity for the formation soil is consider as 0.6 MPa in most codes even AREMA.

2.3 Sleeper Spacing

The spacing of ties or sleepers affects rail flexure stress, compressive stress on ballast and roadbed and the flexure stress generated in the ties themselves. For a given set of tie dimensions and wheel loads, the consequences of increasing tie spacing are higher rail bending moments and stresses within the individual ties. For the case of constant tie, ballast and subgrade characteristics, wider tie spacing bring about larger track depression per unit of wheel load i.e. lowered track modulus. Conversely, reduction of tie spacing lowers unit stress and increases track modulus. These specifications consider concrete ties intended for track designs using center-to-center spacing of crossties of between 20 inches and 30 inches, (510 and 760 mm) [1]. This is mainly because of erratic nature of the ground but it is possible to consider uniform ground for some tack length. Hence some recent research outputs have been summarized as follows those are all deal on the effect of sleeper spacing which is distributed uniformly or randomly.

A research by Roman Bogacz, et al come up with a finding of periodicity of sleeper spacing is the basic qualitative feature for classic railway track in order to minimize resonance but doesn't specify how to determine the sleeper spacing [6]. In the case of classic periodically supporting sleepers, we can observe the passing bands in the frequency of moving and oscillating forces. The solution method which allows determining the stopping and passing bands in the case of track with periodically spaced sleepers and stationary motion is based on direct application of Floquet's theorem.

The other paper by Louis Le Pen, et al (2016) on Sleeper end resistance of ballasted railway tracks was done to investigate the effect of sleeper dimensioning on its resistance, ballast influence zone using model test and limit equilibrium calculation, and the effect of ballast shoulder on sleeper end resistance [8]. Here also Sleeper spacing which has its effect on resistance is not considered. The study was done by modal test and limit equilibrium calculation to know sleeper spacing on resistance. The output from both model tests and limit equilibrium calculation shows that the sleeper resistance increases with ballast shoulder width up to a certain threshold value which coincides with the position at which the failure surface daylights.

Other researchers Jason Nairn and Nick Stevens (2010) have developed a new study on rational design method for pre stressed concrete sleepers using numeric method while measured or assumed wheel loading spectrum is a key design input for existing infrastructure [14]. Their study was in response to issues that infrastructure owners and maintainers are increasingly having in respect of maintenance and replacement of existing timber sleeper track but didn't considered sleeper spacing in design. So, in this research, the effect of maintainability on spacing of pre stressed concrete sleeper will be investigated for ballasted track system.

The resonant behavior of railway track having random sleeper spacing was also studied by Kazuhisa Abe, et al using numeric analysis. They come up with a new finding of the resonance response which is amplified at a comparative small deviation in the sleeper position, while it will decrease for rather large deviations [14].

The other paper by those authors in 2014 was on the Influence of sleeper spacing on vibration and noise of railway tracks which is mainly focused on how to reduce noise and vibration by considering randomness on sleeper spacing using numerical experiments. They conclude amplitude of rail deflection excited due to stationary harmonic loading is sensitive to sleeper spacing for pinned - pinned resonance and sleeper spacing irregularity can reduce the expected value of pinned – pinned resonance amplitude which leads to reduce vibration and noise [14]. Therefore, sleeper spacing is placed randomly in order to minimize the resonance amplitude however some codes like Indian national railway standard express the spacing of sleepers as sleeper density which specifies the number of sleepers per rail length or track length in case of welded rails.

Sleepers in ballasted track should be designed and placed properly by considering all parameters so have a direct effect on track performance which was investigated in detail by Taufan Abadi et al. in 2019. Their study concludes on only a small number of ballast grains support the sleeper base. The resulting localized contact stresses can be very high, especially for modern concrete sleepers on hard igneous ballast. This may result in damage to both sleepers and ballast and reduce the stability of the interface and they come out results from cyclic loading tests carried out to explore the potential for performance improvement through the adoption of different sleeper types and modifications to the sleeper/ballast interface [16].

The functions of the sleepers are to transfer the vertical, lateral and longitudinal rail seat loads to the ballast and formation, and to maintain the track gauge and alignment by providing a reliable support for the rail fasteners. The performance of a sleeper to withstand lateral and longitudinal loading is dependent upon the sleeper's size, shape, surface geometry, weight and spacing. So far, different countries recommended different values for sleeper spacing.

However, as being the train has a huge load it emits excess noise and disturbance to the environment or the city for this matter most scholars recommended to provide sleepers at random spacing while placing the sleeper in dense way around highly critical regions like turnouts, curved sections, and where the subgrade is weak in capacity.

2.4 Spacing of Sleepers according to Codes

1. Australian Code

The Australian national railway recommends a minimum spacing of 533 mm for standard gauge concrete sleepers [20].

Sleeper Length (m)	2.44	2.51	2.59	2.67	2.74
Sleeper Spacing (mm)	650	650	650	650	650
Flexure Resistance Capacity (kN.m)	1.7	6.025	9.05	10.325	13.15

Table 2 Australian standard for concrete sleeper spacing

Considering the two extreme cases i.e. the maximum and minimum spacing of sleepers which is 762 mm and 533 mm respectively from Australian standard code shows as around 550 sleepers per kilometer difference exist which is too expensive.

2. Engineering Standard Code, ESC 230

According to engineering standard code, ESC 230 also depending on the load from train as heavy or medium type sleeper spacing of pre stressed concrete is shown below.

Parameter	Heavy Duty	Medium Duty
Length	2390-2500 mm	
Width at base	220-255 mm	
Depth at center of rail seat	Max. 230 mm	Max. 180 mm
Rail seat area, flat surface	28800 mm^2	25620 mm^2

Table 3 Concrete sleeper dimension as per ESC 230

On Mixed Passenger Freight Main Lines, the selection of heavy duty or medium duty concrete sleeper is governed by the following requirement:

- On sharp curves with maximum 400m radius where Pandrol e-2003 clips are installed, heavy duty insulators shall be used for new installations and for replacement of insulators.
- Heavy duty insulators are not required with 'Fast clip' installation.

Operating Class	Sleeper spacing (mm)	Tolerance	Tolerance limit /m
All Track	600	±20	10/6(±50 mm)
Maximum spacing (siding only)			
< 25 tone axle load	720	±20	11/7.920(±60 mm)
25 tone	650	±20	16/11(±80 mm)
30 tone	600	±20	10/6(±50 mm)

Table 4 Concrete sleeper spacing as per ESC 230

From this standard as well, the maximum and minimum sleeper spacing is 720 mm and 600 mm respectively which result in variation of approximately 275 sleepers per kilometer. From those two standards nearly 20% of sleepers’ deviation exist. So, provision of sleepers should be through detail analysis and investigation.

3. AREMA-2010

Generally, the effect of sleeper spacing on different criteria has been done by different researchers in order to improve the railroad transportation system. But till now we don’t have a general numeric formula for computing sleeper spacing which leads to waste more cost for sleepers. So far different codes including AREMA-2010 recommend using the spacing of sleeper as 600 mm, in which it may be safe or not from serviceability and strength criteria like settlement and flexure or shear resistance capacity of sleepers respectively. Even providing more sleepers to achieve strength resistance of the track, but it is too expensive.

4. Chines Standard

The chines rail standard also recommends using a constant numeric value in the construction of Ethiopian light rail system. Therefore, in order to obtain the optimum spacing it is better to undergo the analysis considering all factors which affect sleeper spacing like axle load and speed, type and section of rails, type and strength of sleepers, type of ballast and ballast resistance, and nature of formation or sub base. So, on this study the optimum sleeper spacing can be derived considering all the factors aforementioned earlier. According to chines code the spacing depends on the number of sleepers provided per km of track length. Hence the maximum and minimum number of sleepers per km of track length is 1840 and 1670 respectively [21].

5. Indian Standard

The standard spacing specifications adopted for a fish-plated-track on Indian Railways are given in Table below. The notations used in this table are explained in Fig. below.

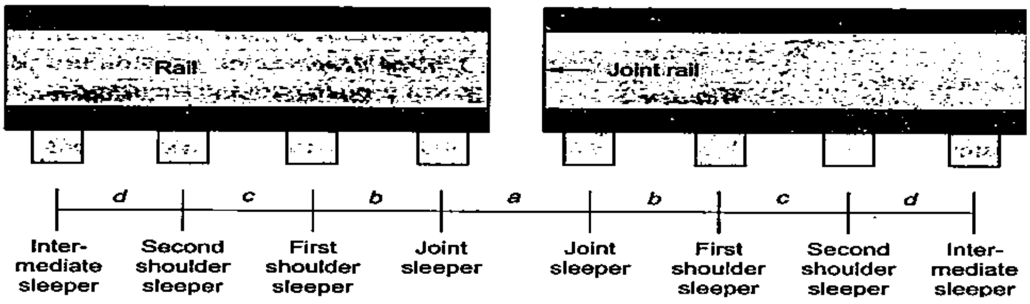


Fig 7 Spacing near to Joints as per Indian Railway Standard

According to this code spacing of sleepers varies from 720 mm to 500 mm as shown in figure above in which the spacing is closer near to weak regions of the track like joints, crossings, switches and curved track geometries.

2.5 Study variables

1. Effect of axle load on deformation

With an increase in axle load, deformation of the track structure also increases the magnitude depending on the design and composition, as well as the interaction between track components. According to research referred to [15], it has been found that an increase in axle load from 20 to 22.5 ton considerably increases deterioration of the track quality and geometry, but not the ballast stress. Maintenance costs are also expected to increase along with this increase in axle load.

The other known effect of increased axle loading is increased resilient track deflection. Maximum vertical deflection occurs directly below the train axle and reduces with increasing depth of the track structure. Previous study models have shown that, for a given subgrade, the ballast depth and sleeper spacing are the most important factors influencing vertical track deflection as a result of train loading.

The selection of subgrade material is also important because with the increase in stress due to axle load, strain hardening may occur in the case of good, granular material, while strain softening may occur in the case of poor, cohesive material. Higher axle loads in general require stronger infrastructure in addition to high-quality subgrade materials. This will lead to higher investment costs, but produce a larger return on investment. The literature on rail track performance does not indicate what the relationship between axle load and track deflection would be when the axle load is increased.

2. Train Speed Effect

Development of railway networks for high-speed trains is rapidly growing in many countries around the world, to meet the increasing demand for faster transportation. Therefore, train speed is a major important factor that influences track performance and spacing of sleepers. Generally, as the design train speed is maximum which directly increase the dynamic load factor that has a great influence on sleeper spacing to be minimum as much as possible.

Obviously, for any train speed, the peak of ground vibrations occurs at the track center and reduces with the increasing distance from the track center, as we expect. In addition, it can be observed that the zone from the track center until about 8 m away from the track center experiences a considerable level of ground vibrations, for all train speeds particularly for the critical speed, it could be detrimental for train operations and may also be a possible source of failure for the neighboring structures.

3. Rail Strength and Section Type Effect

Rail, as the most important track element, should be able to securely sustain wheel loads in the vertical, lateral, and longitudinal directions and subsequently transfer them to the underlying supports. Type and strength of the rail has a great effect on spacing of sleepers; while strong and wear resisting rails are used spacing of sleepers is large which intern reduce the cost for sleepers.

The deflection and flexural stress on the rail material is determined by using Winkler Elastic Beam model which basically assume that the deflection of the rail at any point is proportional to the supporting pressure under the rail which is continuously supported.

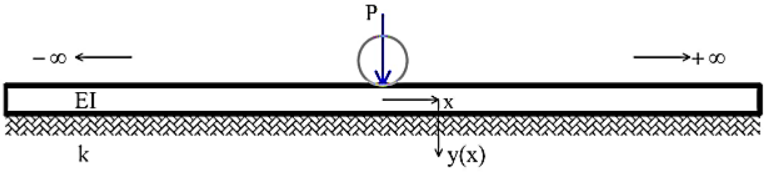


Fig 8 Beam on elastic foundation

The corresponding equations for the calculation of rail bending moment and rail deflection are as follows [19]:

$$y(x) = \frac{P\beta e^{-\beta x}}{2u}(cos\beta x + sin\beta x)$$

$$M(x) = \frac{P}{4\beta}e^{-\beta x}(cos\beta x - sin\beta x)$$

Where: $y(x)$ and $M(x)$ are the vertical deflection and the bending moment of the rail at the distance “x” from the load point, respectively. Parameter β is defined by the following equation:

$$\beta = \left(\frac{u}{4EI}\right)^{0.25}$$

Therefore; the effet of rail strength and its type on spacing of aparticular sleeper is further explained in this research through classic optimization technique.

4. Track Stiffness Effect

Track stiffness as the elastic rail deflection that takes place under a wheel loading. This generic track stiffness is a function of the structural properties of the

- Rail, resilient pads in the track structure, sleepers, ballast, sub-ballast and subgrade soil(s).
- Fundamental analysis of track stiffness has typically been approached by means of the Beam on Elastic Foundation (BOEF) approach
- This analysis technique is known to be reasonably representative, but introduces the concept of the track modulus, i.e. the stiffness of the spring k per unit length of track

The modulus therefore represents the equivalent series stiffness of all the components of the track is computed as follows [19].

$$\frac{1}{K_{total}} = \frac{1}{\sum_{\mathrm{i=1}}^{\mathrm{n}} K_i} = \frac{1}{K_{rail}} + \frac{1}{K_{pad}} + \frac{1}{K_{sleeper}} + \frac{1}{K_{ballast}} + \frac{1}{K_{subgrade}}$$

Track stiffness includes the bending stiffness of the rail, whereas track modulus is concerned only with the support condition below the rail. Optimal values of the vertical stiffness which optimize maintenance costs and the costs for dissipated energy of a train versus the vertical track stiffness but the optimum vertical track stiffness should be between 70 and 80 kN/mm.

CHAPTER THREE

3 STUDY METHODS AND METHODOLOGY

3.1 Study Methods

This research is basically targeted in avoiding the wastage of cost spent for sleepers by placing it at optimum spacing while maintaining functionality and safety of the railway system. To come at reasonable and significant output the following methods and procedures are used.

The study is done using classic optimization technique. It is differing from pure or mathematical optimization in such case it is done through try and error procedure. Optimization is the act of obtaining the best result under the given circumstances through minimizing the effort required and maximizing the desired benefits. It is the process of finding the conditions that give the minimum (or maximum) value of a function, where the function represents the effort required (or the desired benefit) [25]. Here the objective function is the parameter going to be optimized i.e. sleeper spacing while design variables are those which affect the objective function directly as listed out earlier.

The study is done analytically and numerically; while Analytically the study is done through first reviewing different recent literatures and the required data are collected from Ethiopian Railways Corporation (ERC) and also data on spacing of sleepers is reviewed from different code recommendation like AREMA 2010, Australian Standard, Engineering Standard Codes ESC 230, and Chines railway standard which is used in our country. From each code the allowable maximum and minimum sleeper spacing should be recorded for the selected sleeper type and used as input for comparative study.

In numeric method, the principles of classic optimization technique and finite element analysis concept is directly applied through considering sleeper spacing as a study variable and the factors which affect spacing i.e. axle load and train speed, ballast stiffness, and rail strength as constraints through considering different track curvature values. From those different alternative options, the response for actions is done using finite element software i.e. ANSYS or LISAN.

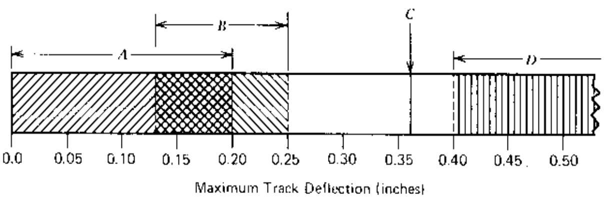
In this method the analysis is done considering serviceability criteria basically deflection and equivalent stress then the spacing of sleepers is fixed depending on the allowable deflection also the theory of mechanics is used for modeling and optimization of the design and analysis.

3.2 Study Methodology

The same sleeper type in geometry, strength, and material type is considered i.e. pre stressed concrete sleeper Type -II is used and constraint material property are also constant. Sleepers are generally made as single blocks (mono block), except for concrete sleepers, which it may also be in the form of a twin block. A twin-block sleeper comprises two concrete blocks, one beneath each rail, tied together by a steel rod. In terms of cost and performance, it is unclear which is better, and there is strongly held but conflicting views. For this study mono block pre stressed concrete sleeper is used.

The study is done using ANSYS software by classic optimization techniques while sleeper type and strength, and track type remain constant. The axle loads used for this study are 25 tons, 27.5 tons, and 30 tons while the train speeds are 70km/h, 100km/h, and 120km/h. Similarly, concerning the track geometry effect the following track radius are 50m, 200m, and 500m for each case spacing of sleepers to be considered are 0.55m, 0.60m, 0.65m, and 0.70m. The study is done through varying the main parameters like axle load, train speed, and track geometry. The effect of design variables for each particular sleeper spacing, rail type and ballast stiffness should be done then the spacing which gives minimum track deflection and stress is considered as the optimum value for sleepers spacing.

Finally, comparative study is done in terms of amount of sleepers required per kilometer or cost, ultimate deflection, and maintainability for both findings i.e. numeric analysis output and code recommendation values. Based on the findings through comparison verification of standards on sleeper spacing is confirmed and analysis result should be checked for maintainability of the track system. The allowable track deflection depending on safety and comfort is 0.2in (5.08 mm) which is the deflection range for track that will last indefinitely.



Range	Track Behavior
A	Deflection range for track that will last indefinitely
B	Normal maximum desirable deflection for heavy track to give requisite combination of flexibility and stiffness
C	Limit of desirable deflection for track of light construction (≤100 lb)
D	Weak or poorly maintained track that will deteriorate quickly

Table 5 Allowable track deflection for different track behavior

3.2.1 Materials and their Property

The property of materials used for modeling the rail track are explained and briefly described in detail below. Their property here is for this study in which they are currently used in AALRT. The feasibility study shows the spacing of sleepers is 60 cm and other information are summarized in tabular form below.

Parameters	Values
Axle Load	25 tone
Speed	20 – 120 km/hr.
Sleeper Spacing	60 cm
Load Distribution Factor	51 %
Ballast Pressure	600 – 750 kPa
Track Modulus	20 – 40 MPa
Concrete Grade	C- 55/67
Rail Grade	60 kg/m
Design Life	30 – 40 yrs.
Rail type	Both CWR & Jointed Rail

Table 6 General information of the existing track as per ERC

1) Rail Geometry Dimension

Rails are the members of the track laid in two parallel lines to provide an unchanging, continuous, and level surface for the movement of trains. To be able to withstand stresses, they are made of high-carbon steel. The most commonly used rail is flat footed rail type with dimension values indicated in figure below and each values are given for our case the rail material type is 60 kg/m.

Rail section	Wt./m (kg)	Area of Section (mm^2)	Dimensions (mm)					
			A	B	C	D	E	F
52 kg(IRS)	51.89	6615	156.0	136.0	67.0	15.5	51.0	29.0
60kg(UIC)	60.34	7686	172.0	150.0	74.3	16.5	51.0	31.5

Table 7 Dimensions for the rail material

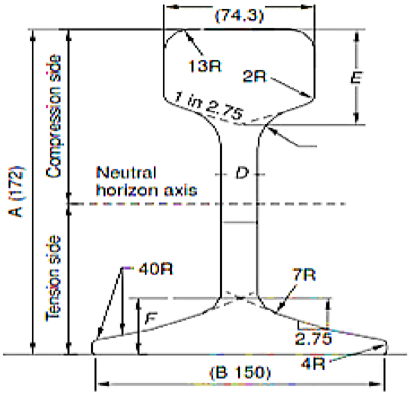


Fig 9 Rail Cross Section dimensions

2) Sleeper Section and Dimensions

The use of higher strength concrete is necessary in the production of concrete sleepers due to the use of Pre stressing. AREMA suggested that the minimum 28-day-design compressive strength of concrete used for concrete sleeper shall be 7,000 psi (48 MPa) as determined by ASTM Method of Test C 39 [3] Likewise, the Australian code recommended that the characteristic compressive strength (f'c) shall be not less than 50 MPa [18] for our case we use C-55/67 which is within the allowable range.

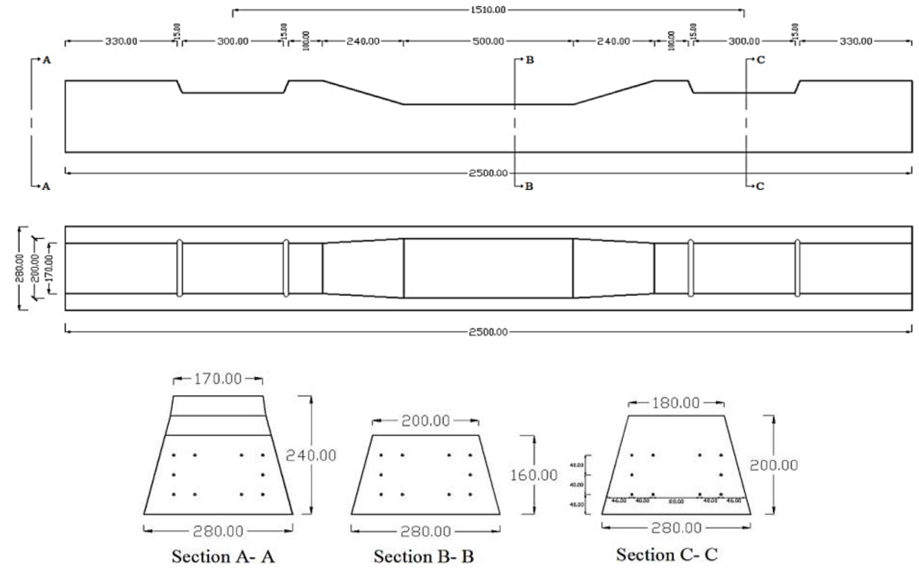


Fig 10 type II- pre stressed concrete sleeper geometry dimension

No.	Properties of concrete		Value
1	Density (ρ_c) in kg/m^3		2400
2	Young's modulus (E_s) in MPa		34,400
3	Poisson's ratio (ν_s)		0.2
4	Concrete grade		C - 55/67
5	Characteristic cube compressive strength (fc) in MPa		67
6	Characteristic cylindrical compressive strength (fc) in MPa		55
7	Permissible bending stress	Compressive in MPa	52
		Tensile in MPa	2.85

Table 8 Typical properties of concrete used as input data according to Chinese code

Pre stressing steel provide the necessary tensile resistance to support the flexural loads imparted by the trains. Pre stressing in concrete sleepers consist of either the 7-wire strand or steel wire (AREMA 2010). 5mm wire and 9.3 mm 7-wire strand are the most widely used tendons. Wire tendons shall be stress-relieved indented wires not larger than 8 mm nominal diameter conforming to AS 1310. Similarly, the Chinese code GB50010-2002, recommend stress-relieved steel wires (indented) with nominal diameter of 5mm and 7mm.

Item	Pre Stressing Parameters	Values
1	Density (ρ_s) in kg/m^3	7800
2	Young's modulus (E_s) in GPa	200
3	Poisson's ratio (ν_s)	0.3
4	Number strands (Stress-relieved indented wire)	10ϕ5.0mm
5	Characteristic strength for pre stressed steel (f_{ptk}) in MPa	1570

Table 9 Typical properties of Pre stressing steel used as input data (GB50010-2002)

3) Ballast and Sub Ballast Properties

In addition to tie size and spacing, ballast depth and subgrade modulus are also significant in the manner a particular track design distributes vertical loading. Increasing ballast depth tends to spread individual tie loads over a wider area of subgrade, thereby reducing the unit subgrade load and consequent track depression. Thus, the effect of increased ballast depth can be more significant, within limits, than that of reduced tie spacing. Ballast and sub-ballast materials used as track structural component have the following engineering properties as shown in table below.

Materials	Young's modulus (MPa)	Unit Weight (kN/m^3)	Shear Strength (MPa)	Tensile Strength (MPa)	Poisson ratio
Ballast	200	20	40	16	0.2
Sub-Ballast	150	18.5	24	11	0.25

Table 10 Ballast and Sub ballast materials engineering property

The ballasted track bed with prestressed concrete sleeper shall be used for ground line; the track bed is single layer ballast bed with the thickness of 300mm; the ballast is of Class I.

Track ballast forms the track bed upon which railroad ties or sleepers are laid. It is packed between, below, and around the ties. It is used to bear the load from the railroad ties, to facilitate drainage of water, and also to keep down vegetation that might interfere with the track structure. Ballast also holds the track in place as the trains roll over it. It typically consists of crushed stone, although other, less suitable, materials have sometimes been used such as burnt clay. The term "ballast" comes from a nautical term for the stones used to stabilize a ship.

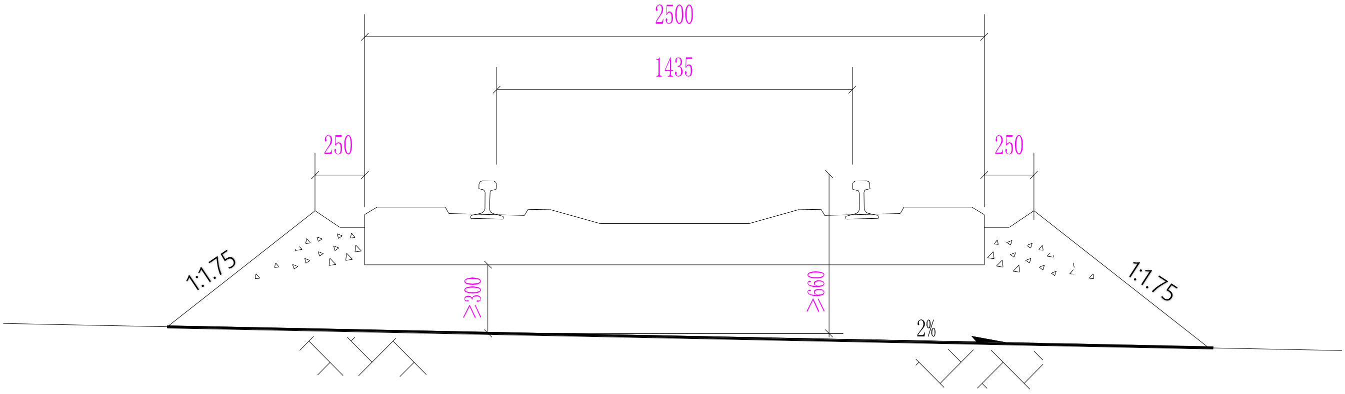


Fig 11 Schematic representation of single ballasted track structure

3.2.2 Design Principles

The track structure shall ensure the operation safety and running stability of the train, the comfortableness of passengers, enough strength, rigidity, stability and durability, proper flexibility, and minimum maintenance work.

The track structure shall be as simple as possible; the components thereof shall have practicability, universality and interchangeability; standard parts shall be preferable; loading and unloading shall be convenient, so as to facilitate construction and maintenance.

The experience of other urban mass transportation projects shall be learned; the track structure scheme shall be reliable in performance, reasonable in cost and mature in technology, so as to improve the reliability of the tracks.

Vehicle Dimension

The vehicle used in AALRT has a total length of 29.7 m with wheel base diameter of 1900 mm and 1800 mm for motor bogie and driven bogie respectively. The governing loading condition should be driven bogie at 1.8m axle spacing.

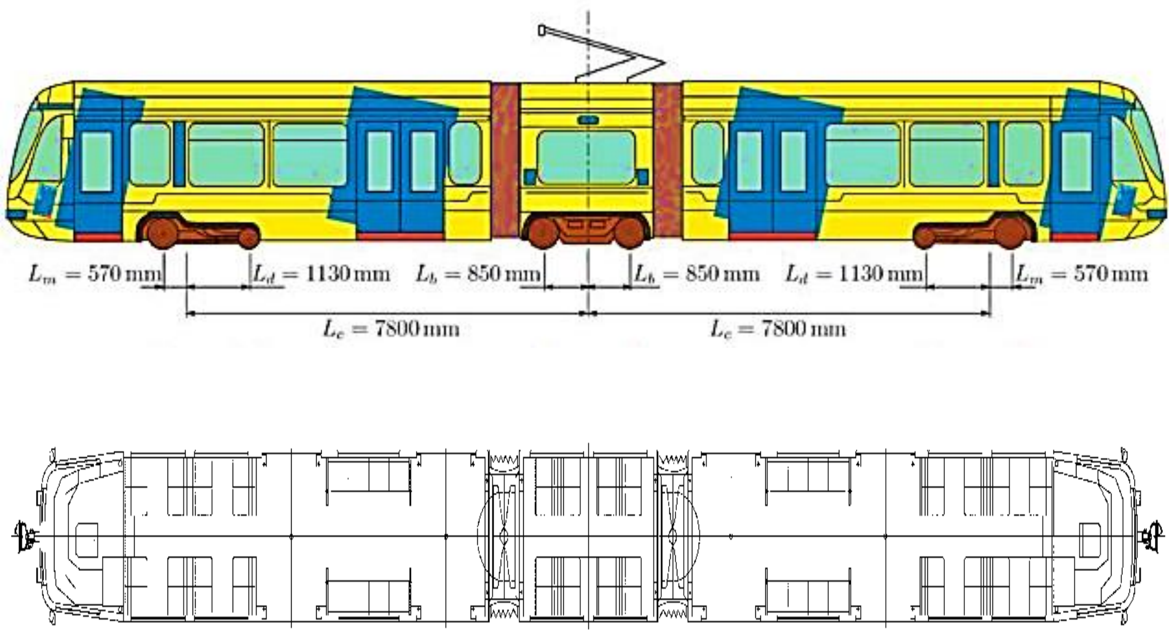


Fig 12 AALRT single train front and side view schematic representation

Axle Load

It is one of the main parameter which greatly affects the spacing of sleepers but also the requirements for the bearing strength and quality of the track (track classification) depend to a large extent on axel load beside to train speed and annual tonnage.

It is the static vertical load transferred to the rail through axle of the train. The axle shares half of the load to the corresponding wheel. So, axle load or wheelset load is twice of the wheel load.

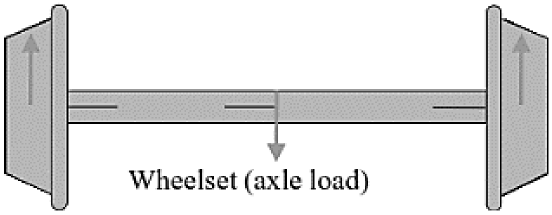


Fig 13 Axle Load or Wheelset Load

Therefore, the wheel load for each becomes $25\, tones\; x\, \frac{1}{2} = 12.5\, tones = 250\; kN\; x\, \frac{1}{2} =$ $125\; kN$. While this loading is at 1.9 m and 1.8 m spacing for motor bogies and driven bogies respectively. The loads from wheel which acts on the rail can be vertical, lateral or longitudinal.

So, the total vertical track load on the rail can be computed as:

$$Q_{total} = Q_o + Q_{centrifugal} + Q_{wind} + Q_d$$

Where:

Q force Explanation	*Symbol*	*Magnitude*
Static wheel force	Q_o	100 %
Quasistatic due to curving	Q_{qst}	0 – 40 %
Dynamic contribution due to track irregularity	Q_{dt}	0 – 300 %
Dynamic contribution due to wheel irregularity	Q_{dw}	0 – 300 %
Change in wheel loads due to traction or braking force	Q_{db}	0 – 20 %

Table 11 load magnification percentage for axle load to account dynamic effect

According to UIC Code 518 the maximum permissible vertical load is 200 kN for vehicle operating speed less than 160 km/hr. Total horizontal force exerted by a wheel on rail is also computed as follows:

$$Y_{total} = Y_{flange} + Y_{center} + Y_{wind} + Y_{dynamic}$$

In order to determine the lateral loads in the track, the Office of Research and Experiments (ORE) performed test programs for train speeds up to 200 km/h. These studies indicated that the lateral load is influenced only by the radius of the curve, and the following empirical equation was suggested to use:

$$Y = 35 + \frac{7400}{R} > \left\{ 10 + \frac{Q}{3} \leq 60 \text{ kN} \right\}$$

Where:

Y is the design lateral load in kN.

R is the track curve radius in m.

Q is the axle load in kN.

According to UIC518 code the limit for the quasistatic lateral forces (for track fatigue) is not more than 60 kN. But longitudinal loads as a result of temperature variation, acceleration, and braking of the train are not considered on this thesis.

Train Speed

It is the second study variable which greatly affect spacing of sleepers. Its effect shall be acted as vertical load depending on speed magnitude of the train. According to the United Kingdom railway group standard (GC/RT5021), the vertical dynamic load is calculated as the sum of the maximum static wheel load and associated low frequency dynamic forces P_2. For the double line of AALRT the operating and commercial speed is 70 km/h and 20 km/h respectively.

$$P_2 = P_0 + \alpha v \sqrt{k m_u}$$

Where:

P_o = Static wheel load

α = kink angle

k = equivalent track stiffness

m_u = unsprung mass

v = train speed

Track Geometry

The geometric parameters such as horizontal and vertical track curvatures, gradient, super elevation are all closely linked to topography, operational parameters and cost of construction. These elements are related to the vehicle behavior expressed based on safety, comfort, and cost-effectiveness which can be related in terms of operating parameters like speed, the load, and the acceleration of the train. EN 13803-1:2010 Railway applications track alignment design parameters the track type is metric gauge of 1435 mm and wider.

Safety and comfort parameters in case of curved tracks can be compensated through providing super elevations and also transition curves. But the lateral loads can be computed using simple mechanics from centrifugal acceleration but generally it is not more than 40% of axle load. For the main lines from AALRT the minimum curve radius is 50m generally and 30m for complicated sections. Generally, it is clear that as track components engineering properties increase their resistance capacity can increase parallel.

Therefore, for this thesis study the strength of materials remain constant and all engineering materials are listed below in table as summary.

	Rail	Pre stressed Sleeper		Ballast
		Concrete	wire	
Designation	60 kg UIC	C-55/67	Ø5mm	
Density	7850 kg/m^3	2400 kg/m^3	7850 kg/m^3	20 kg/m^3
Tensile Strength	460 MPa	2.85 MPa	1570 MPa	16 MPa
Compressive Strength	250 MPa	52 MPa	1570 MPa	—
Young’s modulus	210 GPa	34.4 GPa	210 GPa	200 MPa
Poisons ratio	0.3	0.2	0.3	0.2

Table 12 Engineering Properties of Materials

CHAPTER FOUR

4 ANALYSIS RESULTS AND DISCUSSION

4.1 Introduction

For each study variables i.e. axle load, train speed, and track geometry or radius the input data can be prepared as follow while properties and dimensions for materials of rail, sleeper, and ballast remains constant.

The study is done using classic optimization technique. So, the spacing of sleepers is selected randomly from real application those are 55cm, 60cm, 65cm, and 70cm. The controlling parameters are deflection and stress while those which give us minimum deformation are considered as optimum values. But for the stress case the maximum pressure at ballast area should not be more than 0.6 MPa.

The input values for the study variables are arranged as shown below in detail for each variables of axle load, train speed, and radius of the track. Track length used for this study has 5.0 m depending on the sensitivity analysis result and number of sleepers can be computed as follows for each spacing.

Spacing of Sleepers (mm)	No. Sleepers	Remark
550	10	Commonly provided at curved tracks
600	9	Commonly provided at tangent tracks
650	8	Needs verification
700	8	Needs verification

Table 13 Number of sleepers for 5m track length

For the train used in AALRT has both motor and driven bogie. The spacing of motor and driven bogies is more than 8.5m which ensures than the influence of wheel load location from motor bogie to driven bogie or in reverse direction is negligible. Therefore, the critical loading arrangement is selected in which the axle load is located at 1800 mm from driven bogie. Therefore, the loading arrangement on each rail is shown in figure below.

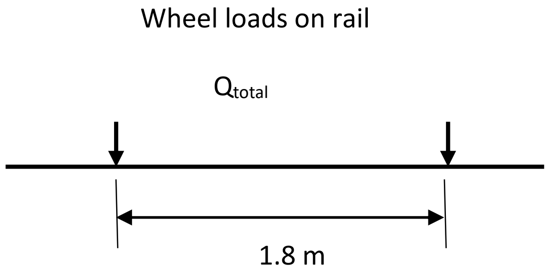


Fig 14 Schematic representation for wheel load on rail

Axle load effect:

$$Q_{total} = Q_o + Q_{centrifugal} + Q_{wind} + Q_d$$

Axle Load (ton)	Wheel load on rail (kN)	Remark
25.0	(25x10) / 2 = 125.0	Light Rail
27.5	(27.5x10) / 2 = 137.5	Passenger coach motor
30.0	(30x10) / 2 = 150.0	Heavy haul

Table 14 Total vertical wheel loads on rail

Train speed effect:

$$Q_d = DAF \text{ x } Q_o$$

Train Speed (km/hr.)	Load on rail due to speed effect (kN)	Remark
70	3.20 x Q_o	Operating speed AALRT
100	5.17 x Q_o	
120	6.20 x Q_o	

Table 15 Vertical load due to train speed effect

Track geometry effect:

Q_d= % N x Q_o and $Vmax = \sqrt{\frac{h*R}{7.6}}$ h= 150 mm and R =radius in m.

Track radius (m)	Load on rail due to radius effect (kN)	Max. Speed (km/hr.)	Remark
50	0.4 x Q_o	31	
200	0.1 x Q_o	69	
500	0.04 x Q_o	99	

Table 16 Vertical load on rail considering track radius effect

The percentage values for train speed and track radius effect on vertical load computation on rail is done through considering their critical effect using linear interpolation.

The analysis is done separately for both tangent and curved tracks for each sleeper spacing values but the speed for curved tracks is obtained considering the maximum super elevation of 150 mm and depending on the radius magnitude the speed is determined then consider the load due to dynamic effect through obtaining the corresponding factor times wheel load on rail. Therefore, the design total vertical loads on rail for analysis is computed as follows:

4.2 Tangent tracks Analysis

According to UIC Code the dynamic effect on rail due to wheel irregularity or track irregularity, and braking or traction of train is considered as 600%, and 20% of the axle load respectively. Therefore, the corresponding factors is estimated using linear interpolation while the maximum value is for the critical parameter.

Hence for 120 km/h train speed the corresponding axle load factor is 620% for the rest train speeds load factors are derived as 517% and 320% of the axle load for 100 km/h and 70 km/h train speed respectively.

The total vertical load on each rail at wheel contact is computed as shown in figure below through considering train speed or dynamic effect of the train.

Axle Load	Train Speed	Wheel load on rail (kN)		
		From axle	Speed effect	Total vertical load
25 ton	70 km/hr.	125	3.20 x 125 = 452.50	577.50
	100 km/hr.	125	5.17 x 125 = 646.25	771.25
	120 km/hr.	125	6.20 x 125 = 775.00	900.00
27.5 ton	70 km/hr.	137.5	3.20 x 137.5 = 497.75	635.25
	100 km/hr.	137.5	5.17 x 137.5 = 710.88	848.38
	120 km/hr.	137.5	6.20 x 137.5 = 852.50	990.00
30 ton	70 km/hr.	150	3.20 x 150 = 543.00	693.00
	100 km/hr.	150	5.17 x 150 = 775.50	925.50
	120 km/hr.	150	6.20 x 150 = 930.00	1080.00

Table 17 total vertical load on rail from wheel for tangent tracks

4.3 Curved Tracks Analysis

The maximum speed on curves is obtained considering the maximum super elevation which is 150 mm and for each speed the dynamic effect on rail is computed as the dynamic allowance factor times axle load beside to the load from curvature effect. Similarly using the UIC code the maximum allowable vertical load due to curvature is 40% of axle load depending on the magnitude of track radius. For simplicity the maximum factor is assigned for maximum curvature and linear interpolation is applied to compute for others. In this study 40% ,10%, and 4% of axle load on rail is applied as vertical loads for 50m, 200m, and 500m track cure radius respectively.

In addition to the vertical loads lateral loads are computed through considering curvature of the track which is the centrifugal load but other lateral environmental loads are ignored like earthquake and wind loads. Therefore, lateral loads can be computed using the formula shown below but as being lateral deformation is neglected the load is not used for analysis.

$$Y = 35 + \frac{7400}{R} > \left\{ 10 + \frac{Q}{3} \leq 60\ \text{kN} \right\}$$

The total vertical and lateral load on each rail at wheel contact is computed as shown in figure below through considering primarily the curvature of the track.

Axle Load	Track Radius (m)	Wheel load on rail (kN)				
		From axle	Curvature Effect	Speed effect	Total vertical load	Total lateral load
25 ton	50	125	0.4x125	1.62x125	565.00	183
	200	125	0.1x125	3.25x125	731.25	72
	500	125	0.04x125	5.13x125	958.75	51.67
27.5 ton	50	137.5	0.4x137.5	1.62x137.5	621.50	183
	200	137.5	0.1x137.5	3.25x137.5	804.38	72
	500	137.5	0.04x137.5	5.13x137.5	1054.63	55.83
30 ton	50	150	0.4x150	1.62x150	678.00	183
	200	150	0.1x150	3.25x150	877.50	72
	500	150	0.04x150	5.13x150	1150.50	60

Table 18 Total vertical load on rail for curved tracks

4.4 Track Modeling

The modeling is done using 3D ANSYS while for study the data is taken from AALRT as explained earlier. The study is done using classic optimization methodology. So, four models are prepared based on spacing of sleepers and for each three different analyses are done depending on axle load, train speed, and track radius variation.

The modeling is the same for both tangent and curved tracks the only difference is the load magnitude. In case of tangent tracks, we have vertical wheel loads at axle spacing of 1.8m trough considering the driven bogie where as in curved track we do have lateral loads on outer tracks in addition to the vertical loads for each wheel on the rail but this load has insignificance on result. Therefore, for each spacing the modeling is shown in figure below for 5m track length and the loading is taken at driven bogie with 1.8m wheel load spacing.

The corresponding materials i.e. rail, concrete, wire, and ballast their engineering properties are assigned for each as explained in the previous chapter.

The basic assumptions applied here are; the surface interaction in between the rail and sleeper is considered as laterally restrained but free in longitudinal axis and also the uniformly rough interaction surface is considered in between the sleeper and ballast. However, rigid or fixed support is applied at the bottom of ballast surface as being it rests on the ground at great depth and the default meshing is applied which gives reasonably fine mesh elements.

Some representative models are shown in figures below for 25-ton axle loads for all sleeper spacing which varies from 550 mm, 600 mm, 650 mm, and 700 mm. for all the track length remains constant but number of sleepers vary depending on sleeper spacing values.

Therefore, once the model is done through applying different load magnitudes for each case as computed from various conditions like train speed, track curvature value, axle loads the analysis is done later for each conditions.

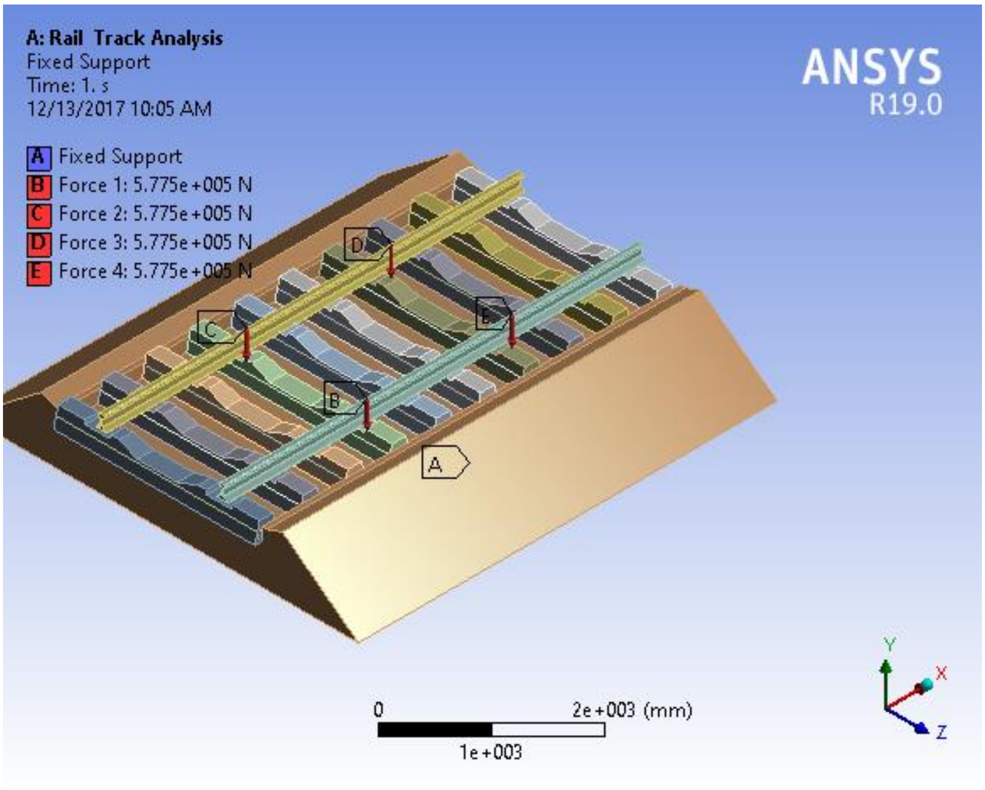


Fig 15 Track Model for 25-ton axle load with train speed 70km/h with spacing 550mm

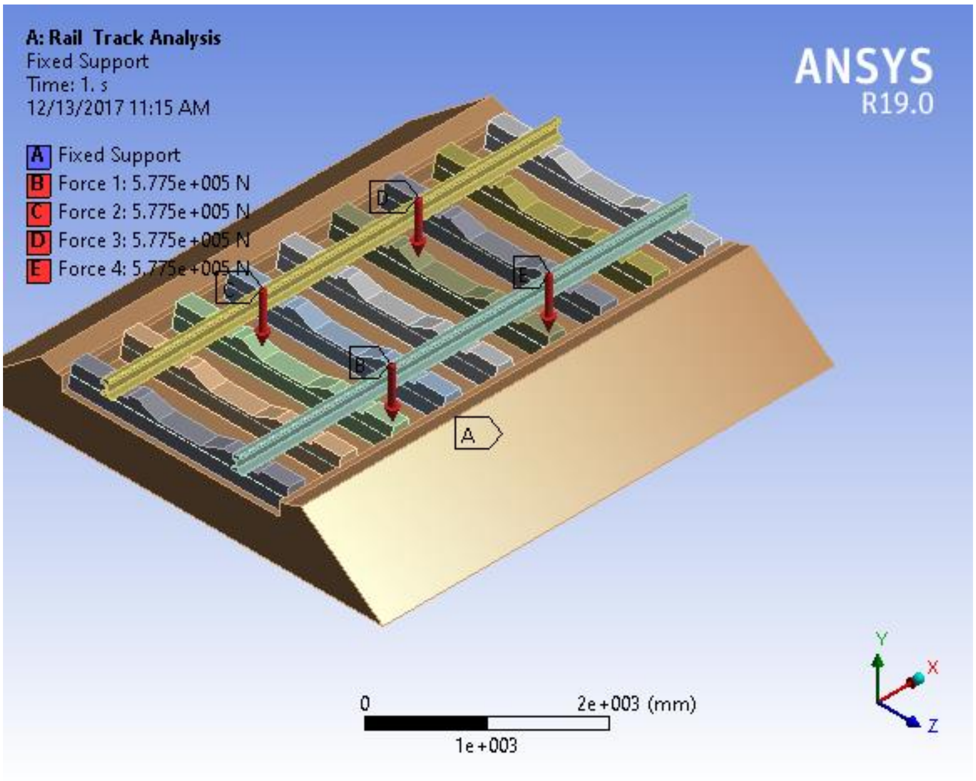


Fig 16 Track Model for 25-ton axle load with train speed 70km/h with spacing 600mm

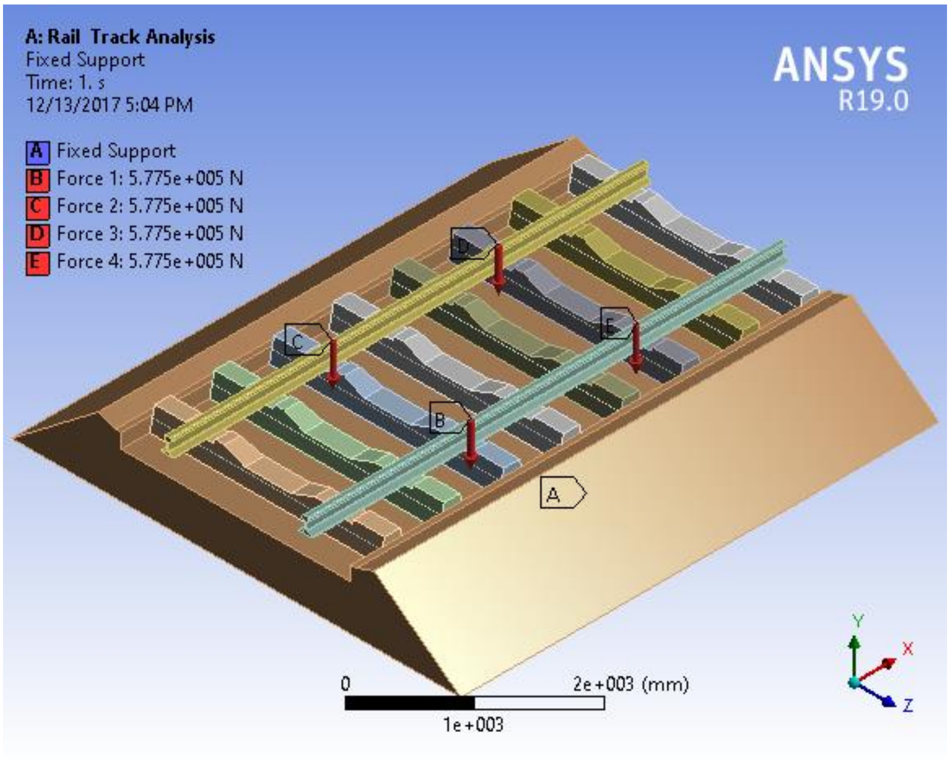


Fig 17 Track Model for 25-ton axle load with train speed 70km/h with spacing 650mm

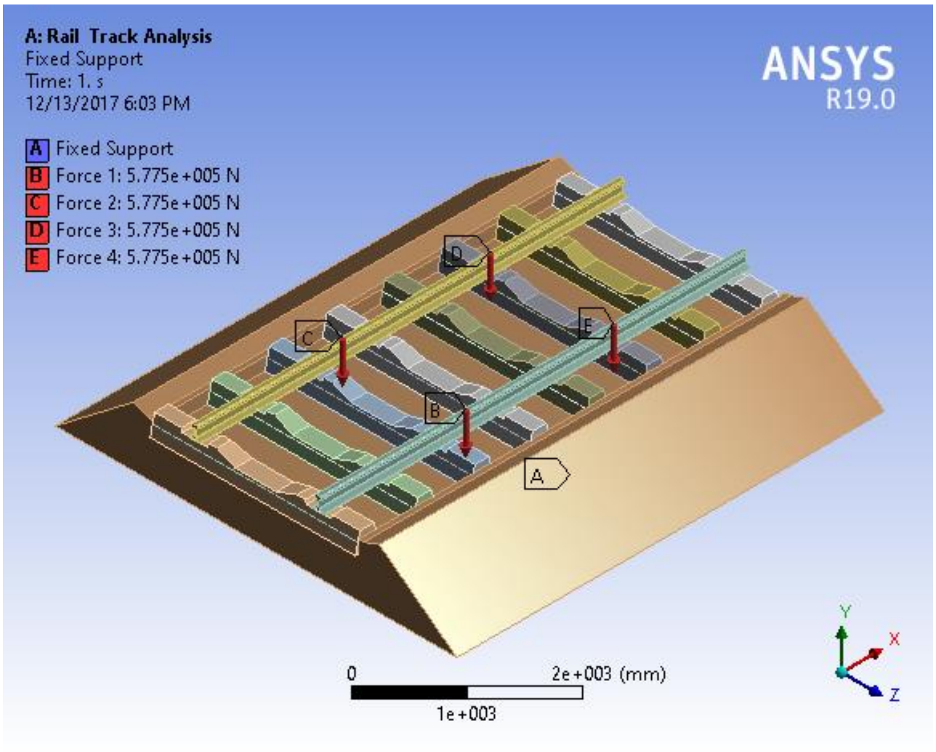


Fig 18 Track Model for 25-ton axle load with train speed 70km/h with spacing 700mm

4.5 Analysis Results

Once the modeling is done depending on selected sleeper spacing, the study follows separately for both tangent and curved tracks. Here below for some models the analysis results are presented as sample and for the whole the output is shown in tabular form for both tangent and curved tracks.

The ANSYS 3D analysis result for some critical cases are shown in figure below for equivalent stress and vertical deformation in MPa and mm respectively.

Case 1. Tangent Tracks with train speed less than or equal to 70 km/hr.

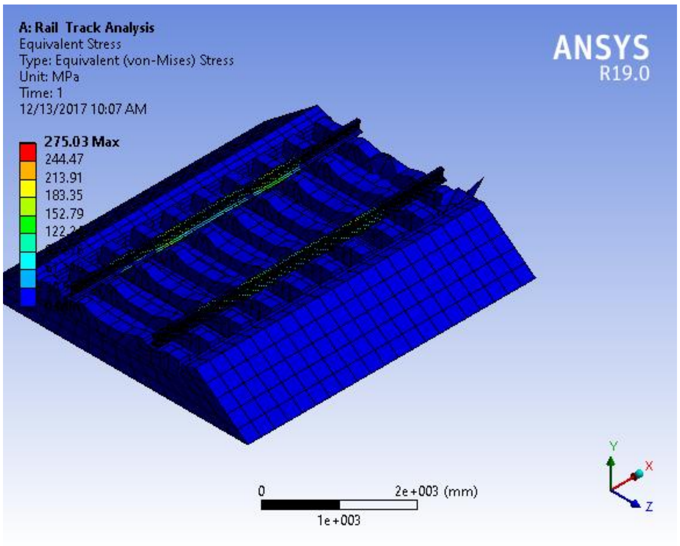


Fig 19 Equivalent stress for 25-ton axle load at 550mm sleeper spacing

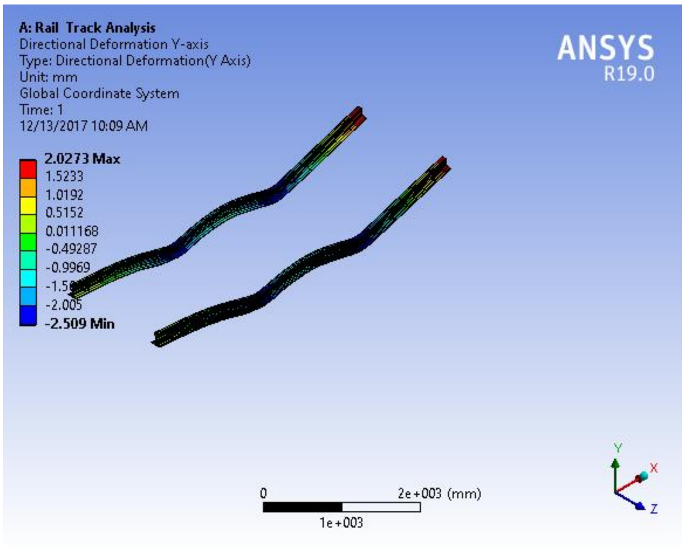


Fig 20 Vertical deformation for 25-ton axle load at 550mm sleeper spacing

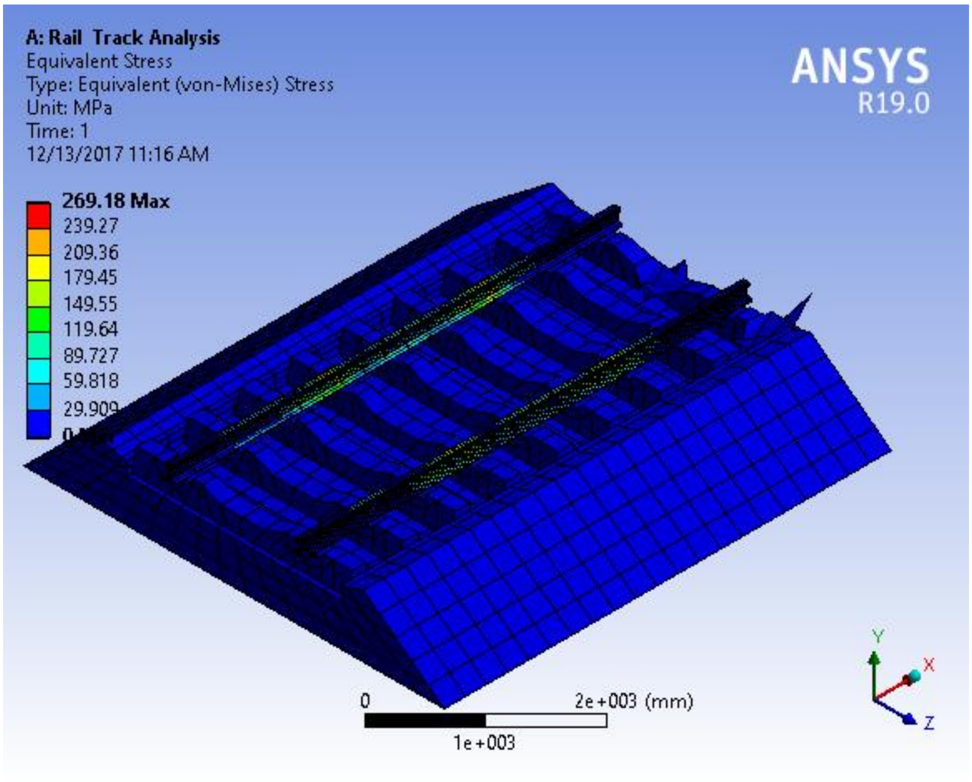


Fig 21 Equivalent stress for 25-ton axle load at 600mm sleeper spacing

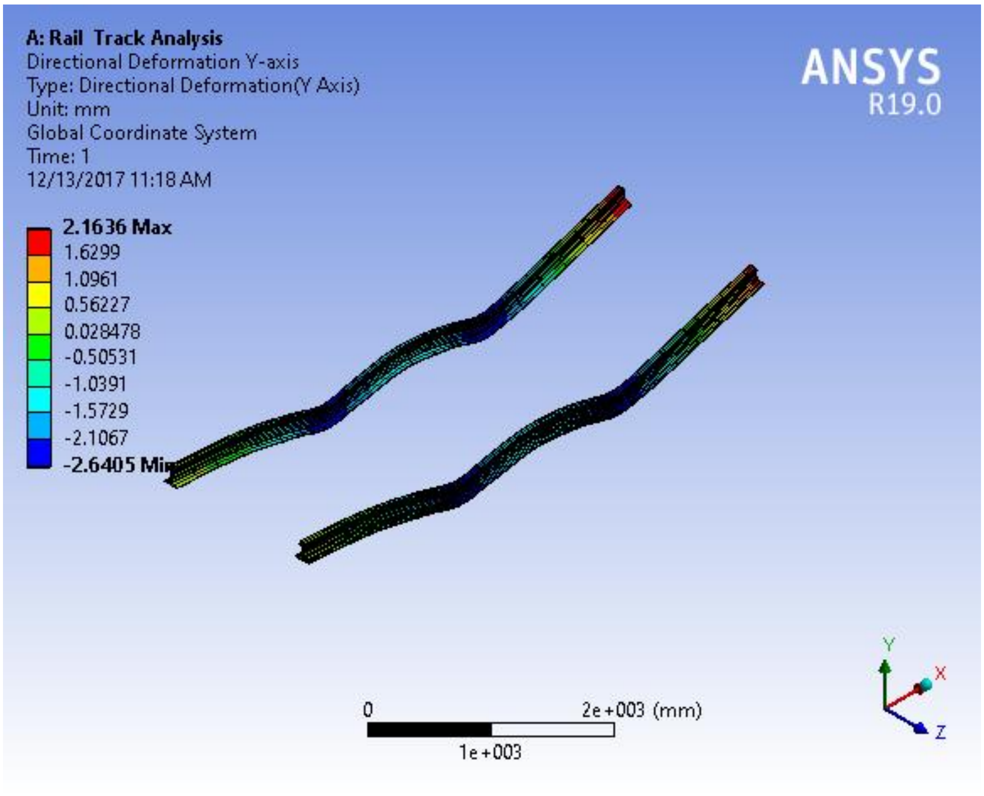


Fig 22 Vertical deformation for 25-ton axle load at 600mm sleeper spacing

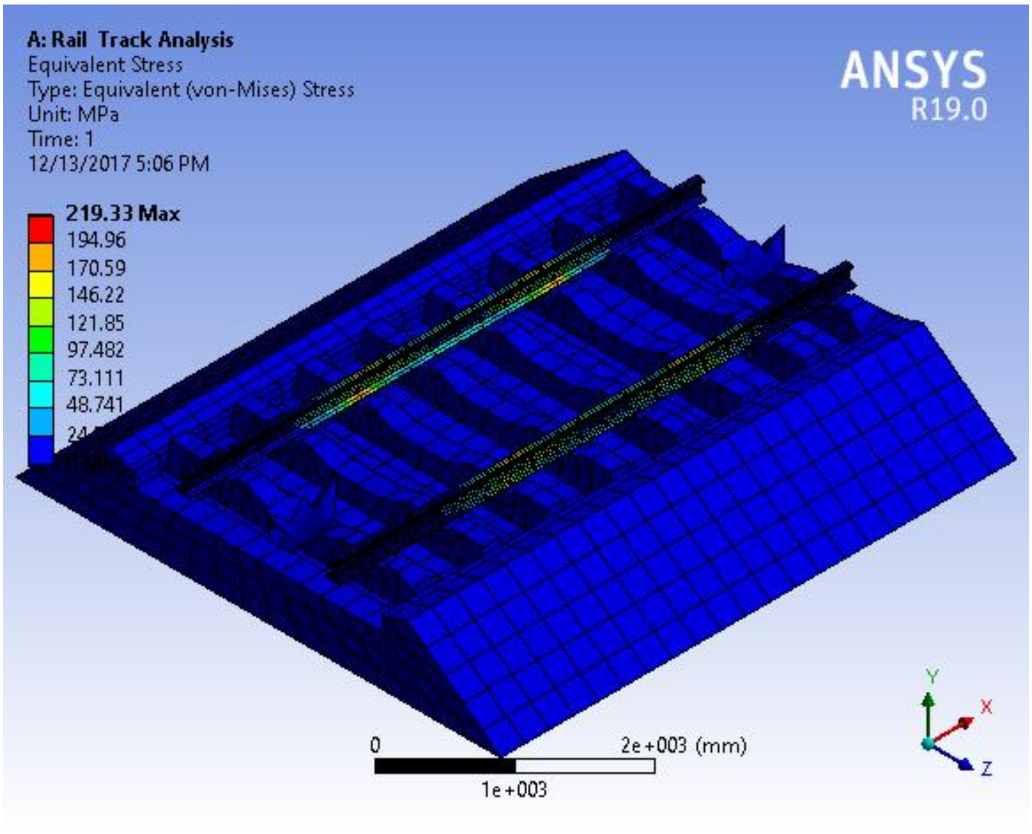


Fig 23 Equivalent stress for 25-ton axle load at 650mm sleeper spacing

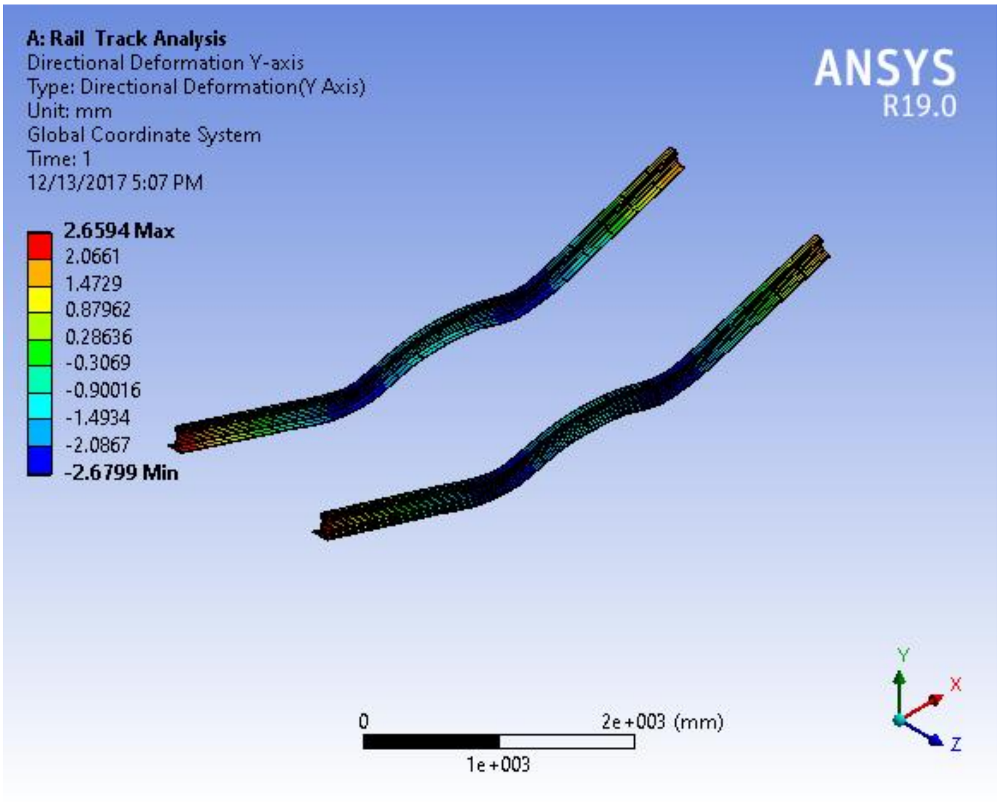


Fig 24 Vertical deformation for 25-ton axle load at 650mm sleeper spacing

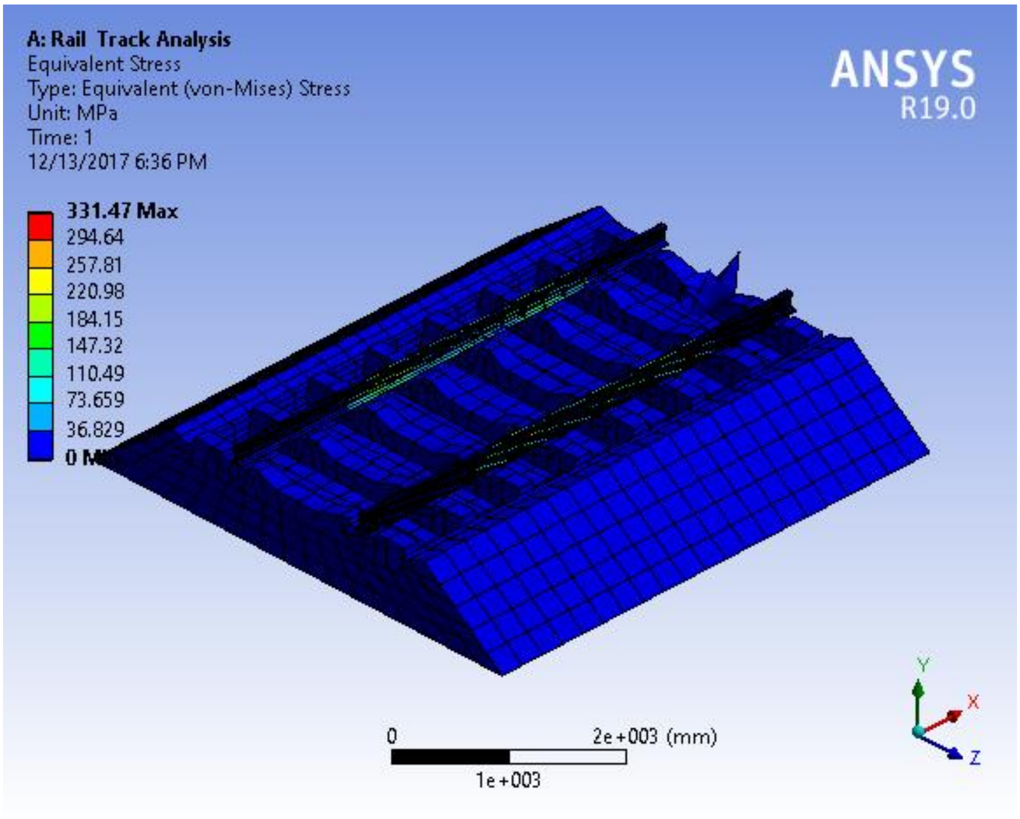


Fig 25 Equivalent stress for 25-ton axle load at 700mm sleeper spacing

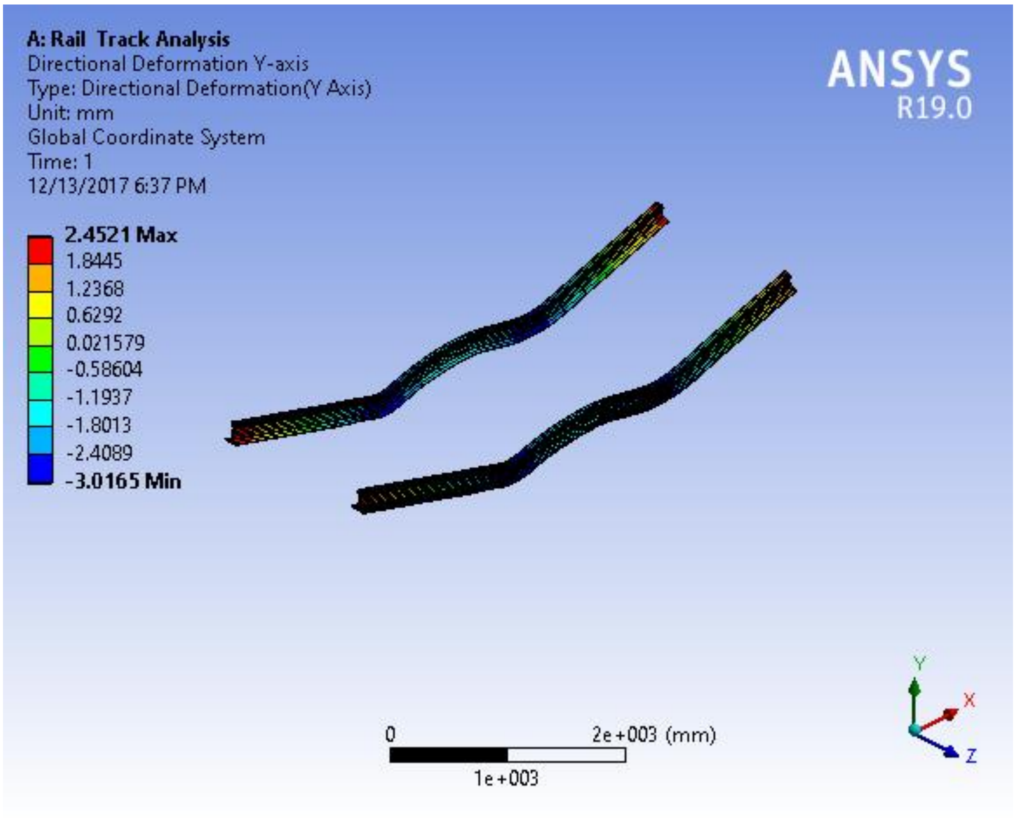


Fig 26 Vertical deformation for 25-ton axle load at 700mm sleeper spacing

Input Data						Analysis Result	
Sleeper Spacing (mm)	Axle Load (Ton)	Train Speed (km/hr.)	Wheel Load (kN)	Dynamic Load on Rail (kN)	Total Vertical load on Rail (kN)	Max. Vertical Deflection (mm)	Max. stress (N/mm^2)
550	25	70	125	452.50	577.50	2.03	275.03
		100	125	646.25	771.25	2.62	366.39
		120	125	775.00	900.00	3.00	426.86
	27.5	70	137.5	497.75	635.25	2.73	302.30
		100	137.5	710.88	848.38	3.52	402.21
		120	137.5	852.50	990.00	4.01	468.72
	30	70	150	543.00	693.00	2.95	329.00
		100	150	775.50	925.50	3.79	438.74
		120	150	930.00	1080.00	4.31	509.94
600	25	70	125	452.50	577.50	2.64	269.18
		100	125	646.25	771.25	3.39	355.57
		120	125	775.00	900.00	3.88	411.95
	27.5	70	137.5	497.75	635.25	2.87	295.16
		100	137.5	710.88	848.38	3.68	389.47
		120	137.5	852.50	990.00	4.02	450.96
	30	70	150	543.00	693.00	3.10	320.93
		100	150	775.50	925.50	3.97	423.07
		120	150	930.00	1080.00	4.52	489.68
650	25	70	125	452.50	577.50	2.68	219.33
		100	125	646.25	771.25	3.45	294.00
		120	125	775.00	900.00	3.92	343.26
	27.5	70	137.5	497.75	635.25	2.94	241.80
		100	137.5	710.88	848.38	3.72	323.48
		120	137.5	852.50	990.00	4.24	377.72
	30	70	150	543.00	693.00	3.17	263.97
		100	150	775.50	925.50	4.01	353.10
		120	150	930.00	1080.00	4.57	412.56
700	25	70	125	452.50	577.50	3.07	331.47
		100	125	646.25	771.25	3.90	440.96
		120	125	775.00	900.00	4.44	513.47
	27.5	70	137.5	497.75	635.25	3.28	363.58
		100	137.5	710.88	848.38	4.12	483.75
		120	137.5	852.50	990.00	4.82	564.16
	30	70	150	543.00	693.00	3.54	396.58
		100	150	775.50	925.50	4.53	527.50
		120	150	930.00	1080.00	5.15	614.44

Table 19 Summarized results for tangent track

Input Data								Analysis Result	
Sleeper Spacing (mm)	Axle Load (Ton)	Track Curve (m)	Wheel Load (kN)	Dynamic Load on Rail (kN)	Load Due to Curvature (kN)	Total Vertical load on Rail (kN)	Total Lateral Load (kN)	Max. Vertical Deflection (mm)	Max. stress (N/mm2)
550	25	50	125	202.50	50	565.00	183	2.46	269.11
		200	125	406.25	12.5	731.25	72	3.09	347.38
		500	125	641.25	5	958.75	51.67	3.90	452.74
	27.5	50	137.5	222.75	55	621.50	183	2.69	295.78
		200	137.5	446.88	13.75	804.38	72	3.36	381.73
		500	137.5	705.38	5.5	1054.63	55.83	4.23	498.61
	30	50	150	243.00	60	678.00	183	2.89	322.58
		200	150	487.50	15	877.50	72	3.61	415.58
		500	150	769.50	6	1150.50	60	4.55	542.75
600	25	50	125	202.50	50	565.00	183	2.59	263.55
		200	125	406.25	12.5	731.25	72	3.25	337.88
		500	125	641.25	5	958.75	51.67	4.08	437.52
	27.5	50	137.5	222.75	55	621.50	183	2.81	289.00
		200	137.5	446.88	13.75	804.38	72	3.52	370.10
		500	137.5	705.38	5.5	1054.63	55.83	4.43	478.78
	30	50	150	243.00	60	678.00	183	3.04	314.26
		200	150	487.50	15	877.50	72	3.79	402.18
		500	150	769.50	6	1150.50	60	4.78	519.92
650	25	50	125	202.50	50	565.00	183	2.65	214.80
		200	125	406.25	12.5	731.25	72	3.30	278.59
		500	125	641.25	5	958.75	51.67	4.14	366.11
	27.5	50	137.5	222.75	55	621.50	183	2.85	235.89
		200	137.5	446.88	13.75	804.38	72	3.56	306.10
		500	137.5	705.38	5.5	1054.63	55.83	4.47	402.33
	30	50	150	243.00	60	678.00	183	3.10	258.15
		200	150	487.50	15	877.50	72	3.83	334.58
		500	150	769.50	6	1150.50	60	4.82	439.49
700	25	50	125	202.50	50	565.00	183	2.96	324.29
		200	125	406.25	12.5	731.25	72	3.71	418.45
		500	125	641.25	5	958.75	51.67	4.64	545.50
	27.5	50	137.5	222.75	55	621.50	183	3.22	356.29
		200	137.5	446.88	13.75	804.38	72	4.02	459.28
		500	137.5	705.38	5.5	1054.63	55.83	5.08	600.48
	30	50	150	243.00	60	678.00	183	3.47	388.20
		200	150	487.50	15	877.50	72	4.32	500.64
		500	150	769.50	6	1150.50	60	5.44	654.08

Table 20 Summarized results for curved track

4.6 Discussion on Results

The analysis result for both tangent and curved tracks in order to obtain the optimum sleeper spacing considering particular parameters shows that as the load increases the sleeper spacing decreases in proportion.

According to the allowable track deflection value from serviceability, comfort, and safety criteria the ultimate deflection is 5.08 mm for long life track consideration. Since for this thesis only vertical loads are considered for analysis and those conditions which give the minimum deviation from deflection depending on their curvature value for both tangent and curved tracks is considered as the optimum value.

Therefore, the finding of this research can be summarized as follows:

- For tangent track with maximum train speed of 120 km/h; 550 mm sleeper spacing is best and optimum value for axle load less than or equal to 30 tons and greater than or equal to 27.5 tons. Whereas 600 mm spacing is optimum for axle loads less than 27.5 tons and greater than or equal to 25 tons. But 650 mm spacing is best for axle loads less than 25 tons. However, if the maximum train speed is 100 km/h the optimum spacing of sleepers for 30 tons is 550 mm, for axle loads ≥ 27.5 ton but less than 30 tons is 600 mm, and 650 mm is best for axle loads ≥ 25 tons but less than 27.5 tons. Similarly, while train speed is 70 km/h for axle loads $30 \leq X \geq 27.5$ optimum sleeper spacing is 600 mm and for axle loads $27.5 < X \geq 25$ the optimized spacing is 650 mm.
- For curved tracks with maximum radius of 50 m at maximum train speed of 30 km/hr. with all axle loads the optimum spacing is 550 mm. However, for track curve of radius 200 m 550 mm spacing of sleeper is optimum for axle loads ≥ 25 tons and 600 mm spacing is best for axle loads less than 25 tons. But for track curve of radius 500m the analysis result is almost the same as the findings of tangent tracks.
- Finally, the analysis results of this research for both maximum vertical deflection and equivalent stresses are shown in tabular form below.

Input Data						Analysis Result		Allowable deflection Vertical Deflection(mm)	Deviation in vertical deflection	Remark
Sleeper Spacing (mm)	Axle Load (Ton)	Train Speed (km/hr.)	Wheel Load (kN)	Dynamic Load on Rail (kN)	Total Vertical load on Rail (kN)	Max. Vertical Deflection (mm)	Max. stress (N/mm^2)			
550	25.0	120	125	775.00	900.00	3.00	426.86	5.08	2.08	Best for axle loads $30 \leq X \geq 27.5$
	27.5	120	137.5	852.50	990.00	4.01	468.72		1.07	
	30.0	120	150	930.00	1080.00	4.31	509.94		0.77	
600	25.0	120	125	775.00	900.00	3.88	411.95		1.20	Best for axle loads $27.5 < X > 25$
	27.5	120	137.5	852.50	990.00	4.02	450.96		1.06	
	30.0	120	150	930.00	1080.00	4.52	489.68		0.56	
650	25.0	120	125	775.00	900.00	3.92	343.26		1.16	Best for axle loads $X \leq 25$
	27.5	120	137.5	852.50	990.00	4.24	377.72		0.84	
	30.0	120	150	930.00	1080.00	4.57	412.56		0.51	
700	25.0	120	125	775.00	900.00	4.44	513.47		0.64	Not effective in Serviceability
	27.5	120	137.5	852.50	990.00	4.82	564.16		0.26	
	30.0	120	150	930.00	1080.00	5.15	614.44		-0.07	

Table 21 Optimum sleeper spacing depending on axle load for 120 km/h train speed

Table 22 Optimum sleeper spacing depending on axle load for 100 km/h train speed

Input Data						Analysis Result		Allowable deflection Vertical Deflection(mm)	Deviation in vertical deflection	Remark
Sleeper Spacing (mm)	Axle Load (Ton)	Train Speed (km/hr.)	Wheel Load (kN)	Dynamic Load on Rail (kN)	Total Vertical load on Rail (kN)	Max. Vertical Deflection (mm)	Max. stress (N/mm^2)			
550	25.0	100	125	646.25	771.25	2.62	366.39	5.08	2.46	Best for 30 ton axle load
	27.5	100	137.5	710.875	848.375	3.52	402.21		1.56	
	30.0	100	150	775.5	925.5	3.79	438.74		1.29	
600	25.0	100	125	646.25	771.25	3.39	355.57		1.69	Best for axle loads $30 < X \geq 27.5$
	27.5	100	137.5	710.875	848.375	3.68	389.47		1.40	
	30.0	100	150	775.5	925.5	3.97	423.07		1.11	
650	25.0	100	125	646.25	771.25	3.45	294.00		1.63	Best for axle loads $27.5 < X \geq 25$
	27.5	100	137.5	710.875	848.375	3.72	323.48		1.36	
	30.0	100	150	775.5	925.5	4.01	353.10		1.07	
700	25.0	100	125	646.25	771.25	3.90	440.96		1.18	Not effective in Serviceability
	27.5	100	137.5	710.875	848.375	4.12	483.75		0.96	
	30.0	100	150	775.5	925.5	4.53	527.50		0.55	

Input Data						Analysis Result		Allowable deflection Vertical Deflection(mm)	Deviation in vertical deflection	Remark
Sleeper Spacing (mm)	Axle Load (Ton)	Train Speed (km/hr.)	Wheel Load (kN)	Dynamic Load on Rail (kN)	Total Vertical load on Rail (kN)	Max. Vertical Deflection (mm)	Max. stress (N/mm^2)			
550	25.0	70	125	452.50	577.50	2.03	275.03	5.08	3.05	Not Economical
	27.5	70	137.5	497.75	635.25	2.73	302.30		2.35	
	30.0	70	150	543.00	693.00	2.95	329.00		2.13	
600	25.0	70	125	452.50	577.50	2.64	269.18		2.44	Best for axle loads 30 ≤ X ≥ 27.5
	27.5	70	137.5	497.75	635.25	2.87	295.16		2.21	
	30.0	70	150	543.00	693.00	3.10	320.93		1.98	
650	25.0	70	125	452.50	577.50	2.68	219.33		2.40	Best for axle loads 27.5 < X ≥ 25
	27.5	70	137.5	497.75	635.25	2.94	241.80		2.14	
	30.0	70	150	543.00	693.00	3.17	263.97		1.91	
700	25.0	70	125	452.50	577.50	3.07	331.47		2.01	Not Effective
	27.5	70	137.5	497.75	635.25	3.28	363.58		1.80	
	30.0	70	150	543.00	693.00	3.54	396.58		1.54	

Table 23 Optimum sleeper spacing depending on axle load for 70 km/h train speed

Input Data								Analysis Result		Allowable Vertical Deflection (mm)	Deviation in Vertical Deflection	Remark
Sleeper Spacing (mm)	Axle Load (Ton)	Track Curve (m)	Wheel Load (kN)	Dynamic Load on Rail (kN)	Load Due to Curvature (kN)	Total Vertical load on Rail (kN)	Total Lateral Load (kN)	Max. Vertical Deflection (mm)	Max. stress (N/mm2)			
550	25.0	50.0	125.0	202.50	50.0	377.5	183.0	2.46	269.11	2.90	0.44	Best all axle ≥ 25 tons
	27.5	50.0	137.5	222.75	55.0	415.3	183.0	2.69	295.78		0.21	
	30.0	50.0	150.0	243.00	60.0	453.0	183.0	2.89	322.58		0.01	
600	25.0	50.0	125.0	202.50	50.0	377.5	183.0	2.59	263.55		0.31	
	27.5	50.0	137.5	222.75	55.0	415.3	183.0	2.81	289.00		0.09	
	30.0	50.0	150.0	243.00	60.0	453.0	183.0	3.04	314.26		-0.14	
650	25.0	50.0	125.0	202.50	50.0	377.5	183.0	2.65	214.80		0.25	
	27.5	50.0	137.5	222.75	55.0	415.3	183.0	2.85	235.89		0.05	
	30.0	50.0	150.0	243.00	60.0	453.0	183.0	3.10	258.15		-0.20	
700	25.0	50.0	125.0	202.50	50.0	377.5	183.0	2.96	324.29		-0.06	
	27.5	50.0	137.5	222.75	55.0	415.3	183.0	3.22	356.29		-0.32	
	30.0	50.0	150.0	243.00	60.0	453.0	183.0	3.47	388.20		-0.57	

Table 24 Optimum sleeper spacing depending on axle load for 50 m track radius

Input Data								Analysis Result		Allowable Vertical Deflection (mm)	Deviation in Vertical Deflection	Remark
Sleeper Spacing (mm)	Axle Load (Ton)	Track Curve (m)	Wheel Load (kN)	Dynamic Load on Rail (kN)	Load Due to Curvature (kN)	Total Vertical load on Rail (kN)	Total Lateral Load (kN)	Max. Vertical Deflection (mm)	Max. stress (N/mm2)			
550	25.0	200.0	125.0	406.25	12.5	537.5	72.0	3.09	347.38	3.39	0.30	Best all axle ≥ 25 tons
	27.5	200.0	137.5	446.88	13.8	591.3	72.0	3.36	381.73		0.03	
	30.0	200.0	150.0	487.50	15.0	645.0	72.0	3.61	415.58		-0.22	
600	25.0	200.0	125.0	406.25	12.5	537.5	72.0	3.25	337.88		0.14	Best for axle 25 ton
	27.5	200.0	137.5	446.88	13.8	591.3	72.0	3.52	370.10		-0.13	
	30.0	200.0	150.0	487.50	15.0	645.0	72.0	3.79	402.18		-0.40	
650	25.0	200.0	125.0	406.25	12.5	537.5	72.0	3.30	278.59		0.09	
	27.5	200.0	137.5	446.88	13.8	591.3	72.0	3.56	306.10		-0.17	
	30.0	200.0	150.0	487.50	15.0	645.0	72.0	3.83	334.58		-0.44	
700	25.0	200.0	125.0	406.25	12.5	537.5	72.0	3.71	418.45		-0.32	
	27.5	200.0	137.5	446.88	13.8	591.3	72.0	4.02	459.28		-0.63	
	30.0	200.0	150.0	487.50	15.0	645.0	72.0	4.32	500.64		-0.93	

Table 25 Optimum sleeper spacing depending on axle load for 200 m track radius

Input Data								Analysis Result		Allowable Vertical Deflection (mm)	Deviation in Vertical Deflection	Remark
Sleeper Spacing (mm)	Axle Load (Ton)	Track Curve (m)	Wheel Load (kN)	Dynamic Load on Rail (kN)	Load Due to Curvature (kN)	Total Vertical load on Rail (kN)	Total Lateral Load (kN)	Max. Vertical Deflection (mm)	Max. stress (N/mm2)			
550	25.0	500.0	125.0	641.25	5.0	530.0	51.7	3.90	452.74	5.08	1.18	Best all axle ≥ 25 tons
	27.5	500.0	137.5	705.38	5.5	583.0	55.8	4.23	498.61		0.85	
	30.0	500.0	150.0	769.50	6.0	636.0	60.0	4.55	542.75		0.53	
600	25.0	500.0	125.0	641.25	5.0	530.0	51.7	4.08	437.52		1.00	Best for axle 25 tons with train speed < 50 km/hr.
	27.5	500.0	137.5	705.38	5.5	583.0	55.8	4.43	478.78		0.65	
	30.0	500.0	150.0	769.50	6.0	636.0	60.0	4.78	519.92		0.30	
650	25.0	500.0	125.0	641.25	5.0	530.0	51.7	4.14	366.11		0.94	Best for axle 25 tons with train speed ≥ 50 km/hr.
	27.5	500.0	137.5	705.38	5.5	583.0	55.8	4.47	402.33		0.61	
	30.0	500.0	150.0	769.50	6.0	636.0	60.0	4.82	439.49		0.26	
700	25.0	500.0	125.0	641.25	5.0	530.0	51.7	4.64	545.50		0.44	Not Effective
	27.5	500.0	137.5	705.38	5.5	583.0	55.8	5.08	600.48		0.00	
	30.0	500.0	150.0	769.50	6.0	636.0	60.0	5.44	654.08		-0.36	

Table 26 Optimum sleeper spacing depending on axle load for 500 m track radius

CHAPTER FIVE

5 CONCLUSION AND RECOMMENDATION

5.1 Conclusion

The cost for constructing ballasted railway structure greatly affected by the amount of sleepers to be used per track length. Hence, sleepers should be provided according to the analysis result rather than blindly following the code recommendations.

This thesis highly optimizes the spacing of pre stressed sleepers through ensuring strength, serviceability, and economy which is done both numerically and analytically using ANSYS and classic optimization respectively. The analysis result interpretation is with respect to the allowable maximum deflection of the track which is commonly 5.08 mm. Those which give us smallest deviation from the allowable value for both tangent and curved tracks are considered as the optimum sleeper spacing.

Therefore, the output of this study shows that for tangent tracks of axle load in between 27.5 and 30 tons the optimum value of 550 mm sleeper spacing is economical and 600mm spacing is economical for axle load in between 27.5 and 25 tons but for axle loads equal to 25 ton or less 650 mm spacing is optimum. Similarly, in curved tracks as well for sharp curves with curve radius less than or equal to 50 m the optimum spacing of sleeper is 550 mm for all axle loads. But if curve radius is 200 m still for axle loads ≥ 27.5 ton 550 mm spacing of sleepers is economical and for axle loads ≤ 25-ton sleeper spacing at 600 mm is optimum. The analysis output for curve radius 500 m the spacing for different axle loads is almost the same as for tangent tracks at the same allowable train speed.

Generally, this study shows us through considering AALRT case 650 mm spacing of sleepers is optimum while the train speed is 70 km/h with axle load of 25 tons but on ground 600 mm spacing is provided which is too costly around 120 sleepers are wasted which is equivalent to 7.2 % of sleeper cost can be saved per kilometer of track length. So, to provide sleepers for ballasted track system detail analysis should be done.

5.2 Recommendation

This research is targeted at obtaining the optimum spacing of sleepers at ballasted track systems by finite element methods using ANSYS 19. The finding of this analysis concludes that increasing the load on the track decreases the spacing in between sleepers for constant engineering parameters of track structure. Hence, the following recommendations are made:

- Sleeper ballast interaction which is considered as uniformly rough surface is another parameter which is out of the scope but it influences the load which is transferred to the underneath of sleeper.
- The provided sleeper spacing in AALRT is confirmed in my study as being it is safe but around 7.2% of cost for sleeper can be saved per kilometer of track length. Therefore, one of my recommendation for newly constructed rail tracks is that it is better to provide sleepers depending on the analysis outputs rather than using codes.
- Lastly, the effect of lateral and longitudinal loads on sleeper spacing are not considered on this thesis. So, the idea may be used as a topic for other scholars those are interested on optimizing the spacing of sleepers.

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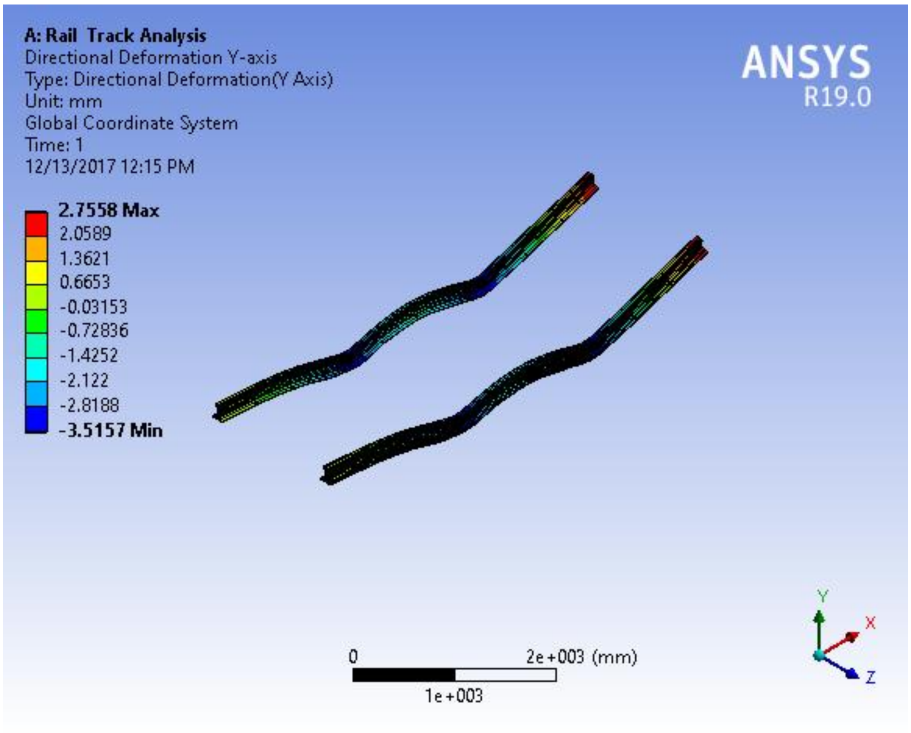
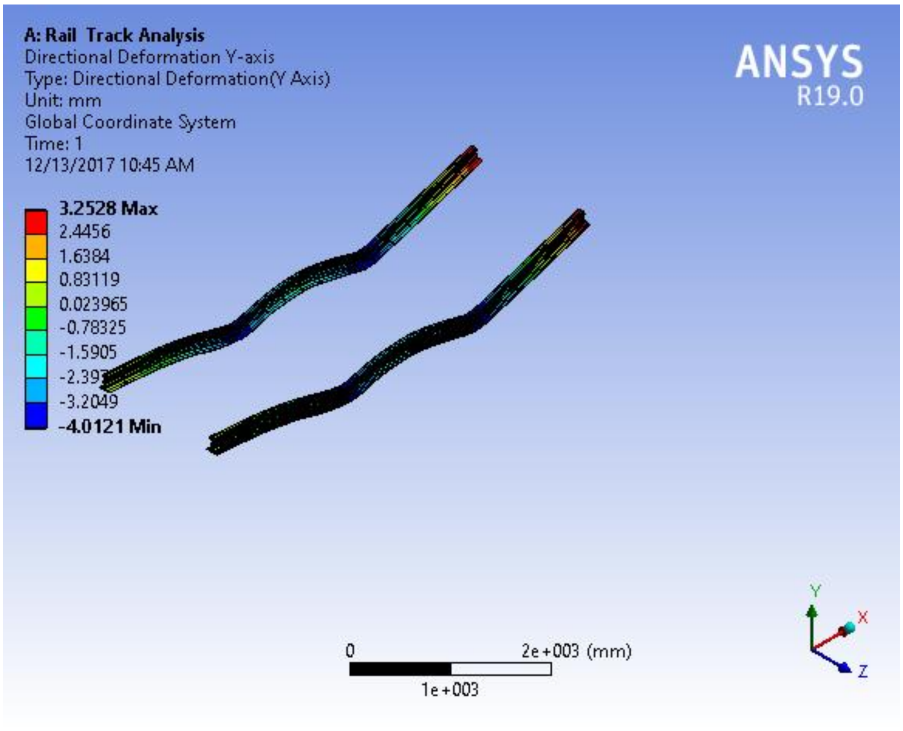
Appendix

Appendix I: ANSYS analysis result for Tracks

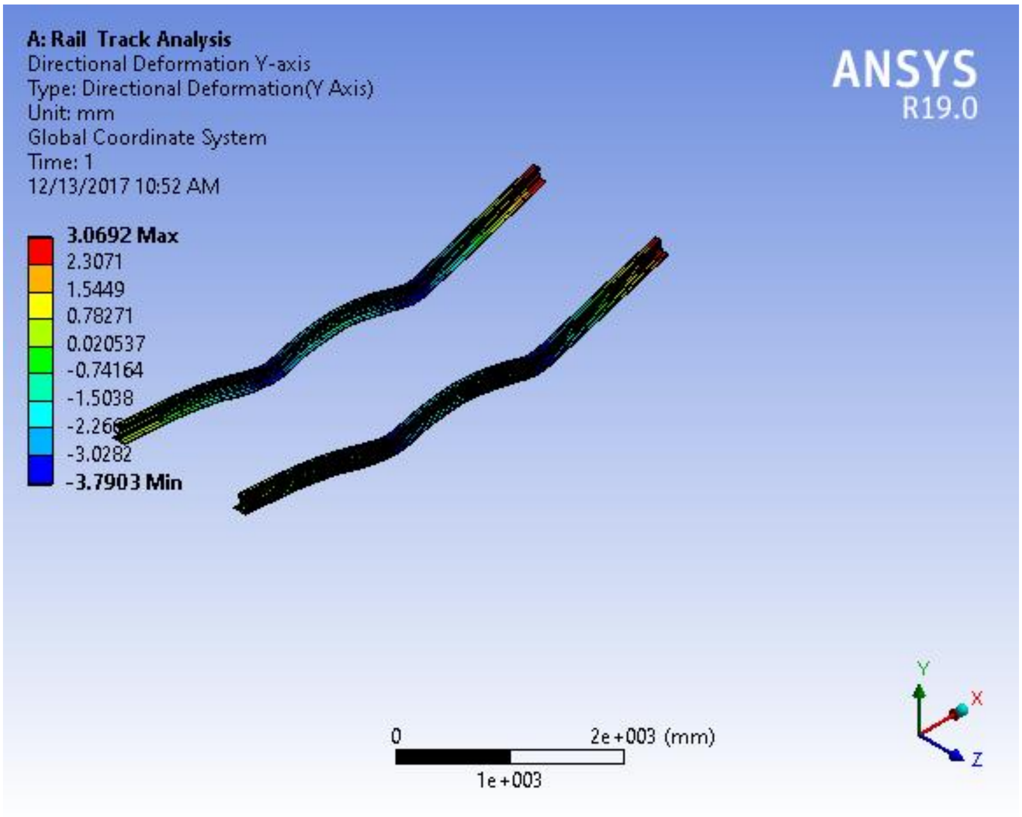
1. Vertical Deformation



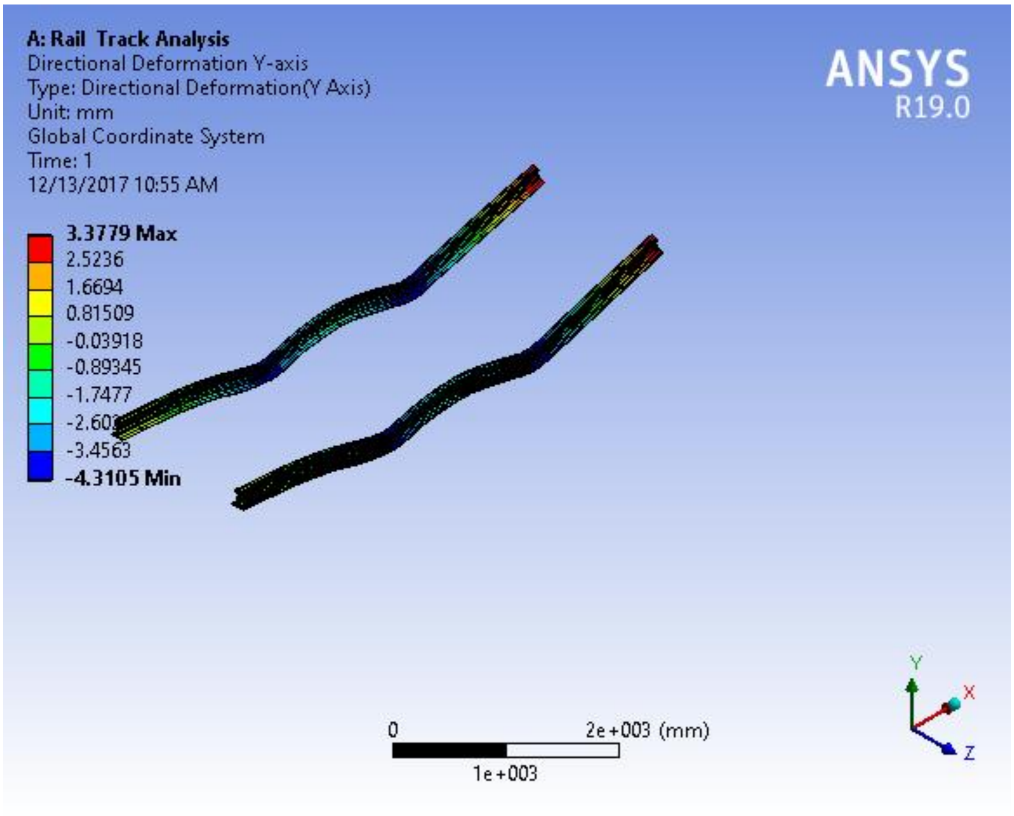
Spacing of Sleeper at 550 mm for Axle load 27.5 ton at train speed 100 km/hr.



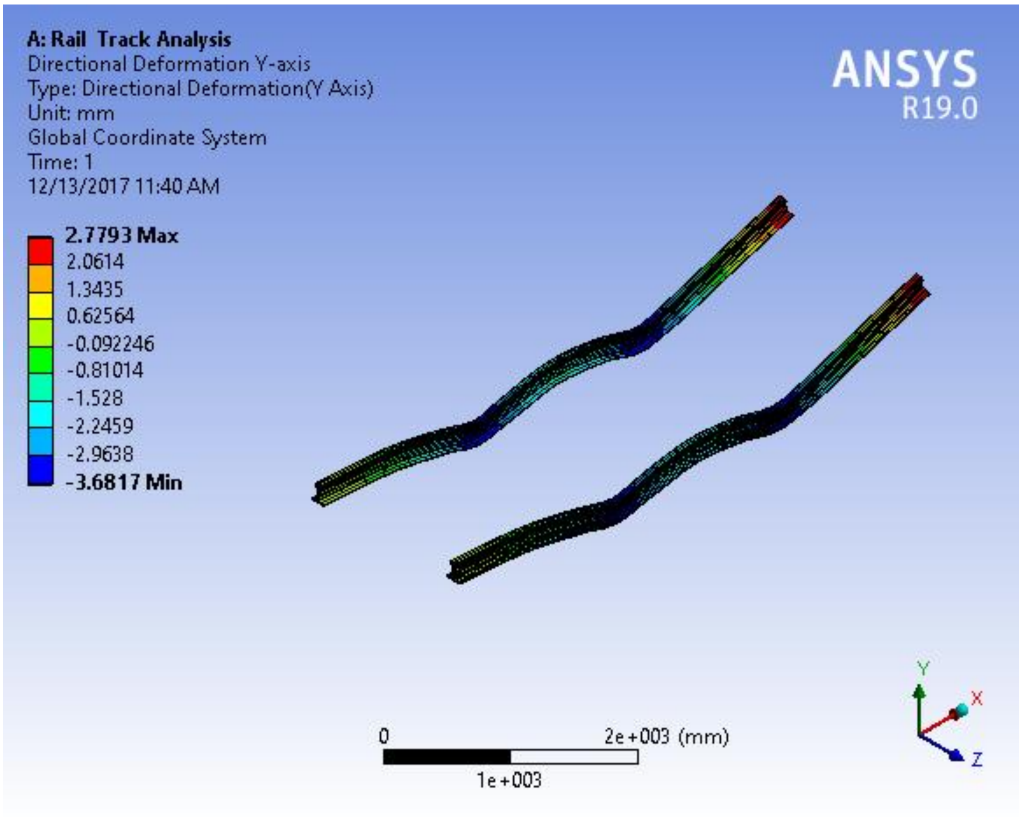
Spacing of Sleeper at 550 mm for Axle load 27.5 ton at train speed 120 km/hr.



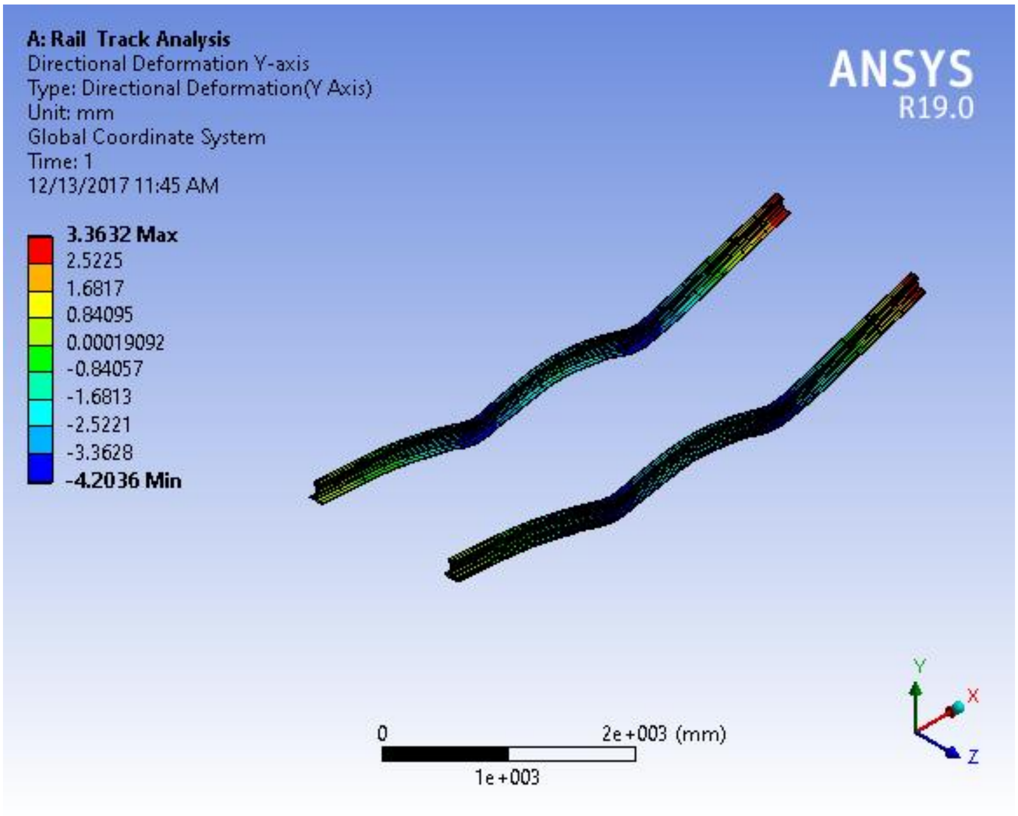
Spacing of Sleeper at 550 mm for Axle load 30 ton at train speed 100 km/hr.



Spacing of Sleeper at 550 mm for Axle load 30 ton at train speed 120 km/hr.



Spacing of Sleeper at 600 mm for Axle load 27.5 ton at train speed 100 km/hr.



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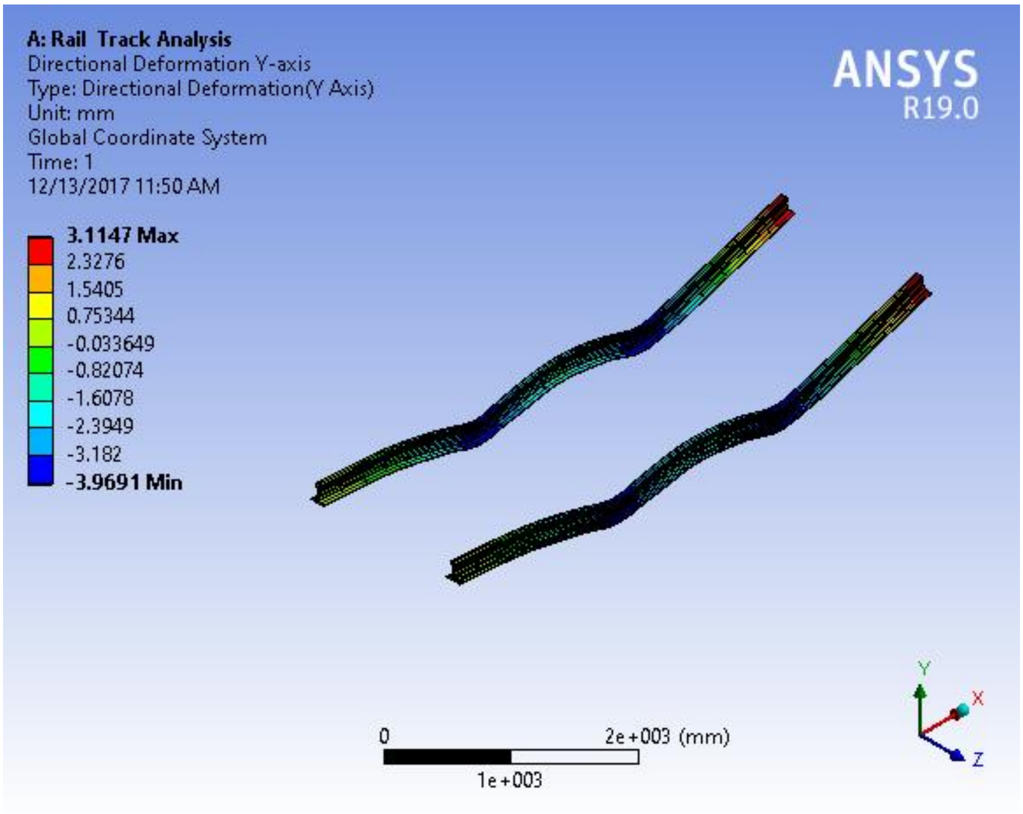

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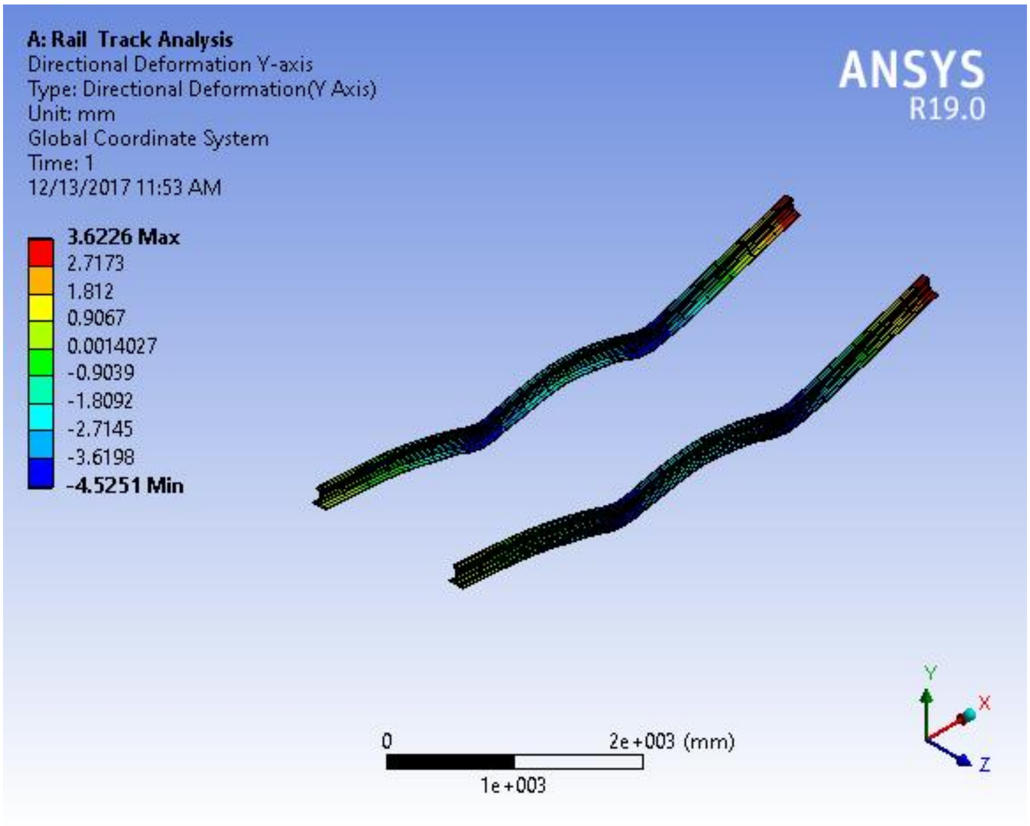
Spacing of Sleeper at 600 mm for Axle load 30 ton at train speed 100 km/hr.



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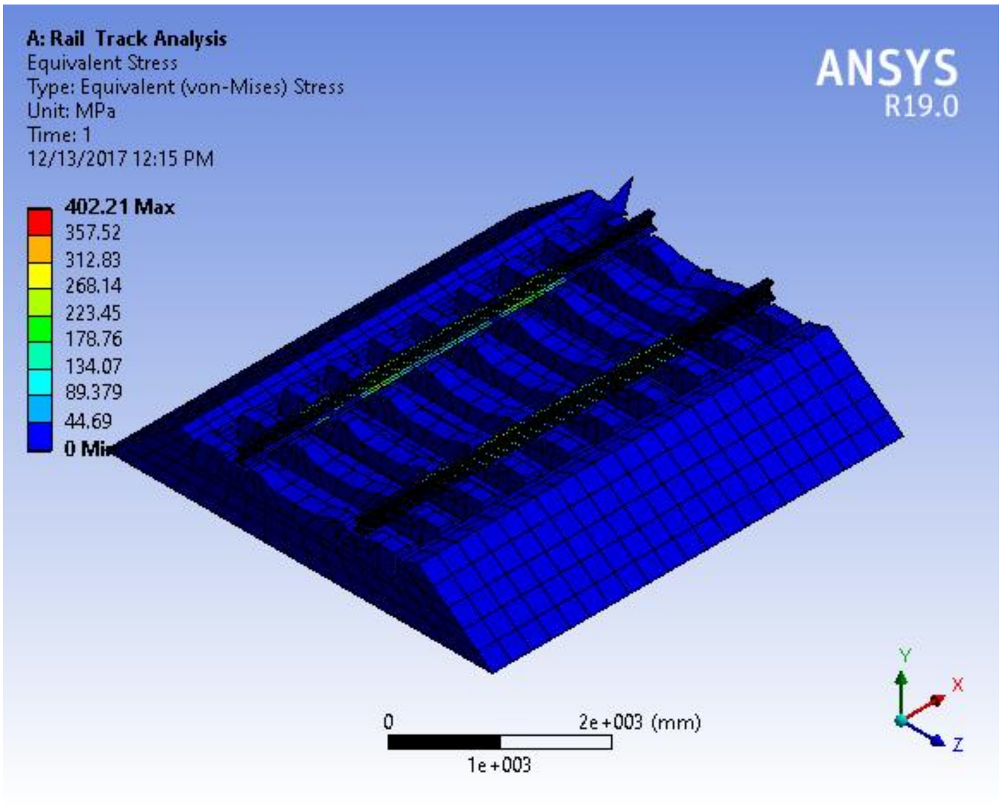
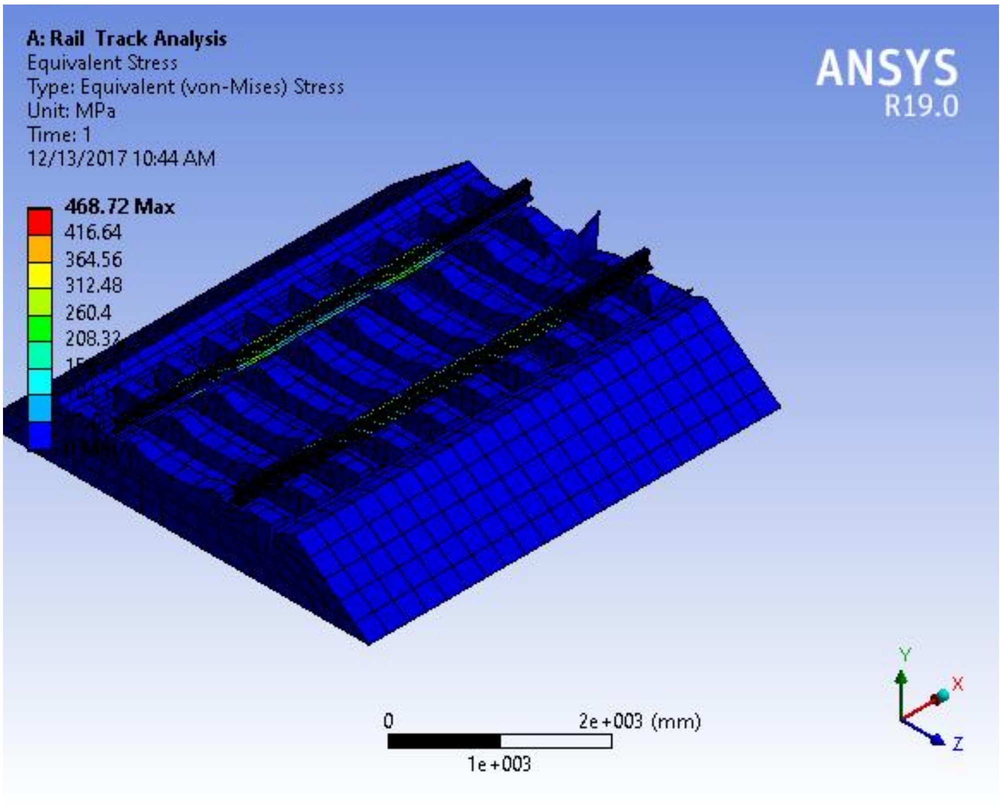
Spacing of Sleeper at 600 mm for Axle load 30 ton at train speed 100 km/hr.

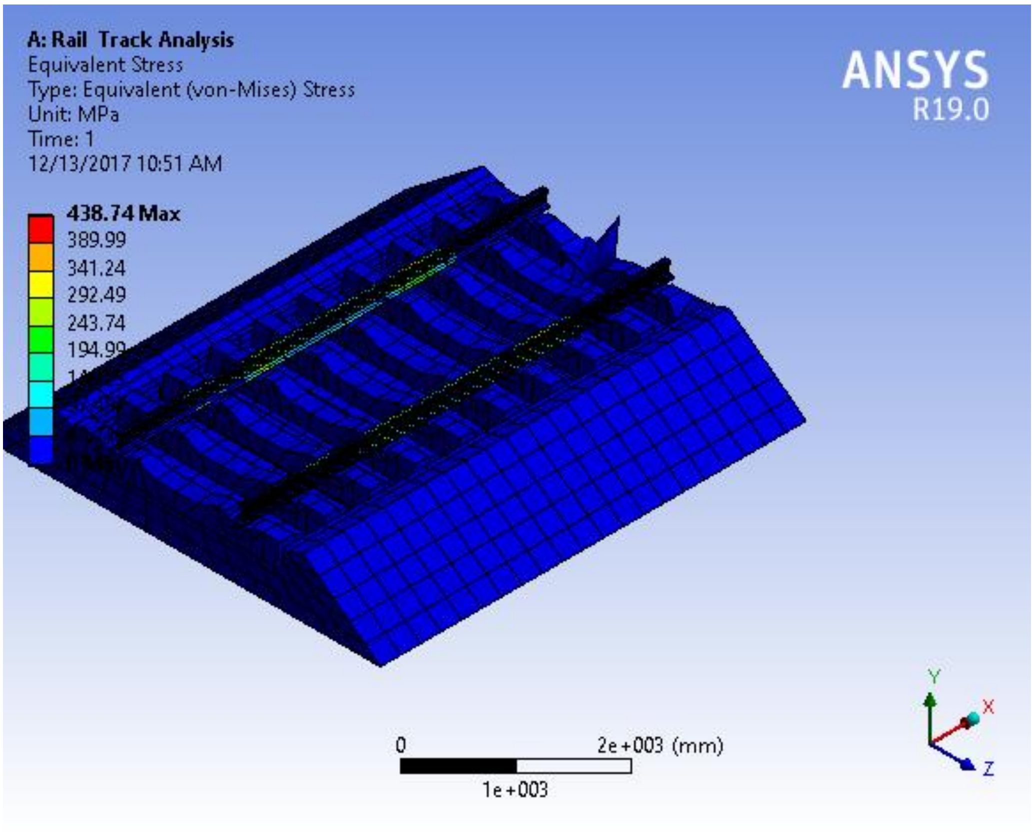
2. Equivalent stress



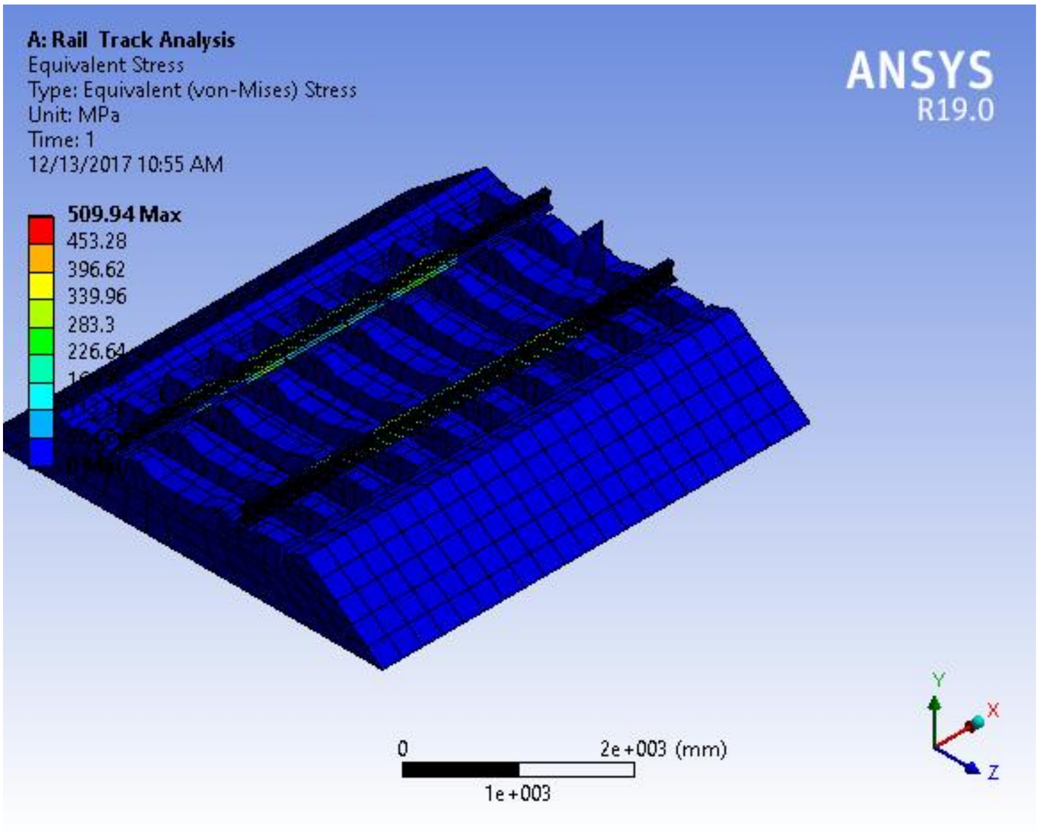
Spacing of Sleeper at 550 mm for Axle load 27.5 ton at train speed 100 km/hr.



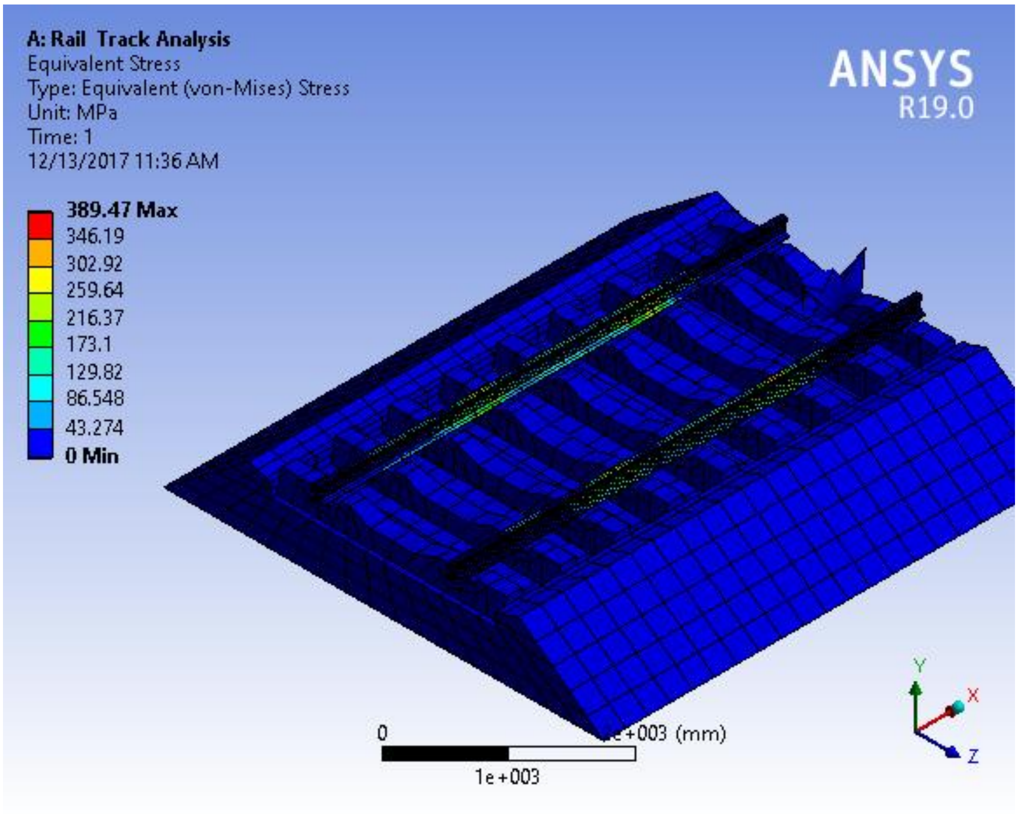
Spacing of Sleeper at 550 mm for Axle load 27.5 ton at train speed 120 km/hr.



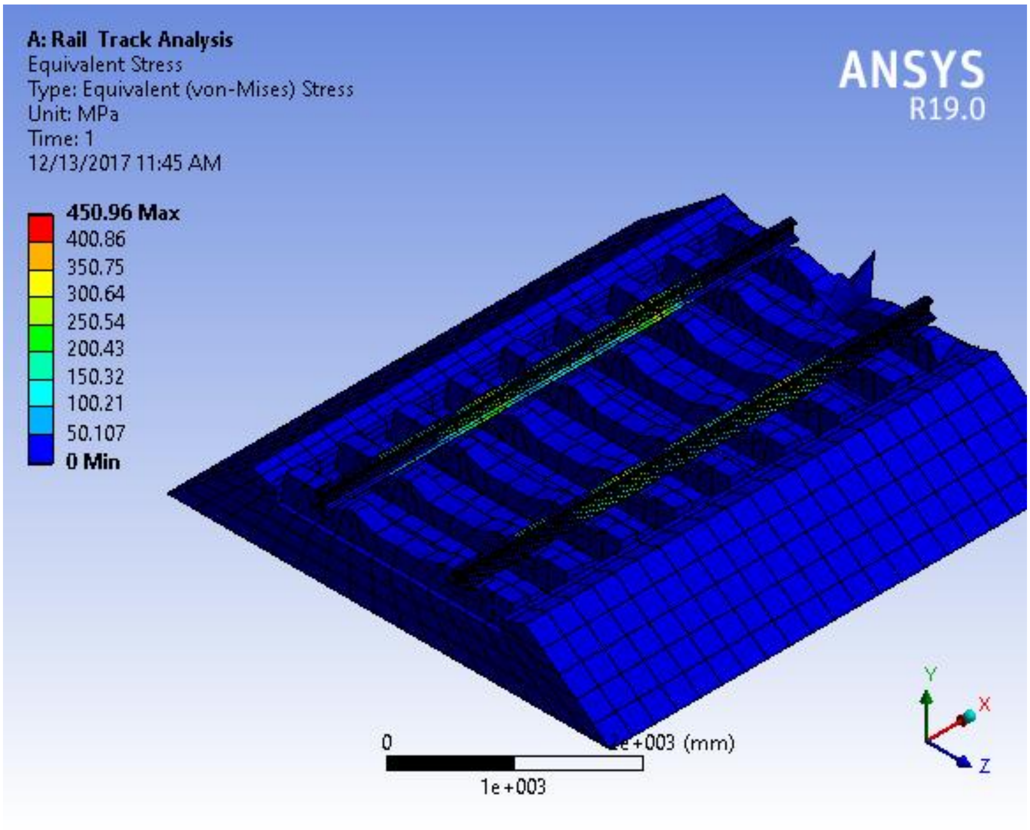
Spacing of Sleeper at 550 mm for Axle load 30 ton at train speed 100 km/hr.



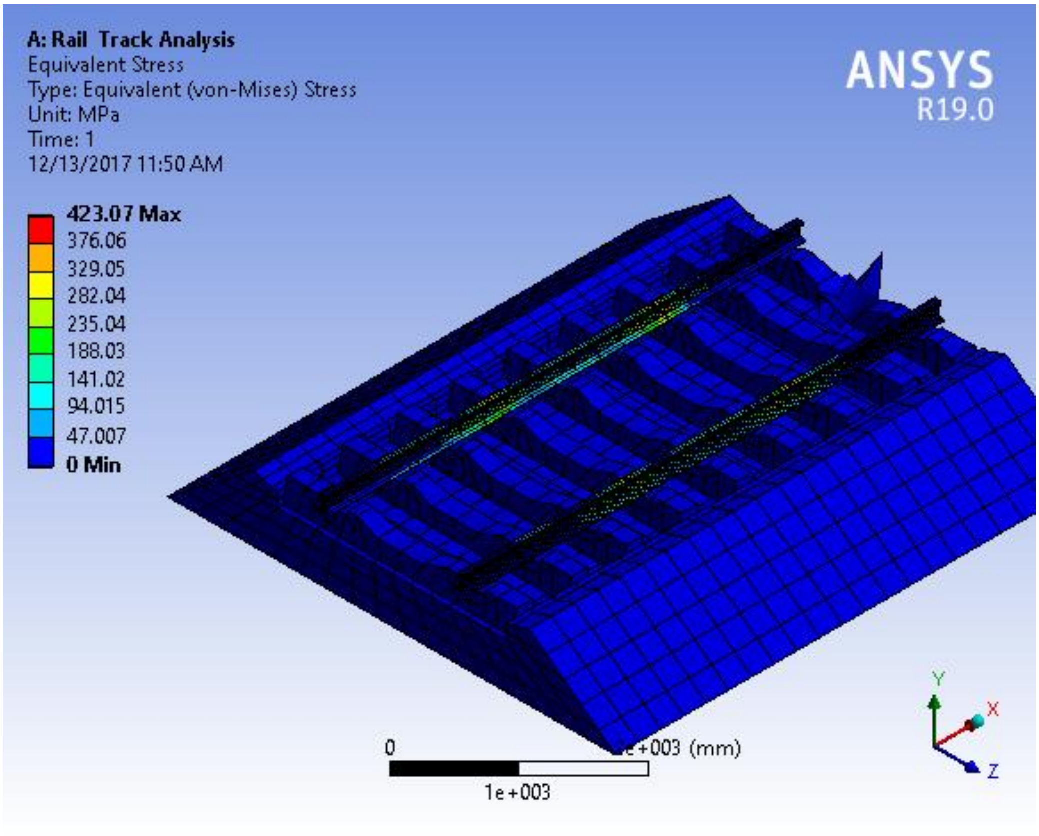
Spacing of Sleeper at 550 mm for Axle load 30 ton at train speed 120 km/hr.



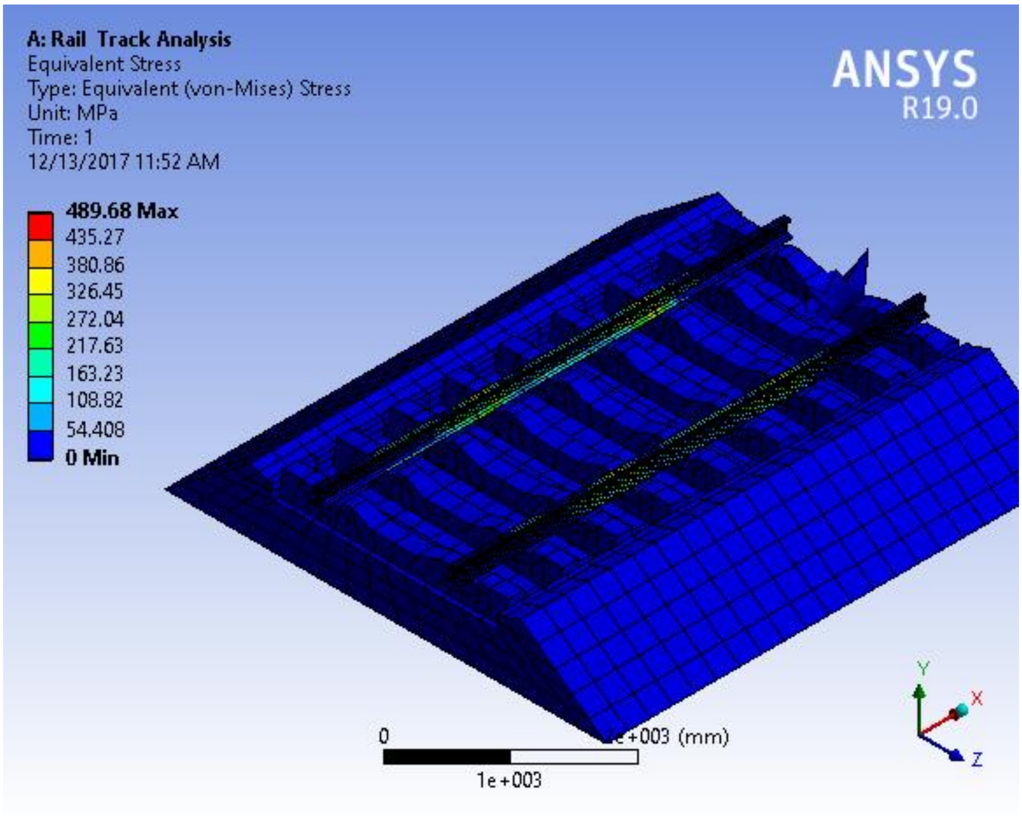
Spacing of Sleeper at 600 mm for Axle load 27.5 ton at train speed 100 km/hr.



Spacing of Sleeper at 600 mm for Axle load 27.5 ton at train speed 120 km/hr.



Spacing of Sleeper at 600 mm for Axle load 30 ton at train speed 100 km/hr.



Spacing of Sleeper at 600 mm for Axle load 30 ton at train speed 120 km/hr.

Curved Radius 50 m				
axle 25 ton				
Spacing	550	600	650	700
max def.	2.46	2.59	2.65	2.96
27.5 ton				
Spacing	550	600	650	700
max def.	2.69	2.81	2.85	3.22
30 ton				
Spacing	550	600	650	700
max def.	2.89	3.04	3.10	3.47

Curved Radius 200 m				
axle 25 ton				
Spacing	550	600	650	700
max def.	3.09	3.25	3.30	3.71
27.5 ton				
Spacing	550	600	650	700
max def.	3.36	3.52	3.56	4.02
30 ton				
Spacing	550	600	650	700
max def.	3.61	3.79	3.83	4.32

Curved Radius 500 m				
axle 25 ton				
Spacing	550	600	650	700
max def.	3.90	4.08	4.14	4.64
27.5 ton				
Spacing	550	600	650	700
max def.	4.23	4.43	4.47	5.08
30 ton				
Spacing	550	600	650	700
max def.	4.55	4.78	4.82	5.44

Appendix II: Analysis Comparison

Tangent Tracks 70 km/hr.				
axle 25 ton				
Spacing	550	600	650	700
max def.	2.03	2.64	2.68	3.07
27.5 ton				
Spacing	550	600	650	700
max def.	2.73	2.87	2.94	3.28
30 ton				
Spacing	550	600	650	700
max def.	2.95	3.10	3.17	3.54

Tangent Tracks 100 km/hr.				
axle 25 ton				
Spacing	550	600	650	700
max def.	2.62	3.39	3.45	3.90
27.5 ton				
Spacing	550	600	650	700
max def.	3.52	3.68	3.72	4.12
30 ton				
Spacing	550	600	650	700
max def.	3.79	3.97	4.01	4.53

Tangent Tracks 120 km/hr.				
axle 25 ton				
Spacing	550	600	650	700
max def.	3.00	3.88	3.92	4.44
27.5 ton				
Spacing	550	600	650	700
max def.	4.01	4.02	4.24	4.82
30 ton				
Spacing	550	600	650	700
max def.	4.31	4.52	4.57	5.15