

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



**TRACK SURVEYING AND SPEED OPTIMIZATION (CASE
STUDY ADDIS ABABA – ADAMA LINE)**

*A Thesis Submitted to the School of Graduate Studies of Addis Ababa
University in Partial Fulfillment of the Requirements for the Degree of
Masters of Science in Railway Engineering*

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UNDERTAKING

I certify that research work titled ‘**Track Surveying and Speed Optimization (Case Study Addis Ababa – Adama Line)**’ is my own work. The work has not been presented elsewhere for assessment. Where material has been used from other sources it has been properly acknowledged / referred.

Fayera Mosisa

Abstract

Speed Optimization is a means of improving the geometric alignment, infrastructure and construction materials and structure performance during the working cycles under some manufacturing, operational and failure conditions as well as cost limitations.

The new Ethiopian national railway network design speed is about 120Km/h which is too low when compared with some developed countries rail speed. Construction of new high speed line needs huge investment that may not be viable for a developing country like Ethiopia and optimization of existing line using different techniques is the available option. The major anticipated problems/demand behind for high speed for the country national rail network and Addis Ababa – Adama line in particular are for that it is Competitive with toll road of same speed, located along the development axis area of Ethiopian economy, located along country's industrial zone highly polluted by industry emission, national image building, attracting investor and delay of freight at sea port.

Optimization of speed were done by enquiring and analyzing existing track geometry and track super structures, construction materials and other speed related parameters to identify restrictive sections and the maximum allowable speed of the line. Geometric analysis and design were done by Bentley Inrail software in the optimization process and finite element methods were used for analyzing of track component response under optimized speed.

From the analysis result, the existing track construction materials and infrastructures are within recommendable limit for introducing high speed. The geometry of the track is allowable for speed up to 130km/h by modifying cant of sharp horizontal curves. Two optimization techniques were identified for the study. The first optimization technique is introducing tilting coach and the second is upgrading existing geometric alignment. On the existing track, 160km/h speed can be operated by introducing tilting coach without upgrading the track alignment. It is possible to achieve 160km/h for conventional train by upgrading sharp horizontal curves less than 1325m. By combination of both techniques 205km/h speed can be achieved, but due to vertical curve limitation speed more than 170km/h is not viable on the line. By all optimization techniques, the recommendable level of optimization percentage is 33%. Introducing tilt coach technology is recommendable technology as it is easy for application and economically feasible option. Since the entire Ethiopian national rail network are similar, the work done for Addis Ababa – Adama line can be projected for other routes to increase consistency system throughout the country.

Keywords: *Speed optimization, conventional train, tilting coach, allowable design speed, high speed, track geometry, Bentley Inrail Software*

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Symbols and Abbreviations

AASHTO = American Association of State Highway and Transportation Officials

AEIF = European Association for Railway Interoperability

APT = Advanced Passenger Train

AREMA = American Railway Engineering and Maintenance-of-way Association

a_y = Horizontal acceleration

CEN = European Committee for Standardization

Conv. = conventional

CWC = Characteristic Wind Curves

CWR = Continuously Welded Rail

C = constant ($11.8 \text{ mm.m.h}^2/\text{km}^2$)

CA = Standard aggregate crushing rate

CB = Ballast aggregate crushing rate

Cogo = Coordinate geometry

D = Applied track cant

Deq = Equilibrium cant the sum of track cant and cant deficiency)

dD/ds = cant gradient

dD/dt = rate of change of cant

dI/dt = the rate of change of cant deficiency

E = cant excess

V = train speed (km/h)

V_F = Max speed for freight trains,

V_{\min} = minimum train speed

V_{\max} = maximum speed

ERRI = European Rail Research Institute (former part of UIC, ceased 2004)

FACT = Research programme Fast and Comfortable Trains

I = Cant deficiency

I_{limit} = limit for cant deficiency

IP = Standard aggregate impact toughness

JBV = Jernbane Verket

K = Stone abrasive hardness coefficient

KTH = Royal Institute of Technology (Stockholm, Sweden)

LAA = Los Angeles Abrasion rate

LD = length of cant transitions

LL = Limestone liquid limit

O&M = Operation and Maintenance

Pm = Permeability coefficient

PL = Limestone plastic limit

Rec. = Recommended

Rv = vertical radius curve

S&C = Switch and Cross

TSI = Technical Specification for Interoperability

UIC = Union Internationale des Chemins de Fer (International Union of Railways)

UIC 60 = Standard rail profile

2b = Distance between the nominal centre points of the two contact patches of a wheel set on track (e.g. about 1500 mm for track gauge 1435 mm)

\dot{I} = Limit for rate of change of cant deficiency (mm/s)

\dot{I}_C = Limit for rate of change of cant deficiency, conv. non-tilting trains (mm/s) [9]

\dot{I}_T = limit for rate of change of cant deficiency, tilting trains (mm/s)

X2000 = Swedish tilting train

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CHAPTER-1: BACKGROUND OF THE THESIS

1.1. Introduction

Railway is a means of transportation guided by rails giving access to trains to move passenger or freight from one place to another place. Now days, high speed railway demand is becoming high in the world wide; for that it is competition for securing greater share of passenger market, batter utilization of rolling stock, public demand for cutting down the journey time, image building at national level, reduce manpower, and increasing service capacity.

Both transit professionals and politicians believe now is the time. Momentum and support to build high speed rail have never been greater. (Francis, 2011)

In many countries like America, China, Japan and India governments are practicing construction of high speed railway line using different techniques. For instance, India is one of the country adopting speed optimization by up grading existing track structures. (Vivek), (Singh)

The construction of new high speed railway track line needs high finance that may not be feasible in developing countries like Ethiopia.

Ethiopia is now constructing 5,000 km of modern railway line of 120km/h speed which is too slow with compare to other countries railway track speed. From this Addis Ababa - Adama line on which Addis Ababa to Djibouti, Addis Ababa to Mekele, and Addis Ababa to Hawasa will pass is about 111 km and its traffic is too heavier than other routes.

Accordingly, this study focuses on techniques of optimizing speed for Addis Ababa - Adama railway line by up-grading existing track components and introducing tilting coaches' technologies after analyzing scenario existing track.

1.2. Statement of the Problem

A review of high speed rail in many countries indicates that demand of high speed rail is increasing from time to time due to social, economic development, technological development, to achieve competitive mode of transportation, utilization of tracks and environmental issues. High speed rail has a vital contribution on accelerating economic growth of the country, in reduction transportation sector pollution, to make towns and urban alive with new jobs, increase passenger market, better utilization of rolling stock, public demand for cutting down the journey time and image building at national level.

Ethiopian government is strongly working on accessing fast, efficient, comfortable and environmental friendly transportation system in the country. However, due to budget limitation, speed and comfort of transportation system is relatively low. The maximum running speed designed for the new Ethiopian national rail network is about 120km/h which is far behind from 21st century speed demand. Construction of new high speed railway line needs huge investment that may not be feasible for developing countries like Ethiopia. Speed optimization on existing track line using different techniques is economical option of introducing high speed rail especially for developing country. For instance, India is one of the country adopting speed optimization by up grading existing track structures to achieve high speed on the existing line.

Addis Ababa – Adama line is about 111km on Addis Ababa – Djibouti national route, which is on development axis area of Ethiopia's Economy, Industrial zone of the country, competitive line with toll road of same speed and collector of regional and national routes. There is a need to do a research for the line to resolve the current and future problem and demands of high speed. The major anticipated problems/demand behind for high speed for the country national rail network and Addis Ababa – Adama line particular are for that it is Competitive with toll road of same speed, Located along the development axis area of Ethiopian economy, Located along country industrial zone of highly polluted by industry emission, National image building, Attracting investor and Delay of freight at sea port.

1.3. Objectives

1.3.1. General Objective

The general objective of the study is to survey scenario of track geometry and speed related track components for Addis Ababa - Adama route to optimize speed that economically and technically feasible.

1.3.2. The specific objectives

The specific objectives are:-

- To examine and analyze existing track geometry, track component, construction material and other speed related parameters to identify restrictive sections and the maximum allowable speed of the line.
- To identify speed optimizing techniques which are technically and economically feasible for Ethiopian railway track,
- To estimate cost of different speed optimization techniques on the existing track.

1.4. Scope of the study

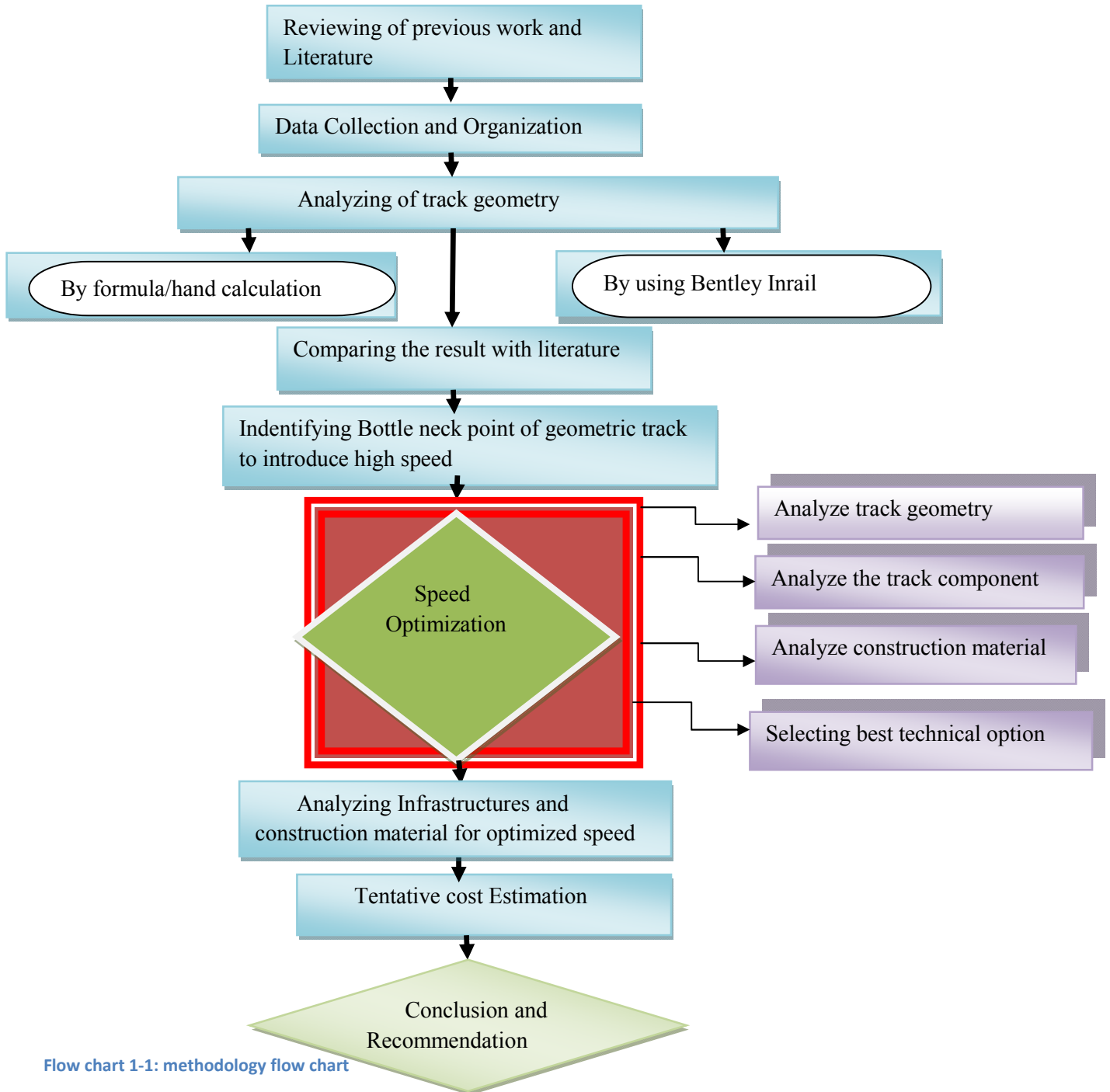
This study is limited to speed optimization and super track infrastructures and materials analysis for high speed. Bentley Inrail software's were used for geometric analysis during speed optimization process.

Introduction of tilting coach and upgrading the alignment were the technical solution identified to optimize the speed. The geometric analysis results by using Inrail software were compared with known literature for further checking. Due to time and as it need team of professional experts; the following area is not included in the study.

- ✓ Operation and maintenance guide lines for optimize speed,
- ✓ Cross-sectional drainage structure capacity i.e6. bridge and culvert.

1.5. Methodology

To achieve the study objective previous study, books and different country design code were reviewed. Necessary data were collected from Ethiopian railway head office and from the field. The optimization was under taken after existing track was analyzed. The detail is presented in the following flowchart.



Flow chart 1-1: methodology flow chart

1.6. Organization of the Thesis

This thesis has seven Chapters and Annex. The first Chapter contains background of the thesis, objectives, materials and methods and scope of the thesis.

Chapter two covers a literature review regarding track geometry parameters, tilting coach technology and revision of different countries design standards.

The third Chapter is about data collection and organization. Chapter four is about data analysis and discussion. Chapter five is about speed optimization. Chapter six is about tentative cost estimation for upgraded track section to get high speed.

Chapter seven contains conclusions and recommendations. Annex which contain software analysis results are presented after the reference

CHAPTER-2 LITERATURE REVIEW

2. General

High speed trains are transforming Europe and Asia, bringing cities and countries within a few hours of each other. Towns and industries have come alive with new jobs and economies being created and with air travel becoming more obsolete, air pollution is being drastically cut. (Francis, 2013)

2.1. Definition of high speed

The definitions vary according to the criteria used since high speed rail corresponds to a complex reality. At all events, high speed is a combination of all the elements which constitute the "system": infrastructure, rolling stock and operating conditions.

Infrastructure:

- a) Those built specially for High Speed travel, those specially upgraded for High Speed travel. They may include connecting lines, in particular junctions of new lines upgraded for High Speed with town center stations located on them, on which speeds must take account of local conditions.
- b) High Speed lines shall comprise specially built High Speed lines equipped for speeds generally equal to or greater than 250 km/h, specially upgraded High Speed lines equipped for speeds of the order of 200 km/h, and specially upgraded High Speed lines which have special features as a result of topographical, relief or town-planning constraints, on which the speed must be adapted to each case.

Compatibility of infrastructure and rolling stock:

High Speed train services presuppose excellent compatibility between the characteristics of the infrastructure and those of the rolling stock. Performance levels, safety, quality of service and cost depend upon that compatibility.

Selection of High Speed System:

The decision on the type of traffic is very important, for it has immediate and basic consequences for the route of the track, the maximum, permissible axle loads, the conditions and the equipment for operation and maintenance.

Tilting Trains are not very popular now days. However, it is conceivable, in principle, to design tilting trains in the future for high speeds above which could operate on the high speed lines with larger cant deficiencies than are allowed for conventional high speed trains. (A.K.GOEL, 2008)

2.2. Techniques of introducing high speed

Techniques used for introducing high speed are: (Singh)

- a) Dedicated high speed rail corridors
- b) Up gradation of existing conventional rail systems
- c) Combination of the above two types of techniques.
- d) Introducing tilt coach technology

2.3. Track alignment design parameters

The following are important geometric design parameters : (*EN 13803, 2010*)

- ✓ radius of horizontal curve $R(m)$ (*S);
- ✓ cant D (mm) (*S);
- ✓ cant deficiency I (mm) (*S);
- ✓ cant excess E (mm);
- ✓ cant gradient $dD/ds(mm/m)$ (*S);
- ✓ rate of change of cant dD/dt (mm/s);
- ✓ rate of change of cant deficiency (and/or cant excess) $dI/dt(mm/s)$;
- ✓ length of cant transitions $LD(m)$ (*S);
- ✓ length of transition curves in the horizontal plane $L_R(m)$; length of alignment elements (circular curves and straights) between two transition curves $L_i(m)$;
- ✓ radius of vertical curve $R_v(m)$;
- ✓ speed $V(km/h)$ (*S).

Parameters followed by the (*S) note indicate safety-related parameters

2.4. Track geometric Design parameters Definitions and standards

1. Track gauge

Track gauge is the distance between the inner faces of the rail heads of the track. The track gauge is measured 14 mm below the top of the rail on the inner face. Standard track gauge is 4 feet, 8-1/2 inches or approximately 1435 mm. (*Rickard Persson, 2011*)

2. Circular horizontal curve

Circular horizontal curve is a curve in the horizontal plane with constant radius. The circular horizontal curve is characterized by its radius R which is related to the track center line. The circular horizontal curve may also be characterized by its curvature which is the inverse to the radius. (*Rickard Persson, 2011*)

The largest curve radii and transition permitted by track design constraints should be used where possible.

Normal limit for radius is 190 m and exceptional limit is 150 m. Note that these small radii will result in a permissible speed less than 80 km/hr. Hence, normal and exceptional limits for the radius shall also be derived from the requirements below.

The parameters that shall be considered in the determination of the minimum curve radius are:

- The maximum and minimum speeds;
- The applied cant;
- The limits for cant deficiency and cant excess.

For every combination of maximum speed V_{max} and maximum cant deficiency I_{lim} , the minimum permissible curve radius shall be calculated using the following equation.

$$R_{min} = \frac{c}{D + I_{lim}} \cdot V^2 \dots\dots\dots 2-1$$

Where $c = 11.8 \text{ mm.m.h}^2/\text{km}^2$ (for standard gauge track)

Where $D > E_{lim}$,

The maximum permissible speed curve radius for the minimum speed V_{min} shall be calculated using the following equation:

$$R_{max} = \frac{c}{D - E_{lim}} \cdot V^2_{min} \dots\dots\dots 2-2$$

Where $c = 11.8 \text{ mm.m.h}^2/\text{km}^2$, and $D > E_{lim}$

NOTE 1: It is recommended that the radius of tracks alongside platforms should not be less than 500 m. This is to restrict the gap between platform and vehicles to facilitate safe vehicle access and egress by passengers.

NOTE 2: Small radius curves may require gauge widening in order to improve vehicle curving. (EN 13803, 2010)

3. Transition curve

Transition curves are used to connect straight track to circular horizontal curves or to connect two circular horizontal curves. The transition curve is characterized by its curvature as function of the longitudinal position. The most common transition curve has linear variation of the curvature; this type of transition curve is called clothoid. (Rickard Persson, 2011)

4. Track cant

Track cant D (or super elevation) is the amount one running rail is raised above the other running rail (in a curve). Track cant is positive when the outer rail is raised above the inner rail. (Rickard Persson, 2011)

Cant shall be determined in relation to the following considerations: (EN 13803, 2010)

- High cant on small-radius curves increases the risk of low-speed freight wagons derailing. Under these conditions, vertical wheel loading applied to the outer rail is much reduced, especially when track twist (defined in EN 13848-1) causes additional reductions;
- Cant exceeding 160 mm may cause freight load displacement and the deterioration of passenger comfort when a train makes a stop or runs with low speed (high value of cant excess). Works vehicles and special loads with a high centre of gravity may become unstable;
- High cant increases cant excess values on curves where there are large differences between the speeds of fast trains and slow trains.

Normal limit for cant is 160 mm

NOTE: it is recommended that cant should be restricted to 110 mm for tracks adjacent to passenger platforms. Some other track features, such as level crossings, bridges and tunnels may also, in certain local circumstances, impose cant restrictions.

Exceptional limit for cant is 180 mm.

To avoid the risk of derailment of torsion ally-stiff freight wagons on small radius curve ($R < 320$ m), cant should be restricted to the following limit: (EN 13803, 2010)

$$D_{lim} = \frac{R - 50m}{1.5m/mm} \dots\dots\dots 2-3$$

Where, D_{lim} = normal limit applied cant and R = Radius of horizontal curve

5. Cant deficiency

Cant deficiency I arises when the installed cant is lower than the cant of equilibrium. The cant deficiency is characterized by the additional cant needed to receive equilibrium. (*Rickard Persson, 2011*)

For given values of local radius R and cant (D), the cant deficiency (I) shall determine the maximum permissible speed through a full curve such that:

$$I = C \cdot \frac{V^2}{R} - D = E - D \leq I_{lim} \dots\dots\dots 2-4$$

Where, I = Cant deficiency, R = Radius of horizontal curve, V = permissible speed, D = applied cant, E = equilibrium cant, I_{lim} = normal limit of cant deficiency

Normal and Exceptional Limits for Cant Deficiency

Table 2-1: Cant deficiency Ilim (EN 13803, 2010)

	Normal limits	Exceptional limits
Non-tilting trains		
80km/h < V ≤ 200km/h	130mm	183mm
200km/h < V ≤ 230km/h	130mm	168mm ^{ab}
230km/h < V ≤ 250km/h	130mm	153mm ^{ab}
250km/h < V ≤ 300km/h	100mm	130mm ^{abc}
Tilting trains		
80km/h < V ≤ 260km/h	275mmb	306mmb
<i>^a Trains complying with EN 14363, equipped with a cant deficiency compensation system other than tilt, may be permitted by the Infrastructure Manager to run with higher cant deficiency values.</i>		
<i>^b The Infrastructure Manager may require qualification of a part of a line for the introduction of trains running at these or higher cant deficiencies, taking into account the required track quality and other conditions.</i>		
<i>^c The limit may be raised to 153 mm for non-ballasted track.</i>		
<i>^d Currently, there are no lines used or planned where maximum speed for tilting trains exceeds 260 km/h</i>		

6. Cant Excess (E)

There is cant excess when the following has a positive value:

$$E = D - C \cdot \frac{V^2}{R} \dots\dots\dots 2-5$$

Where, C= 11. 8 mm·m·h²/km², Normal limit for cant excess E_{lim} is 110 mm.

The value of E affects inner-rail stresses induced by slow trains, since the quasi-static vertical wheel/rail force of an inner wheel is increased. (EN 13803, 2010)

7. Cant transitions

Cant transitions (or super elevation ramps) are used to connect two different track cants. The cant transition has in most cases the same longitudinal position as the transition curve. The cant gradient is

characterized by its longitudinal distance to raise one unit (normally expressed as 1 in X, where X is the longitudinal distance in units). The most common cant transition has a linear variation of the track cant. (Rickard Persson, 2011)

8. Rate of change of cant

Rate of change of cant is the rate of which cant is increased or decreased at a defined speed. The rate of change of cant is characterized by the cant change per time unit dD/dt . The most common cant transition has constant rate of change of cant. (Rickard Persson, 2011)

9. Rate of change of cant dD/dt for non-tilting trains

Cant transitions are normally found in transition curves. However, it may be necessary to provide cant transitions in circular curves and straights

For cant transitions with constant cant gradient, the following relationship with ΔD being the cant variation shall apply: (EN 13803, 2010)

$$\frac{dD}{dt} = \frac{\Delta D}{L_D} \cdot \frac{V}{q_v} < \left(\frac{dD}{dt}\right)_{lim} \dots\dots\dots 2-6$$

Where, L_D = the length of the cant transition in meters, dD/dt = rate of change of cant, ΔD = applied cant variation, V = vehicle speed in km/h and $q_v = 3.6 \text{ km} \cdot \text{s} / (\text{h} \cdot \text{m})$.

Table 2-2: Rate of change of cant deficiency for non-tilting coach (EN 13803, 2010)

	Normal limits	Exceptional limits
Non –tilting trains $V \leq 200\text{km/h}$		
$I \leq 168 \text{ mm}$	50 mm/s	70 mm/s ^a
$168 < I \leq 183 \text{ mm}$	50 mm/s	50 mm/s
Non –tilting trains $200\text{km/h} \leq V < 300\text{km/h}$		
	50 mm/s	60 mm/s

For cant transitions with variable cant gradient, the value of dD/dt is not constant.

$$\left(\frac{dD}{dt}\right)_{\max} < \left(\frac{dD}{dt}\right)_{lim}$$

Normal limit $\left(\frac{dD}{dt}\right)_{lim} = 55 \text{ mm/s}$, Exceptional limit $\left(\frac{dD}{dt}\right)_{lim} = 76 \text{ mm/s}$

10. Rate of change of cant dD/dt for tilting trains

Both active and the passive tilt systems need certain time to adapt the angle of tilt to the curve radius and it is for this reason that curves shall include transition sections of sufficient length.

The transition curves should coincide with the cant transitions. If they do not, then special running tests are recommended to determine to what extent the maximum cant deficiency may need to be reduced.

The clothoid is normally used for transition curves, giving a linear variation of curvature. Where using transition curves with non-constant gradients, the function of the tilt system shall be taken into account for the analysis of the complex interaction between the vehicle and the track. (EN 13803, 2010)

Normal limit $\left(\frac{dD}{dt}\right)_{lim} = 75 \text{ mm/s}$ and Exceptional limit $\left(\frac{dD}{dt}\right)_{lim} = 76 \text{ mm/s}$

11. Rate of change of cant deficiency

Rate of change of cant deficiency is the rate of which cant deficiency is increased or decreased at a defined speed. The rate of change of cant deficiency is characterized by the cant deficiency change per time unit dI/dt . The most common transition curve / cant transition has constant rate of change of cant deficiency.

For track elements with a variation of curvature and/or a variation of cant the following relationship has to be fulfilled. (Rickard Persson, 2011)

$$\frac{dI}{dt} = \frac{\Delta I}{L_D} \cdot \frac{V}{q_v} < \left(\frac{dI}{dt}\right)_{lim} \dots \dots \dots 2.7$$

Where, L_D = the length of the cant transition in meters, ΔI = variation of cant deficiency, V = vehicle speed in km/h and $q_v = 3.6 \text{ km} \cdot \text{s} / (\text{h} \cdot \text{m})$

Table 2-3: Rate of change of cant deficiency (dI/dt) for constant can gradient (EN 13803, 2010)

	Normal limit	Exceptional limits
Non-tilting trains $v \leq 200$ km/h		
$I \leq 168$ mm	55mm/s	100mm/s
$168 < I \leq 183$ mm	55mm/s	90mm/s
Non-tilting trains $200 \text{ km/h} < v \leq 300 \text{ km/h}$		
	55 mm/s	75 mm/s

In case of using tilting trains on given alignment, the values of dI/dt are higher. The tilt control system creates transient states at the entry to curves, which may give rise to even more pronounced jerks. Both active and the passive tilt systems need certain time to adapt the angle of tilt to the curve radius and it is for this reason that curves shall include transition sections of sufficient length.

normal limit: $\left(\frac{dI}{dt}\right)_{lim} = 100 \text{ mm/s}$

12. Track gradient

Track gradients are used to connect tracks at different altitudes. The track gradient is normally characterized in per mile (or per cent), but in certain countries as longitudinal distance to raise one unit (normally expressed as 1 in X, where X is the longitudinal distance in units). (Rickard Persson, 2011)

13. Cant Gradient dD/ds

The following limits apply everywhere along the track where cant is varying:

$$\left(\frac{dD}{ds}\right)_{max} \leq \left(\frac{dD}{ds}\right)_{lim} \dots\dots\dots 2-8$$

$$\text{Normal limit: } \left(\frac{dD}{ds}\right)_{lim} = 2.25 \text{ mm/m, and Exceptional limit: } \left(\frac{dD}{ds}\right)_{lim} = 2.5 \text{ mm/m}$$

For cant transitions with constant cant gradient, $\left(\frac{dD}{ds}\right)_{max}$ can be calculated from the overall cant variation ΔD and the length LD:

$$\frac{dD}{ds} = \frac{\Delta D}{LD} \leq \left(\frac{dD}{ds}\right)_{lim} \dots\dots\dots 2-9$$

There is no further special limit for the tilting trains. (EN 13803, 2010)

14. Vertical curve

Vertical curves are used to connect two different track gradients. Vertical curves are normally circular curves. The vertical curve is characterized by its radius R_v . (Rickard Persson, 2011)

Vertical curves should be at least 20 m long and may be designed without vertical transition curves.

NOTE: Vertical curves are normally designed as parabolas (2nd degree polynomials) or as circular curves.

A vertical curve shall be provided where the difference in slope between adjacent gradients is more than:

- 2 mm/m for permissible speeds up to 230 km/h;
- 1 mm/m for permissible speeds over 230 km/h

15. Radius of vertical curve R_v

The normal limit for radius of vertical curve is: (EN 13803, 2010)

$$R_{v, \text{lim}} = qR, \text{lim} \cdot V^2 \dots\dots\dots 2-10$$

NOTE 1: On lines where most of the passengers may be standing, it is recommended that qR should be greater than $0.77 \text{ m} \cdot \text{h}^2/\text{km}^2$

The exceptional limit for radius of vertical curve is:

$$R_{v, \text{limit}} = qR, \text{itm} \cdot V^2 \dots\dots\dots 2-11$$

Where, $qR, \text{lim} = 0.13 \text{ m} \cdot \text{h}^2 / \text{km}^2$ for sag and $qR, \text{lim} = 0.16 \text{ m} \cdot \text{h}^2 / \text{km}^2$ for crest.

2.5. Introduction of Tilting Coaches' Technology

A tilting train deploys tilting mechanism which enables increase of speed of the special stock on existing track. As we know, any train negotiating the curve subjects the objects inside the train, which is otherwise in a non-inertial frame to centrifugal forces around center of curvature.

The tilting coaches are designed to counteract these forces and accordingly the passenger coaches are tilted sideways depending on the type and degree of the curve. Such type of system is used in many Railway worlds over including Spain, British rail, Switzerland and Italy. Swedish railway, in fact has high-speed services called EX. 2000, which uses tilting technology to be able to run at a high speed of 200 kmph on existing track. (Vivek)

To overcome the limitation of speed on account of tight curves on mixed traffic routes, where it is not possible to cant the track, carriages having tilting mechanisms can be used. Trains that tilt can go up to 25% to 40% faster around curves than conventional trains without upsetting the passengers and this can significantly increase the speed on existing lines.

Tilting trains can negotiate curves at up to full speed, which is 35 to 45 percent faster than conventional trains without any effect on the quality of ride. ([A.K.Yadav])

The tilt mechanism reduces the lateral acceleration perceived by the passengers. Therefore, tilting trains, if provided with a suitable running gear, may run at higher cant deficiencies than non-tilting trains. However, the nominal track geometry still defines a ceiling for permissible train speed, but at a higher level. (Vivek)

1. Tilting train

Train with capability to tilt the car body inward in track curves, thus reducing the lateral acceleration perceived by the passengers. (*Rickard Persson, 2011*)

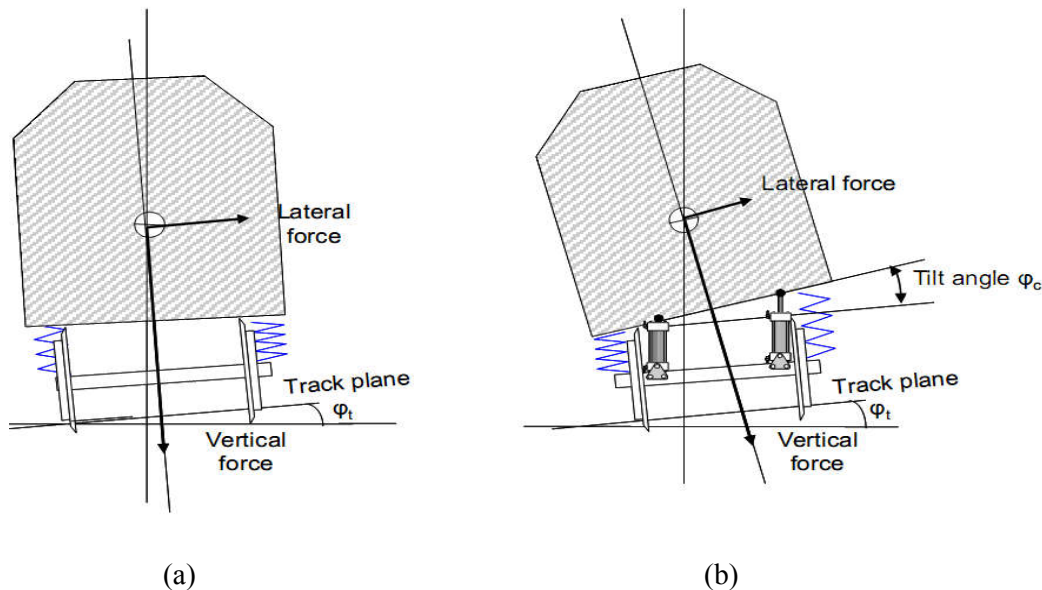


Figure 2-1: (a) Conventional train and (b) Tilting train

2. Tilt compensation (effective)

Proportion of track plane acceleration removed by tilt with reference to the car body floor plane (net value when also deflections in primary and secondary suspensions have been taken into account (*Rickard Persson, 2011*))

3. Tilt angle (effective)

Proportion of track plane acceleration removed by tilt with reference to the car body floor plane (net value when also deflections in primary and secondary suspensions have been taken into account)

2.6. Enhanced Permissible Speed for Tilting Trains

Two countries have reported special rules for the relation of permissible speed for conventional trains and enhanced permissible speed for tilting trains

In Italy, enhanced permissible speed for tilting trains is (at a maximum) 18% higher than permissible speed for conventional trains of Category C, and 31% faster than permissible speed for conventional trains of Category A.

In Sweden, the transponders for the APT-system give the permissible speed for conventional trains of Category A. The transponders also contain information whether full, half or no enhanced speed is permitted. The enhanced speed is defined as a percentage in the on-board computer on the train. Tilting trains use 30% as relative enhanced speed. Finally, the enhanced speed is rounded downwards to the nearest multiple of 5 km/h. Hence, tilting trains in Sweden do not run more than 30% faster than conventional trains of Category A. (KUFVER, 2005)

2.6.1. Enhanced Permissible Speed on Circular Curves

The permissible speed on the circular portion of a curve may be expressed as: (KUFVER, 2005)

$$V = \sqrt{R \cdot \frac{I_{lim} + D_{lim}}{11.8}} \dots\dots\dots 2-12$$

Where; V = permissible speed (km/h), I_{lim} = permissible cant deficiency (mm), standard gauge, D_{lim} = permissible cant (mm), standard gauge, R = radius of horizontal curve (m), 11.8 = factor applicable for standard gauge 1435 mm

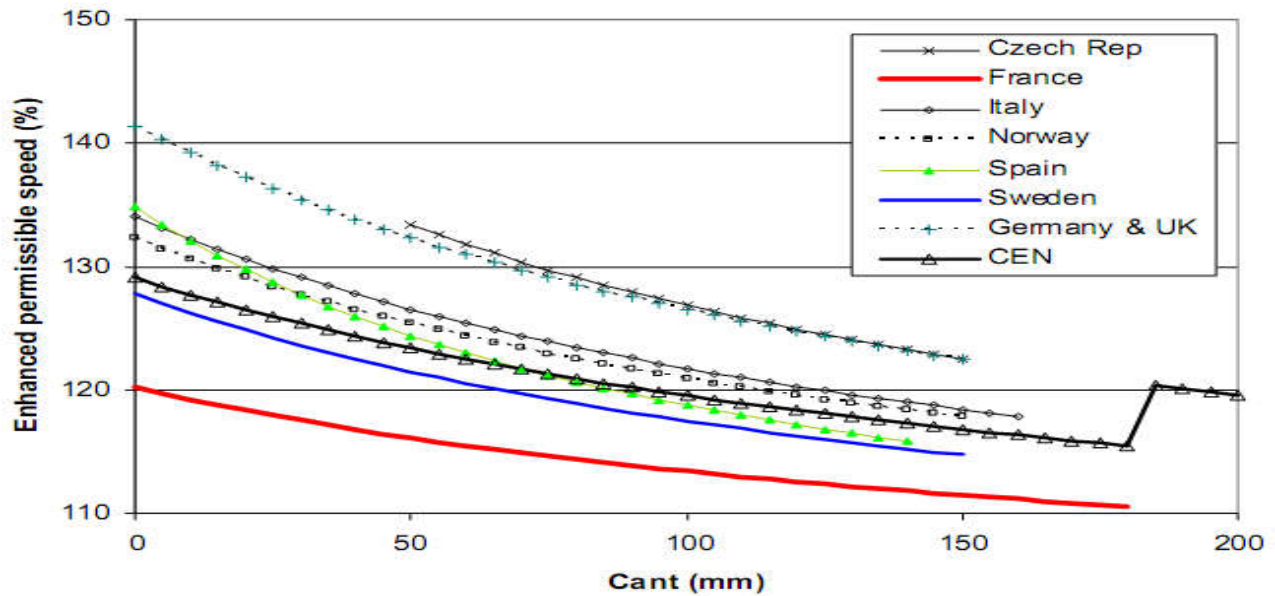


Figure 2-2: Enhanced permissible speeds for tilting trains as a percentage of permissible (KUFVER, 2005)

2.6.2. Enhanced Permissible Speed on Super Elevation Ramps

On super elevation ramps, the relation between enhanced permissible speed for tilting trains (V_T) and permissible speed for conventional trains (V_C) on super elevation ramps may be calculated according to the following formula.

$$\frac{V_T}{V_C} = \frac{D_T}{D_C} \dots\dots\dots 2-13$$

Where, \dot{D}_T = limit for rate of change of cant, tilting trains (mm/s), \dot{D}_C = limit for rate of change of cant, conventional non-tilting trains (mm/s), V_T = Speed of tilting trains (km/h), V_C = Speed of conventional non-tilting trains (km/h)

The relation between enhanced permissible speed (EPS) for tilting trains and permissible speed for conventional trains on super elevation ramps can be found in the range from 100% to 131%. Hence, certain railway companies do not allow enhanced speed for tilting trains on super elevation ramps where the rate of change of cant is binding for the permissible speed. (KUFVER, 2005)

2.6.3. Enhanced Permissible Speed on Transition Curves

On transition curves several limits apply: The cant deficiency, the rate of change of cant deficiency, and, if combined with a super elevation ramp, the cant gradient and the rate of change of cant. In this section,

the cases (“very short transition curves”) where the combination of the rate of change of cant and the rate of change of cant deficiency is binding are in focus.

The cant gradient becomes a problem only at low speed applications, where this criterion becomes binding instead of the rate of change of cant. For cases where cant or cant deficiency becomes binding, together with the rate of change of cant deficiency or rate of change, the enhanced permissible becomes within the range of the enhanced permissible on circular curves and the enhanced permissible speed on very short transition curves.

For very short transition curves, the permissible speed depends on the choice of cant in the following way. The highest permissible speed is achieved when both the limit for rate of change of cant and rate of change of cant deficiency is fully used.

The equation applies for a transition curve between a straight and a circular curve.

$$\dot{D} + \dot{I} = 11.8 \cdot \frac{V^2}{R} \cdot \frac{V}{3.6L_t} \dots\dots\dots 2-14$$

Where, \dot{D} = limit for rate of change of cant (mm/s), \dot{I} = limit for rate of change of cant deficiency (mm/s), V = train speed (km/h), R = curve radius (m), L_t = length of transition curve (m)

The application of Equation [2-14] assumes that the amount of cant is fine-tuned to balance the limits \dot{D} and \dot{I} . The relation between the enhanced permissible speed for tilting trains (V_T), when cant is optimized for these trains, and the permissible speed for conventional non-tilting trains (V_C), when the amount of cant optimized for conventional trains, becomes: (KUFVER, 2005)

$$\frac{V_T}{V_C} = \sqrt{\frac{\dot{D}_T + \dot{I}_T}{\dot{D}_C + \dot{I}_C}} \dots\dots\dots 2-15$$

Where, \dot{D}_T = limit for rate of change of cant, tilting trains (mm/s), \dot{I}_T = limit for rate of change of cant deficiency, tilting trains (mm/s), \dot{D}_C = limit for rate of change of cant, conventional non-tilting trains (mm/s) and \dot{I}_C = limit for rate of change of cant deficiency, conv. non-tilting trains (mm/s)

2.6.4. Enhanced Permissible Speed at Instantaneous Changes of Curvature

In the track standards reported to FACT, and in a draft CEN (2004b) standard, there are two different methods to define the permissible speed at instantaneous changes of curvature.

Railway companies that apply a limit on the instantaneous change of cant deficiency will achieve the same permissible speed for all types of trains where the instantaneous change of curvature determines the permissible speed. No enhanced speed for tilting trains will be permitted.

Railway companies that use the concept of virtual transitions (assuming a transition curve with a length that represents the bogie distance within the vehicle) will apply the same equations as for transition curves. However, the transition length is very short (10m for Italy, 12.2m for United Kingdom). Over this short distance, there will be almost no space to arrange a super elevation ramp. If the tilt system requires a cant gradient to activate, no enhanced speed will be achieved. If the tilt system activates also where cant gradients are not present, the enhanced speed may be calculated as the following Equation. (KUFVER, 2005)

$$\frac{v_T}{v_C} = \sqrt{\frac{\dot{I}T}{\dot{I}C}} \dots\dots\dots 2-16$$

Where; $\dot{I}T$ = limit for rate of change of cant deficiency, tilting trains (mm/s) and $\dot{I}C$ = limit for rate of change of cant deficiency, conv. non-tilting trains (mm/s)

2.6.5. Enhanced Permissible Speed for Vertical Curves

The tilt system cannot compensate for high level of vertical acceleration on a vertical curve. Hence, there is no reason to have different limits for vertical radii for tilting and non-tilting trains.

It may be reasonable to take tilt aspects into account when designing new lines.

For a given horizontal radius, preferred vertical radius is larger and preferred lengths of transition curves are longer compared to an alignment optimized for non-tilting trains.

On existing lines, vertical radii may be difficult to increase. However, transition curves may be lengthened with or without simultaneous reductions of horizontal radii (In order to minimize necessary slewing of the track) such modifications of the track geometry may be achieved at small marginal cost during track renewals. (KUFVER, 2005)

Vertical curves should be at least 20 m long and may be designed without vertical transition curves.

NOTE: - Vertical curves are normally designed as parabolas (2nd degree polynomials) or as circular curves.

2.7. Vertical Curve Radius, R_v Limitation

The normal limit for radius of vertical curve is calculated as follow. [EN 13803, 2010]

$$R_{v, \text{lim}} = q_{R, \text{lim}} \cdot V^2 \dots\dots\dots 2-17$$

Where $q_{R, \text{lim}} = 0,35 \text{ m} \cdot \text{h}^2/\text{km}^2$

NOTE:- On lines where most of the passengers may be standing, it is recommended that (q_R) should be greater than $0.77 \text{ m} \cdot \text{h}^2/\text{km}^2$

The exceptional limit for radius of vertical curve is

$$R_{v, \text{lim}} = q_{R, \text{lim}} \cdot V^2 \dots\dots\dots 2-18$$

Where, $q_{R, \text{lim}} = 0,13 \text{ m} \cdot \text{h}^2/\text{km}^2$ for sag, and $q_{R, \text{lim}} = 0.16 \text{ m} \cdot \text{h}^2/\text{km}^2$ for crest.

2.8. Different countries design standard

Limits for the track variables, such as cant deficiency, rate of change of cant deficiency rate of change of cant, construction material and track component dimension are vary among different countries design standard. The following are some countries design standard review.

2.8.1. France

The French track standards distinguish between non-tilting trains running at lower and higher speeds than 200km/h, respectively.

Table 2-4: Certain limits in the French track standards (KUFVER, 2005)

Train category	Conventional trains		Tilting Trains
	V ≤ 200km/hr	V > 200km/h, V ≤ 220km/h	
Max Cant, D(mm)	*180 **160	*180 **160	*180 **160
Max Cant, Deficiency, I(mm)	*180 **50	160	260
max rate of change of cant dD/dt (mm/s)	*60 **50	*60 **50	*60 **50
Max rate of change of cant deficiency, dI/dt (mm/s)	*90 **55	*75 **50	No limit
Min length between super- elevation ramps(m)	50	50	50

Where, * Recommended and ** Limit

No limits on rate of change of cant deficiency for tilting trains have been reported to FACT. Assuming that running a tilting train run on a straight into a curve at a given cant (D), cant deficiency (I), and rate of change of cant (dD/dt), the following equation may be used to calculate the corresponding rate of change of cant deficiency.

$$(dI/dt)_T = (dD/dt)_T \cdot \frac{I_T}{D} \dots\dots\dots 2-12$$

With (dD/dt) = 60 mm/s, I = 260 mm, and D = 180 mm, the rate of change of cant deficiency (dI/dt) becomes 87 mm/s. At lower cant values, the rate of change of cant deficiency may be higher. For example, with 60 mm of cant, the rate of change of cant deficiency may be 260 mm/s.

2.8.2. Germany

The German railways define two categories of trains: Non-tilting and tilting trains.

Table 2-5: Certain limits in the German track standards Source: (DB 1999)

Train category	Conventional	Tilting
Max Cant, D(mm) (Note A)	160-180	160 -180
Max Cant, D(mm) at Switches and crossing	100-150	100-150
Max cant deficiency , I(mm)	150	300
Max cant deficiency , I(mm) at Switch & Crossing	72 – 150	150
Max rate of change of cant, dD/dt (mm/s)	46	46
Max rate of change of cant deficiency, dI/dt mm/s	69	Not specified
Min length between super-elevation ramps meter per Km/h	V/10(in certain cases)	Not specified

Note A: On curves with small radii, another limit for cant is $(R-50 \text{ m})/1.5$ (mm per meter).

The limit for cant deficiency at switch and crossing (S&C) depends on the permissible speed and the type of turnout or diamond crossing.

2.8.3. Norway

The Norwegian National Rail Administration (Jernbaneverket, JBV) defines three categories of trains: Normal trains, Express trains and Tilting trains. There are no pre-defined relations between permissible speeds for the train categories. Table 2.8-3 shows certain limits in the Norwegian track standards.

Table 0-6: Certain limits in the Norwegian track standards. Source: JBV (1999)

Train category	old conventional passenger trains and freight	conventional express trains	Tilting Trains
Max cant, D(mm) (Note A)	150	150	150
Max cant Deficiency, I(mm)	R<290m: 100, 290m≤R≤600m: 130, R>600m: 150	160	280
Max cant Deficiency, I(mm), at stiff track (Note B)	R≤350m: 100, R>350m: 130	R≤350m: 100, R>350m: 130	180
Max rate of change of cant, (mm/s)	55	69	75
Max. rate of change of cant deficiency, (mm/s)	80	100	140
Max cant excess (for freight trains)	R≤600m: 90, R>600m: 110	-	-
Max speed for freight trains, V _F (km/hr)	90	-	-

Table 2-7: Certain track geometry limits for plain track - exceptional values. (Dr B. KUFVER, 2005)

	Cant D (mm)	dD/dt (mm/s)	Cant def. I (mm)	dI/dt (mm/s)
CEN- Conventional Trains	180-200	55-60	150 -180	75-90
CEN - Tilting trains	180-200	75	300	No limit
TSI - Conventioonal Trains	180-200	No limit	180	No limit
Czech Rep. - Conv. Trains	150	35	100	70
Czech Rep. - Express Trains	150	35	130	70
Czech Rep. - Tilting trains	150	46	270	115
France - conv. Trains	180	60	180	90
France - Tilting. Trains	180	60	260	No limit
Germany - Conv. Trains	180	46	150	69
Germany - Tilting Trains	180	46	300	Not specified
Italy - conv. Trains A	160	54	92	38
Italy - conv. Trains B	160	57	122	54
Italy - conv. trains C	160	60	153	66
Italy- Tilting Trains	160	71	275	120
Norway - Conv. Trains	150	55	150	80
Norway - Express Trains	150	69	160	100
Norway - Tilting trains	150	75	280	140
Spain - conv. Trains (equivalent for std gauge)	160 (139)	45 (39)	115 (100)	35 (30)
Spain-Tilting Trains (equivalent for std gauge)	160 (139)	50 (43)	210 (182)	55(48)
Sweden - Conv. Trains A	150	46	100	46
Sweden - Conv. Trains B	150	44	150	55
Sweden - Tilting trains	150	60	245	79
UK -Conv. Trains	180	85	110	70
UK -Express Trains	180	85	150	70
UK - Tilting trains	180	95	300	150

2.9. Design Speed Related Track Component and Materials

2.9.1. Ballast

Almost all leading world railways provide a layer of sub-ballast along with ballast. However, there is wide variation in the practices followed in different countries of the world. The depth of ballast and sub ballast which are in use on the various railways are given below: (MITTAL,)

Table 2-8: Characteristics of ballast and sub-ballast. (MITTAL,)

S.N	Railway system	Depth of		Remark
		Ballast(mm)	Sub-ballast(mm)	
1	Australia	200-300	150	
2	England	225-375	Variable	
3	France	150-350	Variable	
4	UIC	250-550	Variable up to 450	
5	Japan	300	200	
6	Swedish Railway	240	90	
7	USA	300	300	

2.9.2. Rail

There is general agreement between the various railways on the fact that it is not necessary to use different types of rail for different speeds. Thus both for 300 km/h and for 350 km/h, it is the rail type UIC 60 which is recommended.

The quality of the rail is not, in principle, affected by the increase in speed above 300 km/h, if the rail to be laid is of the “top of the range” type. However, it is recommended that attention should be paid to the aspects: acceptance assembly, welding, surface defects etc.

Certain railways consider that the length of the individual rails should not be close to 36 meters, to avoid running on some particular points due to the welding which have a critical wave length. Standard length of 25m in Japan, 54m/62m in Germany and 108m in France has been utilized. CWR is used to improve the ride quality and to reduce noise and vibrations.

The inclination of the rail is 1:20 as is normally used in all the countries concerned, with the sole exception of Germany which uses 1:40. The STIs recommend 1:20 for speeds above 280 km/h. However now for high speed 1 in 40 is being recommended and used.

The STIs specify the values of the distance apart, inclination and wheel profiles which enable the lowest possible equivalent conicity to be obtained above 280 km/h (without distinction between 300, 350km/h, etc.) Other things being equal, the higher the speed, the less should be the equivalent conicity. It is necessary to study the wear profile, vis-à-vis the economy of operation and to observe the equivalent theoretical conicity.

Generally 60 kg/m rail track is considered acceptable all over the world for high speed corridor . Thus, it is proposed to have 60 kg 90 UTS FF UIC new rails with CWR/LWR over the entire stretch as per the provision of permanent way manual for Indian High Speed Corridor .

There is no problem with the quality of the rail, but attention needs to be paid to aspects such as, acceptance assembly, welding and surface defects. The equivalent conicity should be further and further reduced as the speed is increased and the wear profiles should also be monitored. (KUFVER, 2005)

2.9.3. Sleeper

Parameters of different types of sleepers such as space, weight, length, width, height, effective surface area per rail and other characteristics used by the railway depending on the tracks speed. The pre stressed concrete sleepers have been a better choice as they have long life 50 to 60 years. (Rajesh, 2008)

The effective surface area of the sleepers is an essential factor for the distribution of the vertical forces exerted on the ballast, but the magnitude of this surface area and its possible variation depending on the speed have not been dealt with in an explicit manner . There are no obvious problems for sleepers (checking of the bearing surface only).

Table 2-9: sleeper's parameters used by railways in different countries (Rajesh, 2008)

Parameter	Country									
	France		Germany		Italy		Spain		Belgium	SIT
speed KMPH	300	350	300	300/350	300	300/350	300	350	350	350
Type	Two block/mono block	Two block/mono block	mono block B 90	mono block B 75	mono block	mono block	mono block	mono block	mono block	
Sleeper(spacing number of sleeper/km)	1666	1666	1666	1587	1666	1666	1666	1666	1666	1600
weight (kg)	245/290	245/290	330	380	400	400	300	320	300	>220
Length (mm)	2415/2500	2415/2500	2600	2800	2600	2600	2500	2600	2500	2250
Width (mm)	290	290	320	330	300	300	300	300	300	300
height (mm)	220	220	180	200	220	220	222	242	200 to 215	
Effective surface area per rail (cm ²)	2436/3344	2436/3344	3340	3730	3900	3010	310	3010	3668 (approx.)	

CHAPTER -3 DATA COLLECTION

3. General

Addis Ababa – Adama rail line design speed related data have been collected from Ethiopian Railway Corporation Head Office and from field observation. These data are center line data/alignment data, construction material data, infrastructure, crossing type and location, right of way data and topographic data. The Addis Ababa – Adama rail line route is shown in following map.

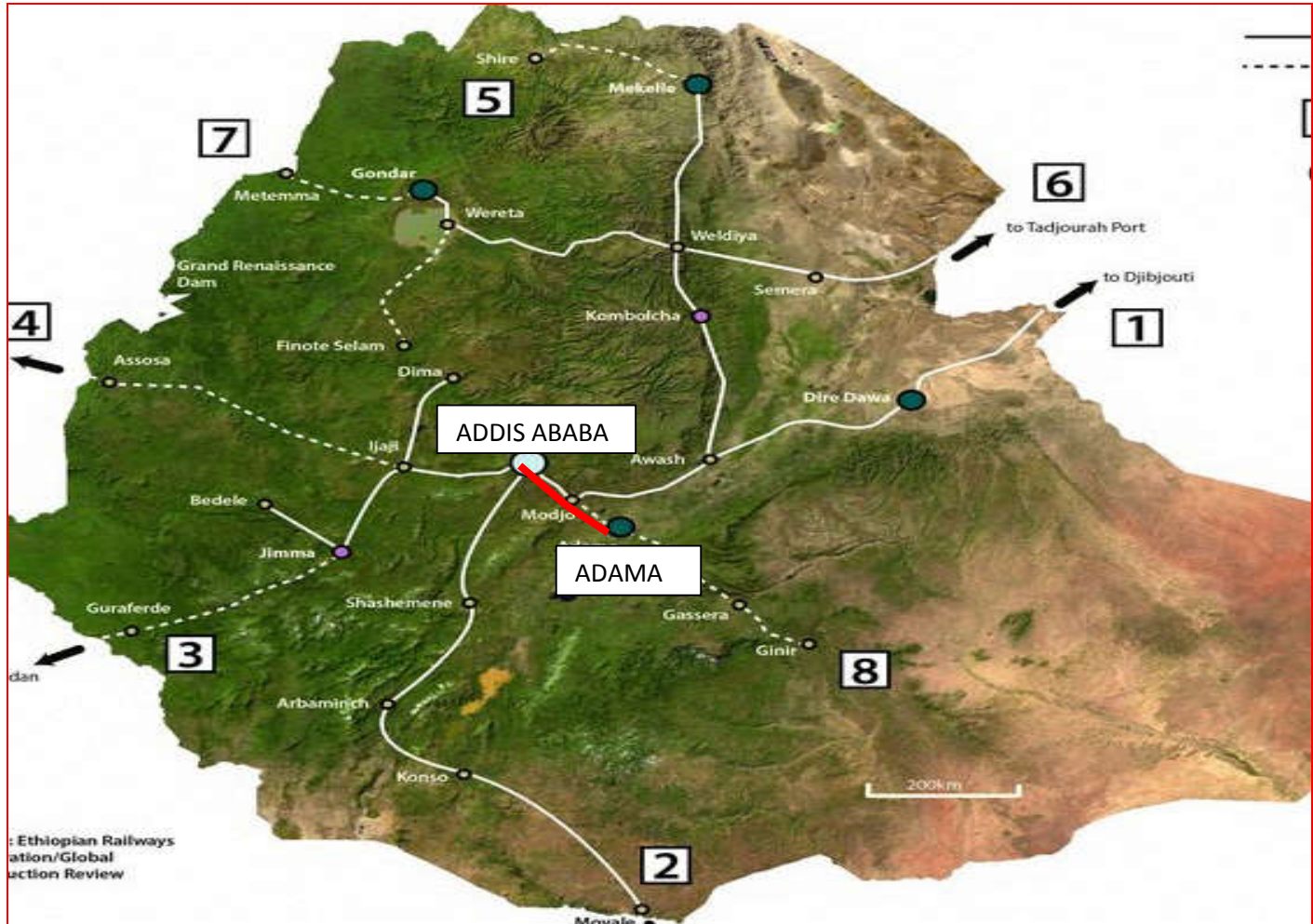


Figure 3-1: New Ethiopian Railway routes

3.1. Salient Feature of Addis Ababa - Adama Line

The salient features of the line are:

- Track typeBallast track
- Number of track laneDouble track
- Length (Route Km)111 km
- Ruling gradient18.5 in 400
- Maximum algebraic difference.....12 0/00
- Minimum horizontal curve radius (m)800
- Maximum horizontal curve radius (m).....3500
- Minimum/maximum vertical curve radius (m)10,000
- Maximum permissible speed (km/h).....120
- Track gauge (mm).....1435
- Level crossing (No.)34
- The annual precipitation amount (mm).....500~1100
- Maximum temperature (°C).....40
- Minimum temperature (°C).....5
- Maximum basic wind speed (m/s).....25
- Structural design wind speed (m/s).....30
- Traction mass in short term stage (t).....3500
- Traction mass in long term stage (t).....4000

3.2. Geometric Alignment data

The Addis Ababa (Sebeta) - Adama route alignment has number of horizontal and vertical curves. The detail characters of the alignment are stated as follow;

3.2.1. Horizontal curves

The total numbers of the horizontal curves constructed along the study track line are 54. Their degree of curvature classification is as below:

- $2^\circ < D < 2.25^\circ = 28$,
- $1^\circ < D < 2^\circ = 14$,
- $0.6^\circ < D < 1^\circ = 6$,
- $0.4^\circ < D < 0.6^\circ = 6$.

Table 3-1: summary of horizontal curve detail

Radius (m)	Numbers	Remark
800	28	Very sharp and strongly restrictive for high speed
$800 < R \leq 1600$	14	Sharp and restrictive for high speed
$1600 < R \leq 2000$	5	Less restriction to high speed
$2000 < R \leq 2500$	1	Recommendable for high speed
$2500 < R \leq 3000$	5	Recommendable for high speed
$R > 3000$	1	Recommendable for high speed

As shown from the above table most horizontal curves are very sharp and restrictive for high speed. These sharp curves are due to plateau platform, Low Mountain, geological/geotechnical problem, river and shallow hill. During field observation it was seen and discussed that, some location of sharp horizontal curves topography has less restrictive for widening.



Figure 3-2: Sharp horizontal curve at station 27+600 between Labu and Indode

3.2.2. Vertical curves

The Addis Ababa - Adama Rail track line geometry has the number of vertical curves and gradients. The radii of all vertical curves are 10,000m and the maximum gradient is 18.5 in 400.

3.3. Level Crossing

Level crossing is one of the factors that restrict the track speed. The following table shows summary of level crossing location in the study area.

Table 3-2: Summary of the level crossing location:

S.N	Stations	Crossing type	S.N	Stations	Crossing type	S.N	Station	Crossing type
1	2+640	Level crossing	13	41+330	Level crossing	25	75+450	level crossing
2	3+450	Level crossing	14	44+950	Level crossing	26	76+689	level crossing
3	6+814	Level crossing	15	46+920	Level crossing	27	78+739	Level crossing
4	9+04	Level crossing	16	48+750	Level crossing	28	80+00	Level crossing
5	13+850	Level crossing	17	49+920	Level crossing	29	83+539	Level crossing
6	16+306	Level crossing	18	51+300	Level crossing	30	85+272	Level crossing
7	19+368	Level crossing	19	57+050	Level crossing	31	88+640	Level crossing
8	26+066	Level crossing	20	63+524	Level crossing	32	89+850	Level crossing
9	31+200	Level crossing	21	64+630	Level crossing	33	97+500	Level crossing
10	35+300	Level crossing	22	67+423.62	Level crossing	34	106+300	Level crossing
11	36+873	Level crossing	23	69+420	Level crossing	35	111+900	Level crossing
12	39+186	Level crossing	24	73+267.4	Level crossing			

3.4. Important Construction Materials For Design of track Speed

3.4.1. Ballast and sub-ballast

Top of the ballasted track bed is flush with the mid top of the sleeper. The material performance of ballast (surface ballast), grade of ballast (surface ballast) and the selected ballast parameters are showed in the following table.

Table 3-3: Material Performance of Ballast

Property	Parameter	Technical index
Anti-wear and anti-shock property	Los Angeles abrasion rate (LAA %)	$27 \leq \text{LAA} < 32$
	Standard aggregate impact toughness (IP)	$10 < \text{IP} \leq 95$
	Stone abrasive hardness coefficient (K), dry grinding	$17 < K, \text{ dry grinding} \leq 18$
Resistance to crushing	Standard aggregate crushing rate (CA), %	$9 \leq \text{CA} < 14$
	Ballast aggregate crushing rate (CB)	$18 \leq \text{CB} < 22$
Water permeability	Permeability coefficient (Pm), 10-6cm/s	$3 < \text{Pm} \leq 4.5$
Water permeability	Limestone specimen compressive strength (σ), MPa	$0.4 \leq \sigma < 0.55$
	Limestone liquid limit (LL), %	$20 \geq \text{LL} > 16$
	Limestone plastic limit (PL), %	$11 \geq \text{PL} > 9$
Resistance to atmospheric corrosion and damage	Loss rate after immersion with sodium sulfate solution, %	< 10
Stability	Density (g/cm^3)	> 2.55
	Unit weight (g/cm^3)	> 2.5
Soft particle	Compressive Strength at Uniaxial and Saturated Condition, MPa	Content of soft particle is less than 10% (mass ratio)

Table 3-4: Ballast Gradation

Side length of square mesh sieve (mm)	16	25	35.5	45	56	63
Mass percentage of passing (%)	0 ~ 5	5 ~ 15	25 ~ 40	55 ~ 75	92 ~ 97	97 ~ 100

3.4.2. Rail

The new Ethiopian railway rail specification detail is as follow.

Table 3-5: rail specification

Type	length (m)	Weight(kg/m)
U71Mn hot-rolled new rails with bolt hole	25	50

3.4.3. Rail joint

All rails are joined by continuous Welding rail system (CWR) to each other to provide a joint-less smooth track.

3.5. Sleeper and fastening

1. Sleeper:

- ✓ The new type II pre-stressed concrete sleeper is used in general sections. The total numbers of sleeper used per kilometer is 1680;
- ✓ Type II ZQ-C concrete bridge sleeper is fixed in the sections to be provided with guard rails, such as bridges, 1680 sleepers/km;
- ✓ The pre-stressed concrete turnout sleeper matched with the turnout is used in the turnout section.

2. Fastening of sleeper to rail

Elastic-rod type I types of fastening is used to fix rails to sleeper for the study line as shown in figure 3.5.1 above.

3.6. Station & Yard

Addis ababa - Adama line has passenger stations and intermediate station. Passenger station is a station to provide passenger transport service, whereas intermediate station is a station to handle train passing, and meeting, overtaking and passenger & cargo services.

Five stations are passenger transport business including Sebeta, Labu, Bishoftu, Mojo and Adama and four freight transport business stations including Sebeta, Indode, Mojo and Adama. The detail services of the stations are described in the following table.

Table 3-6: The general situation of station track between Addis Ababa – Adama line

S.N	station Name	Type	Arrival - departure line	Freight line	Towing line	Shunting line	Locomotive departure siding	Track division on siding	Distance b/n two station
1	Sebeta	Intermediate Station	4	1					Starting station
2	Labu	Passenger transport station	4						13+500
3	Indode	Intermediate Station	4	2	1	1	12	3	16+100
4	Bishoftu	Intermediate Station	4						37+390
5	Mojo	Intermediate Station	4	1	1				23+695
6	Adama	Intermediate Station	4	1	1			2	20+315

3.7. Turnout

The main lines and the access road of passenger car all adopt No.12 Turnout; other lines adopt No.12 or No.9 Turnout as per different requirements; section, depot, storage yard, work area and freight yard adopt No.9 Turnout.

3.8. Track Sub-grade

Sub-grade cross slope

The main line part generally adopts 4%; arrival-departure lines and other station lines generally adopt 2%. And a slope is generally set by 2~4 lines.

Width of sub-grade surface

Width of sub-grade surface in straight section for double track for both cutting and Embankment is 11.7m. Sub-grade surface in curve section of track shall be widened at the outside of the curve, and the widening values shall be linearly decreased in transition curve range.

Shape of sub-grade surface

Sub-grade surface shall be shaped as triangle crown, and transverse drainage slope of 4% shall be set from center line of sub-grade to both sides. Sub-grade surface shall remain in triangle while curve section is widened.

Sub-grade bed

(1) The thickness of sub-grade bedding is designed as 2.5m and the thickness of top layer is 0.6m. Filling materials of Group A should be adopted as priority and filling materials of Group B are the second choice. Filling materials of Group A, B and C should be used at the bottom layer of sub-grade bedding. And when filling materials of Group C are adopted, its plasticity index should be less than 12 and the liquid limitation should not be over 32%. Otherwise, improvement and reinforcement measures should be taken.

Soil within thickness range of bottom layer of cutting bedding shall meet: specific penetration resistance of static sounding $P_s \geq 1.2\text{MPa}$ or basic bearing capacity $\sigma_0 \geq 0.15\text{MPa}$. When the P_s and σ_0 values fail to meet the requirements, rolling compaction by machinery should be adopted for reinforcement and compaction standards. The filling materials for the bottom layer of bedding, with a length of 0.3m~1.0m, should be adopted for the replacement filling of swelling soil cutting.

3.9. Transition section

Transition sections are to be set at the location where embankment is connected to abutment. Filling materials of Group A shall be used to fill the part below surface layer of transition section and shall be compacted according to the compaction standard for bottom layer of bedding reaction.

3.10. power

Basic information and data for calculation of power supply

1. Locomotive type

The passenger locomotive shall adopt single locomotive SS9 traction, while the freight locomotive shall adopt dual locomotive SS4 traction.

2. The number of trains

Table 3-7: The Number of Passenger/Freight Trains unit in pair/day

Stage	Interval	the number of trains (pair/day)			
		passenger train	Freight train	set out	sub total
preliminary stage	Sebeta- Adama	4	4	1	9
short term	Sebeta- Adama	6	7	1	14
long term	Sebeta- Adama	10	8	1	27

Two independent and reliable 132kV power sources are introduced in to supply power for each power substation, and the two lines are mutually heat reserved. The required power and power consumption of traction power supply along the line is as below.

Table 3-8: Required Power and Power Consumption of Traction Power Supply

location traction sub station	Annual power consumption 10 ⁴ KWh			Annual average power required 10 ⁴ KW		
	Initial stage	short term	long term	initial stage	short term	long term
Sebeta	1018	1653	3053	0.116	0.189	0.349
Indode	2188	3556	6565	0.25	0.406	0.749
Bishoftu	1577	2563	4732	0.18	0.293	0.54
Mojo	2595	2592	4785	0.296	0.296	0.546
Merebe	1639	2576	4683	0.187	0.294	0.535

Note: the annual average total utilization hour is calculated as 8760h

3.11. Bridge and culvert

Design of Bridge and culvert was done depending on characteristics of the main river system and relevant natural conditions including topography, hydrology, meteorology, engineering geology, hydrogeology, seismic ground motion parameter, etc. Pre-stressed concrete simply-supported T beam is adopted as the priority for the superstructure of bridge.

3.12. Block sections

Semi-automatic block is adopted for the whole line.

CHAPTER-4 DATA ANALYSIS

4. General

After data collection and organization, data analyses were conducted by using Bentley Inrail software. The Bentley Inrail software is one of the American Bentley Institute software used to design Rail track geometries, drainage structures and crossing and switch. Also it is compatible for speed optimization by iterating design parameters and has the advantages of checking design parameters at the meantime.

The input data used for the software are (X, Y, Z) coordinate or geometric alignment data. The software output include contour, rail centerline alignment, rail geometric design parameters, switch and crossing design, and drainage structure design.

From the analysis result the obtained outputs were geometric alignment and design speed related parameters such as equilibrium cant, applied cant, cant deficiency, non-compensated acceleration, rate of change of cant, rate of change of cant deficiency, speed, curve radius and applied gradient.

The Addis Ababa-Adama rail line design speed for conventional train is about 120km/hr which is far behind of speed currently achieved by many countries. It needs speed optimization by identifying bottleneck location for introduction of high speed. Speed optimization is required for the line to overcome problem stated in chapter one of statement problem.

4.1. Software Used

4.1.1. Bentley software

Bentley Inroad provides a comprehensive set of tools for transportation system design, civil and site engineering for railways, highways, water ways and airports. The software lets you in a graphic environment to create a 3-D model, horizontal and vertical alignments, cut profiles, define template criteria and roadway condition, generate cross-sections, calculate volumes, generates reports, evaluate the design, and create plan and profile sheets. (V8i, 2008)

The inroads product group consists of a single source tree of civil engineering applications designed to run on Microstation or AutoCAD.

The complete Inroads group consists of the following products:

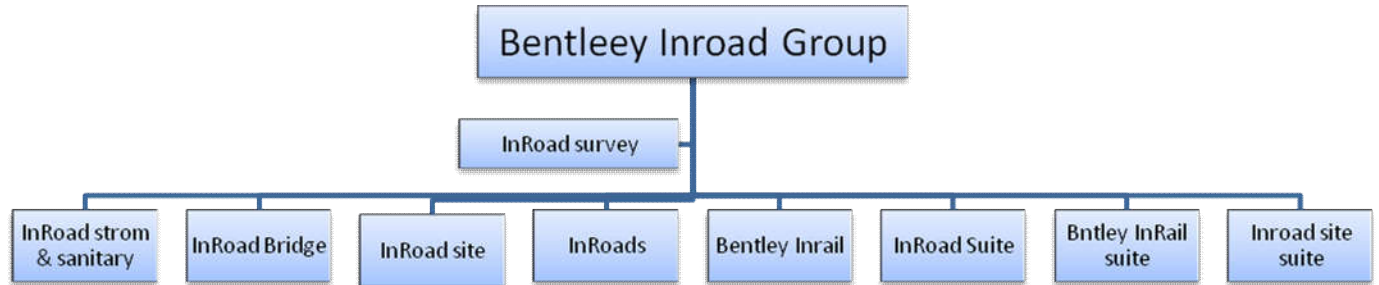


Figure 4-1: Bentley inroad products

4.1.2. Bentley Inrail Suite Software Design Procedures

Bentley Inrail suite is a single product containing all the functionality of Bentley InRail, Inroads, Bridge, Inroads site, C&S and Inroad survey. The following procedure is under taken for rail track alignment design by using Bentley inrail software.

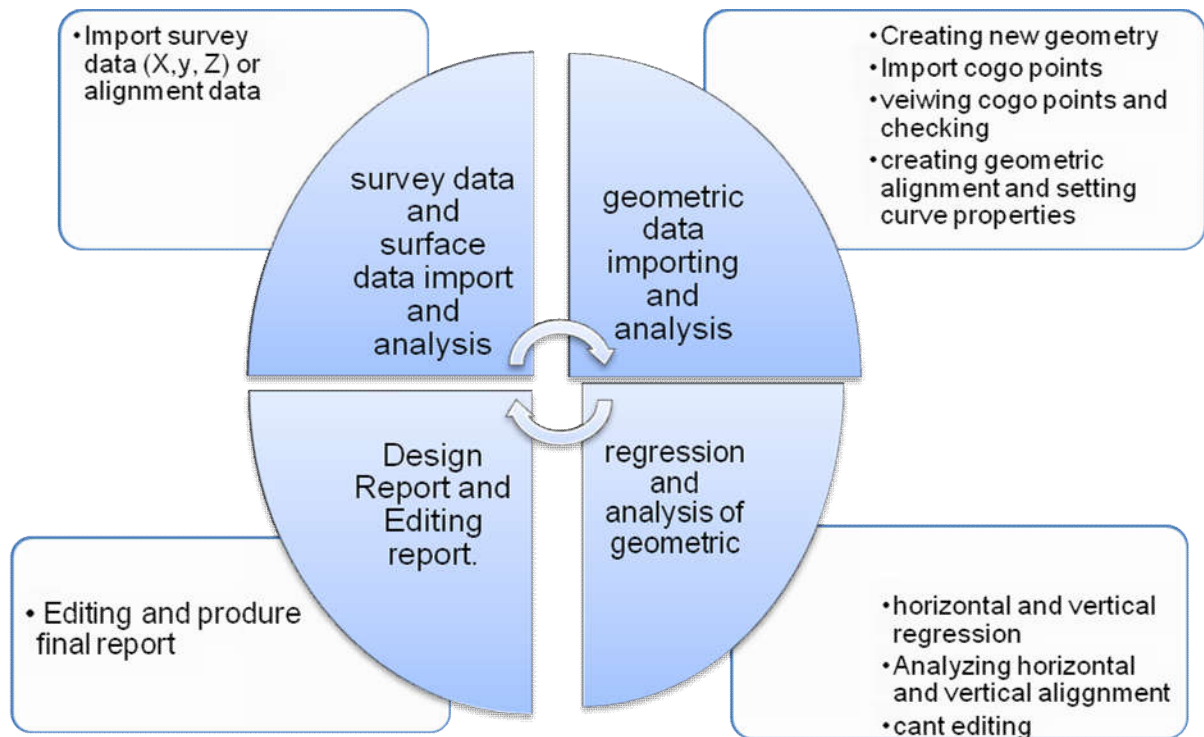


Figure 4-2: Geometric design procedure Bentley Inrail software.

4.2. Analyzing existing Geometric track

4.2.1. Horizontal curve

1. Circular horizontal curve

The minimum horizontal curve radius provided on the line between Addis Ababa – Adama is 800m. The maximum allowable speed is calculated using the following equation at the circular curve.

$$R = \frac{C}{D+I_{lim}} \cdot v^2 \dots\dots\dots 4-1$$

Where,

R = 800m and C = 11.8mm.m.h²/km² for standard gauge

The value of I_{lim} and D is 83mm and 130mm respectively from collected data. For checking design speed is calculated as follows:

$$v = \sqrt{\frac{(D+I_{lim}) \cdot R}{C}} \dots\dots\dots 4-2$$

$$v = \sqrt{\frac{(83\text{mm} + 130\text{mm}) \cdot 800\text{m}}{11.8\text{mm.m.h}^2/\text{km}^2}} = 120\text{km/hr}$$

By using applied cant of 150mm and cant deficiency 100mm which is commonly used by many countries, the design speed is calculated as follows:

$$v = \sqrt{\frac{(100\text{mm} + 150\text{mm}) \cdot 800\text{m}}{11.8\text{mm.m.h}^2/\text{km}^2}} = 130\text{km/m}$$

2. Length of transitions curve

Speed corresponding to the length of the transition curves calculated by the following formula, (SATISH, 2007)

$$L_D = 0.008C_a V_m \dots\dots\dots 4-3$$

Where,

C_a = the value of actual cant in mm, V_m = the maximum permissible speed in km/h and L_D = length of transition curve in (m). For $C_a = 130$ mm, and minimum $L_D = 180$ m the maximum allowable speed is calculated as follow,

$$V_m = L_D / 0.008 C_a$$

$$V_m = 180 / (0.008 * 130) = 173.07 \text{ km/h}$$

Hence, the provided transition curves length at the sharp curve permits speed operation up to 173km/hr.

3. Rate of change of cant dD/dt

Rate of change of cant dD/dt for non-tilting train is calculated by the following equation.

$$\frac{dD}{dt} = \frac{\Delta D}{L_D} \cdot \frac{V}{q_v} \dots\dots\dots 4-4$$

Where, $q_v = 3.6$ km.s/(m.h), $V = 120$ km/hr, $D = 130$ mm and $L_D = 180$ m (the minimum provided transition curve length for Addis Ababa – Adama)

$$\frac{dD}{dt} = \frac{130 \text{ mm}}{180 \text{ m}} \cdot \frac{120 \text{ km/hr}}{3.6 \text{ km.s/(m.h)}}$$

$$dD/dt = 24 \text{ mm/s} < \text{normal limit}$$

4. Rate of change of cant deficiency dI/dt

Rate of change of cant deficiency dI/dt for non-tilting train is calculated by the following equation.

$$\frac{dI}{dt} = \frac{\Delta I}{L_D} \cdot \frac{V}{q_v} \dots\dots\dots 4-5$$

Where, $q_v = 3.6$ km.s/(m.h), $V = 120$ km/hr, $I = 1$ mm and $L_D = 180$ m (the minimum provided transition curve length for Addis ababa – Adama)

$$\frac{dI}{dt} = \frac{83 \text{ mm}}{180 \text{ m}} \cdot \frac{120 \text{ km/hr}}{3.6 \text{ km.s/(h.m)}}$$

$$dI/dt = 15.3 \text{ mm/s} < \text{normal limit}$$

5. Cant Gradient dD/ds

Cant gradient dD/ds for non-tilting train is calculated by the following equation

$$\frac{dD}{ds} = \frac{\Delta D}{L_D} \dots\dots\dots 4-6$$

$$\frac{dD}{ds} = \frac{130mm}{180m} = 0.722mm/m < \text{normal limit}$$

4.2.2. Vertical Curve

1. Radius of vertical curve

The vertical curve radius from Addis Ababa - adama is about 10,000m throughout. The allowable speed for vertical radius is calculated as follow

$$R_v = q_r v^2 \dots\dots\dots 4-7$$

Where, $q_r = 0.35 \text{ m.h}^2/\text{km}^2$ for normal limit, and $0.16 \text{ m.h}^2/\text{km}^2 =$ for exceptional limit

By rearranging the above equation for speed (V)

$$v = \sqrt{\frac{R_v}{q_r}} \dots\dots\dots 4-8$$

For normal limit;

$$v = \sqrt{\frac{10000m}{0.35m.km^2.h^2}} = 169km/hr.$$

The provided vertical is allowable up to 170km/hr speed

For exceptional limit;

$$v = \sqrt{\frac{10000m}{0.16m.km^2.h^2}} = 250km/h$$

2. Length of a Vertical Curve

The length of a vertical curve depends upon the algebraic difference between the gradients and the type of curve formed (summit or sag). The required length of a vertical curve for achieving the maximum permissible speed is given by the following formula. (SATISH, 2007)

$$L = \left(\frac{v}{v_r}\right)^2 * 30.5m \dots\dots\dots 4-9$$

Where L = the length of the vertical curve in m,

a = the per cent algebraic difference between successive gradients, and

r = the rate of change of the gradient, which is 0.1% for summit curves and 0.05% for sag curves.

For Addis Ababa – Adama, a = 12 %

For summit curves: $-L = \left(\frac{12\%}{0.1\%}\right) * 30.5m = 3660m$; for sag curves:-

$$L = \left(\frac{12\%}{0.05\%}\right) * 30.5m = 7320m$$

Not that, the all vertical curves length is greater than or equal to 10,000m

3. Gradient

The ruling gradient for Addis Ababa - Adama line is about 4.63% and it is relatively within recommendable limit.

4.3. Analysis by Bentley Inrail Software

4.3.1. Horizontal Curve Analysis

The input data used in geometric analysis for the study is predesigned geometric alignment data and (X, Y, Z) coordinate center line field data assembled from Ethiopian Railway Corporation office. The maximum allowable design speed and bottlenecks points were identified from Bentley software analysis and the detail result of the software were attached at Annex.

The following table shows Bentley Inrail software analysis result for conventional trains of sharpest horizontal curves having characters of radius R=800m and transition curve length =180m.

Table 4-1: Bentley software analysis result for sharp horizontal curve

Description		Speed (km/hr)						
		160	150	140	135	130	125	120
Cant (mm)	Applied cant	225	200	175	160	150	140	130
	Cant deficiency	152	131.87	114.1	108.82	99.275	90.469	82.4
	Equilibrium cant	377	331.87	289.1	268.82	249.27	230.469	212.4
Non –compensated acceleration (m/s ²)		0.99	0.863	0.747	0.712	0.65	0.592	0.54
Rate of change Applied cant (mm/s)		55.556	46.29	37.8	33.33	30.09	27	24.07
Rate of change Deficiency cant(mm/s)		37.7	30.526	24.65	22.67	19.92	17	15.259
Applied gradient		800	900	1029	1125	1200	1286	1385

4.3.2. Comparison with literature

The software analysis results were compared with literature review stated in chapter two and from the comparison discussion the 130km/h speed is within recommendable limits.

Table 4-2: Comparison of selected Bentley result at speed of 130 km/hr with literature

Description	Software results	Chinese standard	Other country (maximum value)					Remark
			Italy	Indian	France	UK	AREMA	
Radius(m)	800	800-1200	-	-	-	-	800	Recommendable
Transition length	180	170	-	120	-	-	-	Safe
Equilibrium cant(mm)	250	-		300			300	Safe
Cant(mm)	150	-	160	200	180	180	-	Safe
Cant deficiency(mm)	99.3	-	92	100	180	110	-	Safe
Rate of change of cant(mm)	30	-	54	-	60	85	-	Safe
Rate of change of cant deficiency(mm)	19.9	-	38	35	90	70		Safe
Non-composted acceleration (mm/s ²)	0.65	-	-	-	-	-	-	Recommendable
App. Gradient	1200	-	-	720	-	-	-	Safe
The minimum track spacing(m)	4	4		-	-	-	-	Safe

Recommened and minimum horizontal curve radius of different country

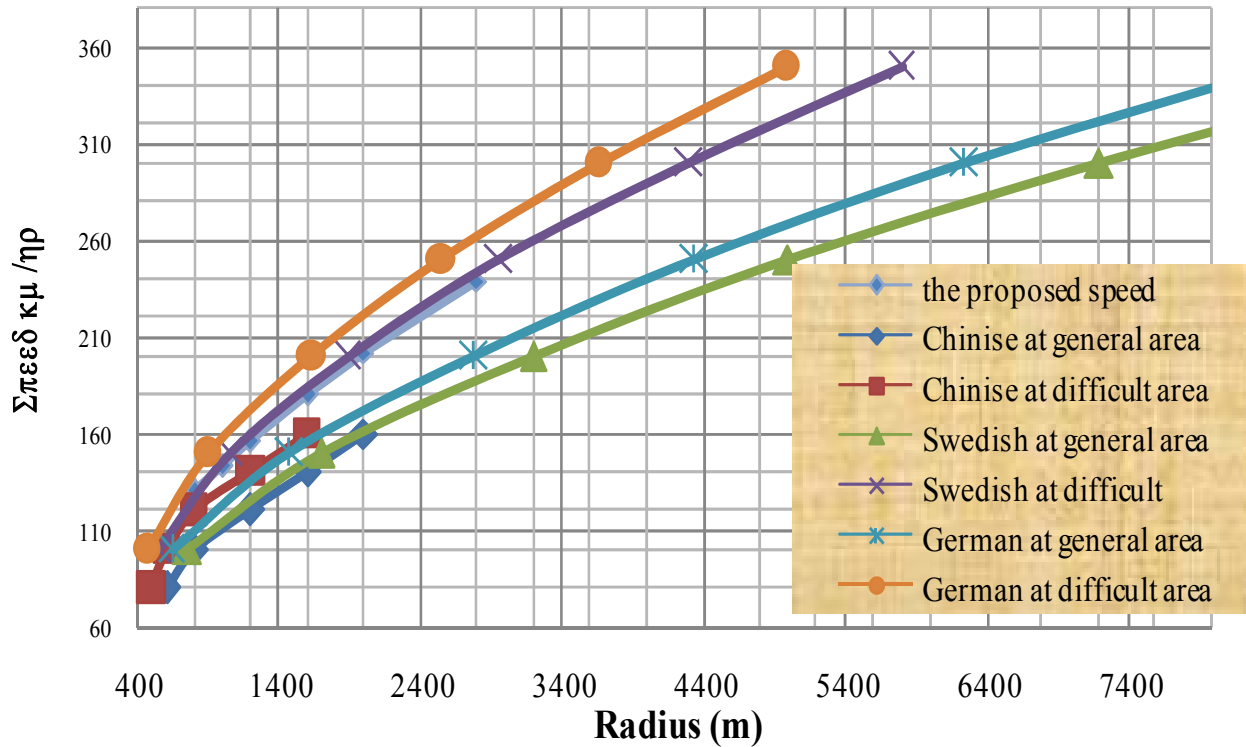


Figure 4-3: Different countries horizontal curve radius design standard comparison

Table 4-3: comparison of provided vertical curve parameters with Chinese and other country design standards

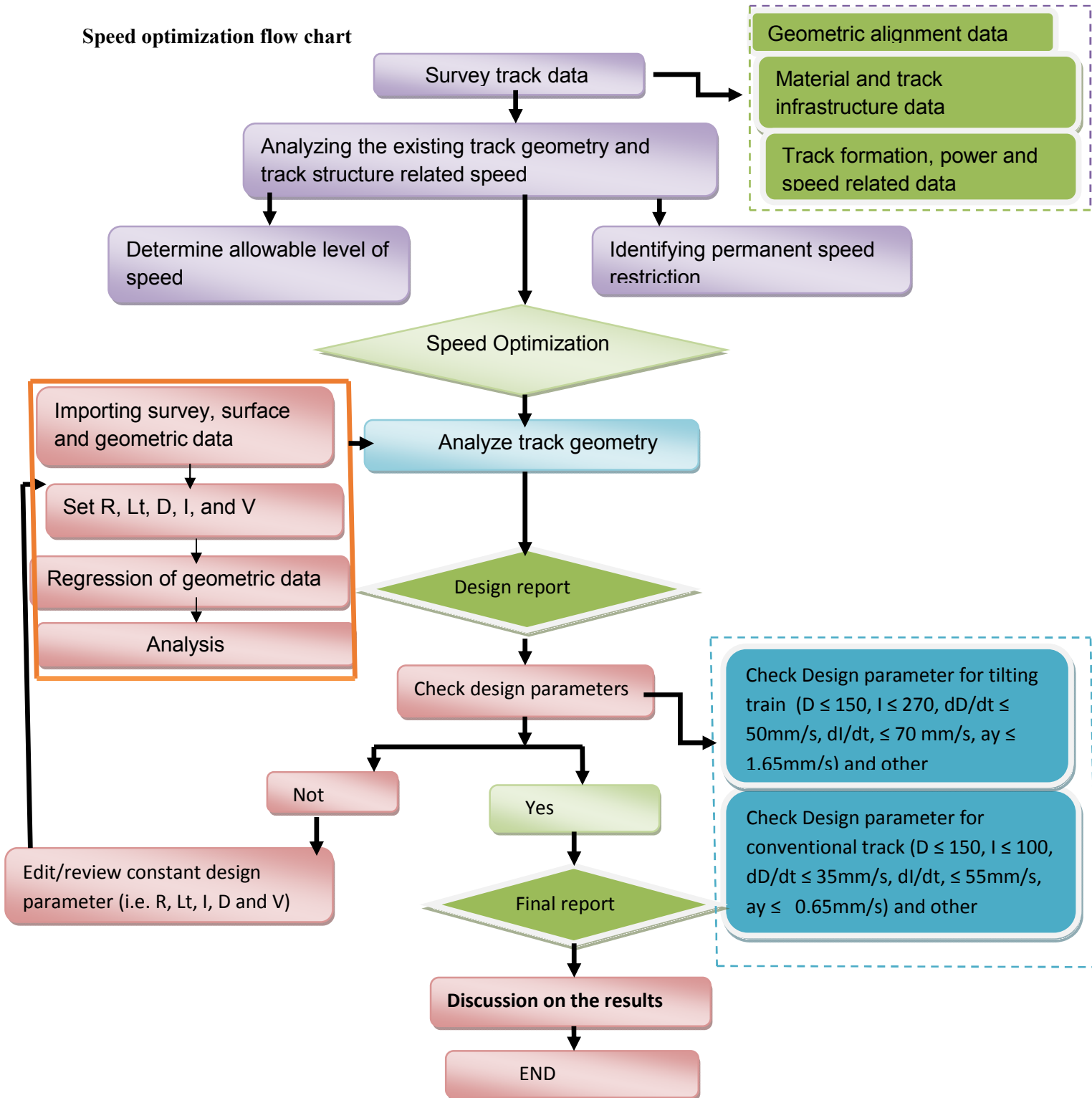
Description	Existing vertical curve alignment properties	Chinese Standard	Other country standard		Remarks
			AREMA	Sweden	
Minimum grade length(m)	400	>200	>150	-	Recommendable
Radius(m)	10,000	10,000 for $v \leq 160\text{km/hr}$	-	=>4096	Recommendable
Gradient (%)	18.5 in 400	15-20	-	30	Recommendable

CHAPTER -5 SPEED OPTIMIZATION

5. Introduction

When the behavior of the railway track geometry and infrastructure has been analyzed, the next step is speed optimization. Optimization of a speed generally means improving the geometric alignment, infrastructure, construction materials and structure performance during the working cycles under some manufacturing, operational and failure conditions as well as cost limitations. In the traditional design of such geometric and infrastructure the speed optimization is carried out in a primitive way by modification of separate design parameters and repeated numerical analyses. But for this study speed optimization process is undertaken by using Bentley in-rail software for geometric analyze.

Speed optimization flow chart



Flow chart 5-1 : speed optimization flow chart

5.1. Existing Line Requirements from Civil Engineering Perspective

There are about 26 horizontal curves with radius, $R = 800\text{m}$ (2.2°) and all vertical curves with radius $R = 10,000\text{m}$ and ruling gradient 18.5 in 400 on existing network resulting in imposition of permanent speed restrictions. Imposition of speed restriction brings down average speed substantially based on severity of restriction. Aim of Civil engineer, therefore, is to provide infrastructure suitable to run train at nominated maximum permissible speed.

The various impediments, however, in achieving high speeds more than 130 Km/h on existing network are:

- i. Existence of sharper curves resulting in imposition of speed restriction
- ii. Vulnerable locations like level crossings

5.2. Existence of sharper curves resulting in imposition of speed restriction

For the train to achieve more full potential speed than 130 km/hr on standard gauge, it needs realignment of bottlenecks points resulting in imposition of permanent speed restrictions. Imposition of speed restriction brings down average speed substantially based on severity of restriction.

The existing alignment of Railway track is laid on consideration of connectivity to various small to medium towns along the alignment, the mountain, crossing major rivers at appropriate location to restrict length of bridge and various valleys. Many existing curves in the alignment can be eliminated if above considerations are dispensed with. The same is, thus, not considered financially viable. Many bottlenecks of restrictive speeds can, however, be removed/ relaxed by realigning the existing curves by marginally widening of geometric within existing railway land. Case to case study for individual curve with considerations of feasibility may have to be looked into in greater detail to arrive at a decision for level of optimization. The most sharp horizontal curve data was collected with their corresponding topographic feature as shown in the table 5.3 below.

The existing geometric alignment analysis done in chapter four shows the allowable speed is 130km/h for conventional train.

Specific action will have to be taken either to realign the existing curves or use tilting coach's technology to get speed more than 130Km/h on existing route. Both the techniques are available and a cost effective and long term decision is required for further course of action. Available technical remedies to improve speed potential on existing network are:

- i) Introduction of tilting coaches' technology.
- ii) Realignment of curves to restrict sharpness within permissible limits.
- iii) Combination of tilting coach and upgrading techniques

5.3. Introduction of tilting coaches' technology

A tilting train deploys tilting mechanism which enables increase of speed of the special stock on existing track. The tilt mechanism reduces the lateral acceleration perceived by the passengers. Therefore, tilting trains, if provided with a suitable running gear, may run at higher cant deficiencies than non-tilting trains.

5.3.1. Horizontal Curve Analysis for Tilt Coach by Bentley Inrail Software

Bentley Inrail software is used in process of speed optimization as shown in the flow chart 5.1 above.

From Bentley analysis of sharpest horizontal curve characterized with R=800m, tailing transition curve length = 180m, ending transition curve length = 180m. The most recommendable operation speed by introducing tilting coach is 160Km/h by keeping applied cant (130mm).

Track design parameters from Bentley Inrail software result at 160km/h Speed for tilting coach are:

I=130mm, D = 247.6mm, Equilibrium cant = 377.6mm, Non-compensated acceleration = 1.62m/s², Rate of change of applied cant = 32.09 mm/s, Rate of change cant deficiency = 61.136 mm/s and Applied gradient = 1385

5.3.2. Analysis Horizontal Curve for Tilting Coach By Hand calculation

1. Equilibrium Cant

Equilibrium cant can be calculated as the following formula as stated in literature

$$E = \frac{G}{127R} V^2 \dots\dots\dots 5-1$$

Where

G = rail center to center clearance (mm), R = radius (m), and V = design speed (Km/h)

$$E = \frac{1500mm}{127*800m} * 160^2 = 377.952mm$$

Equilibrium cant result from both literature and Bentley is the same. So let calculate the cant deficiency.

2. Cant deficiency

Cant deficiency is calculated as follows:

$$E = D + I \dots\dots\dots 5-2$$

Where; E = equilibrium cant, I = cant deficiency and D = applied cant

By rearranging the above equation for I:

$$I = E - D = (377.6 - 130) \text{ mm} = 247.6 \text{ mm}$$

Equilibrium cant = 377.6mm

Cant deficiency I = 247.6mm are within recommendable limit and tilting coach can be operated on the alignment up to speed of 160km/hr.

3. Enhanced permissible speed on circular curves

$$v = \sqrt{R \cdot \frac{11.8 \text{ mm} + D \text{ mm}}{11.8}} \dots\dots\dots 5-3$$

$$v = \sqrt{800 \cdot \frac{130 + 247.6}{11.8}} = 160 \text{ km/h}$$

Horizontal circular curve is allowable up to 160km/h speed for tilting coach.

4. Enhanced permissible speed on super elevation

$$\frac{VT}{Vc} = \frac{\dot{D}T}{\dot{D}c} \dots\dots\dots 5-4$$

$$\frac{dD}{dt} = \frac{\Delta D}{LD} \cdot \frac{V}{qv} < \left(\frac{dD}{dt}\right)_{lim} \dots\dots\dots 5-5$$

Where; $l_D = 180\text{m}$ and $qv = 3.6\text{km.s}/(\text{h.m})$, $Vc = 120\text{km/h}$ and $VT = 160\text{km/h}$ is proposed on circular .

$$\dot{D}c = \frac{dD}{dt} = \frac{V}{qv} \cdot \frac{\Delta D}{Lk} \dots\dots\dots 5-6$$

$$\dot{D}c = \frac{dD}{dt} = \frac{120\text{km/h}}{3.6 \text{ m.s}/(\text{h.m})} \cdot \frac{130\text{mm}}{180\text{m}} = 24.07\text{mm/s}$$

$$\dot{D}T = \frac{dD}{dt} = \frac{V}{qv} \cdot \frac{\Delta D}{Lk} < \frac{dl}{dt}$$

$$\dot{D}_C = \frac{dD}{dt} = \frac{160\text{km/h}}{3.6 \text{ m.s/(h.m)}} \cdot \frac{130\text{mm}}{180\text{m}} = 32.098\text{mm/s}$$

$$VT = Vc \cdot \frac{\dot{D}T}{\dot{D}_C}$$

$$VT = 120\text{km/h} \cdot \frac{32.098\text{mm}}{24.07\text{mm}} = 160.03\text{km/h}$$

From the result on super elevation ramp track operated up to 160km/h speed.

5. Enhanced permissible speed on transition curves

$$\dot{D} + i = 11.8 \frac{v^2}{R} \cdot \frac{v}{3.6Lt} \dots\dots\dots 5-7$$

Where, Lt = transition length (m), R = radius (m), V = design speed (km/h), $dD/dt = \dot{D} = 32.099\text{mm/s}$,
 $dI/dt = i = 61.13\text{mm/s}$

Solving for speed V

$$V = \frac{\sqrt[3]{(800\text{m} * 180\text{m} * 3.6 * (32.099\text{mm} + 61.136\text{mm}))}}{11.8}$$

$$v = \sqrt[3]{R * Lt * 3.6 * (\dot{D} + i) / 11.8}$$

$$v = \sqrt[3]{800 * 180\text{m} * 3.6 * (32.099\text{mm} + 61.136\text{mm}) / 11.8} = 160\text{km/h}$$

From the above result on transition section of horizontal curve is allowable up to speed of 160km/h for tilting coach.

6. Enhanced Permissible Speed at Instantaneous Changes of Curvature

$$\frac{VT}{Vc} = \sqrt[3]{\frac{\dot{I}T}{iC}} \dots\dots\dots 5-8$$

Where, $\dot{I}T = 61.13\text{mm}$, $iC = 24.07\text{mm}$, $Vc = 120\text{km/hr}$

$$VT = 120 \cdot \sqrt[3]{\frac{61.13}{24.07}} = 163.722 \text{ km/hr.}$$

Hence, from the above result the existing instantaneous Changes of Curvature section of horizontal curve is allowable up to 163.7km/h speed for introducing tilting coach operation.

Table 0-1: Comparison of design parameter for tilting coach with different countries design standard.

Description	software result at 160 Km/hr	Chinese standard	Other country properties			Remarks
			French	German	Norway	
Max cant D(mm)	130	***	180	160-180	150	The proposed cant is fair
Max deficiency I (mm)	247.6	***	260	300	280	The proposed cant deficiency is fair
Max rate of change of cant dD/dt (mm/s)	32.09	***	60	46	75	The proposed dD/dt is fair
Max rate of change of cant deficiency dI/dt (mm/s)	61.136	***	No limit	Not specified	140	The proposed dI/dt is fair
Non-compensated acceleration(mm/s ²)	1.62	***	***	***	***	-

Note: - *** shows standard is silent

The following figure shows the average enhanced Permissible speed by tilting trains on the existing track.

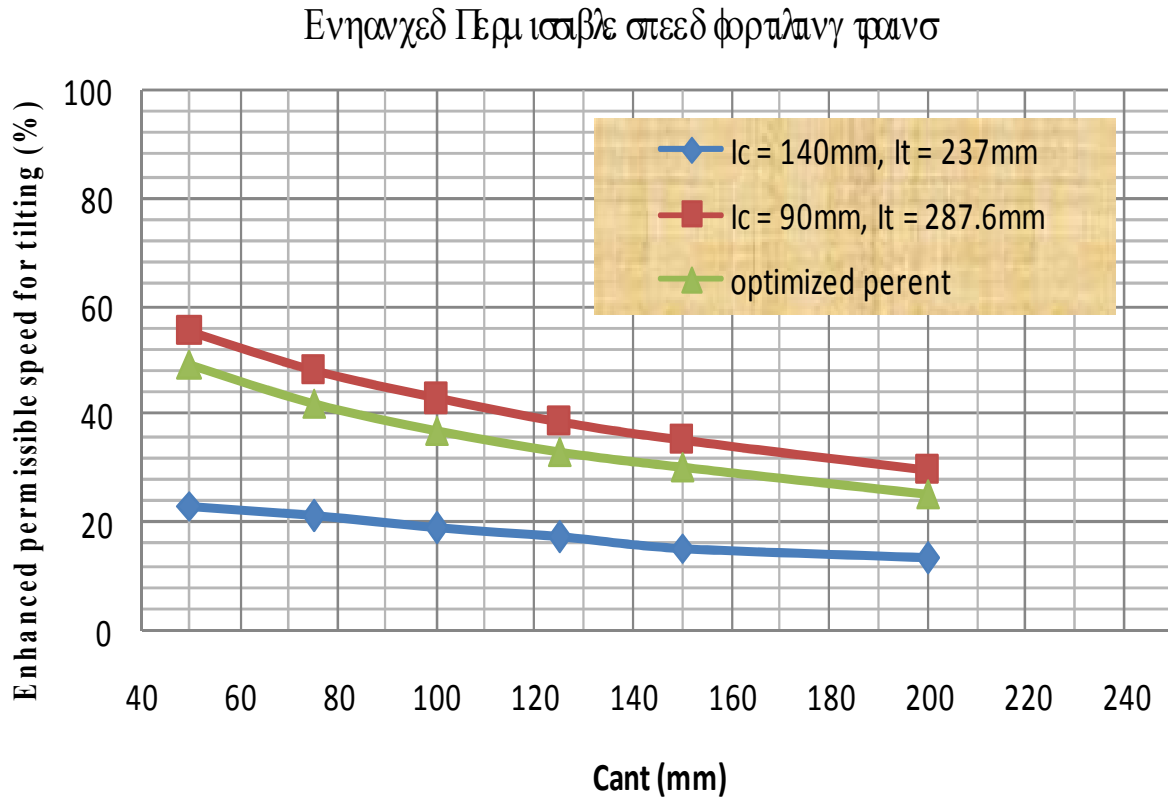


Figure 5-1: Enhanced permissible speeds for tilting trains as a percentage of permissible Speed for conventional trains on horizontal circular curves

5.4. Realignment of Curves to Restrict Sharpness

5.4.1. Analysis of Horizontal Curve by Bentley Inrail Software

Optimization was done as the procedure presented in the flow chart 5.1 above. Accordingly, from the chapter four analyses, optimization undertaken by using software results and looking for geometric, material, infrastructure conditions and cost of upgrading, 160km/h speed is the justifiable.

For the train to achieve full potential of 160 km/h speed on standard Gauge, the minimum radius of curve is 1325 m (1.3°) is required for conventional train. There are large numbers of curves sharper than 1.3° on existing geometric alignment resulting in imposition of permanent speed restrictions as shown in table 5.1 above. Imposition of speed restriction brings down average speed substantially based on severity of restriction.

Specific action will have to be taken on the existing curves for conventional train to achieve 160km/h speed potential on existing route. Bentley Inrail analysis result report sample is presented in the following table.

Table 5-2: speed related parameters of Bentley In-rail software result at R = 1325m

Type	Speed (kph)	Radius (m)	Transition	Cant (mm)			Lateral acceleration (m/s ²)	Rate of Change (mm/s)		App. Gradient
				E	D	I		Applied cant	Cant efficiency	
POB	160	0	Linear	0.00	0	0.00	0.00	0.00	0.00	0
TS	160	0	Clothoid	0.00	0	0.00	0.00	33.33	22.96	1333
SC	160	-1325	Circular	227.9	135	92.9	0.61	0.00	0.00	0
CS	160	-1325	Clothoid	227.9	135	92.9	0.61	33.33	22.96	1333
ST	160	0	Linear	0.00	0	0.00	0.00	0.00	0.00	0
TS	160	0	Clothoid	0.00	0	0.00	0.00	32.10	21.18	1385

5.4.2. Analyzing Relaxed Horizontal Curve Geometric Alignment

1. Circular Horizontal Curve

The minimum relaxed horizontal curve radius provided for the line between Addis Ababa – Adama is about 1325m. The maximum allowable speed is calculated using the following equation

$$R = \frac{C}{D + I_{lim}} \cdot v^2 \dots\dots\dots 5-10$$

Where, C = 11.8mm.m.h²/km² for standard gauge, R = 1325m

By taking the value of I_{lim} = 93mm and D = 135mm, which is gained from software analysis result and it is within recommendable limit for standard gauge.

$$v = \sqrt{\frac{(D + I_{lim}) \cdot R}{C}}$$

$$v = \sqrt{\frac{(93\text{mm} + 135\text{mm}) \cdot 1325\text{m}}{11.8\text{mm.m.h}^2/\text{km}^2}} = 160 \text{ km/h}$$

2. Length of Transitions Curve

Speed corresponding to the length of the transition curve is calculated by the following formula, (SATISH, 2007)

$$L_D = 0.008 \cdot D \cdot V_m \dots\dots\dots 5-11$$

Where, D = the value of actual cant in mm, V_m = the maximum permissible speed in km/h, L_D = length of transition curve in m

For Ca = 135mm, and minimum LD = 180m the max allowable speed is calculated as follow,

$$V_m = L_D / 0.008 \cdot D$$

$$V_m = 180 / (0.008 \cdot 135) = 166.7 \text{ km/h}$$

Hence, the provided transition curves length at the sharp curve permits speed operation up to 166.7km/hr.

3. Rate of change of cant dD/dt

Rate of change of cant dD/dt for non-tilting train is calculated by the following equation.

$$\frac{dD}{dt} = \frac{\Delta D}{L_D} \cdot \frac{V}{q_v} \dots\dots\dots 5-12$$

Where, $q_v = 3.6\text{km.s}/(\text{m.h})$, $V = 160\text{km/hr}$, $D = 135\text{m}$, $L_D = 180\text{m}$ (the minimum provided transition curve length for Addis Ababa – Adama)

$$\frac{dD}{dt} = \frac{135\text{mm}}{180\text{m}} \cdot \frac{160\text{km/hr}}{3.6\text{km.s}/(\text{m.h})}$$

$$dD/dt = 33\text{mm/s} < \text{normal limit}$$

4. Rate of change of cant deficiency dI/dt

Rate of change of cant deficiency dI/dt for non-tilting train is calculated by the following equation

$$\frac{dI}{dt} = \frac{\Delta I}{L_D} \cdot \frac{V}{q_v} \dots\dots\dots 5-13$$

Where, $q_v = 3.6\text{km.s}/(\text{m.h})$, $V = 160\text{km/hr}$, $I = 93\text{mm}$ and

$L_D = 180\text{m}$ (the minimum provided transition curve length for Addis ababa – Adama)

$$\frac{dI}{dt} = \frac{93\text{mm}}{180\text{m}} \cdot \frac{160\text{km/hr}}{3.6\text{km.s}/(\text{m.h})}$$

$$dI/dt = 22.96\text{mm/s} < \text{normal limit},$$

5. Cant Gradient dD/ds

Cant Gradient dD/ds for non-tilting train is calculated by the following equation

$$\frac{dD}{ds} = \frac{\Delta D}{L_D} \dots\dots\dots 5-14$$

$$\frac{dD}{ds} = \frac{135\text{mm}}{180\text{m}} = 0.75\text{mm/m} < \text{normal limit}$$

The available remedies proposed to improve speed potential on existing network track for conventional train is presented in the following table

Table 5-3: - Sharpest curves topographical features and action proposed to relax for high speed

S.N	Station	curve radius	Existing condition curve		Proposed route for Relaxing	
			Profile description	Depth (m)	Profile description	Depth(m)
1	13+500	800	Cut	1.15	Embankment	2.31
2	18+400	800	cut	0.93	cut	12
3	19+950	800	Embankment	1.21	cut	10.95
4	21+00	800	Bridge	-	Bridge	-
5	22+050	800	Embankment	10.2	Cut	5
6	22+950	800	Bridge	-	Bridge	-
7	23+800	800	Bridge	-	Bridge	-
8	24+600	800	Embankment	4.43	Medium cut	6.14
9	26+00	800	Embankment	2.12	Cut	0.92
10	27+600	800	Bridge	-	Bridge	-
11	32+300	800	Cut	1.8	Cut	2.2
12	37+50	800	Cut	0.25	Cut	3.22
13	50+100	800	Cut	37.32	Small tunnel / cut	41.88
14	51+500	800	Embankment	1.49	Embankment /bridge	4.19
15	68+00	1000	Embankment	1.28	Embankment	3.81
16	87+300	800	Bridge	-	Bridge	-
17	93+930	1200	Bridge	-	Bridge	-
18	94+700	800	Cut	0.43	Cut	1
19	95+600	800	Bridge	-	Bridge	-
20	98+500	1000	Cut	3.62	Cut	7.82
21	99+450	800	Cut	16.3	Tunnel/huge cut	16.9
22	100+400	800	Bridge	-	Bridge	-
23	101+350	800	Bridge	-	Bridge	-
24	103+900	800	Huge cut	39.13	Tunnel	47.69
25	105+250	1200	cut	4.81	Embankment	2.04
26	107+300	800	Fill	4.12	Embankment	10.11
27	108+195	800	Bridge	-	Bridge	-
28	108+850	800	Bridge	-	bridge	-
29	109+900	800	Cut	2.32	Cut	6
30	111+100	800	Cut	5.16	Cut	2

Comparison of upgraded sharpest horizontal curves with different countries Design standards.

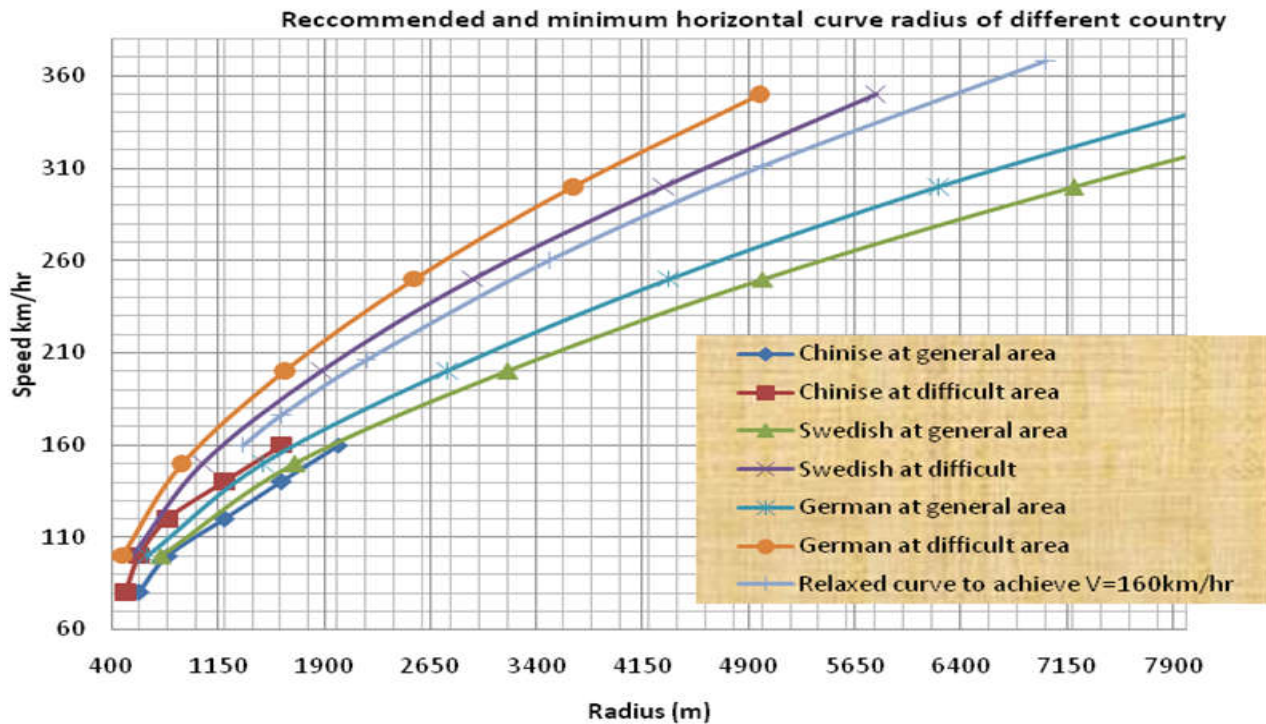


Figure 5-2: Recommended and minimum horizontal curve radius of different country and comparison with relaxed radius for speed optimization.

Note: from above figure the relaxed radius to achieve 160km/hr speed is within recommendable limit as compared with different countries design standards.

5.5. Upgrading Vertical Curves for Both Tilt Coach and Conventional Train

Vertical curves requirement and limitation for both conventional and tilt coach is the same. Existing vertical curve parameter can tolerate up to speed of 170km/hr and if the speed demand extends above 170km/hr realigning of vertical curve is mandatory action. But upgrading of vertical curves is technically difficult (KUFVER, 2005) and may not economical.

5.6. Combination of Upgrading and tilting coach technology speed optimization techniques

By combination of both tilting coach technology techniques and upgrading techniques it is possible to achieve 205km/h full potential speed on horizontal curve alignment. Vertical geometric alignment is within recommendable limit up to 170km/h speed and up to 250km/h speed is within exceptional range. Since increasing vertical curve radii is difficult, it is better to limit speed optimization up to 170km/hr.

5.7. Level Crossings

There are about 34 numbers of level crossings (LC) between Addis Ababa - Adama section. The existing level crossing along the route has high limitation to achieve 120km/h uniform full potential speed. And it has high limitation for introduction of high speed on the route. For higher speed operation, it is desirable to eliminate all the level crossings and provide grade separators in the form of elevated bridge. Elimination of LC gates or provision of alternative right of way through additional opening in adjacent to existing bridge will have to be considered to achieve ZERO LC gates on high speed routes.

In India like Nagpur division of Central Railway, they have been able to eliminate/close about 40 LC gates to upgrade speed of existing route. Cattle menace is a safety hazard for any high speed operation and therefore fencing of track is necessarily required before introduction of high-speed trains. The fencing will also help in demarcating railway area clearly and avoid trespassing. (Vivek)

5.8. Examining construction material and infrastructure for optimized speed

Track infrastructure and construction material has its own limitation for speed determination. Accordingly different country has their own design standard for material and infrastructure as stated in literature part of chapter two.

5.8.1. Rail

The Indian Railways, in the year 1959, designed a heavier rail section of 52 kg/m to meet the requirements of heavier and faster traffic. This rail section was recommended for use on all BG main line routes with future speeds of up to 130kmph and traffic density of 20–25 GMT. The 60-kg UIC section rail has been designed for speeds of up to 160kmph and a traffic density of about 35 GMT. (SATISH, 2007)

Table 5-4: comparison of provided rail with other countries design standards

S.N.	Description	Country				
		Chinese	France	Japan	German	Ethiopian
1	Length (m)	25	25	25	25	25
2	Weight (KG/m)	50, for class III, $v \leq 120 \text{ km/h}$	60, $v \geq 300 \text{ km/h}$	60, $v > 300 \text{ km/h}$	60, $v > 300 \text{ km/hr}$	50
3	Type	-	UIC 60	UIC 60	UIC 60	U71Mn hot-rolled

The Ethiopian rail is 50kg/m weight, 25 m-long standard U71Mn hot-rolled new rails with bolt hole.

Table 5-4 above does not show clear effect of rail under different speed and loads and it needs further investigation.

Rail analysis by Finite Element Method

Rail was analyzed by finite element method to see its effect under the optimized speed. The Abaqus software is used to analyze rail deflection and stress under 160km/h speed. The applied data, track model and the result is presented as follows.

The rail data

- Rail : U71Mn hot-rolled, moment of Inertia = 2.037cm^4 , weight = 50kg/m, modulus of elasticity = 210×10^9 pa, poissons ratio = 0.3, tensile strength = 800N/mm^2
- Rail pad stiffness: $k_h = 1.25 \times 10^9$ N/m
- Track: ballasted track, optimized speed = 160km/hr, Ballast depth = 45cm,

Finite Element Method Model of Track

To analyze the rail effect under 250kN Axle load and 160km/hr speed; the 10m long track is modeled by Abaqus software. The track model is shown in the following figure.

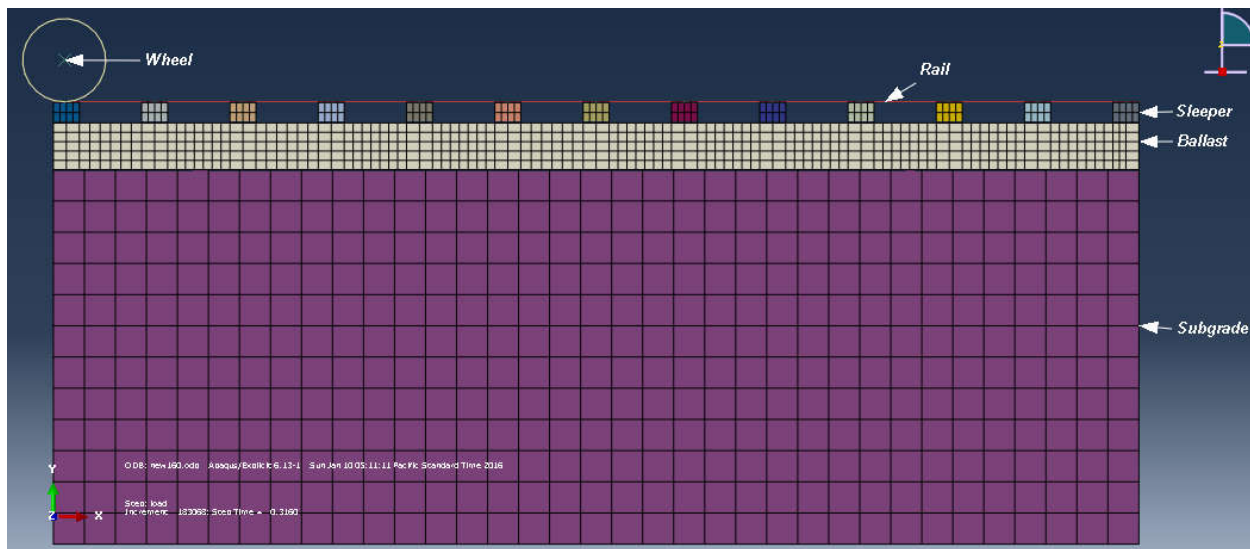


Figure 0-3: Finite Element Method Model of Track

Result of software

A. Rail deflection result;

The rail deflection from the Abaqus analysis results is presented in the following table. The maximum deflection is 3.2mm.



Figure 5-4: Rail deflection

B. Rail stress;

The rail stresses under 160km/hr speed from the analysis result are presented in the following figure. The maximum stress is nearest 20Mpa and the minimum is 2.8Mpa.

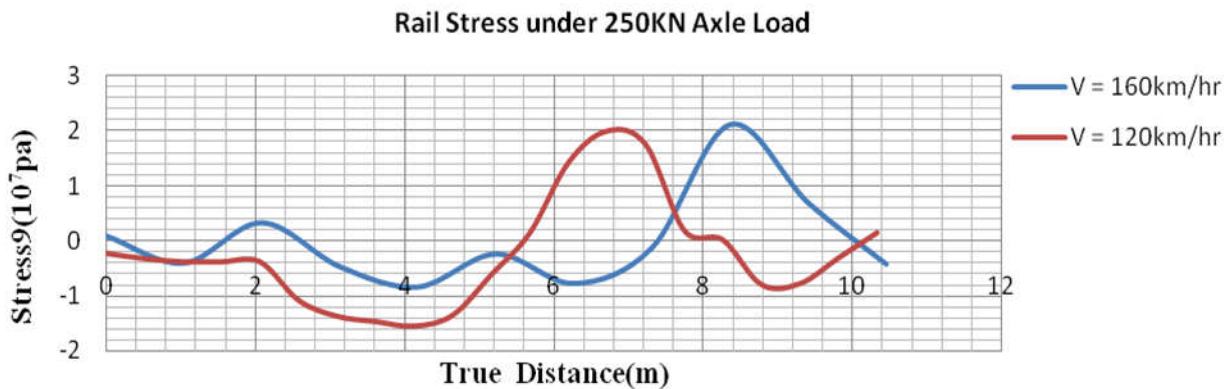


Figure 5-5: Rail stress

C. Discussion on the Result

The stress and deflection in Railway track increase due to increase in speed of train. The strength of each component member should be greater than the stresses, which each is required to bear. From the above Abaqus analysis results, the maximum vertical deflection of the rail under 160km/hr speed and 250kN axle load is 3.2mm where as the maximum stress developed is about 21.2Mpa.

Clarke (1957) has suggested that the value of the allowable rail bending stress should not exceed 50 per cent of the rail yield stress σ_y . It would appear that the AREA (1 973) manual recommendation of a maximum allowable vertical deflection is 6.35mm (0.25 in) (Doyle, 1980).

From the above discussion, stress and deflection developed under 125kN wheel load and 160km/hr speed is within recommendable limit.

5.8.2. Rail joint

All rails are joined by continuous Welding (CWR) on the study area. All rail joints are welded to provide a joint-less smooth track.

The process and quality control system for the thermal welding system proposed should have an intrinsic reliability equivalent to that of flash butt welds (Reddy, 2008). CWR is jointing system used for high speed railway track. (Rajesh, 2008)

5.8.3. Ballast

Almost all leading world railways provide a layer of sub-ballast along with ballast. However, there is wide variation in the practices followed in different countries of the world. The depth of ballast and sub ballast which are in use on the various railways are given below.

Table 5-5: Comparison of ballast depth among different country design manual standards (MITTAL,)

S.N	Railway system	Depth		Speed(kpm)	Axle Load
		Ballast(mm)	Sub-ballast(mm)		
1	Australia	200-300	150	>250	32.5T
2	England	225-375	Variable	>250	32.5T
3	France	150-350	Variable	>250	32.5T
5	UIC	250-550	Variable up to 450	>250	32.5T
6	Japan	300	200	>250	32.5T
7	Swedish Railway	240	90	>250	32.5T
8	USA	300	300	>250	32.5T
9	New Ethiopian rail	250	200	>160	25T

The ballast and Sub-ballast depth used for the Addis Ababa - Adama track line is within recommendable limit to introduce high speed as compared with different countries design standards in the above table 5-5.

Other properties such as rock type, basic quality, and angular particle structure providing sharp corners and elongated pieces, aggregate impact toughness (IP), stone abrasive hardness coefficient (K), aggregate

crushing rate, permeability coefficient, liquid limit, plastic limit, density and unit weight are with recommendable limit for the optimize speed. (MITTAL,)

The maximum ballast deflection and stress under 160km/hr speed and 25kN axle load is 1.6mm and 88000Pa respectively. The analysis result is within recommendable limit and it is attached at annex-4.

5.8.4. Sleeper

The sleeper material and size used for new Ethiopian railway track presented in chapter three. Comparison with different countries is presented in the following table.

Table 5-6: comparison of new Ethiopian railway track sleeper with other countries Design standard.

S.NO.	Description	Country				
		Chinese	France	Italy	German	Ethiopian
1	Sleeper spacing number of sleeper /km	1666	1666	1666	1666	1680
2	Type of sleeper	concrete type II	concrete two/mono block	concrete two /mono block	concrete two /mono block	type II pre-stressed concrete
3	Weight (KG)	-	245/290	400	330	318
4	Length (mm)	-	2415/2500	2600	2600	2500
5	Width (mm)	-	290	300	320	200
6	height (mm)	-	220	220	180	200
7	Effective surface area rail (cm ²)	-	2436/3944	3900	3340	23500

Accordingly, the sleeper specification used for the study area is appropriate for the optimized speed form the above comparison with different countries design standards.

The maximum Sleeper deflection and stress under 160km/hr speed and 25kN axle load is 1.7mm and 350000Pa respectively. The analysis result is within recommendable limit. The result is attached at annex.

5.8.5. Fastening of Sleeper to Rail

The fastenings shall be designed to hold the two rails of the track strongly to the supporting structure in right position by resisting the vertical, lateral and longitudinal loads and vibrations. In slab track, it shall also correct track distortions and act as a buffer, and provide environmental protection from noises and vibrations.

The fastenings shall be of a reputed make with a proven track record and shall be designed in a manner that incorporates the minimum number of components. The fastenings shall provide insulation to take care of return current of third rail traction.

The fastening shall also provide for retrofitting to enable reduction in noise level (N.V.S. Reddy, 2008)

Rail fastenings used on main track shall be in accordance with those specified in the following table

Table 5-7: Type of Rail Fastenings (Chinese Railway Design, 2005)

Classification of track	class 1, class 2	class 2, class 3, class 4	Class 5
Type of rail fastenings	Elastic clip Type II fastenings for sleepers with apron Elastic rod Type III for sleepers without apron	Elastic clip Type II or I fastening	Elastic clip Type I fastenings

Elastic-rod type I types of fastening is used for new Ethiopian track to fix rails to sleeper which commonly used for high speed track.

5.8.6. Analysis of sub-grade for optimized speed.

1. Analysis of the Bearing capacity

Static sounding specific penetration specific resistance value P_s , of natural foundation in range of thickness of bottom layer of sub grade bed: not less than 1.2MPa for Grade I railway line, not less than 1.0MPa for Grade II railway line, or basic bearing capacity σ_0 : not less than 0.15MPa for Grade I railway line, not less than 0.12MPa for Grade II railway line. Otherwise strengthening measure shall be carried out. (Chinese Railway Design, 2005)

The static penetration parameter P_s for natural foundation of bottom layer of sub-grade is not less than 150KPa for high-speed mixed traffic and first class railways, 120KPa for second class railways.

The base bearing force σ_0 : not less than 180KPa for high-speed mixed traffic and first class railways, not less than 150KPa for second class railways. (*Ethiopian Railways Standard, 2014*)

The bearing capacity and static penetration of sub grade for new Addis Ababa –Adama track is $\sigma_0 > 0.15\text{MPa}$ and $P_s > 0.12\text{MPa}$ respectively along the line.

The stress and deflection developed under 160km/h speed and 250KN axle load is 23kpa and 1.19mm respectively. The Abaqus software analysis result is attached at annex 4.

Hence, when compared with above the design codes and from software analysis, the bearing capacity and penetration parameter of the sub grade is within recommendable for optimized speed.

2. Width and thickness of Sub grade

The following table shows the width and thickness of track formation with relation of traffic volume and speed.

Table 5-8: Track formation width on tangent sections (*Ethiopian Railways Standard, 2014*)

Parameters		Units	Class of Railway						
			High speed mixed traffic	I	II	III	IV		
Traffic volume (net)		Mt/km		>30	30-20	20-10	<10		
Design speed		km/h	<200	<160	<160	<120	<80		
Track spacing		m	4.2	4.2	4	4	4		
Track formation width		m	3.5	3.4	3.4	3	2.9		
Type of sub grade layer	Sandy and clayey soils, waste products, suitable for embankment filling	Ballast section width		m	0.5	0.5	0.4	0.4	0.35
		Double track	Fill	m	12.3	12.2	11.7	11.2	10.5
			Cut	m	11.9	11.8	11.3	10.8	10.1
	Rocky non-friable hard formations	Double Ballast section width		m	0.35	0.35	0.3	0.3	0.25
		Ballast section width		m	11.3	11.2	10.7	10.4	9.9
	Sorted (fractional) Crushed stone or gravel	Ballast section width		m	0.3	0.3	-	-	-
		Double track	Fill	m	11.5	11.4	-	-	-
			Cut	m	11.1	11	-	-	-

Hence, when compared with the above table 5-8 width of ballast section, width of track formation, width sub-grade for cut and fill is within recommendable limit.

The maximum sub grade deflection and stress under 160km/hr speed and 25kN axle load is 1.1mm and 23000Pa respectively. The analysis result is within recommendable limit and it is attached at annex-4.

5.8.7. Station and yards

The distance between the stations is very important for introducing high speed. The minimum distance between the stations on the study area is 13.5km while the maximum is 37.4km. Accordingly, the station distance recommendable 160km/h speed. The station dimension, sub grade, material and location have no problem for optimized speeds.

5.8.8. Analysis of Bridge capacity for optimized speed

Dynamic analysis of bridge structures is necessary in case of resonance appearance.

Resonance is a dangerous phenomenon, which occurs due to high speeds and regularly spaced axle groups of the trains. For the speed ≤ 200 km/h, dynamic analysis is not required for the bridge. (Borlänge, 2004)

5.8.9. Transition section

Filling materials used to fill the part below surface layer of transition section and the compaction standard for bottom layer of bedding reaction used for the study area is the one recommendable for high speed track.

5.8.10. Block section

The type of block system for single and double railway should be of semi-automatic block system and automatic block system respectively. When the design running speed of passenger train is more than 120 km/h, in double railway section should adopt speed differential automatic block system and in one section should adopt the same type of block system. (Chinese Railway Design, 2005)

The type of block system used on the study area is Sami - automatic block system. Accordingly, for optimized speed, it need make fully automatic block system.

5.8.11. Turnout

Within the section where the train passing speed in straight direction is 100-160 km/h, the turnout on main track shall be of at least 1: 12. It may use 1: 9 turnouts in a reconstructed district station or larger stations under difficult conditions.

For the turnout to receive and dispatch passenger train in side direction, it shall be no less than 1:12, or, under difficult conditions, uses 1:9 symmetrical turnouts to receive and dispatch passenger train on tracks other than main track.

Main tracks shall not adopt double slip switches, if it is necessary to use under difficult conditions, it shall be no less than 1:12. (Chinese Railway Design, 2005)

From the above reference the turnout provided for Addis Ababa – Adama line is recommendable for the optimized speed.

5.9. Analyzing the power system

As regards the variation in energy consumption (and therefore in emissions) on varying the high speed train's maximum and average speed, the following order of magnitude can be estimated all other factors being equal for a typical Spanish case: (Alberto, 2010)

$$E_{PM} = \frac{0.371}{412} \times V^{0.8805} \times M \dots\dots\dots 5-15$$

Where; E_{PM} = Energy imported to pantograph (KWh/km.train), M = the train mass (in t) and V = is average speed

The energy consumption of a train has been calculated for different speeds according to the average speed (imported and net in the pantograph) (Alberto, 2010)

Calculating Energy consumption for optimized speed

Using the above 5-15 equation the energy consumption of train through pantograph is calculated as follow. For this case the required energy needed is calculated at three stages.

1. Energy needed at preliminary stage:

At preliminary stage the traffic data are:

The train mass = 3500t, Number of train = 9 train and Length of track = 112km

$$E_{PM} = \frac{0.371}{412} \times 160^{0.8805} \times 3500t = 274.9\text{kwh/km. train}$$

Number of train and distance

$$E_{PM} = \frac{274.9\text{kwh}}{(\text{km.train})} \times 9 \text{ trains/day} \times 112\text{km} = 277099.2\text{kwh/day}$$

The annual power required is:

$$E_{PM} = \frac{277099.2\text{kwh}}{\text{day} \times 365} \text{ day} = 101141208\text{KWh} = 10114 \times 10^4\text{KWh}$$

The existing annual power at preliminary stage = $9017 \times 10^4\text{KWh}$

Additional power required for optimized speed at preliminary stage calculated as follows:

$$E_{PM(160)} - E_{PM(120)} = (10,114 - 9,017) \times 10^4 \text{KWh} = 1097.121 \times 10^4 \text{KWh}$$

2. Energy needed at short term stage:

At short term stage the traffic data:

The train mass = 3500t, Number of train = 14 train and Length of track = 112km

$$E_{PM} = \frac{274.9 \text{ kwh}}{(\text{km.train})} \times 14 \text{ trains/day} \times 112 \text{ km} = 431,043.2 \text{ KWh/day}$$

The annual power required is:

$$E_{PM} = 431043.2 \text{ KWh/day} \times 365 \text{ day} = 157,330,768 \text{ KWh} = 15,733 \times 10^4 \text{ KWh}$$

The existing annual power at short term stage = $12940 \times 10^4 \text{ KWh}$

Additional power required for optimized speed at short term stage calculated as follows:

$$E_{PM(160)} - E_{PM(120)} = (15,733 - 12940) \times 10^4 \text{ KWh} = 2,793 \times 10^4 \text{ KWh}$$

3. Energy needed at long term stage:

At long term stage the traffic data:

The train mass = 4000t, Number of train = 27 train, and Length of track = 112km

$$E_{PM} = \frac{0.371}{412} \times 160^{0.8805} \times 4000 \text{ t} = 314.1714 \text{ KWh}/(\text{km. train})$$

$$E_{PM} = \frac{314.17 \text{ kwh}}{(\text{km.train})} \times 27 \text{ trains/day} \times 112 \text{ km} = 950,050.08 \text{ KWh/day}$$

The annual power required is:

$$E_{PM} = 950,050 \text{ KWh/day} \times 365 \text{ da} = 346,768,279 \text{ KW} = 34,676.828 \times 10^4 \text{ KWh}$$

The existing annual power at long term stage = $23818 \times 10^4 \text{ KWh}$

Additional power required for optimized speed at long term stage calculated as follows:

$$E_{PM(160)} - E_{PM(120)} = (34,676.8 - 23,818) \times 10^4 \text{ KWh} = 10,858.8 \text{ K} \times 10^4 \text{ KWh}$$

5.10. Passenger comfort

During speed optimization one of the crucial things is checking the passenger comfort level.

Comfort is often defined as the well-being of a person or absence of mechanical disturbance in relation to the induced environment. This well-being can be achieved and also disturbed by very different factors, both physiological (expectation, individual sensitivity, etc.) and by physical environment (motions,

temperature, noise, seating characteristics, etc.). For these reasons, the same values of vibration might be judged uncomfortable in one environment and acceptable in another. (Lauriks, 2003)

Table 5-9: Certain typical values for motions quantities on circular curves (**KUFVER, 2005**)

Radius(m)	Speed	Compensation ratio	lateral acc. (m/s ²)
393	100	No tilt	1.16
1572	120	No tilt	1.16
1572	240	36%	1.16
1572	240	47%	0.97
1572	240	70%	0.55

Table 5-10: Permissible cant deficiency and the corresponding lateral acceleration (**Martin, 2001**)

Train category	Permissible cant deficiency (mm)	Lateral acceleration, a_y (m/s ²)
A	100	0.65
B	150	0.98
S	245	1.6

The different train categories in Table 18 above have the following meaning:

- Category A conventional vehicles with older running gear and freight trains
- Category B vehicles with improved running gear, according to approval;
- Category S vehicles with improved running gear and car body tilt system

Hence, from the above tables, the cant deficiency and corresponding Lateral acceleration for the proposed speed is within recommendable limit for passenger comfort and safety.

Track Infrastructures and Materials analyze result summary for the Optimized Speed

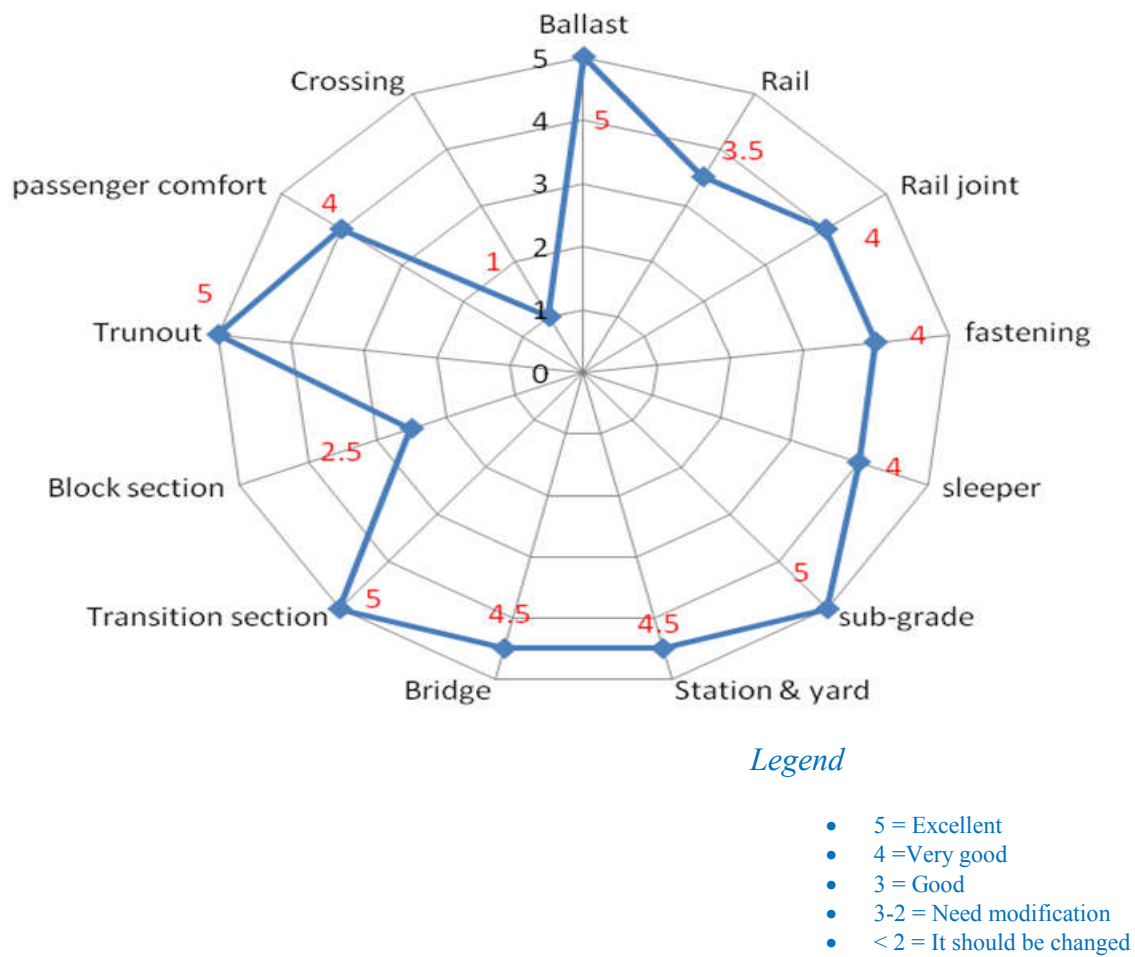


Figure 5-6: Track structures and material analysis summary for optimized speed.

CHAPTER-6 Cost Estimation

6. Tentative Cost repercussions for realignment of the curves

For the introduction of high-speed for Addis Ababa - Adama sections, tentative cost approximate requirement of funds for civil engineering assets can be summarized as under: (Vivek) and (Addis Ababa – Adama line feasibility study, 2012)

6.1. Necessary data and assumption for realignment cost estimation

Double-line sub-grade embankment width = 11.7m

Double –line sub-grade cut width = 11.7m

Length of tight curve (R = 800m) = 963m

Length of realigned curve (R = 1325m) = 1.5km

Track superstructure materials such as rail, sleeper, electrical and traffic equipment will be used for the realignment curves by dismantling from the tight curves.

The unit price is coated from feasibility study and detail design of Ethiopian railway route along awash-Armenya line (*AWASH – ARMENYA feasibility study and tender document, 2012*) and quantity of work is estimated from Addis Ababa- Adama feasibility study (*Ethiopia/Sebeta ~ Djibouti/Nagad Railway Feasibility Study, 2012*)

Table 6-1: Tentative cost estimation for upgraded section

S.N	Station	curve radius	Proposed for Relaxing				Amount (ET birr)
			Profile description	Unit	QTY	Unit Rate	
1	13+500	800	Embankment	M ³	40,540.5	189.98	7,701,884.19
2	18+400	800	Cut	M ³	126,360	181.43	22925494.8
3	19+950	800	Cut	M ³	1,153,030	181.43	20919514.01
4	21+00	800	Bridge	Lkm	0.9	12,000,000	10800000
5	22+050	800	Cut	M ³	87750	181.43	15920482.5
6	22+950	800	Bridge	Lkm	0.9	12,000,000	10,800,000
7	23+800	800	Bridge	Lkm	0.9	12,000,000	10,800,000
8	24+600	800	Cut	M ³	86205	181.43	15639419.95
9	26+00	800	Cut	M ³	10764	181.43	1952912.2
10	27+600	800	Bridge	Lkm	2	12,000,000	24,000,000
11	32+300	800	Cut	M ³	20592	181.43	3736006.56
12	37+50	800	Cut	M ³	41441	184.43	7518713.2
13	50+100	800	tunnel	Lkm	1.2	157,281,586	188737903.8
14	51+500	800	Embankment	M ³	58827	189.98	11176067.45
15	68+00	1000	Embankment	M ³	4457	181.43	8068437
16	87+300	800	Bridge	Lkm	900	12,000,000	10,800,000
17	93+930	1200	Bridge	Lkm	7500	12,000,000	10,800,000
18	94+700	800	Cut	M ³	17550	181.43	3,176,550
19	95+600	800	Bridge	Lm	900	12,000,000	10,800,000
20	98+500	1000	Cut	M ³	137241	181.43	24899634.63
21	99+450	800	Tunnel	Lkm	1	157,281,586	157,281,586
22	100+400	800	Bridge	Lkm	900	12,000,000	10,800,000
23	101+350	800	Bridge	Lkm	900	12,000,000	10,800,000
24	103+900	800	tunnel	Lkm	1.3	157,281,586	204466062.5
25	105+250	1200	Embankment	M ³	19094	189.98	3,627,554.112
26	107+300	800	Embankment	Lkm	1.5	12,000,000	18,000,000
27	108+195	800	Bridge	Lkm	1.5	12,000,000	18,000,000
28	108+850	800	bridge	Lkm	1.5	12,000,000	18,000,000
29	109+900	800	Cut	M ³	77220	181.43	13,976,820
30	111+100	800	Cut	M ³	35100	181.43	6,353,100
31	Elimination of level crossing			No	34	9,000,000	306,000,000
32	Infrastructure/material as required						75,000,000

Total in ETB	1,291,018,143.81
Total in USD	64,550,907.19
Contingence and supervision cost (10%)	129,101,814.38
Grand total in ETB	1,420,119,958.19
Grand total in USD	71,005,997.91

Tentative investment needed to upgrade civil Engineering assets for introduction of high speed for Addis Ababa - Adama section is about 71 USD Million. In order to assess the feasibility on overall basis, the investment with regard to rolling stock, and overhead signaling equipments will also have to be calculated and added.

6.2. Tentative cost repercussions for introduction of tilt coach technology

The civil engineering assets needed to improve for introduction of high-speed for Addis Ababa - Adama section by introducing tilting coach technology is only elimination of level crossing. The tentative investment required for level crossing elimination is about 15.3 USD Million.

Comparatively introducing tilt coach technology cost is inexpensive than upgrading/realignment of geometric track for conventional train.

Optimization techniques and with cost summary

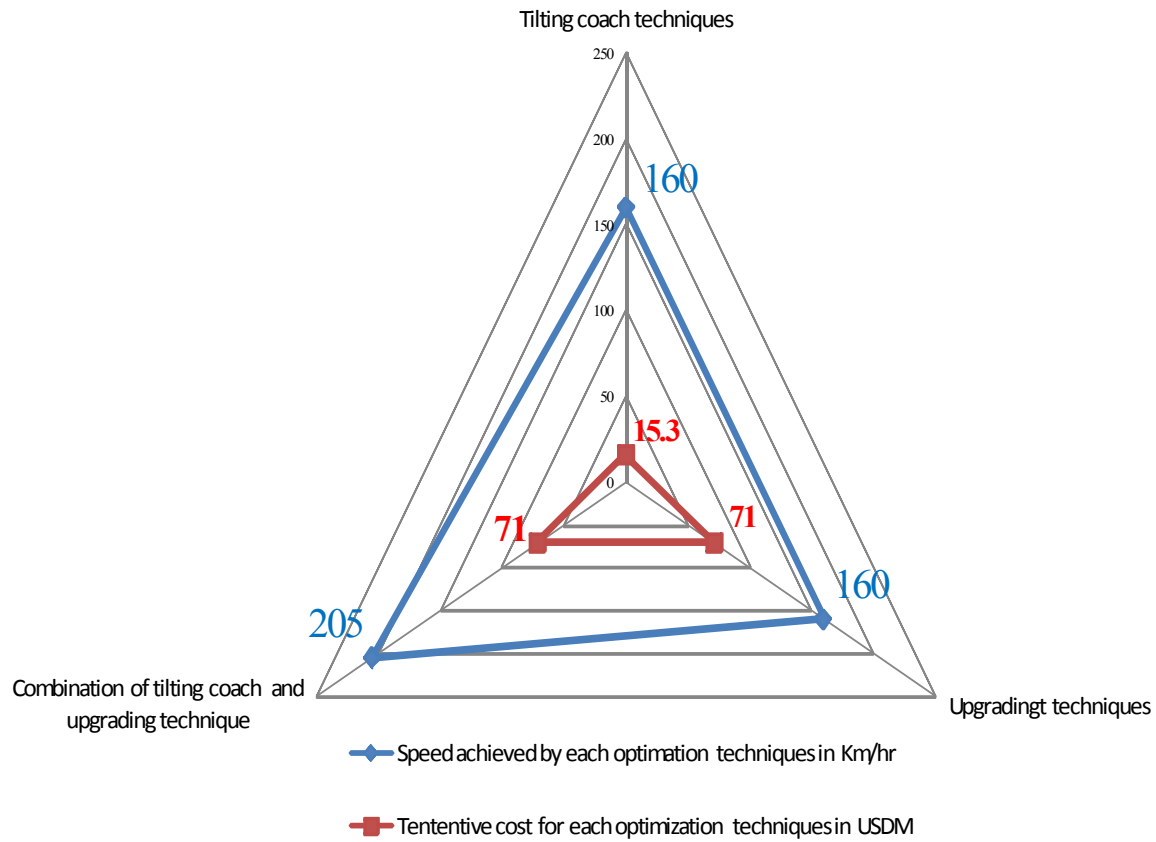


Figure 6-1 : Speed optimization techniques summary with cost

CHAPTER-7 CONCLUSION AND RECOMMENDATION

7. General

The purpose of this thesis was to optimize speed and examine infrastructure and construction material for high speed rail network in particular for Abbis Ababa - Adama line. Conclusions and recommendations of the research findings are presented as follows.

7.1. Conclusion

This study has focused on speed optimization of route from Addis Ababa to Adama. Geometric analyses have been performed using Bentley software to determine the design speed and other design speed related parameters. In addition, construction materials and infrastructures were investigated for the optimized speed. From the analysis result materials and infrastructures used were recommendable up to 160km/hr. The software result were compared with known literature for further checking. Based on the analysis result obtained the following conclusions may be drawn.

- ✚ Geometric alignment of Addis Ababa – Adama line is most restrictive for introducing high speed due to Existence Mountain, small town/cities along the alignment, crossing major rivers at appropriate location to restrict length of bridge, gully, swamp, and geology/ground fissure. The sharpest horizontal curve is allowable for 120km/hr design speed. For sharpest curves 130km/hr speed can be achieved by modifying applied cant from 130mm to 150mm. whereas vertical curve is allowable for 170 km/h speed and 170km/h -250km/h is within exceptional range.
- ✚ From the analysis result 160km/h speed can be achieved on the existing track by introducing tilting coach technology without major track upgrading.
160km/h Speed can be achieved on existing track by upgrading sharp horizontal curves less than $R=1325m$ for conventional train.
- ✚ By combination of tilting coach technology optimization techniques and track alignment upgrading optimization techniques, it is possible to achieve 205 km/h. But it is within exceptional range of vertical alignment i.e. 170km/h - 250km/h.
- ✚ From three optimization techniques 33% is the average level of optimized speed.
- ✚ It is required to eliminate all level crossings by constructing elevated bridge to introduce a uniform speed on the line. If not possible, it is required to provide appropriate traffic signal and sign at all level crossings to minimize traffic delay that reduces the average speed of the route.

- ✚ Stress and deflection in Railway track increases due to increase in train speed. The strength of each component member should be greater than the stresses, which each is required to bear. Adequacies of existing track structure, sleeper, track formation, ballast, rail, rail and sleeper fastening and transition section were checked. The 50kg/m weight, 25m-long standard U71Mn hot-rolled rails, sleeper, ballast, and sub-grade were analyzed by finite element method to examine the structures response under 160km/h train speed and 250KN axle load. Stress and deflection response result shows all structures are within recommendable limit for optimized speed.
- ✚ Train power consumption is increased due to increase of train speed. From the analysis result, 1097.121×10^4 KWh, $2,793 \times 10^4$ KWh and $10,858.8 \times 10^4$ KWh power is required at preliminary stage, short term stage and long term stage respectively to augment the optimized speed power requirement.
- ✚ The optimized speed line offers Ethiopian citizens a safe, fast, Comfortable, economical development, reduced traffic and urban sprawl, transit-oriented development and communities, energy efficient and ecological mode of transport. But if continuous with existing speed, customers will change their preference to other modes of transportation and it lead loss of revenue due to non-availability of track.

7.2. Recommendation and Future study

From the study the following recommendation can be drawn:

- ✚ Raising of speed from 120km/hr to 160km/h and subsequently to higher speeds would give excellent exposure to railway engineers, ERC, and the rail users in general.
- ✚ Upgrading existing track technology is expensive, takes time and needs design review.
- ✚ For under construction line it is better to use applied cant of 150mm which commonly used by many countries to achieve 130km/h speed on sharp horizontal curve (R= 800m)
- ✚ It is recommended that tilting coach technology for Ethiopian railway projects to achieve high speed on the existing line for the following reason and advantages.
 - ✓ High give fast and effective solution for difficult of Ethiopian topography to introduce high speed track with very low cost
 - ✓ Easy technology for implementation
 - ✓ Take short time and
 - ✓ alignment upgrading is not required
 - ✓ Easily adopted without very complicated technologies and it can be easily replaced the conventional train
- ✚ Since the entire Ethiopian national rail network is similar, the work done for Addis Ababa – Adama line can be projected for other routes to increase consistency system throughout the country.
- ✚ Ethiopian Railways Design Standard Code has no clear and detail specification for all speed related parameters. Tilting coach technology design is nixed from the code, it is better if included in the code.
- ✚ Operation, maintenance and management guide line manuals are required for the optimized speed.
- ✚ Detail/revision of cost and structure design is required with multi-discipline professionals before implementing optimization.

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Annex

Field survey for Addis Ababa-Adama was done on 19 June 2015 and 20 June 2015. Data such as topographic future of the alignment, existing structures, sharpest curve location and its difficulties, available alternative solution for curve widening and level crossing area was visited.

In general all Addis Ababa-Adama track line has about 54 curves of which 29 is sharpest and cause for reduction of average speed of the route. This sharpest curve was provided at mountain area, valley, road crossing, river and some sloped areas.

The annex contains the speed related design parameter results at different speed and horizontal curve radius. Some necessary topographic photos are also attached.

Annex 1 : software result for convention train with speed related parameters

Type	Station	V (kph)	Radius m	Transition	Equil. Cant (mm)	App. Cant (mm)	Def. Cant (mm)	Non-Comp.g Lat.Accel. (m/s*s)	App. Rate of Change (mm/s)	Def. Rate ofChange (mm/s)	App. Gradient
POB		130	0	Linear	0	0	0	0	0	0	0
TS		130	0	Clothoid	0	0	0	0	15	10	2400
SC	3+450	130	-1600	Circular	124.6	75	49.6	0.33	0	0	0
CS	3+450	130	-1600	Clothoid	124.6	75	49.6	0.33	15	10	2400
TS		130	0	Clothoid	0	0	0	0	14	8.8	2571
SC	8+750	130	3500	Circular	56.98	35	22	0.14	0	0	0
CS	8+750	130	3500	Clothoid	56.98	35	22	0.14	14	8.8	2571
ST		130	0	Linear	0	0	0	0	0	0	0
TS		130	0	Clothoid	0	0	0	0	30.1	19.9	1200
SC	19+950	130	800	Circular	249.3	150	99.3	0.65	0	0	0
CS	19+950	130	800	Clothoid	249.3	150	99.3	0.65	30.1	19.9	1200
ST		130	0	Linear	0	0	0	0	0	0	0
SC	30+600	130	2200	Circular	90.65	55	35.6	0.23	0	0	0
CS	30+600	130	2200	Clothoid	90.65	55	35.6	0.23	11	7.2	3273
ST		130	0	Linear	0	0	0	0	0	0	0
TS		130	0	Clothoid	0	0	0	0	30.1	19.9	1200
SC	32+300	130	800	Circular	249.3	150	99.3	0.65	0	0	0
CS	32+300	130	800	Clothoid	249.3	150	99.3	0.65	30.1	19.9	1200
ST		130	0	Linear	0	0	0	0	0	0	0
POE		130	0	Linear	0	0	0	0	0	0	0

Annex 2: software analysis result for tilt coach 160km/h

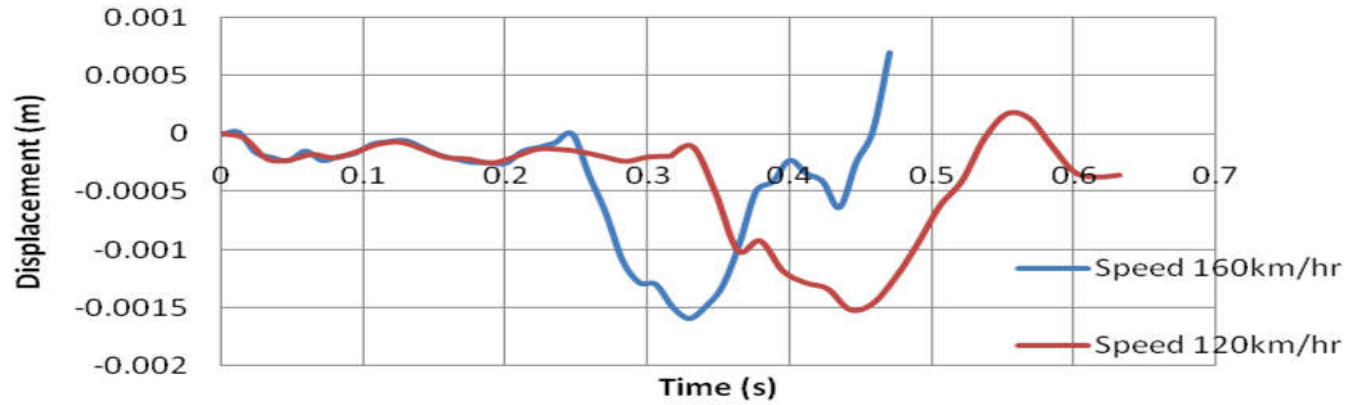
Type	Station	V (kph)	Radiu s (m)	Transiti on	Equil. Cant (mm)	App. Cant (mm)	Def. Cant (mm)	Non-Comp.g Lat.Accel . (m/s*s)	App. Rate of Change (mm/s)	Def. Rate ofChange (mm/s)	App. Gradient
POB		160	0	Linear	0	0	0	0.00	0.00	0.00	0
TS		160	0	Clothoid	0	0	0	0.00	28.40	18.22	1565
SC	3+450	160	-1600	Circular	188.8	115	73.8	0.48	0.00	0.00	0
CS	3+450	160	-1600	Clothoid	188.8	115	73.8	0.48	28.40	18.22	1565
ST		160	0	Linear	0	0	0	0.00	0.00	0.00	0
TS		160	0	Clohtoid	0	0	0	0.00	24.69	17.93	1800
SC	8+750	160	3500	Circular	86.30	50	36.3	0.24	0.00	0.00	0
CS	8+750	160	3500	Clothoid	86.30	50	36.3	0.24	24.69	17.93	1800
ST		160	0	Linear	0	0	0	0.00	0.00	0.00	0
TS		160	0	Clothoid	0	0	0	0.00	32.10	61.14	1385
SC	18+400	160	800	Circular	377.6	130	247.6	1.62	0.00	0.00	0
CS	18+400	160	800	Clothoid	377.6	130	247.6	1.62	32.10	61.14	1385
ST		160	0	Linear	0	0	0	0.00	0.00	0.00	0
TS		160	0	Clothoid	0	0	0	0.00	20.99	12.92	2118
SC	30+600	160	2200	Circular	137.3 1	85	52.31	0.34	0.00	0.00	0
CS	30+600	160	2200	Clothoid	137.3 1	85	52.31	0.34	20.99	12.92	2118
ST		160	0	Linear	0	0	0	0.00	0.00	0.00	0
POE		160	0	Linear	0	0	0	0.00	0.00	0.00	0

Annex 3: software analysis result for the upgraded curve at speed 160km/hr

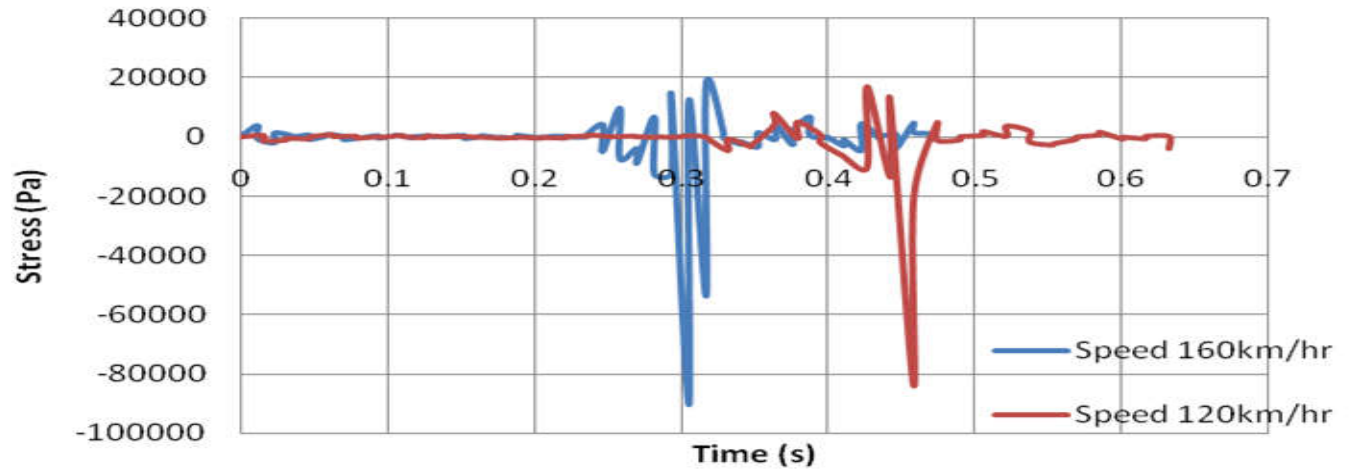
Type	Station	V (kph)	Radiu s (m)	Transiti on	Equil. Cant (mm)	App. Cant (mm)	Def. Cant (mm)	Non-Compensat ing Lateral acc. (m/s*s)	App. Rate of Change (mm/s)	Def. Rate of Change (mm/s)	App. Gradie nt
POB	0+000	160	0	Linear	0.00	0	0.00	0.00	0.00	0.00	0
TS	9+380	160	0	Clothoid	0.00	0	0.00	0.00	33.33	22.96	1333
SC	11+180	160	-1325	Circular	227.99	135	92.99	0.61	0.00	0.00	0
CS	18+860	160	-1325	Clothoid	227.99	135	92.99	0.61	33.33	22.96	1333
ST	20+660	160	0	Linear	0.00	0	0.00	0.00	0.00	0.00	0
TS	26+700	160	0	Clothoid	0.00	0	0.00	0.00	32.10	21.18	1385
SC	28+500	160	1400	Circular	215.77	130	85.77	0.56	0.00	0.00	0
CS	33+030	160	1400	Clothoid	215.77	130	85.77	0.56	32.10	21.18	1385
ST	34+830	160	0	Linear	0.00	0	0.00	0.00	0.00	0.00	0
TS	40+310	160	0	Clothoid	0.00	0	0.00	0.00	32.10	21.95	1385
SC	42+110	160	-1380	Circular	218.90	130	88.90	0.58	0.00	0.00	0
CS	47+150	160	-1380	Clothoid	218.90	130	88.90	0.58	32.10	21.95	1385
ST	48+950	160	0	Linear	0.00	0	0.00	0.00	0.00	0.00	0
PI	68+290	160	0	Linear	0.00	0	0.00	0.00	0.00	0.00	0
TS	87+700	160	0	Clothoid	0.00	0	0.00	0.00	33.33	21.92	1333
SC	89+500	160	-1350	Circular	223.76	135	88.7	0.58	0.00	0.00	0
CS	93+580	160	-1350	Clothoid	223.76	135	88.7	0.58	33.33	21.92	1333
ST	95+380	160	0	Linear	0.00	0	0.00	0.00	0.00	0.00	0

Annex 4: Abaqus analysis result of track structure and materials

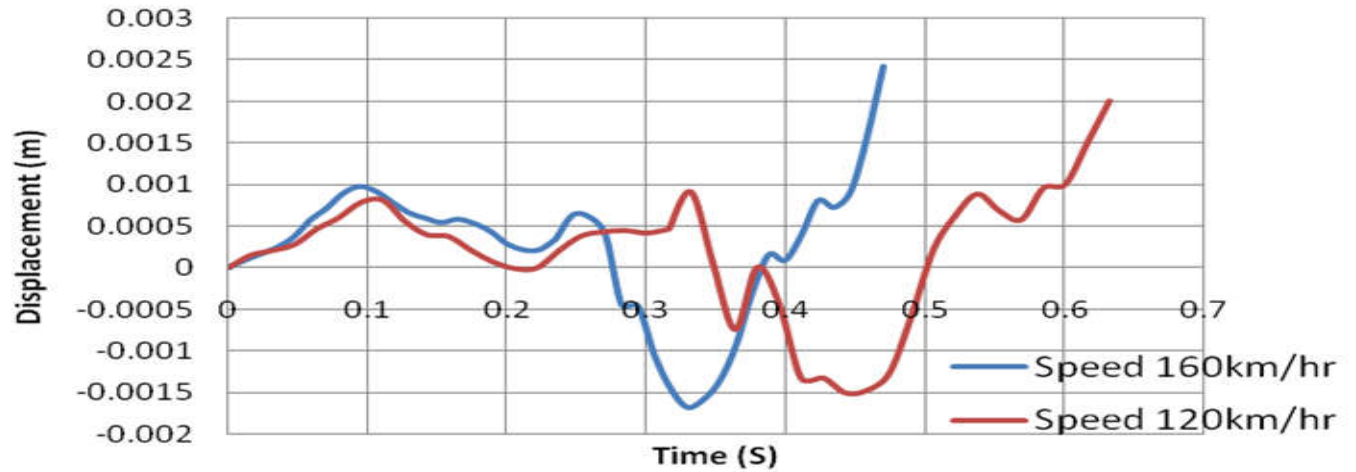
Ballast Displacement



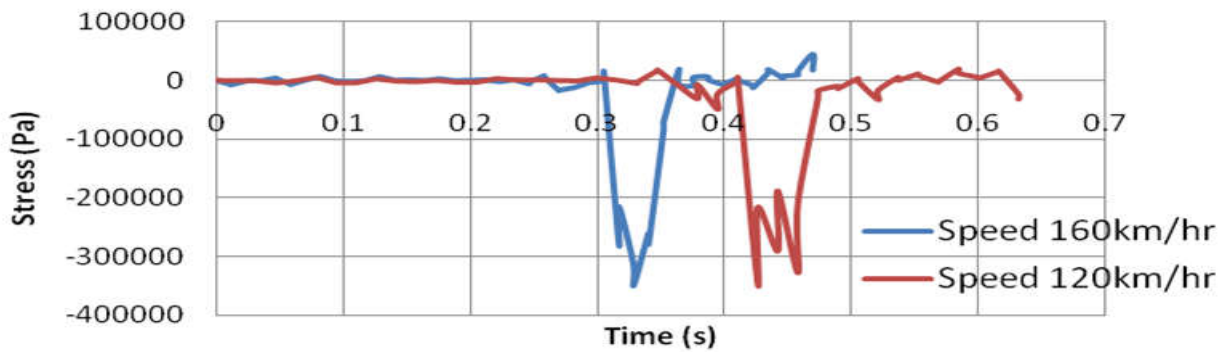
Ballast Stress



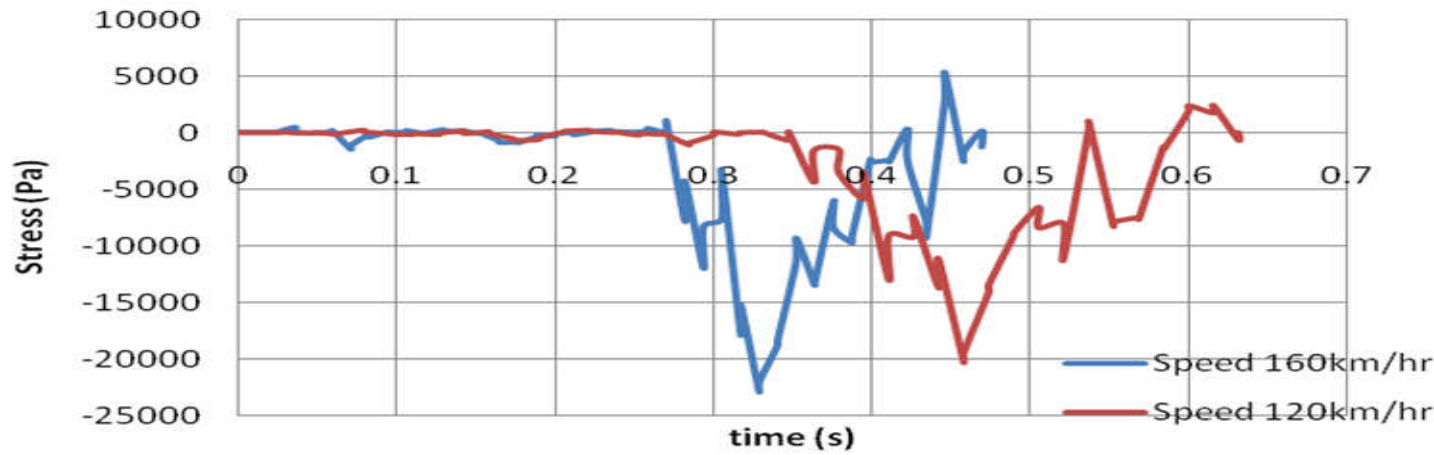
Sleeper displacement



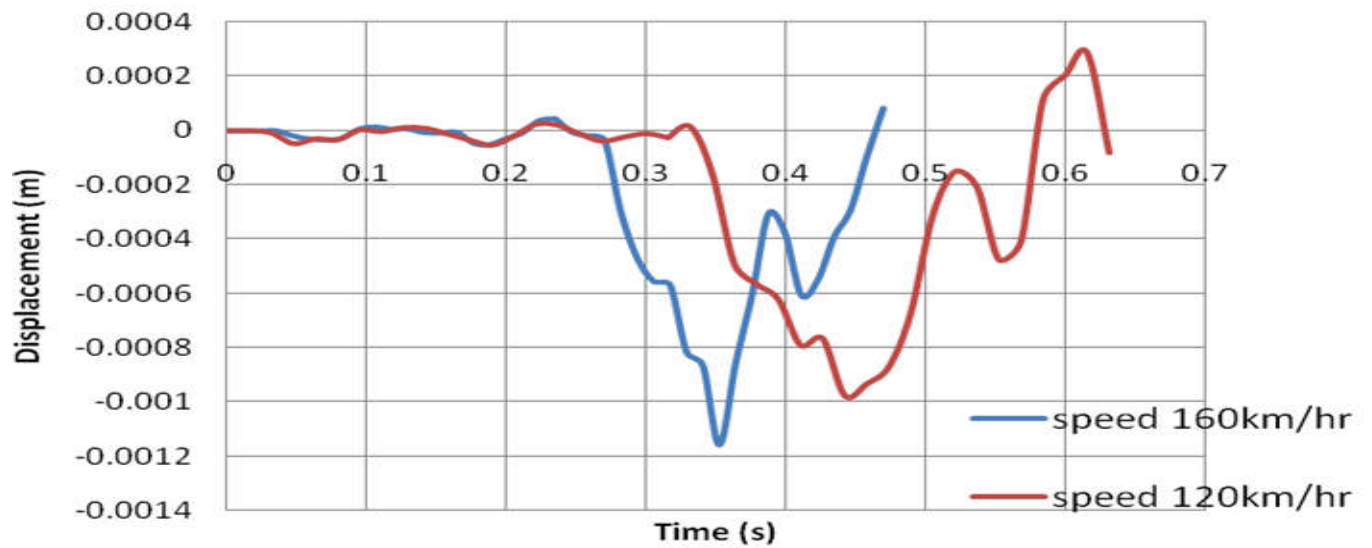
Sleeper Stress



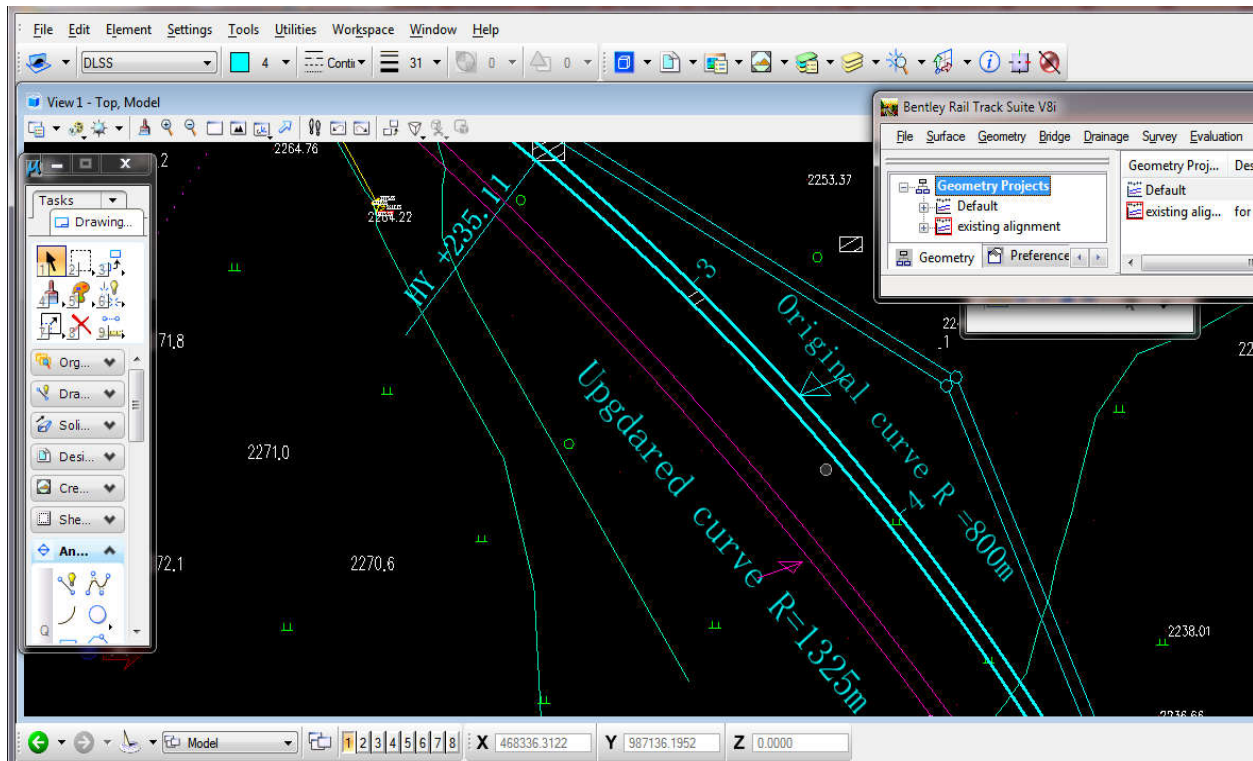
Subgrade stress



Subgrade displacement



Annex 5: The realignment of horizontal Curves to achieve 160km/hr for conventional train



Annex 6: some restrictive track alignment section pictures



Vertical gradient at Station 37+50



Sharp horizontal curve at station 27+600



Bridge at station 101+350



Huge cut at station 95+450



Medium cut at station 50+50



Track super structure material