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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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 superstructures, 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 method 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

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

CA = Standard aggregate crushing rate

CB = Ballast aggregate crushing rate

Cogo = Coordinate geometry

$D =\text{Applied track cant}$

$Deq = \text{Equilibrium cant the sum of track cant and cant deficiency})$

$dD/ds = \text{cant gradient}$

$dD/dt = \text{rate of change of cant}$

$dl/dt = \text{the rate of change of cant deficiency}$

$E = \text{cant excess}$

$V = \text{train speed (km/h)}$

$V_f = \text{Max speed for freight trains}$

$V_{min} = \text{minimum train speed}$

$V_{max} = \text{maximum speed}$

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

FACT = Research programme Fast and Comfortable Trains

$I = \text{Cant deficiency}$
\[ I_{\text{limit}} = \text{limit for cant deficiency} \]

\[ \text{IP} = \text{Standard aggregate impact toughness} \]

\[ \text{JBV} = \text{Jernbane Verket} \]

\[ K = \text{Stone abrasive hardness coefficient} \]

\[ \text{KTH} = \text{Royal Institute of Technology (Stockholm, Sweden)} \]

\[ \text{LAA} = \text{Los Angeles Abrasion rate} \]

\[ \text{LD} = \text{length of cant transitions} \]

\[ \text{LL} = \text{Limestone liquid limit} \]

\[ \text{O&M} = \text{Operation and Maintenance} \]

\[ \text{Pm} = \text{Permeability coefficient} \]

\[ \text{PL} = \text{Limestone plastic limit} \]

\[ \text{Rec.} = \text{Recommended} \]

\[ \text{Rv} = \text{vertical radius curve} \]

\[ \text{S&C} = \text{Switch and Cross} \]

\[ \text{TSI} = \text{Technical Specification for Interoperability} \]

\[ \text{UIC} = \text{Union Internationale des Chemins de Fer (International Union of Railways)} \]

\[ \text{UIC 60} = \text{Standard rail profile} \]

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

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

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

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

\[ X2000 = \text{Swedish tilting train} \]
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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 undertaken 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) dl/dt(mm/s);
- length of cant transitions LD(m) (*S);
- length of transition curves in the horizontal plane L_K(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 (*) 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 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.

$$ R_{min} = \frac{c}{(D+E_{lim})} V^2 $$

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:
\[ R_{\text{max}} = \frac{c}{D - E_{\text{lim}}} \times V^2 \text{min} \]

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

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)

\[ D_{\text{lim}} = \frac{R-80}{150} \text{mm/mm} \]

Where, \( D_{\text{lim}} \) = 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:

\[ I = C \frac{V^2}{R} - D = E - D \leq I_{\text{lim}} \]

Where, \( I \) = Cant deficiency, \( R \) = Radius of horizontal curve, \( V \) = permissible speed, \( D \) = applied cant, \( E \) = equilibrium cant, \( I_{\text{lim}} \) = normal limit of cant deficiency
Normal and Exceptional Limits for Cant Deficiency

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

<table>
<thead>
<tr>
<th>Non-tilting trains</th>
<th>Normal limits</th>
<th>Exceptional limits</th>
</tr>
</thead>
<tbody>
<tr>
<td>80km/h &lt; V ≤ 200km/h</td>
<td>130mm</td>
<td>183mm</td>
</tr>
<tr>
<td>200km/h &lt; V ≤ 230km/h</td>
<td>130mm</td>
<td>168mm&lt;sup&gt;ab&lt;/sup&gt;</td>
</tr>
<tr>
<td>230km/h &lt; V ≤ 250km/h</td>
<td>130mm</td>
<td>153mm&lt;sup&gt;ab&lt;/sup&gt;</td>
</tr>
<tr>
<td>250km/h &lt; V ≤ 300km/h</td>
<td>100mm</td>
<td>130mm&lt;sup&gt;abc&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

Tilting trains

| 80km/h < V ≤ 260km/h | 275mmb        | 306mmb              |

<sup>a</sup> 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.

<sup>b</sup> 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.

<sup>c</sup> The limit may be raised to 153 mm for non-ballasted track.

<sup>d</sup> Currently, there are no lines used or planned where maximum speed for tilting trains exceeds 260 km/h

6. Cant Excess (E)

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

\[ E = D - \frac{C}{R} V^2 \]

Where, \( C = 11.8 \, \text{mm} \cdot \text{m}^2 \cdot \text{h}^2 / \text{km}^2 \), Normal limit for cant excess \( E_{\text{lim}} \) 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)

\[ \frac{dD}{dt} = \frac{\Delta D}{L_D} \cdot \frac{V}{q_v} \leq \left( \frac{dD}{dt} \right)_{lm} \]

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

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

<table>
<thead>
<tr>
<th>Non –tilting trains ( V \leq 200 \text{km/h} )</th>
<th>Normal limits</th>
<th>Exceptional limits</th>
</tr>
</thead>
<tbody>
<tr>
<td>( I \leq 168 \text{ mm} )</td>
<td>50 mm/s</td>
<td>70 mm/s *</td>
</tr>
<tr>
<td>( 168 &lt; I \leq 183 \text{ mm} )</td>
<td>50 mm/s</td>
<td>50 mm/s</td>
</tr>
<tr>
<td>Non –tilting trains 200 km/h ( V &lt; 300 \text{km/h} )</td>
<td>50 mm/s</td>
<td>60 mm/s</td>
</tr>
</tbody>
</table>

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

\[ (\frac{dD}{dt})_{max} < (\frac{dD}{dt})_{lm} \]

Normal limit \( (\frac{dD}{dt})_{lm} = 55 \text{ mm/s} \), Exceptional limit \( (\frac{dD}{dt})_{lm} = 76 \text{ mm/s} \)
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 $\left( \frac{dD}{dt} \right)_{lim} = 75$ mm/s and Exceptional limit $\left( \frac{dD}{dt} \right)_{lim} = 76$ 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)

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

Where, $L_D =$ the length of the cant transition in meters, $\Delta I =$ variation of cant deficiency, $V =$ vehicle speed in km/h and $qv = 3.6$ km·s / (h·m)
Table 2-3: Rate of change of cant deficiency (dI/dt) for constant can gradient (EN 13803, 2010)

<table>
<thead>
<tr>
<th></th>
<th>Normal limit</th>
<th>Exceptional limits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non- tilting trains v&lt;=200 km/h</td>
<td></td>
<td></td>
</tr>
<tr>
<td>I &lt;= 168 mm</td>
<td>55mm/s</td>
<td>100mm/s</td>
</tr>
<tr>
<td>168 &lt; I &lt;=183 mm</td>
<td>55mm/s</td>
<td>90mm/s</td>
</tr>
<tr>
<td>Non- tilting trains 200km/h &lt; v &lt;=300km/h</td>
<td>55 mm/s</td>
<td>75 mm/s</td>
</tr>
</tbody>
</table>

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.

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

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). \textit{(Rickard Persson, 2011)}

13. Cant Gradient dD/ds

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

\[
\left( \frac{dD}{ds} \right)_{\text{max}} \leq \left( \frac{dD}{ds} \right)_{\text{lim}} \]

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

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

\[
\left( \frac{dD}{ds} \right) = \frac{\Delta D}{LD} \leq \left( \frac{dD}{ds} \right)_{\text{lim}} \]

There is no further special limit for the tilting trains. \textit{(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 (2\(^{nd}\) 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)

\[
R_{vlm} = qR_{lim} V^2
\]

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

The exceptional limit for radius of vertical curve is:

\[
R_{vlim} = qR_{lim} V^2
\]

Where, \( qR_{lim} = 0.13 \) m \( \cdot \) h\(^2\)/km\(^2\) for sag and \( qR_{lim} = 0.16 \) m \( \cdot \) h\(^2\)/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)

![Diagram of conventional and tilting trains](image)

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)

\[ V = \sqrt{\frac{R \cdot (I_{lim} + D_{lim})}{118}} \]

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
2.6.2. Enhanced Permissible Speed on Super Elevation Ramps

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

\[
\frac{V_T}{V_C} = \frac{\dot{D}_T}{\dot{D}_C}
\]

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.

\[ \frac{D}{I} = 11.6 \frac{v^2}{lt} \frac{V}{R} \] 2-14

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

The application of Equation [2-14] assumes that the amount of cant is fine-tuned to balance the limits \( D \) and \( I \). 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)

\[ \frac{V_T}{V_C} = \sqrt{\frac{D_T}{D_C}} \frac{1}{\sqrt{I_T}} \] 2-15

Where, \( D_T \) = limit for rate of change of cant, tilting trains (mm/s), \( I_T \) = limit for rate of change of cant deficiency, tilting trains (mm/s), \( D_C \) = limit for rate of change of cant, conventional non-tilting trains (mm/s) and \( I_C \) = 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 transitions 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)

\[
\frac{v_t}{v_c} = \sqrt{\frac{\dot{I}_T}{\dot{I}_C}}
\]

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, Rv Limitation**

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

\[ R_{v,\text{lim}} = q_{R,\text{lim}} v^2 \]

Where \( q_{R,\text{lim}} = 0.35 \text{ m}^2\text{/km}^2 \)

NOTE: On lines where most of the passengers may be standing, it is recommended that \( (q_{R}) \) should be greater than 0.77 m\(^2\)/km\(^2\)

The exceptional limit for radius of vertical curve is

\[ R_{v,\text{lim}} = q_{R,\text{lim}} v^2 \]

Where, \( q_{R,\text{lim}} = 0.13 \text{ m}^2\text{h}/\text{km}^2 \) for sag, and \( q_{R,\text{lim}} = 0.16 \text{ m}^2\text{h}/\text{km}^2 \) 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)

<table>
<thead>
<tr>
<th>Train category</th>
<th>Conventional trains V ≤ 200km/hr</th>
<th>Conventional trains V &gt; 200km/h, V ≤ 220km/h</th>
<th>Tilting Trains</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max Cant, D(mm)</td>
<td>*180</td>
<td>*180</td>
<td>*180</td>
</tr>
<tr>
<td></td>
<td>**160</td>
<td>**160</td>
<td>**160</td>
</tr>
<tr>
<td>Max Cant, Deficiency, l(mm)</td>
<td>*180</td>
<td>160</td>
<td>260</td>
</tr>
<tr>
<td></td>
<td>**50</td>
<td>**50</td>
<td>**50</td>
</tr>
<tr>
<td>Max rate of change of cant dD/dt (mm/s)</td>
<td>*60</td>
<td>*60</td>
<td>*60</td>
</tr>
<tr>
<td></td>
<td>**50</td>
<td>**50</td>
<td>**50</td>
</tr>
<tr>
<td>Max rate of change of cant deficiency, dl/dt (mm/s)</td>
<td>*90</td>
<td>*75</td>
<td>No limit</td>
</tr>
<tr>
<td></td>
<td>**55</td>
<td>**50</td>
<td></td>
</tr>
<tr>
<td>Min length between super-elevation ramps(m)</td>
<td>50</td>
<td>50</td>
<td>50</td>
</tr>
</tbody>
</table>

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.

\[(\frac{dI}{dt})_F = (\frac{dD}{dt})_F \frac{I}{D} \] ............................................................................. 2-12

With \((dD/dt) = 60 \text{ mm/s}, I = 260 \text{ mm},\) and \(D = 180 \text{ mm},\) 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)

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

Note A: On curves with small radii, another limit for cant is (R–50 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)

<table>
<thead>
<tr>
<th>Train category</th>
<th>old conventional passenger trains and freight</th>
<th>conventional express trains</th>
<th>Tilting Trains</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max cant, D(mm) (Note A)</td>
<td>150</td>
<td>150</td>
<td>150</td>
</tr>
<tr>
<td>Max cant Deficiency, l(mm)</td>
<td>R&lt;290m: 100, 290m&lt;R&lt;600m: 130, R&gt;600m: 150</td>
<td>160</td>
<td>280</td>
</tr>
<tr>
<td>Max cant Deficiency, l(mm), at stiff track (Note B)</td>
<td>R&lt;350m: 100, R&gt;350m: 130</td>
<td>R&lt;350m: 100, R&gt;350m: 130</td>
<td>180</td>
</tr>
<tr>
<td>Max rate of change of cant, (mm/s)</td>
<td>55</td>
<td>69</td>
<td>75</td>
</tr>
<tr>
<td>Max. rate of change of cant deficiency, (mm/s)</td>
<td>80</td>
<td>100</td>
<td>140</td>
</tr>
<tr>
<td>Max cant excess (for freight trains)</td>
<td>R&lt;600m: 90, R&gt;600m: 110</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Max speed for freight trains, V_f (km/hr)</td>
<td>90</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
Table 2-7: Certain track geometry limits for plain track - exceptional values. (Dr B. KUFVER, 2005)

<table>
<thead>
<tr>
<th>Design Speed Related Track Component and Materials</th>
</tr>
</thead>
<tbody>
<tr>
<td>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,)</td>
</tr>
</tbody>
</table>
Table 2-8: Characteristics of ballast and sub-ballast. (MITTAL,)

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

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)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>France</th>
<th>Germany</th>
<th>Italy</th>
<th>Spain</th>
<th>Belgium</th>
<th>SIT</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>speed KMPh</strong></td>
<td>300</td>
<td>300</td>
<td>300/350</td>
<td>300</td>
<td>300/350</td>
<td>350</td>
</tr>
<tr>
<td>type</td>
<td>Two block/mono block</td>
<td>Two block/mono block</td>
<td>mono block B 90</td>
<td>mono block B 75</td>
<td>mono block</td>
<td>mono block</td>
</tr>
<tr>
<td>Sleeper(spacing number of sleeper/km)</td>
<td>1666</td>
<td>1666</td>
<td>1587</td>
<td>1666</td>
<td>1666</td>
<td>1666</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>245/290</td>
<td>245/290</td>
<td>330</td>
<td>400</td>
<td>300</td>
<td>300</td>
</tr>
<tr>
<td>Length (mm)</td>
<td>2415/2500</td>
<td>2415/2500</td>
<td>2600</td>
<td>2600</td>
<td>2500</td>
<td>2500</td>
</tr>
<tr>
<td>Width (mm)</td>
<td>290</td>
<td>290</td>
<td>320</td>
<td>300</td>
<td>300</td>
<td>300</td>
</tr>
<tr>
<td>Height (mm)</td>
<td>220</td>
<td>220</td>
<td>180</td>
<td>220</td>
<td>222</td>
<td>242</td>
</tr>
<tr>
<td>Effective surface area per rail (cm²)</td>
<td>2436/3344</td>
<td>2436/3344</td>
<td>3340</td>
<td>3900</td>
<td>310</td>
<td>310</td>
</tr>
</tbody>
</table>
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.

![Map of Ethiopian Railway routes](image)

Figure 3-1: New Ethiopian Railway routes
3.1. **Salient Feature of Addis Ababa - Adama Line**

The salient features of the line are:

- Track type .......................................................Ballast track
- Number of track lane ............................................Double track
- Length (Route Km) ..............................................111 km
- Ruling gradient .................................................18.5 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>
<thead>
<tr>
<th>Radius (m)</th>
<th>Numbers</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>800</td>
<td>28</td>
<td>Very sharp and strongly restrictive for high speed</td>
</tr>
<tr>
<td>$800 &lt; R \leq 1600$</td>
<td>14</td>
<td>Sharp and restrictive for high speed</td>
</tr>
<tr>
<td>$1600 &lt; R \leq 2000$</td>
<td>5</td>
<td>Less restriction to high speed</td>
</tr>
<tr>
<td>$2000 &lt; R \leq 2500$</td>
<td>1</td>
<td>Recommendable for high speed</td>
</tr>
<tr>
<td>$2500 &lt; R \leq 3000$</td>
<td>5</td>
<td>Recommendable for high speed</td>
</tr>
<tr>
<td>$R &gt; 3000$</td>
<td>1</td>
<td>Recommendable for high speed</td>
</tr>
</tbody>
</table>

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:

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

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

<table>
<thead>
<tr>
<th>Property</th>
<th>Parameter</th>
<th>Technical index</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anti-wear and anti-shock property</td>
<td>Los Angeles abrasion rate (LAA %)</td>
<td>27≤LAA&lt;32</td>
</tr>
<tr>
<td></td>
<td>Standard aggregate impact toughness (IP)</td>
<td>10&lt;IP≤95</td>
</tr>
<tr>
<td></td>
<td>Stone abrasive hardness coefficient (K), dry grinding</td>
<td>17&lt;K, dry grinding≤18</td>
</tr>
<tr>
<td>Resistance to crushing</td>
<td>Standard aggregate crushing rate (CA), %</td>
<td>9≤CA&lt;14</td>
</tr>
<tr>
<td>Water permeability</td>
<td>Ballast aggregate crushing rate (CB)</td>
<td>18≤CB&lt;22</td>
</tr>
<tr>
<td>Water permeability</td>
<td>Permeability coefficient (Pm), 10-6cm/s</td>
<td>3&lt;Pm≤4.5</td>
</tr>
<tr>
<td>Water permeability</td>
<td>Limestone specimen compressive strength (σ), MPa</td>
<td>0.4≤σ&lt;0.55</td>
</tr>
<tr>
<td>Resistance to atmospheric corrosion and damage</td>
<td>Limestone liquid limit (LL), %</td>
<td>20≥LL&gt;16</td>
</tr>
<tr>
<td></td>
<td>Limestone plastic limit (PL), %</td>
<td>11≥PL&gt;9</td>
</tr>
<tr>
<td>Stability</td>
<td>Density (g/cm$^3$)</td>
<td>&gt;2.55</td>
</tr>
<tr>
<td>Stability</td>
<td>Unit weight (g/cm$^3$)</td>
<td>&gt;2.5</td>
</tr>
<tr>
<td>Soft particle</td>
<td>Compressive Strength at Uniaxial and Saturated Condition, MPa</td>
<td>Content of soft particle is less than 10% (mass ratio)</td>
</tr>
</tbody>
</table>

### Table 3-4: Ballast Gradation

<table>
<thead>
<tr>
<th>Side length of square mesh sieve (mm)</th>
<th>16</th>
<th>25</th>
<th>35.5</th>
<th>45</th>
<th>56</th>
<th>63</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass percentage of passing (%)</td>
<td>0 ~ 5</td>
<td>5 ~ 15</td>
<td>25 ~ 40</td>
<td>55 ~ 75</td>
<td>92 ~ 97</td>
<td>97 ~ 100</td>
</tr>
</tbody>
</table>

### 3.4.2. Rail

The new Ethiopian railway rail specification detail is as follow.

### Table 3-5: rail specification

<table>
<thead>
<tr>
<th>Type</th>
<th>length (m)</th>
<th>Weight( kg/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>U71Mn hot-rolled new rails with bolt hole</td>
<td>25</td>
<td>50</td>
</tr>
</tbody>
</table>
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

<table>
<thead>
<tr>
<th>S.N</th>
<th>station Name</th>
<th>Type</th>
<th>Arrival departure line</th>
<th>Freight line</th>
<th>Towing line</th>
<th>Shunting line</th>
<th>Locomotive departure siding</th>
<th>Track division on siding</th>
<th>Distance b/n two station</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Sebeta</td>
<td>Intermediate Station</td>
<td>4</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Labu</td>
<td>Passenger transport station</td>
<td>4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>13+500</td>
</tr>
<tr>
<td>3</td>
<td>Indode</td>
<td>Intermediate Station</td>
<td>4</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>12</td>
<td>3</td>
<td>1 6+100</td>
</tr>
<tr>
<td>4</td>
<td>Bishoftu</td>
<td>Intermediate Station</td>
<td>4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>37+390</td>
</tr>
<tr>
<td>5</td>
<td>Mojo</td>
<td>Intermediate Station</td>
<td>4</td>
<td>1</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td>23+695</td>
</tr>
<tr>
<td>6</td>
<td>Adama</td>
<td>Intermediate Station</td>
<td>4</td>
<td>1</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td>20+315</td>
</tr>
</tbody>
</table>
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, it’s 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 $\sigma_0$ 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

<table>
<thead>
<tr>
<th>Stage</th>
<th>Interval</th>
<th>the number of trains (pair/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>passenger train</td>
</tr>
<tr>
<td>preliminary stage</td>
<td>Sebeta- Adama</td>
<td>4</td>
</tr>
<tr>
<td>short term</td>
<td>Sebeta- Adama</td>
<td>6</td>
</tr>
<tr>
<td>long term</td>
<td>Sebeta- Adama</td>
<td>10</td>
</tr>
</tbody>
</table>

Two independent and reliable 132kV power sources are introduced 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

<table>
<thead>
<tr>
<th>location traction sub station</th>
<th>Annual power consumption 10^4KWh</th>
<th>Annual average power required 10^4KW</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Initial stage</td>
<td>short term</td>
</tr>
<tr>
<td>Sebeta</td>
<td>1018</td>
<td>1653</td>
</tr>
<tr>
<td>Indode</td>
<td>2188</td>
<td>3556</td>
</tr>
<tr>
<td>Bishoftu</td>
<td>1577</td>
<td>2563</td>
</tr>
<tr>
<td>Mojo</td>
<td>2595</td>
<td>2592</td>
</tr>
<tr>
<td>Merebe</td>
<td>1639</td>
<td>2576</td>
</tr>
</tbody>
</table>

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:

![Bentley Inroad Group diagram](image)

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 undertaken for rail track alignment design by using Bentley inrail software.

![Geometric design procedure Bentley Inrail software](image)

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.

\[ R = \frac{C}{D + I_{\text{lim}}} v^2 \] ..........................4-1

Where,

\( R = 800 \text{m} \) and \( C = 11.8 \text{mm.m.h}^2/\text{km}^2 \) for standard gauge

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

\[ v = \sqrt{\frac{(D + I_{\text{lim}}) \times R}{C}} \] ..........................4-2

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

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

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

2. Length of transitions curve

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

\[ L_D = 0.008C_{\text{a}}V_D \] ..........................4-3
Where,

\[ Ca = \text{the value of actual cant in mm}, \quad V_m = \text{the maximum permissible speed in km/h} \quad \text{and} \quad L_D = \text{length of transition curve in (m)}. \]

For \( Ca = 130\text{mm} \), and minimum \( L_D = 180\text{m} \) the maximum allowable speed is calculated as follow,

\[ V_m = \frac{L_D}{0.008Ca} \]

\[ V_m = \frac{180}{(0.008 \times 130)} = 173.07\text{km/h} \]

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.

\[ \frac{dD}{dt} = \frac{\Delta D \cdot V}{L_D \cdot q_v} \]

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

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

\[ \frac{dD}{dt} = 24\text{ mm/s} < \text{normal limit} \]

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.

\[ \frac{dI}{dt} = \frac{\Delta I \cdot V}{L_D \cdot q_v} \]

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

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

\[ \frac{dI}{dt} = 15.3\text{mm/s} < \text{normal limit} \]
5. Cant Gradient dD/ds

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

$$\frac{dD}{ds} = \frac{dD}{Lb}$$

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

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

$$R_v = q_r v^2$$

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

By rearranging the above equation for speed ($V$)

$$v = \sqrt{\frac{R_v}{q_r}}$$

For normal limit;

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

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

For exceptional limit;

$$v = \sqrt{\frac{10000m}{0.16 \text{ m.h}^2/\text{km}^2}} = 230\text{km/h}$$

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)

$$L = \left(\frac{\Delta}{v}\right) \times 30.5m$$

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:
\[ L = \left( \frac{12\%}{0.1\%} \right) \times 30.5m = 3660m; \]

For sag curves:
\[ L = \left( \frac{12\%}{0.05\%} \right) \times 30.5m = 7320m \]

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

<table>
<thead>
<tr>
<th>Description</th>
<th>Speed (km/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>160</td>
</tr>
<tr>
<td>Cant (mm)</td>
<td></td>
</tr>
<tr>
<td>Applied cant</td>
<td>225</td>
</tr>
<tr>
<td>Cant deficiency</td>
<td>152</td>
</tr>
<tr>
<td>Equilibrium cant</td>
<td>377</td>
</tr>
<tr>
<td>Non-compensated acceleration (m/s²)</td>
<td>0.99</td>
</tr>
<tr>
<td>Rate of change Applied cant (mm/s)</td>
<td>55.556</td>
</tr>
<tr>
<td>Rate of change Deficiency cant(mm/s)</td>
<td>37.7</td>
</tr>
<tr>
<td>Applied gradient</td>
<td>800</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Description</th>
<th>Software results</th>
<th>Chinese standard</th>
<th>Other country (maximum value)</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radius(m)</td>
<td>800</td>
<td>800-1200</td>
<td>Italy</td>
<td>Indian</td>
</tr>
<tr>
<td>Transition length</td>
<td>180</td>
<td>170</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Equilibrium cant(mm)</td>
<td>250</td>
<td>-</td>
<td>300</td>
<td>-</td>
</tr>
<tr>
<td>Cant(mm)</td>
<td>150</td>
<td>-</td>
<td>160</td>
<td>200</td>
</tr>
<tr>
<td>Cant deficiency(mm)</td>
<td>99.3</td>
<td>-</td>
<td>92</td>
<td>100</td>
</tr>
<tr>
<td>Rate of change of cant(mm)</td>
<td>30</td>
<td>-</td>
<td>54</td>
<td>-</td>
</tr>
<tr>
<td>Rate of change of cant deficit(mm)</td>
<td>19.9</td>
<td>-</td>
<td>38</td>
<td>35</td>
</tr>
<tr>
<td>Non-compounded acceleration (mm/s²)</td>
<td>0.65</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>App. Gradient</td>
<td>1200</td>
<td>-</td>
<td>720</td>
<td>-</td>
</tr>
<tr>
<td>The minimum track spacing(m)</td>
<td>4</td>
<td>4</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
Recommmended and minimum horizontal curve radius of different country

![Graph showing recommended and minimum horizontal curve radius for different countries.](image)

**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

<table>
<thead>
<tr>
<th>Description</th>
<th>Existing vertical curve alignment properties</th>
<th>Chinese Standard</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum grade length(m)</td>
<td>400</td>
<td>&gt;200</td>
</tr>
<tr>
<td></td>
<td></td>
<td>&gt;150</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Recommendable</td>
</tr>
<tr>
<td>Radius (m)</td>
<td>10,000</td>
<td>10,000</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>=&gt;4096</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Recommendable</td>
</tr>
</tbody>
</table>
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.
Flow chart 5-1: speed optimization flow chart

- Survey track data
- Analyzing the existing track geometry and track structure related speed
  - Determine allowable level of speed
  - Identifying permanent speed restriction

**Speed Optimization**

- Importing survey, surface and geometric data
- Set R, Lt, D, I, and V
- Regression of geometric data
- Analysis

**Analyzing the existing track geometry and track structure related speed**

**Design report**

- Check design parameters
  - Check Design parameter for tilting train (D ≤ 150, I ≤ 270, dD/dt ≤ 50mm/s, dl/dt, ≤ 70 mm/s, ay ≤ 1.65mm/s) and other
  - Check Design parameter for conventional track (D ≤ 150, I ≤ 100, dD/dt ≤ 35mm/s, dl/dt, ≤ 55mm/s, ay ≤ 0.65mm/s) and other

**Discussion on the results**

END
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

\[ E = \frac{6}{11400} V^2 \]

Where

\[ G = \text{rail center to center clearance (mm)}, \quad R = \text{radius (m)}, \quad V = \text{design speed (Km/h)} \]

\[ E = \frac{377952mm}{160^2} = 377.952mm \]

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:

\[ E = D + I \]

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 \( I = 247.6 \text{mm} \) 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

\[ v = \sqrt{\frac{R \cdot \frac{130 + 247.6}{118}}{11.8}} \]

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

4. Enhanced permissible speed on super elevation

\[ \frac{V_T}{V_C} = \frac{\frac{dD}{dt}}{\frac{dD}{dt}} \]

\[ \frac{dD}{dt} = \frac{dD}{dt} \cdot \frac{V}{q_v} < \left( \frac{dD}{dt} \right)_{\text{lim}} \]

Where; \( l_D = 180 \text{m} \) and \( q_v = 3.6 \text{km.s}/(\text{h.m}) \), \( V_C = 120 \text{km/h} \) and \( V_T = 160 \text{km/h} \) is proposed on circular.

\[ \dot{D}_C = \frac{\frac{dD}{dt}}{v} \cdot \frac{V}{q_v} \]

\[ \dot{D}_C = \frac{dD}{dt} = \frac{120 \text{km/h}}{180 \text{m.s}^{-1}} \cdot \frac{130 \text{mm}}{180 \text{m}} = 24.07 \text{mm/s} \]
\[
\frac{dD}{dt} = \frac{V}{q_0} \frac{dV}{dt} \leq \frac{dl}{dt}
\]

\[
\frac{dI}{dt} = 32.099\text{mm/s}
\]

\[
VT = V_C \frac{dI}{dt}
\]

\[
VT = \frac{120\text{km/h} \times 32.099\text{mm}}{24.07\text{mm}} = 160.03\text{km/h}
\]

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

5. Enhanced permissible speed on transition curves

\[
\dot{D} + 1 = 11.8 \frac{V^2}{R} \frac{v}{\sqrt{3.6t}}
\]

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

\(dl/dt = \dot{t} = 61.13\text{mm/s}\)

Solving for speed \(V\)

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

\[
v = \sqrt{R \times Lt \times 3.6 \times \frac{(D + 1)}{11.8}}
\]

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

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

\[
\frac{VT}{V_C} = \sqrt{\frac{IT}{IC}}
\]

Where, \(IT = 61.13\text{mm}, IC = 24.07\text{mm}, V_C = 120\text{km/hr}\)
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.

<table>
<thead>
<tr>
<th>Description</th>
<th>software result at 160 Km/hr</th>
<th>Chinese standard</th>
<th>Other country properties</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max cant D(mm)</td>
<td>130</td>
<td>***</td>
<td>180 160-180 150</td>
<td>The proposed cant is fair</td>
</tr>
<tr>
<td>Max deficiency I (mm)</td>
<td>247.6</td>
<td>***</td>
<td>260 300 280</td>
<td>The proposed cant deficiency is fair</td>
</tr>
<tr>
<td>Max rate of change of cant dD/dt (mm/s)</td>
<td>32.09</td>
<td>***</td>
<td>60 46 75</td>
<td>The proposed dD/dt is fair</td>
</tr>
<tr>
<td>Max rate of change of cant deficiency dl/dt (mm/s)</td>
<td>61.136</td>
<td>***</td>
<td>No limit Not specified 140</td>
<td>The proposed dl/dt is fair</td>
</tr>
<tr>
<td>Non-compensated acceleration(mm/s²)</td>
<td>1.62</td>
<td>***</td>
<td>*** *** ***</td>
<td>-</td>
</tr>
</tbody>
</table>

Note: - *** shows standard is silent
The following figure shows the average enhanced Permissible speed by tilting trains on the existing track.

![Enhanced permissible speeds for tilting trains as a percentage of permissible speed for conventional trains on horizontal circular curves](image)

**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

<table>
<thead>
<tr>
<th>Type</th>
<th>Speed (kph)</th>
<th>Radius (m)</th>
<th>Transition</th>
<th>Cant (mm)</th>
<th>Lateral acceleration (m/s²)</th>
<th>Rate of Change (mm/s)</th>
<th>Applied cant</th>
<th>Cant efficiency</th>
<th>App. Gradient</th>
</tr>
</thead>
<tbody>
<tr>
<td>POB</td>
<td>160</td>
<td>0</td>
<td>Linear</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0</td>
</tr>
<tr>
<td>TS</td>
<td>160</td>
<td>0</td>
<td>Clothoid</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>33.33</td>
<td>22.96</td>
<td>1333</td>
</tr>
<tr>
<td>SC</td>
<td>160</td>
<td>-1325</td>
<td>Circular</td>
<td>227.9</td>
<td>135</td>
<td>92.9</td>
<td>0.61</td>
<td>0.00</td>
<td>0</td>
</tr>
<tr>
<td>CS</td>
<td>160</td>
<td>-1325</td>
<td>Clothoid</td>
<td>227.9</td>
<td>135</td>
<td>92.9</td>
<td>0.61</td>
<td>33.33</td>
<td>22.96</td>
</tr>
<tr>
<td>ST</td>
<td>160</td>
<td>0</td>
<td>Linear</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0</td>
</tr>
<tr>
<td>TS</td>
<td>160</td>
<td>0</td>
<td>Clothoid</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>32.10</td>
<td>21.18</td>
<td>1385</td>
</tr>
</tbody>
</table>
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

\[ R = \frac{C}{D + \lim} \sqrt{V^2} \] 5-10

Where, \( C = 11.8 \text{mm.m.h}^2/\text{km}^2 \) for standard gauge, \( R = 1325 \text{m} \)

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

\[ v = \sqrt{\frac{(D + \lim) \times R}{C}} \]

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

2. Length of Transitions Curve

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

\[ L_D = 0.008 \cdot D \cdot V_m \] 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 \( C_a = 135\text{mm} \), and minimum \( L_D = 180 \text{m} \) the max allowable speed is calculated as follow,

\[ V_m = \frac{L_D}{0.008 \cdot D} \]

\[ V_m = \frac{180}{(0.008 \times 135)} = 166.7 \text{ km/h} \]

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.
\[ \frac{dD}{dt} = \frac{\Delta D}{L_D} \frac{V}{q_v} \] .................................5-12

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

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

\( \frac{dD}{dt} = 33\text{mm/s} < \text{normal limit} \)

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

\[ \frac{dI}{dt} = \frac{\Delta I}{L_D} \frac{V}{q_v} \] .................................5-13

Where, \( q_v = 3.6\text{km.s/(m.h)} \), \( V = 160\text{km/hr} \), \( I = 93\text{mm} \) and \( L_D = 180\text{m} \) (the minimum provided transition curve length for Addis Ababa – Adama)

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

\( \frac{dI}{dt} = 22.96\text{mm/s} < \text{normal limit} \),

5. Cant Gradient \( dD/ds \)

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

\[ \frac{dD}{ds} = \frac{\Delta D}{L_D} \] .................................5-14

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

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

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

<table>
<thead>
<tr>
<th>S.N.</th>
<th>Description</th>
<th>Chinese</th>
<th>France</th>
<th>Japan</th>
<th>German</th>
<th>Ethiopian</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Length (m)</td>
<td>25</td>
<td>25</td>
<td>25</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>2</td>
<td>Weight (KG/m)</td>
<td>50 kg/m</td>
<td>60 kg/m</td>
<td>60 kg/m</td>
<td>60 kg/m</td>
<td>60 kg/m</td>
</tr>
<tr>
<td></td>
<td>50, for class III, v≤120km/h</td>
<td></td>
<td>v≥300 km/h</td>
<td></td>
<td>v≥300 km/h</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Type</td>
<td>-</td>
<td>UIC 60</td>
<td>UIC 60</td>
<td>UIC 60</td>
<td>U71Mn hot-rolled</td>
</tr>
</tbody>
</table>

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 x 10$^9$ pa, poisons ratio = 0.3, tensile strength = 800N/mm$^2$
- Rail pad stiffness: $k_h = 1.25 x 10^9$ 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.

![Finite Element Method Model of Track](image)

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.
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.

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 $\sigma_y$. 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,)

<table>
<thead>
<tr>
<th>S.N</th>
<th>Railway system</th>
<th>Depth</th>
<th>Speed(km)</th>
<th>Axle Load</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Ballast(mm)</td>
<td>Sub-ballast(mm)</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Australia</td>
<td>200-300</td>
<td>150</td>
<td>&gt;250</td>
</tr>
<tr>
<td>2</td>
<td>England</td>
<td>225-375</td>
<td>Variable</td>
<td>&gt;250</td>
</tr>
<tr>
<td>3</td>
<td>France</td>
<td>150-350</td>
<td>Variable</td>
<td>&gt;250</td>
</tr>
<tr>
<td>5</td>
<td>UIC</td>
<td>250-550</td>
<td>Variable up to 450</td>
<td>&gt;250</td>
</tr>
<tr>
<td>6</td>
<td>Japan</td>
<td>300</td>
<td>200</td>
<td>&gt;250</td>
</tr>
<tr>
<td>7</td>
<td>Swedish Railway</td>
<td>240</td>
<td>90</td>
<td>&gt;250</td>
</tr>
<tr>
<td>8</td>
<td>USA</td>
<td>300</td>
<td>300</td>
<td>&gt;250</td>
</tr>
<tr>
<td>9</td>
<td>New Ethiopian rail</td>
<td>250</td>
<td>200</td>
<td>&gt;160</td>
</tr>
</tbody>
</table>

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 within 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.

<table>
<thead>
<tr>
<th>S.NO.</th>
<th>Description</th>
<th>Country</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Chinese</td>
</tr>
<tr>
<td>1</td>
<td>Sleeper spacing number of sleeper /km</td>
<td>1666</td>
</tr>
<tr>
<td>2</td>
<td>Type of sleeper</td>
<td>concrete type II</td>
</tr>
<tr>
<td>3</td>
<td>Weight (KG)</td>
<td>-</td>
</tr>
<tr>
<td>4</td>
<td>Length (mm)</td>
<td>-</td>
</tr>
<tr>
<td>5</td>
<td>Width (mm)</td>
<td>-</td>
</tr>
<tr>
<td>6</td>
<td>height (mm)</td>
<td>-</td>
</tr>
<tr>
<td>7</td>
<td>Effective surface area rail (cm2)</td>
<td>-</td>
</tr>
</tbody>
</table>

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 3500000Pa 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)

<table>
<thead>
<tr>
<th>Classification of track</th>
<th>class 1, class 2</th>
<th>class 2, class 3, class 4</th>
<th>Class 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type of rail fastenings</td>
<td>Elastic clip Type II for sleepers with apron Elastic rod Type III for sleepers without apron</td>
<td>Elastic clip Type II or I fastening</td>
<td>Elastic clip Type I fastenings</td>
</tr>
</tbody>
</table>

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 $\sigma_0$: 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 $\sigma_0$: 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)

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Units</th>
<th>Class of Railway</th>
</tr>
</thead>
<tbody>
<tr>
<td>Traffic volume (net)</td>
<td>Mt/km</td>
<td>High speed mixed traffic</td>
</tr>
<tr>
<td>Design speed</td>
<td>km/h</td>
<td>&lt;200</td>
</tr>
<tr>
<td>Track spacing</td>
<td>m</td>
<td>4.2</td>
</tr>
<tr>
<td>Track formation width</td>
<td>m</td>
<td>3.5</td>
</tr>
</tbody>
</table>

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 \( \leq 200 \) 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)

\[ E_{PM} = \frac{0.371}{4\times12} \times V \times 0.895 \times M \]

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

\[ E_{PM} = \frac{0.371}{4\times12} \times 160 \times 0.895 \times 3500t = 274.9\text{kwh/km. train} \]

Number of train and distance

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

The annual power required is:

\[ E_{PM} = \frac{277099.2\text{kwh/day}}{365\text{days}} = 101141208\text{KWh} = 10114 \times 10^4\text{KWH} \]

The existing annual power at preliminary stage = 9017x10^4KWh

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

\[
E_{PM} = \frac{24,959\text{KWh}}{\text{km.train}} \times 14 \text{trains/day} \times 112\text{km} = 431,043.2\text{KWh/day}
\]

The annual power required is:

\[
E_{PM} = 431,043.2\text{KWh/day} \times 365\text{day} = 157,330,768\text{ KWh} = 15,733 \times 10^4\text{KWh}
\]

The existing annual power at short term stage = 12940x10^4KWh

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

\[
E_{PM(160)} - E_{PM(120)} = (15,733 - 12940) \times 10^4\text{KWh} = 2,793x10^4\text{KWh}
\]

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

\[
E_{PM} = \frac{0.371}{412} \times 160 \times 0.0001 \times 4000t = 314.1714\text{KWh/ (km. train)}
\]

\[
E_{PM} = \frac{314.17\text{KWh}}{\text{km.train}} \times 27 \text{trains/day} \times 112\text{km} = 950,050.08\text{KWh/day}
\]

The annual power required is:

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

The existing annual power at long term stage = 23818x10^4KWh

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

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

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)

<table>
<thead>
<tr>
<th>Radius(m)</th>
<th>Speed</th>
<th>Compensation ratio</th>
<th>lateral acc. (m/s²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>393</td>
<td>100</td>
<td>No tilt</td>
<td>1.16</td>
</tr>
<tr>
<td>1572</td>
<td>120</td>
<td>No tilt</td>
<td>1.16</td>
</tr>
<tr>
<td>1572</td>
<td>240</td>
<td>36%</td>
<td>1.16</td>
</tr>
<tr>
<td>1572</td>
<td>240</td>
<td>47%</td>
<td>0.97</td>
</tr>
<tr>
<td>1572</td>
<td>240</td>
<td>70%</td>
<td>0.55</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Train category</th>
<th>Permissible cant deficiency (mm)</th>
<th>Lateral acceleration, ay (m/s²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>100</td>
<td>0.65</td>
</tr>
<tr>
<td>B</td>
<td>150</td>
<td>0.98</td>
</tr>
<tr>
<td>S</td>
<td>245</td>
<td>1.6</td>
</tr>
</tbody>
</table>

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

Legend

- 5 = Excellent
- 4 = Very good
- 3 = Good
- 3-2 = Need modification
- < 2 = It should be changed

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

<table>
<thead>
<tr>
<th>S.N</th>
<th>Station</th>
<th>curve radius</th>
<th>Profile description</th>
<th>Unit</th>
<th>QTY</th>
<th>Unit Rate</th>
<th>Amount (ET birr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>13+500</td>
<td>800</td>
<td>Embankment</td>
<td>M³</td>
<td>40,540.5</td>
<td>189.98</td>
<td>7,701,884.19</td>
</tr>
<tr>
<td>2</td>
<td>18+400</td>
<td>800</td>
<td>Cut</td>
<td>M³</td>
<td>126,360</td>
<td>181.43</td>
<td>229,254,948.8</td>
</tr>
<tr>
<td>3</td>
<td>19+950</td>
<td>800</td>
<td>Cut</td>
<td>M³</td>
<td>1,153,030</td>
<td>181.43</td>
<td>209,195,140.01</td>
</tr>
<tr>
<td>4</td>
<td>21+00</td>
<td>800</td>
<td>Bridge</td>
<td>Lkm</td>
<td>0.9</td>
<td>12,000,000</td>
<td>10,800,000</td>
</tr>
<tr>
<td>5</td>
<td>22+050</td>
<td>800</td>
<td>Cut</td>
<td>M³</td>
<td>87,750</td>
<td>181.43</td>
<td>159,204,825.8</td>
</tr>
<tr>
<td>6</td>
<td>22+950</td>
<td>800</td>
<td>Bridge</td>
<td>Lkm</td>
<td>0.9</td>
<td>12,000,000</td>
<td>10,800,000</td>
</tr>
<tr>
<td>7</td>
<td>23+800</td>
<td>800</td>
<td>Bridge</td>
<td>Lkm</td>
<td>0.9</td>
<td>12,000,000</td>
<td>10,800,000</td>
</tr>
<tr>
<td>8</td>
<td>24+600</td>
<td>800</td>
<td>Cut</td>
<td>M³</td>
<td>86,205</td>
<td>181.43</td>
<td>156,394,199.5</td>
</tr>
<tr>
<td>9</td>
<td>26+00</td>
<td>800</td>
<td>Cut</td>
<td>M³</td>
<td>107,64</td>
<td>181.43</td>
<td>195,291,21.2</td>
</tr>
<tr>
<td>10</td>
<td>27+600</td>
<td>800</td>
<td>Bridge</td>
<td>Lkm</td>
<td>2</td>
<td>12,000,000</td>
<td>24,000,000</td>
</tr>
<tr>
<td>11</td>
<td>32+300</td>
<td>800</td>
<td>Cut</td>
<td>M³</td>
<td>205,92</td>
<td>181.43</td>
<td>373,600,65.6</td>
</tr>
<tr>
<td>12</td>
<td>37+50</td>
<td>800</td>
<td>Cut</td>
<td>M³</td>
<td>414,41</td>
<td>184.43</td>
<td>751,871.32</td>
</tr>
<tr>
<td>13</td>
<td>50+100</td>
<td>800</td>
<td>tunnel</td>
<td>Lkm</td>
<td>1.2</td>
<td>157,281,586</td>
<td>188,737,903.8</td>
</tr>
<tr>
<td>14</td>
<td>51+500</td>
<td>800</td>
<td>Embankment</td>
<td>M³</td>
<td>58,827</td>
<td>189.98</td>
<td>111,760,67.45</td>
</tr>
<tr>
<td>15</td>
<td>68+00</td>
<td>1000</td>
<td>Embankment</td>
<td>M³</td>
<td>4,457</td>
<td>181.43</td>
<td>806,843</td>
</tr>
<tr>
<td>16</td>
<td>87+300</td>
<td>800</td>
<td>Bridge</td>
<td>Lkm</td>
<td>90</td>
<td>12,000,000</td>
<td>10,800,000</td>
</tr>
<tr>
<td>17</td>
<td>93+930</td>
<td>1200</td>
<td>Bridge</td>
<td>Lkm</td>
<td>750</td>
<td>12,000,000</td>
<td>10,800,000</td>
</tr>
<tr>
<td>18</td>
<td>94+700</td>
<td>800</td>
<td>Cut</td>
<td>M³</td>
<td>17,550</td>
<td>181.43</td>
<td>3,176,550</td>
</tr>
<tr>
<td>19</td>
<td>95+600</td>
<td>800</td>
<td>Bridge</td>
<td>Lm</td>
<td>900</td>
<td>12,000,000</td>
<td>10,800,000</td>
</tr>
<tr>
<td>20</td>
<td>98+500</td>
<td>1000</td>
<td>Cut</td>
<td>M³</td>
<td>137,241</td>
<td>181.43</td>
<td>248,996,346.3</td>
</tr>
<tr>
<td>21</td>
<td>99+450</td>
<td>800</td>
<td>Tunnel</td>
<td>Lkm</td>
<td>1</td>
<td>157,281,586</td>
<td>157,281,586</td>
</tr>
<tr>
<td>22</td>
<td>100+400</td>
<td>800</td>
<td>Bridge</td>
<td>Lkm</td>
<td>900</td>
<td>12,000,000</td>
<td>10,800,000</td>
</tr>
<tr>
<td>23</td>
<td>101+350</td>
<td>800</td>
<td>Bridge</td>
<td>Lkm</td>
<td>900</td>
<td>12,000,000</td>
<td>10,800,000</td>
</tr>
<tr>
<td>24</td>
<td>103+900</td>
<td>800</td>
<td>tunnel</td>
<td>Lkm</td>
<td>1.3</td>
<td>157,281,586</td>
<td>204,466,062.5</td>
</tr>
<tr>
<td>25</td>
<td>105+250</td>
<td>1200</td>
<td>Embankment</td>
<td>M³</td>
<td>19,094</td>
<td>189.98</td>
<td>3,627,554.112</td>
</tr>
<tr>
<td>26</td>
<td>107+300</td>
<td>800</td>
<td>Embankment</td>
<td>Lkm</td>
<td>1.5</td>
<td>12,000,000</td>
<td>18,000,000</td>
</tr>
<tr>
<td>27</td>
<td>108+195</td>
<td>800</td>
<td>Bridge</td>
<td>Lkm</td>
<td>1.5</td>
<td>12,000,000</td>
<td>18,000,000</td>
</tr>
<tr>
<td>28</td>
<td>108+850</td>
<td>800</td>
<td>bridge</td>
<td>Lkm</td>
<td>1.5</td>
<td>12,000,000</td>
<td>18,000,000</td>
</tr>
<tr>
<td>29</td>
<td>109+900</td>
<td>800</td>
<td>Cut</td>
<td>M³</td>
<td>77,220</td>
<td>181.43</td>
<td>13,976,820</td>
</tr>
<tr>
<td>30</td>
<td>111+100</td>
<td>800</td>
<td>Cut</td>
<td>M³</td>
<td>35,100</td>
<td>181.43</td>
<td>6,353,100</td>
</tr>
<tr>
<td>31</td>
<td>Elimination of level crossing</td>
<td>No</td>
<td>34</td>
<td>9,000,000</td>
<td>306,000,000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>32</td>
<td>Infrastructure/material as required</td>
<td></td>
<td></td>
<td></td>
<td>75,000,000</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>ETB</td>
<td>USD</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>--------------------------</td>
<td>--------------------------</td>
<td>------------------------</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Total in ETB</strong></td>
<td>1,291,018,143.81</td>
<td>64,550,907.19</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Total in USD</strong></td>
<td>1,291,018,143.81</td>
<td>64,550,907.19</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Contingence and supervision cost</strong> (10%)</td>
<td>129,101,814.38</td>
<td>6,455,090.71</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Grand total in ETB</strong></td>
<td>1,420,119,958.19</td>
<td>71,005,997.91</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Grand total in USD</strong></td>
<td>1,420,119,958.19</td>
<td>71,005,997.91</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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 x 10^4 KWh, 2,793 x 10^4 KWh and 10, 858.8 x 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

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

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Annex 4: Abaqus analysis result of track structure and materials

Ballast Displacement

Ballast 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