Railway Alignment Design and Geometry

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Tyler Dick, HDR, Inc.

Topics
• Horizontal and Vertical geometry
• Clearances
• Turnout design
• Structures and loading
## Railroad vs. Highway – Passenger Vehicles

<table>
<thead>
<tr>
<th></th>
<th>Passenger Car</th>
<th>Light rail vehicle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top speed (mph)</td>
<td>65+</td>
<td>65</td>
</tr>
<tr>
<td>Weight (tons)</td>
<td>1.4</td>
<td>53.5</td>
</tr>
<tr>
<td>Power to weight ratio (hp/ton)</td>
<td>150</td>
<td>9.3</td>
</tr>
<tr>
<td>Length (ft)</td>
<td>15</td>
<td>92 (articulated)</td>
</tr>
<tr>
<td># of passengers</td>
<td>5</td>
<td>160</td>
</tr>
<tr>
<td>Propulsion method</td>
<td>Gasoline engine</td>
<td>Electric (or diesel-electric)</td>
</tr>
</tbody>
</table>
### Railroad vs. Highway – Freight

<table>
<thead>
<tr>
<th></th>
<th>Semi-trailer Truck</th>
<th>Freight (Unit) Train</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top speed (mph)</td>
<td>55+</td>
<td>40+</td>
</tr>
<tr>
<td>Weight (tons)</td>
<td>40</td>
<td>18,000</td>
</tr>
<tr>
<td>Power to weight ratio (hp/ton)</td>
<td>12.5</td>
<td>0.73</td>
</tr>
<tr>
<td>Length (ft)</td>
<td>65</td>
<td>7,000</td>
</tr>
<tr>
<td># of power units</td>
<td>1</td>
<td>1-4</td>
</tr>
<tr>
<td># of trailing units</td>
<td>1</td>
<td>Up to 125</td>
</tr>
<tr>
<td>Propulsion method</td>
<td>Diesel engine</td>
<td>Diesel-electric</td>
</tr>
</tbody>
</table>
Horizontal Geometry – Degree of Curve

- **Arc (Roadway and LRT)**
  - Angle measured along the length of a section of curve subtended by a 100’ arc
  
  \[
  \frac{D}{360} = \frac{100}{2\pi R}
  \]
  
  - 1-deg curve, \( R = 5729.58' \)
  - 7-deg curve, \( R = 818.51' \)

- **Chord (Railroad)**
  - Angle measured along the length of a section of curve subtended by a 100’ chord
  
  \[
  R = \frac{50}{\sin\left(\frac{D}{2}\right)}
  \]
  
  - 1-deg curve, \( R = 5729.65' \)
  - 7-deg curve, \( R = 819.02' \)
Curve length difference

<table>
<thead>
<tr>
<th>Railway D 100 ft chord</th>
<th>Radius (feet)</th>
<th>Equiv. Hwy D 100 ft arc</th>
<th>Arc length (ft) of a 100 ft chord</th>
<th>% of error longer</th>
</tr>
</thead>
<tbody>
<tr>
<td>1° 00’</td>
<td>5,729.65</td>
<td>0° 59’ 59.95”</td>
<td>100.0013</td>
<td>0.0013 %</td>
</tr>
<tr>
<td>3° 00’</td>
<td>1,910.08</td>
<td>2° 59’ 58.77”</td>
<td>100.0114</td>
<td>0.0114 %</td>
</tr>
<tr>
<td>6° 00’</td>
<td>955.37</td>
<td>5° 59’ 50.13”</td>
<td>100.0457</td>
<td>0.0457 %</td>
</tr>
<tr>
<td>9° 00’</td>
<td>637.27</td>
<td>8° 59’ 26.70”</td>
<td>100.1029</td>
<td>0.1029 %</td>
</tr>
<tr>
<td>12° 00’</td>
<td>478.34</td>
<td>11° 58’ 41.09”</td>
<td>100.1830</td>
<td>0.1830 %</td>
</tr>
<tr>
<td>16° 00’</td>
<td>359.26</td>
<td>15° 56’ 53.03”</td>
<td>100.3257</td>
<td>0.3257 %</td>
</tr>
<tr>
<td>20° 00’</td>
<td>287.94</td>
<td>19° 53’ 55.02”</td>
<td>100.5095</td>
<td>0.5095 %</td>
</tr>
<tr>
<td>30° 00’</td>
<td>193.19</td>
<td>29° 39’ 30.52”</td>
<td>101.1515</td>
<td>1.1515 %</td>
</tr>
<tr>
<td>40° 00’</td>
<td>146.19</td>
<td>39° 11’ 33.44”</td>
<td>102.0600</td>
<td>2.0600 %</td>
</tr>
<tr>
<td>60° 00’</td>
<td>100.00</td>
<td>57° 17’ 44.81”</td>
<td>104.7198</td>
<td>4.7198 %</td>
</tr>
<tr>
<td>80° 00’</td>
<td>77.79</td>
<td>73° 39’ 28.92”</td>
<td>108.6100</td>
<td>8.6100 %</td>
</tr>
</tbody>
</table>

Watch out for LONG and SHARP curves
## Horizontal Geometry – Curves

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Highway</th>
<th>Railroad</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Design speed</td>
<td>Freeway:</td>
<td>- Design speed</td>
</tr>
<tr>
<td></td>
<td>- 60 mph, R=1,340, D=4.28</td>
<td>- Allowable superelevation</td>
</tr>
<tr>
<td></td>
<td>- 70 mph, R=2,050, D=2.79</td>
<td></td>
</tr>
<tr>
<td>Typical values</td>
<td>Main lines:</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- High speed: R &gt; 5,729, D&lt;1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Typical: R &gt;2,865, D&lt;2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Low speed: R&gt;1,433, D&lt;4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Industrial facilities:</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- R&gt;764, D&lt;7.5</td>
<td></td>
</tr>
</tbody>
</table>

REES Module #6 - Railway Alignment Design and Geometry 6
## Horizontal Geometry – Superelevation

### Expressed by…

**Highway**

“e” expressed as cross-slope in percent

**Railroad**

“E” is inches of elevation difference between “high rail” (outside) and “low rail” (inside)

### Function of…

**Highway**

Vehicle speed, curve radius and tire side friction  
\[ \frac{0.01e + f}{1 - 0.01ef} = \frac{V^2}{15R} \]

**Railroad**

Function of design speed, degree of curve  
\[ E = 0.0007V^2D - Eu \]

Where Eu is unbalance (1-2” typical)

### Max. values

**Highway**

6-8%

**Railroad**

Freight: 6-7”  
Light Rail: 6”

### Rotation point

**Highway**

Centerline

**Railroad**

“Inside rail”

### Transition

**Highway**

Runoff (2/3 on tangent, 1/3 in curve)

**Railroad**

Spiral
Unbalanced Elevation

- Different maximum allowed speeds for different trains on the same track:
  - passenger, express freight, general freight
- Actual elevation on track to balance head and flange wear of both rails

\[
V_{\text{max}} = \sqrt{\frac{E_a + 3}{0.0007D}}
\]

- \(V_{\text{max}}\) = Maximum allowable operating speed (mph).
- \(E_a\) = Average elevation of the outside rail (inches).
- \(D\) = Degree of curvature (degrees).
Spiral Transition Curves

Railways use the higher length of two formulae:

- To limit unbalanced lateral acceleration acting on passengers to 0.03 g per second:
  \[ L = 1.63 \ E_u \ V \ E_u = \text{unbalanced elevation (in.)} \]

- To limit track twist to 1 inch in 62 feet:
  \[ L = 62 \ E_a \quad \text{9} \quad E_a = \text{actual elevation (in.)} \]
**Superelevation Tables**

### Superelevation of Curves

<table>
<thead>
<tr>
<th>Speed in Miles per Hour</th>
<th>Degree of Curve</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>0.3</td>
</tr>
<tr>
<td>0.2</td>
<td>0.3</td>
</tr>
<tr>
<td>0.5</td>
<td>0.3</td>
</tr>
<tr>
<td>1.0</td>
<td>0.3</td>
</tr>
<tr>
<td>1.5</td>
<td>0.3</td>
</tr>
<tr>
<td>2.0</td>
<td>0.3</td>
</tr>
<tr>
<td>2.5</td>
<td>0.3</td>
</tr>
<tr>
<td>3.0</td>
<td>0.3</td>
</tr>
<tr>
<td>3.5</td>
<td>0.3</td>
</tr>
<tr>
<td>4.0</td>
<td>0.3</td>
</tr>
<tr>
<td>5.0</td>
<td>0.3</td>
</tr>
<tr>
<td>6.0</td>
<td>0.3</td>
</tr>
<tr>
<td>7.0</td>
<td>0.3</td>
</tr>
<tr>
<td>8.0</td>
<td>0.3</td>
</tr>
<tr>
<td>9.0</td>
<td>0.3</td>
</tr>
<tr>
<td>10.0</td>
<td>0.3</td>
</tr>
<tr>
<td>12.0</td>
<td>0.3</td>
</tr>
<tr>
<td>15.0</td>
<td>0.3</td>
</tr>
<tr>
<td>18.0</td>
<td>0.3</td>
</tr>
<tr>
<td>20.0</td>
<td>0.3</td>
</tr>
</tbody>
</table>

### Limits on Superelevation

1. **5” Maximum Superelevation on any Curve.**
2. **4 1/2” Superelevation on curves greater than 3 - 00.** When required to maintain maximum authorized speed.
3. **4” Superelevation on non-signaled branch lines having a maximum authorized speed of 30 mph or less.**
4. **4” Superelevation on grades where freight trains regularly operate below 25 mph.**
5. Curves shall be regularly examined for premature or accelerated wear on the high or low rail. A request for a deviation from the standard superelevation must be submitted on form "Elevation Change Request" to Chief Engineer, Maintenance of Way for concurrence.

### Minimum Length of Spiral

- **Maximum Authorized Speed:**
- **Superelevation:**
  - Minimum Length Per Inch of Superelevation:
    - **New Construction and Existing Tracks Where Practical:**
      - Up to 50: 31 feet
      - 55 to 60: 29 feet
      - 70 to 80: 50 feet
      - 85 and up: 55 feet
    - **Existing Tracks:**
      - Up to 50: 31 feet
      - 55 to 80: 39 feet
      - 85 and up: 50 feet

---

**CSX Transportation**

**Superelevation of Curves**

Reviewed: General Manager, Engineering Standards & Industrial Engineering

Prepared by:
D. N. Witt

Issued March 24, 1997

Revised, November 25, 2002
Avoid Reversed Curves

REVERSE CURVE

SC
PC
CS
TS
ST

Radius of 1st Curve
Center of 1st Curve
Tangent
Radius of 2nd Curve
Center of 2nd Curve

Note: IF THERE IS NO TANGENT BETWEEN THE 1ST & 2ND CURVE, THE POINT WHERE THE TWO CURVES TOUCH IS CALLED THE "POINT OF REVERSED CURVE" OR PRC

Min. 100’ or 3 seconds of running
Time between curves (select greater)!!
Critical Issues with Horizontal Curves

a) Too short tangent between reversed curves
b) “Broken back” curve
c) Curve within turnout
d) Additional horizontal clearance required
Vertical Geometry - Grades

Rail – rarely exceeds 1% (2-2.5% for industry lines)

Highway –
4% common
6% on ramps
Up to 8% on county roads

LRT – maximum 4 to 6%
Up to 10% for short sections
Design Grade for Railways

• Ideal maximum for railway grade:
  • Trains can roll safely down 0.3% grade without wasting energy on brakes
  • <0.1% for tracks for extensive storage
• Railway vertical curves – old formula:
  \[ L = \frac{D}{R} \]
  \( D = \) algebraic difference of grade (ft. per 100-ft. station)
  \( R = \) rate of change per 100-ft. station
• 0.05 ft. per station for crest on main track
• 0.10 ft. per station for sag on main track
• Secondary line may be twice those for main line
New Shorter Vertical Curves

- Old railway formula developed in 1880’s for “hook and pin” couplers in those days
- Present day couplers can accommodate shorter vertical curves
- New formula developed in recent years:
  \[ L = 2.15 \frac{V^2 D}{A} \]
  \[ V = \text{train speed in mph} \]
  \[ D = \text{algebraic difference of grade in decimal} \]
  \[ A = \text{vertical acceleration in ft./sec}^2 \]
  
  0.1 ft./sec\(^2\) for freight, 0.6 ft./sec\(^2\) for passenger or transit
Critical issues with Vertical Curves

a) Overlapping vertical curves
b) Avoid lowering existing tracks
c) No vertical curves within turnouts
d) Provide additional clearance in sag curves
e) No vertical curves within horizontal spirals
Railroad Turnouts

- Allows diverging from one track to another
- Identified by “frog number”

- Typical frog numbers:
  - Mainline No.20 or 24
  - Sidings No.15
  - Yards and Industry No. 11
- Diverging turnout speed ~ 2 x N
#8 RH Turnout
#8 – Offsets & layout

OFFSET DIAGRAM
FOR 15'-0" TRACK CENTERS

OFFSET DIMENSIONS MEASURED FROM GAGE LINE TO GAGE LINE.

OFFSET DIMENSIONS MEASURED FROM GAGE LINE TO GAGE LINE.
FOR TRACK CENTERS OTHER THAN 15'-0" REDUCE OR INCREASE
OFFSET DIMENSIONS BY SAME AMOUNT THAT TRACK CENTERS
ARE INCREASED OR DECREASED FROM 15'-0", AND ADJUST "X" DISTANCE

RAIL LAYOUT DIAGRAM

CSX TRANSPORTATION
NUMBER 8 OFFSET AND LAYOUT DIAGRAMS
WITH RAILBOUND MANGANESE FROG
FOR 115RE, 122CB, 132RE, AND 136RE RAIL

REVIEWED
DIRECTOR, STANDARDS AND TESTING
APPROVED
ASSISTANT VICE PRESIDENT, EQUIPMENT AND TRACK
SYSTEMS ENGINEERING

ISSUED, OCTOBER 28, 1996
REVISED, INITIAL ISSUE
Designing a Turnout in Plans

- Need to know:
  - PS to PI length (B)
  - Angle (C)
  - PS to LLT (A)

- Draw centerline of each track

- Good to mark PS & LLT

- No curves and/or adjacent turnouts between PS and LLT

Legend:
PS = Point of Switch
PI = Point of intersection
LLT = Last long tie
Angle C = Turnout angle

<table>
<thead>
<tr>
<th>T.O.</th>
<th>A</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>#8</td>
<td>97′</td>
<td>30.00′</td>
<td>7° 09′ 10″</td>
</tr>
<tr>
<td>#10</td>
<td>116′</td>
<td>31.25′</td>
<td>5° 43′ 29″</td>
</tr>
</tbody>
</table>
Basic Plan Sheet for Track Design
Track Clearances

- Specific clearances necessary for safe operations
- Size of car clearance envelope is based on dimensions of:
  - Locomotives
  - Cars
  - Potential large loads
- Requirements set by several agencies
Horizontal Clearance

- Constant on tangent track
- Additional clearance:
  - In curves for car end swing and car overhang
  - In superelevated tracks to provide room for cant
- Use clearance chart (next page) to define horizontal clearance for:
  - Main track
  - 5.5 degree curve
  - 2 inch superelevation
  - 10 feet high object
Clearance Chart

1. Standard clearances are to be used for all new construction where there are no legal requirements that dictate greater clearances.

2. Clearances for reconstruction, rehabilitation, and alteration work are dependent on existing physical conditions. Where possible, they will be improved to comply with the standard clearances.

3. State or Canadian clearance laws must not be violated. Legal requirements may be modified only by the governmental body that issued them.

4. Standard clearance may be modified only if approved by the Chief Engineer D & C.

5. Standard clearance diagrams shown are for tangent track and increases must be provided for the effects of curvature and super-elevation.

A. Additional clearance due to curvature.

When a fixed obstruction is located adjacent to a curved track, the horizontal clearance will be increased 1 1/2 inches per degree of curvature on both sides of the track centerline per table 1. Exception: Florida requires 2 inches per degree.

B. Additional clearance due to super-elevation.

When a fixed obstruction is located adjacent to a super-elevated track, the horizontal clearance on the low rail side of the track will be increased to allow for tilt. The minimum increase is shown on graph no. 1.

C. Additional clearance due to curvature and super-elevation.

When a fixed obstruction is located adjacent to a curved and super-elevated track, the horizontal clearance increase will be the sum of the increases obtained using 5.A and 5.B above. Exception: Canada requires a minimum of 2 inches per degree.

D. Additional clearance on tangent tracks.

When a fixed obstruction is adjacent to tangent track but the track is curved within 80 feet of the obstruction, the horizontal clearance will be increased as follows:

<table>
<thead>
<tr>
<th>Distance from Obstruction</th>
<th>Increased Horizontal Clearance</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 TO 20</td>
<td>10% OF PARAGRAPHS 5.C</td>
</tr>
<tr>
<td>21 TO 40</td>
<td>75% OF PARAGRAPHS 5.C</td>
</tr>
<tr>
<td>41 TO 60</td>
<td>50% OF PARAGRAPHS 5.C</td>
</tr>
<tr>
<td>61 TO 80</td>
<td>25% OF PARAGRAPHS 5.C</td>
</tr>
</tbody>
</table>

E. Vertical clearance on super-elevated track is measured from the top of the high rail.

CSX TRANSPORTATION

CLEARANCE DIAGRAMS

Signed

Reviewed: Director, Standards and Testing

Approved: Assistant Vice President, Equipment and Track Systems Engineering

Issued: July 19, 1996

Revised, Initial Issue

TABLE NUMBER 1

<table>
<thead>
<tr>
<th>Degree of Curve</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
</tr>
</thead>
<tbody>
<tr>
<td>All locations except Florida</td>
<td>1 1/2</td>
<td>3</td>
<td>4 1/4</td>
<td>5 1/2</td>
<td>6</td>
<td>7 1/2</td>
<td>9</td>
<td>10 1/2</td>
<td>12</td>
<td>13 1/2</td>
<td>15</td>
<td>16 1/2</td>
</tr>
<tr>
<td>In the State of Florida</td>
<td>2</td>
<td>4</td>
<td>6</td>
<td>8</td>
<td>10</td>
<td>12</td>
<td>14</td>
<td>16</td>
<td>18</td>
<td>20</td>
<td>22</td>
<td>24</td>
</tr>
</tbody>
</table>
Vertical Clearance

• Constant on tangent track
• Additional clearance:
  – In sag vertical curves
  – In superelevated tracks
  – For specialized equipment (double-deck cars)
  – To provide threshold for future track maintenance and equipment changes
• Subgrade top width of 24’ to 30’ for single track
Typical section - multiple tracks

- Track centerlines minimum 13' apart
- Roadbed sloped to drain
- Sometimes wider shoulders for maintenance purposes
Bridge Loading - Highway

- HS-20 truck loading

- Impact Loading
  \[ I = \frac{50}{(L + 125)} \text{ but } I < 0.3 \]
Bridge Loading - Railroad

- Cooper E-80 railroad loading
  
- Developed in 1890s
- “80” refers to 80kip driving axle load on steam locomotive
Bridge Loading – Railroad (cont.)

- Impact Loading
  - The following percentages of Live Load, applied at the top of rail and added to the axle loads (E-80 Loading)

\[
\begin{align*}
\text{For } L & \leq 14 \text{ ft: } I = 60 \\
\text{For } 14 \text{ ft} < L & \leq 127 \text{ ft: } I = \frac{225}{\sqrt{L}} \\
\text{For } L & > 127 \text{ ft: } I = 20
\end{align*}
\]

\[
L = \text{Span Length in ft}
\]
Typical Section – Roadway Superstructure
Typical Section – Railroad Concrete Superstructure
Grade Separations – Road over Rail

- 23’ vertical clearance, plus future track raise
- Allow for maintenance road and future second track
- Collision protection for piers within 25’ of rail centerline
- Do not drain roadway on to tracks!
- Other details vary by specific railroad
Grade Separations – Rail over Road

• Steel preferred structure type as it can be repaired
• Concrete bridges - “sacrificial beam” or “crash beam”
• Depth of structure increases rapidly with span length under railroad loading
  – Decreases clearance or increase required railroad fill
  – Need to minimize skew and span lengths
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