Developing Course Lecture Notes on High-Speed Rail

Submitted to

Erika Hutton, Center Coordinator
Safety and Operations of Large Area Rural/Urban Intermodal Systems
Center for Advanced Transportation Education and Research
Department of Civil and Environmental Engineering
University of Nevada, Reno
1664 N. Virginia St. MS 258
Reno, NV 89557

Submitted by

Hualiang (Harry) Teng, Professor
Department of Civil and Environmental Engineering
Howard R. Hughes College of Engineering
University of Nevada, Las Vegas
4505 Maryland Parkway, Box 454015
Las Vegas, NV 89154-4015

July 15, 2017
Content

1. Introduction
   a. World-wide Development of High-Speed Rail (Japan, Europe, China)
   b. High-speed Rail in the U.S.
2. High-Speed Rail Infrastructure
   a. Geometric Design of High Speed Rail
      i. Horizontal Curve
      ii. Vertical Curve
      iii. Grade and Turnout
   b. Track Design
      i. High Speed Rail Aero-structure
      ii. Track Structure
      iii. Earthwork and Track Bed Design
3. High-Speed Rail Stations
4. High-Speed Rail Traction and power supply
5. HSR Rolling Stock
6. HSR Signal and Control Systems
   a. Signal and Control
   b. Route Setting and Central Train Control
7. HSR Communication Systems
8. HSR Operations
9. HSR Passenger Services
10. HSR Track Maintenance
    a. Rolling stock and its maintenance
    b. Infrastructure safety inspection and maintenance
    c. Environmental safety and warning systems
11. Maglev
12. HSR Planning
High Speed Rail in the World
Definition

• High-speed rail is a type of rail transport that operates significantly faster than traditional rail traffic, using an integrated system of specialized rolling stock and dedicated tracks.

• http://en.wikipedia.org/wiki/High-speed_rail
Countries having HSR

• Austria, Belgium, Britain, China (PRC), France, Germany, Italy, Japan, Poland, Portugal, Russia, South Korea, Spain, Sweden, Taiwan (ROC), Turkey, the United States and Uzbekistan.
Early research

• First experiments
  – On 23 October 1903, the S&H-equipped railcar achieved a speed of 206.7 km/h (128.4 mph) and
  – On 27 October the AEG-equipped railcar achieved 210.2 km/h (130.6 mph)

• Early German high-speed network
  – regular top speed of 160 km/h (99 mph)
  – All high-speed service stopped in August 1939 shortly before the outbreak of World War II
Early research (cont.)

• The American Streamliners
  – Burlington Railroad's set an average speed at 124 km/h (77 mph) with peaks at 185 km/h (115 mph)

• The Italian electric
  – reached 160 km/h (99 mph) in commercial service, and achieved a world mean speed record of 203 km/h (126 mph) near Milan in 1938.

• Great Britain
  – steam locomotive Mallard achieved the official world speed record for steam locomotives at 125.88 mph
Early research (cont.)

• Spain
  – Talgo system, streamlined articulated train

• The first very-high-speed records - France
  – In 1956, broke previous speed records, reaching respectively 320 km/h (199 mph) and 331 km/h (206 mph), again on standard track

• Breakthrough: The Shinkansen
  – The first narrow-gauge Japanese high-speed service, 1957
  – The first Shinkansen trains, 1964, 210 km/h (130 mph)
  – Addressed diverse issues such as tunnel boom noise, vibration, aerodynamic drag, lines with lower patronage ("Mini shinkansen"), earthquake and typhoon safety, braking distance, problems due to snow, and energy consumption
Early research (cont.)

• Revival in Europe and North America
  – In France, in May 1967, a regular service at 200 km/h (124 mph)
  – American Metroliner trains achieve 200 km/h, High Speed Ground Transportation Act of 1965
  – The HST: a diesel high-speed train at 200 km/h, British, 1976
  – In 1977, Germany finally introduced a new service at 200 km/h (124 mph)

• The French TGV
  – The TGV: the first service above 250 km/h, 1981
Early research (cont.)

• In 1991 Germany was the second country in Europe to inaugurate a high-speed rail service
• In 1992, the Madrid–Seville high-speed rail line opened in Spain
• In 2000 "Acela Express“ with a maximum speed of 241 km/h (150 mph) being reached on a small section of its route through Rhode Island and Massachusetts.
Early research (cont.)

• In South Korea, Korea Train Express (KTX) services were launched on April 1, 2004
• First China high-speed rail line, the Qinhuangdao–Shenyang Passenger Railway, was built in 1999 and opened to commercial operation in 2003
• Taiwan High Speed Rail's first and only HSR line opened for service on January 5 2007
Skinkansen (Bullet Train) in Japan
Intercity Express (ICE) - Germany
British Rail High Speed Trains
French TGV

574 km/hr (357mph) test
Taiwan High-Speed Rail

- The total length of the High Speed Rail is 345 km (214 mi.) from Taipei to Kaohsiung and passes through 14 cities and 77 towns.
- Stations to be constructed under the initial phase of the Project:
  - Taipei, Banciao, Taoyuan, Hsinchu, Taichung, Chaify, Tainan, Zuoying (for Kaohsiung)
- Stations planned for later phases of the project: Miaoli, Changhua, Yunlin, Nangang
- Main Workshop: Yanchao (near Kaohsiung)
- Stabling Yard: Sijihh, Wurih, Zuoying
- Infrastructure Maintenance Bases:
  - Sijihh, Lioujia, Wurih, Taibao, Zuoying
- Maintenance Center: Zuoying
Comparison with other modes of transport

• Optimal distance: about 150 – 900 km or 93 – 559 m
• Energy efficiency, In Japan and France, with very extensive high-speed rail networks, a large proportion of electricity comes from **nuclear power**
• High-speed rail can accommodate more passengers at far higher speeds than automobiles
• Although air transit moves at higher speeds, its total time to destination can be increased by check-in, baggage handling, security and boarding
• High-speed rail is one of the safest modes of transportation
High Speed Rail in the U.S.
Definitions in American context

• High-Speed Rail – Express
• High-Speed Rail – Regional
• Emerging High-Speed Rail
• Conventional Rail
History

• Faster inter-urbans (1920 - 1941) and Post-war period (1945-1960)
• First attempts at high-speed rail 1960-1992
  – High Speed Ground Transportation Act of 1965
    • Create regular Metroliner service between New York City and Washington, D.C.
  – The Passenger Railroad Rebuilding Act of 1980
  – Intermodal Surface Transportation Efficiency Act (ISTEA) of 1991
• Acela Express and renewed interest in high-speed rail 1993-2008
  – No dedicated high-speed rail line, although it reaches a maximum speed of 149 mph on small sections of its route
History (cont.)

• Recent plans: 2008–2013
  – The California High-Speed Rail network, which was authorized by voters with Proposition 1A in 2008
  – In 2012, a dedicated high-speed rail line between Washington D.C. and Boston is proposed, with estimated $151 billion and take more than 25 years to design and build the line. The proposed rail line would allow for top speeds of 220 mph (354 km/h)
Current state and regional efforts

• The Northeast
  – Northeast Corridor: Next Generation High-Speed Rail, Northeast Maglev proposal, New Jersey-New York City upgrades, New York State, Pennsylvania

• West Coast
  – California, Pacific Northwest, Colorado/New Mexico

• Mid-Atlantic and the South
  – Florida, Southeast, Texas

• Midwest
  – Illinois and the Midwest, Ohio

• The Southwest
The Northeast

- Northeast Corridor: Next Generation High-Speed Rail

Northeast (cont.)

- Northeast Maglev proposal
  - from Washington DC to New York City with the travel time of 60 minutes
- New Jersey - New York City upgrades
- New York State
- Pennsylvania
West Coast

- California
- Pacific Northwest
- Colorado/New Mexico
• California Proposition 1A
• The Cascadia high-speed rail
• Halted due to safety and other freight service concerns voiced by UPRR
Colorado/New Mexico

• A high-speed rail corridor linking Denver, Albuquerque, and El Paso
• Request up to $5 million in federal funding for a feasibility study
Mid-Atlantic and the South

Florida High-Speed Corridor
• All Aboard Florida
• Southeast
Texas

- 1990: Texas Triangle, Texas TGV Corporation vs. German ICE
  - Opposed by Southwest Airline, McDonald, Days Inn, ...
- 2002, Trans-Texas Corridor, canceled 2009
- 2002, Texas High Speed Rail and Transportation Corporation (THSRTC) formed, Joined by AA and Continental Airline, Texas T-Bone and Brazos Express corridors
- 2010: linking Oklahoma City with Dallas – Fort Worth (Federal), 2011: Dallas to Houston, 2012: Austin to Houston
- 2009, Texas Central Railway, Central Japan Railway Company, 10B
Texas

South Central High-Speed Corridor
Midwest (cont.)

• Ohio Hub
Southwest

- Desert Xpress
XpressWest
California-Nevada Interstate Maglev Project
Federal Proposals High-Speed Rail Initiatives
11 Corridors

1. NEC
2. Southeast Corridor
3. California Corridor
4. Pacific Northwest Corridor
5. South Central Corridor
6. Gulf Coast Corridor
7. Chicago Hub Network
8. Florida Corridor
9. Keystone Corridor
10. Empire Corridor
11. Northern New England Corridor
## 2009 funding

<table>
<thead>
<tr>
<th>Corridor</th>
<th>Grant received (in millions $)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chicago Hub/Ohio</td>
<td>2617</td>
</tr>
<tr>
<td>California</td>
<td>2343</td>
</tr>
<tr>
<td>Florida</td>
<td>1250</td>
</tr>
<tr>
<td>Southeast</td>
<td>620</td>
</tr>
<tr>
<td>Pacific Northwest</td>
<td>598</td>
</tr>
<tr>
<td>Northern New England</td>
<td>160</td>
</tr>
<tr>
<td>Empire</td>
<td>152</td>
</tr>
<tr>
<td>Northeast</td>
<td>112</td>
</tr>
<tr>
<td>Keystone</td>
<td>27</td>
</tr>
</tbody>
</table>
2010 funding

<table>
<thead>
<tr>
<th>Corridor</th>
<th>Grant received (in millions $)</th>
</tr>
</thead>
<tbody>
<tr>
<td>California</td>
<td>898</td>
</tr>
<tr>
<td>Florida</td>
<td>800</td>
</tr>
<tr>
<td>Chicago Hub</td>
<td>428</td>
</tr>
<tr>
<td>Connecticut</td>
<td>121</td>
</tr>
<tr>
<td>Southeast</td>
<td>45</td>
</tr>
</tbody>
</table>
2011 & 2012 Proposals and Rejections of Funding

- China had built 5,000 miles (8,000 km) of dedicated high-speed rail lines in only 6 years
Geometric Design

-- Horizontal Curve
Outline

• Curvature
• Elevation
• Spiral curve
Curvature

• For conventional high speed rail train, curve of one degree or less is desirable

• The desired speed for high-speed tilt trains is one-degree-30” less
• **Chord (Railroad)**
  - Angle measured along the length of a section of curve subtended by a 100’ chord

\[ R = \frac{50}{\sin(D/2)} \]

- 1-deg curve, \( R=5729.65’ \)
- 7-deg curve, \( R=819.02’ \)
• Horizontal Curves
  – Functions of Simple Curves
    • Tangent Distance = TD = R tan \( \frac{I}{2} \)
    • Long Chord = LC = 2R sin \( \frac{I}{2} \)
    • Mid-Ordinate = M = R vers \( \frac{I}{2} \)
    • External Distance = E = R exsec \( \frac{I}{2} \)
Elevation

\[ E = 0.0007V^2D \]

- E = equilibrium elevation in inches
- V = speed in mph
- D = degree of curvature
• Superelevation


\[ F_c = \frac{w \nu^2}{gR} \]

(\(F_c = \text{Centrifugal Force}\))

Where

\(w\) = weight of the car or locomotive in pounds
\(\nu\) = speed in feet per second
\(R\) = radius of the curve in feet
\(g\) = acceleration due to gravity, 32.2 ft/sec/sec
\[ F_c = \frac{w \nu^2}{gR} \]

\[ \frac{e}{F_c} = \frac{4.9}{W} \]

\[ e = \frac{4.9w\nu^2}{gWR} \]

\[ R \approx \frac{5730}{D_c} \]

\[ e = 0.0007D_cV^2 \]
\[ V_{\text{max}} = \sqrt{\frac{E_a + 3}{0.0007D}} \]

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

Figure 6-7 Overbalance, Equilibrium and Underbalanced
Actual super-elevation

• The maximum achievable actual super-elevation on high-speed track is considered: 6 in. - V=90 mph?

• It is common practice to limit actual super-elevation of a curve to 75% of its equilibrium elevation.

• For tracks where trains run at various speed, super-elevation shall be designed to prevent lower speed trains from experiencing overbalanced elevation.

• For high-speed train system with small amount of freight traffic, Ea equals to freight train speed limit-10 mph.
Lateral acceleration

• 0.04 – 0.1 g
  – Influenced by vehicle, track characteristics and trip length

• In Europe, lateral acceleration < 0.05
Figure 5 Track geometry in the transverse vertical plane
Unbalanced elevation

Eu=E-Ea

• Eu is positive, underbalanced < 4 in
  – FRA grants 5 inches for conventional passenger trains and passive tilt HS train
  – FRA grants 9 inches for active tilt HS train

• Eu is negative, overbalanced < 4 in
• http://www.gronataget.se/upload/publikadokument/tiltingtrains.pdf
Clothoid spiral curve

- \( L_s > 62 \ E_a \) (ft)

- \( 60 < V \leq 125 \) mph,
  \( L_s \geq 82.7 \ E_a \)

- \( V \geq 125 \) mph,
  \( L_s = 124 \ E_a \)
Spiral Transition Curves
Clothoid Spiral
Spiral

\[
\frac{\Delta R}{\Delta \theta} = C
\]

http://www.mathematische-basteleien.de/spiral.htm#Clothoide
Jerk Rate

• Jerk rate: the change in lateral acceleration with respect to time

• Clothoid transition spirals shall be long enough to ensure that a proper build up or runoff of lateral acceleration with respect to time is provided.

• Jerk rate $\leq 0.03 \text{ g/s}$

• When jerk rate $< 0.01 \text{ g/s}$, no spiral curve required
Jerk rate (cont.)

- When the jerk rate is known:

\[ L_s \geq vt = 1.46Vt \]

- \( L_s \): spiral curve length in ft
- \( v \): speed in ft/s
- \( V \): speed in mph

\[
t = \frac{\text{Lateral Acceleration}}{\text{Maximum Allowable Jerk Rate}} = \frac{a_L}{[(\Delta a_L)/(\Delta t)]_{\text{allowable}}}
\]
Spiral curve – tilt rate

\[ L_s \geq vt = 1.46Vt \]

\[ t = \frac{\text{max tilt angle}}{\text{max tilt rate}} \]

• \( t \) = time required to tilt in second
Higher Order Spirals

• Provide correct geometry that may be necessitated by high speeds and heavy axle loads

• 2\textsuperscript{nd} order curves: circular curves
• 3\textsuperscript{rd} order curve: clothoid curve
• 4\textsuperscript{th} and 5\textsuperscript{th} order curve: S-shaped, parabolic, sine and cosine

• Not common practice for North American railroads
Why higher order transition curves?

• Provide correct geometry for both horizontal and vertical transitions to ensure comfortable operation of high-speed trains and decreases in track maintenance costs.

• At higher speeds abrupt changes in jerk may be considered to cause a reduction in the smooth operation of high-speed trains and passenger comfort.
TRANSITION CURVE

$$Y = \frac{X^3}{6LR}$$

SHIFT (S) = \frac{L^2}{24R}

Properties

• The shift between a straight and curve at the tangent point is

\[ S = \frac{L^2}{24R} \]

• The tangent point occurs halfway along the baseline of the transition.

• The radius at the tangent point is twice the radius of the curve.

• The offset at the end of the transition is four times the shift at the tangent point.

• At the tangent point the alignment of the transition passes exactly halfway between the straight and the curve, i.e., the offset from the baseline is half the shift.
Problems with Clothoid curve

- Along the transition curve, rotation movement starts suddenly at the starting point and it ends suddenly at the final point.
- Superelevation diagram forms breaks at the starting and final points. At these points vertical acceleration shows sudden changes.
- As a result of the straight-line increase of the lateral acceleration, constant size rate of change of radial acceleration is obtained along the transition curve.
Figure 1 Diagrams of the clothoid: a) situation, b) curvature, c) superelevation, d) lateral acceleration, e) the rate of change of radial acceleration

Figure 2 The diagrams of a fourth degree parabola as a transition curve a) Horizontal geometry b) Curvature c) Superelevation d) The lateral acceleration e) The rate of change of radial acceleration [6]
References:

• A. Pirti, M.A. Yucel, The fourth degree parabola as a transition curve, *Tehnički vjesnik* 19, 1(2012), 19-26

• V.B. Sood, Note on curve for railway

• L.T. Klauder, A better way to design railroad transit spiral, May 20, 2001

• Martin Lindahl, Track Geometry for High Speed Railway, 2001
Figure 17-3-1. Common Spiral Transition Curve Geometries
<table>
<thead>
<tr>
<th>Geometric Features</th>
<th>Cosine</th>
<th>Parabolic</th>
<th>Sine</th>
<th>Clothoid</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Transition Geometry</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$(dg/dt)_{\text{max}} (m^2)$</td>
<td>$\frac{\pi}{2} RL$</td>
<td>$2/(RL)$</td>
<td>$2/(RL)$</td>
<td>Broken function (1/RL)</td>
</tr>
<tr>
<td>$(d^2G/dl^2)_{\text{max}} (m^3)$</td>
<td>$4.93/(RL)$</td>
<td>$8/(RL^2)$</td>
<td>$6.28/(RL^2)$</td>
<td>Theoretically Indefinite</td>
</tr>
<tr>
<td>The approximate value of shift (f)</td>
<td>$L^2/(42.23R)$</td>
<td>$L^2/(48R)$</td>
<td>$L^2/(61.21R)$</td>
<td>$L^2/(24R)$</td>
</tr>
<tr>
<td>The approximate value of “y” end coordinate (m)</td>
<td>$0.149 (L^2/R)$</td>
<td>$0.146 (L^2/R)$</td>
<td>$0.141 (L^2/R)$</td>
<td>$0.16 (L^2/R)$</td>
</tr>
<tr>
<td>The angle of the end tangent (J)</td>
<td>$L/(2R)$</td>
<td>$L/(2R)$</td>
<td>$L/(2R)$</td>
<td>$L/(2R)$</td>
</tr>
<tr>
<td>Increase of length compared to the clothoid geometry with identical shift (%)</td>
<td>33</td>
<td>41</td>
<td>60</td>
<td>-</td>
</tr>
<tr>
<td>Maximum lateral displacement compared to the clothoid, with identical shift</td>
<td>$0.017f$</td>
<td>$0.025f$</td>
<td>$0.024f$</td>
<td>-</td>
</tr>
</tbody>
</table>
Higher order spiral curve length

\[ L_r \geq 1.33L_s \quad \text{for sine spiral} \]

\[ L_r \geq 1.40L_s \quad \text{for parabolic spiral} \]

\[ L_r \geq 1.60L_s \quad \text{for cosine spiral} \]
Tolerances

• Safety standard
  – Safety standards may not be exceeded **without a reduction of the speed limit (slow order) or suspension of service.**

• Maintenance tolerance
  – provide a measure of the track alignment such that maintenance activity can be scheduled and executed to ensure that the track **never degrades to Safety Standard limits,** passenger comfort is maximized, wear and tear on equipment is minimized, the track maintains its reliability and track maintenance remains economical.

• Construction tolerance
  – are the acceptable range of deviation **from the theoretical** (design) alignment that will allow maintenance standards to economically be achieved once the track is entered into service
<table>
<thead>
<tr>
<th>Over track that meets all of the requirements prescribed in this part for—</th>
<th>The maximum allowable operating speed for freight trains is—</th>
<th>The maximum allowable operating speed for passenger trains is—</th>
</tr>
</thead>
<tbody>
<tr>
<td>Excepted track</td>
<td>10</td>
<td>N/A</td>
</tr>
<tr>
<td>Class 1 track</td>
<td>10</td>
<td>15</td>
</tr>
<tr>
<td>Class 2 track</td>
<td>25</td>
<td>30</td>
</tr>
<tr>
<td>Class 3 track</td>
<td>40</td>
<td>60</td>
</tr>
<tr>
<td>Class 4 track</td>
<td>60</td>
<td>80</td>
</tr>
<tr>
<td>Class 5 track</td>
<td>80</td>
<td>90</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Over track that meets all of the requirements prescribed in this subpart for—</th>
<th>The maximum allowable operating speed for trains is—</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class 6 track</td>
<td>110 m.p.h.</td>
</tr>
<tr>
<td>Class 7 track</td>
<td>125 m.p.h.</td>
</tr>
<tr>
<td>Class 8 track</td>
<td>160 m.p.h.²</td>
</tr>
<tr>
<td>Class 9 track</td>
<td>200 m.p.h.</td>
</tr>
</tbody>
</table>
Alignment deviation measurement

Determination of Alignment Uniformity
31-ft. Chord Classes 6 through 9
Alignment deviation measurement (cont.)

- http://www.railroadtraining.biz/TrackSafetyStandardsSubpartC.htm
327(b) Except as provided in paragraph (c) of this section, a single alinement deviation from uniformity may not be more than the amount prescribed in the following table:

<table>
<thead>
<tr>
<th>Class of track</th>
<th>Tangent/Curved track</th>
<th>The deviation from uniformity of the mid-chord offset for a 31-foot chord may not be more than—(inches)</th>
<th>The deviation from uniformity of the mid-chord offset for a 62-foot chord may not be more than—(inches)</th>
<th>The deviation from uniformity of the mid-chord offset for a 124-foot chord may not be more than—(inches)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class 6 track</td>
<td>Tangent</td>
<td>½</td>
<td>¾</td>
<td>1 ½</td>
</tr>
<tr>
<td></td>
<td>Curved</td>
<td>½</td>
<td>⅜</td>
<td>1 ½</td>
</tr>
<tr>
<td>Class 7 track</td>
<td>Tangent</td>
<td>½</td>
<td>⅜</td>
<td>1 ¼</td>
</tr>
<tr>
<td></td>
<td>Curved</td>
<td>½</td>
<td>½</td>
<td>1 ¼</td>
</tr>
<tr>
<td>Class 8 track</td>
<td>Tangent</td>
<td>½</td>
<td>⅜</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Curved</td>
<td>½</td>
<td>½</td>
<td>⅜</td>
</tr>
</tbody>
</table>
### Maintenance tolerances

#### Alignment Maintenance Limits - Single Deviation

<table>
<thead>
<tr>
<th>Class of Track</th>
<th>The Deviation from Uniformity of the Mid-Chord Offset for a 31’ Chord should not be more than (inches):</th>
<th>The Deviation from Uniformity of the Mid-Chord Offset for a 62’ Chord should not be more than (inches):</th>
<th>The Deviation from Uniformity of the Mid-Chord Offset for a 124” Chord should not be more than (inches):</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>3/8</td>
<td>1/2</td>
<td>1</td>
</tr>
<tr>
<td>7</td>
<td>3/8</td>
<td>3/8</td>
<td>7/8</td>
</tr>
<tr>
<td>8</td>
<td>3/8</td>
<td>3/8</td>
<td>1/2</td>
</tr>
<tr>
<td>9</td>
<td>3/8</td>
<td>3/8</td>
<td>1/2</td>
</tr>
</tbody>
</table>

#### Alignment Maintenance Limits - Single Deviation

<table>
<thead>
<tr>
<th>Class of Track</th>
<th>The Deviation from Uniformity of the Mid-Chord Offset for a 31’ Chord should not be more than (inches):</th>
<th>The Deviation from Uniformity of the Mid-Chord Offset for a 62’ Chord should not be more than (inches):</th>
<th>The Deviation from Uniformity of the Mid-Chord Offset for a 124” Chord should not be more than (inches):</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>1/4</td>
<td>3/8</td>
<td>3/4</td>
</tr>
<tr>
<td>7</td>
<td>1/4</td>
<td>1/4</td>
<td>3/8</td>
</tr>
<tr>
<td>8</td>
<td>1/4</td>
<td>1/4</td>
<td>3/8</td>
</tr>
<tr>
<td>9</td>
<td>1/4</td>
<td>1/4</td>
<td>3/8</td>
</tr>
</tbody>
</table>
Construction Tolerances

• The deviation of the designated mid-ordinate from a 62-foot chord should not be more that 1/8 inch for high-speed track up to 200 mph.

• For high-speed tracks where speeds will be greater than 200 mph, analysis of acceptable tolerances for construction should be performed.
Figure 5-3-1. Spiral Applications
Figure 5-3-1 is a diagram illustrating the application of spirals at each end of a circular curve with the stationing from the left. The notation used in the formulas will be evident from this diagram and from the following:

\[ D = \text{degree of circular curve} \]

\[ d = \text{degree of curvature of the spiral at any point} \]

\[ l = \text{Length from the T.S. or S.T., to any point on the spiral having coordinates } x \text{ and } y \]

\[ s = \text{length } l \text{ in 100-foot stations} \]

\[ L = \text{total length of spiral} \]

\[ S = \text{length } L \text{ in 100-foot stations} \]

\[ \delta = \text{central angle of the spiral from the T.S. or S.T. to any point on the spiral} \]

\[ \Delta = \text{central angle of the whole spiral} \]

\[ a = \text{deflection angle from the tangent at the T.S. or S.T. to any point on the spiral} \]

\[ b = \text{orientation angle from the tangent at any point on the spiral to the T.S. or S.T.} \]

\[ k = \text{increase in degree of curvature per 100-foot station along the spiral} \]
\[ d = k_s = \frac{k_l}{100}; \quad D = k_S = \frac{k_L}{100} \]  

\[ \delta = \frac{1}{2} k_s^2 = \frac{d_l}{200}; \quad \Lambda = \frac{1}{2} k_S^2 = \frac{D_L}{200} \]  

\[ a = \frac{1}{3} \delta = \frac{1}{6} k_s^2; \quad A = \frac{1}{3} \Lambda = \frac{1}{6} k_S^2 \]  

\[ b = \frac{2}{3} \delta; \quad B = \frac{2}{3} \Lambda \]  

\[ y = 0.582 \delta s - 0.00001264 \delta^3 s \]  

\[ x = 1 - 0.003048 \delta^2 s \]  

\[ o = 0.1454 \Lambda S \]  

\[ X_0 = \frac{1}{2} L - 0.000508 \Lambda^2 S \]  

\[ T_s = (R + o) \tan \left( \frac{I}{2} \right) + X_0 \]  

\[ E_s = (R + o) \exp \sec \left( \frac{I}{2} \right) + o \]
<table>
<thead>
<tr>
<th></th>
<th>2260+00.72</th>
<th>2272+60.72</th>
<th>R = 50/sin(D/2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>R=</td>
<td>10398</td>
<td></td>
<td></td>
</tr>
<tr>
<td>D=</td>
<td>0.551065</td>
<td>degree of curvature</td>
<td>k</td>
</tr>
<tr>
<td>Ls=</td>
<td>1260</td>
<td>s</td>
<td></td>
</tr>
<tr>
<td></td>
<td>l</td>
<td>s</td>
<td>k</td>
</tr>
<tr>
<td>1</td>
<td>2260</td>
<td>0.72</td>
<td>226000.7</td>
</tr>
<tr>
<td>2</td>
<td>2261</td>
<td>226100</td>
<td>99.28</td>
</tr>
<tr>
<td>3</td>
<td>2262</td>
<td>226200</td>
<td>100</td>
</tr>
<tr>
<td>4</td>
<td>2263</td>
<td>226300</td>
<td>100</td>
</tr>
<tr>
<td>5</td>
<td>2264</td>
<td>226400</td>
<td>100</td>
</tr>
<tr>
<td>6</td>
<td>2265</td>
<td>226500</td>
<td>100</td>
</tr>
<tr>
<td>7</td>
<td>2266</td>
<td>226600</td>
<td>100</td>
</tr>
<tr>
<td>8</td>
<td>2267</td>
<td>226700</td>
<td>100</td>
</tr>
<tr>
<td>9</td>
<td>2268</td>
<td>226800</td>
<td>100</td>
</tr>
<tr>
<td>10</td>
<td>2269</td>
<td>226900</td>
<td>100</td>
</tr>
<tr>
<td>11</td>
<td>2270</td>
<td>227000</td>
<td>100</td>
</tr>
<tr>
<td>12</td>
<td>2271</td>
<td>227100</td>
<td>100</td>
</tr>
<tr>
<td>13</td>
<td>2272</td>
<td>227200</td>
<td>100</td>
</tr>
<tr>
<td>14</td>
<td>2272</td>
<td>60.72</td>
<td>227260.7</td>
</tr>
</tbody>
</table>
HSR – Geometric Design

Vertical Curve
Vertical Curves

- Curves that transition between different grades
- Necessary for smooth train operation
- More difficult to construct than uniform grades
Vertical Curves

- Parabolic in nature
- Sag - concave upwards, valley
- Summit - concave downward, hills
Vertical Curve as a Parabola
Vertical Curve as a Parabola (cont.)

\[ Y = a + bx + cx^2 \]

where \( Y \) = the elevation of the vertical curve at a distance \( x \) feet from the VPC

\[ a = \text{the elevation of VPC (feet)} \]
\[ b = \text{the slope of the entering tangent (ft/ft)} = G_1 \]
\[ c = \text{the rate of change in grade} \]
Vertical Curve as a Parabola (cont.)

• $dY/dx=b+2cx$
  
  — $X=0$, the slope is $G_1$. Therefore, $b=G_1$

• $d^2Y/dx^2=2c$, the rate of change of the slope
  
  — $2c=(G_2-G_1)/L$

• High point

\[
G_1 + \frac{G_2 - G_1}{L} x = 0
\]

\[
x_{hi/lo} = \frac{-G_1}{G_2 - G_1} * L = L * \frac{G_1}{G_1 - G_2}
\]
Vertical Curve as a Parabola (cont.)

- offset: $cx^2$

\[
y = \frac{|G_2 - G_1|}{2L} x^2 = \frac{|G_2 - G_1|}{2} \left(\frac{x}{L}\right)^2 = \frac{A}{2} \left(\frac{x}{L}\right)^2 = \frac{Ax^2}{2L}
\]

Convention: $A = G_2 - G_1$
Vertical Curves

- \( R = \frac{D}{L} \)
  - \( R \) = rate of change per station (standard measurement of vertical curves)
  - \( D \) = change in grades
  - \( L \) = length of vertical curve (in stations)

- \( R \) should equal 0.05 for sags and 0.10 for summits (AREMA)
Example of calculations for a vertical curve

• This method sometimes results in longer vertical curves than really necessary
• Doesn’t take into account train speed or vertical acceleration
• Properly designed vertical curves minimize adverse effects on coupler angles, vertical acceleration
• Rolling stock suspension, ride quality, and train dynamics
New AREMA method

\[ L = \frac{D \cdot V^2 \cdot K}{A} \]

- L = Length of vertical curve
- A = vertical acceleration
  - AREMA recommends a value of 0.10 and 0.60 for freight and passenger operations respectively for both sag and summit curves.
- D = difference in rates of grades
- K = 2.15
- V = train velocity
High Speed Rail

\[ L = \frac{D \times V^2 \times K}{A} \]

- \( A \) = vertical acceleration in feet/sec/sec (ft/Sec2); \( A = 0.10 \) for freight operations; 0.60 for passenger and transit operations
- \( D \) = Absolute value of the difference in rate of grades expressed as a decimal
- \( K \) = 2.15 conversion factor to give \( L \) in feet
- \( L \) = Length of vertical curve in feet
- \( V \) = Speed of the train in miles per hour
SECTION 3.6 VERTICAL CURVES (2002)

a. Vertical curves as calculated in item (f) below should be used to connect all changes in gradients.

b. The length of vertical curve is determined by changes in gradient, vertical acceleration and the speed of the train.

c. The purpose of the vertical curve is to ease the change of the gradients in order to reduce coupler and diaphragm binding and eliminate the danger of breaking trains in two as a direct result of train action. In addition, the proper vertical curve will provide for passenger comfort on passenger trains. Vertical curves should be designed as long as physically and economically possible.

d. A vertical curve which is concave upwards shall be denoted as a sag. A vertical curve which is concave downwards shall be denoted as a summit.

e. The vertical curve may be either circular or parabolic in shape.

f. The minimum length of the vertical curve for both sags and summits is determined by the following formula (except that in no case should the length of the vertical curve be less than 100 feet long):

\[ L = \frac{D \times V^2 \times K}{A} \]

Where:  
- \( A \) = vertical acceleration in feet/sec/sec (ft/sec\(^2\))  
- \( D \) = Absolute value of the difference in rates of grades expressed as a decimal  
- \( K \) = 2.15 conversion factor to give L in feet  
- \( L \) = Length of vertical curve in feet  
- \( V \) = Speed of the train in miles per hour
Example Calculation for Passenger and Transit Operations

Sag curve with 0.50% descending grade meeting a 0.50% ascending grade. Maximum design speed is 75 MPH.

\[ A = 0.60 \text{ feet/sec/sec vertical acceleration (Passenger and Transit)} \]

\[ D = \text{Absolute value of } ((-.005) - (+.005)) = 0.01 \]

\[ K = 2.15 \text{ conversion factor to give } L \text{ in feet} \]

\[ V = 75 \text{ MPH design speed} \]

\[ L = \frac{D \times V^2 \times K}{A} = \text{Length of vertical curve in feet} \]

\[ L = \frac{(0.01) \times (75\text{MPH})^2 \times 2.15}{0.60 \text{ feet/sec/sec}} = 201.56 \text{ feet} \quad \text{say 205 feet} \]
\[ y = \frac{|G_2 - G_1|}{2L} x^2 = \frac{|G_2 - G_1|}{2} \left( \frac{x}{L} \right)^2 = A \frac{L}{2} \left( \frac{x}{L} \right)^2 = \frac{Ax^2}{2L} \]

\[ Y = a + bx + cx^2 \]

where \( Y \) = the elevation of the vertical curve at a distance \( x \) feet from the VPC

- \( a \) = the elevation of VPC (feet)
- \( b \) = the slope of the entering tangent (ft/ft) = \( G_1 \)
- \( c \) = the rate of change in grade
<table>
<thead>
<tr>
<th>$G_1$</th>
<th>$-0.0163$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$G_2$</td>
<td>$0.0008$</td>
</tr>
<tr>
<td>$A$</td>
<td>$0.6$</td>
</tr>
<tr>
<td>$D$</td>
<td>$0.0171$</td>
</tr>
<tr>
<td>$K$</td>
<td>$2.15$</td>
</tr>
<tr>
<td>$L$</td>
<td>$1,380$</td>
</tr>
<tr>
<td>$V$</td>
<td>$150$</td>
</tr>
<tr>
<td>$L$</td>
<td>$1,379$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$a$</th>
<th>$2271.75$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$b$</td>
<td>$-0.0163$</td>
</tr>
<tr>
<td>$c$</td>
<td>$6.19565 \times 10^{-6}$</td>
</tr>
<tr>
<td>$A$</td>
<td>$0.0171$</td>
</tr>
<tr>
<td>$L$</td>
<td>$1,380$</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>-------</td>
<td>-------</td>
</tr>
<tr>
<td>BLEV</td>
<td>2271.75</td>
</tr>
<tr>
<td></td>
<td>207500</td>
</tr>
<tr>
<td></td>
<td>207600</td>
</tr>
<tr>
<td></td>
<td>207700</td>
</tr>
<tr>
<td></td>
<td>207800</td>
</tr>
<tr>
<td></td>
<td>207900</td>
</tr>
<tr>
<td></td>
<td>208000</td>
</tr>
<tr>
<td></td>
<td>208100</td>
</tr>
<tr>
<td></td>
<td>208200</td>
</tr>
<tr>
<td></td>
<td>208300</td>
</tr>
<tr>
<td></td>
<td>208400</td>
</tr>
<tr>
<td></td>
<td>208500</td>
</tr>
<tr>
<td></td>
<td>208600</td>
</tr>
<tr>
<td></td>
<td>208700</td>
</tr>
<tr>
<td>ELEV</td>
<td>2261.47</td>
</tr>
</tbody>
</table>
HSR vertical curve

• The recommended minimum length of the vertical curve = 100 feet.
• The minimum distance between vertical curves shall not be less than 100 feet.
• When making curve length computations, vertical curve lengths are typically rounded up to the next 50 or 100 feet.
• **North American vertical curves are parabolic** while European curves are designed as a function of the radius.
• It is recommended that the designer compare the calculated vertical curve against criteria developed and used in other international high speed system
European Design of Vertical Curve

• A vertical curve is provided if when the two grandients is greater than 2‰

\[ R_{\text{equivalent vertical radius}} = \rho_{\text{equiv}} = \frac{V^2}{2} \]

\[ R_{\text{extreme radius}} = \rho_{\text{ext}} = \frac{V^2}{4} \]

\[ R_{\text{minimum acceptance in Europe}} = \rho_{\text{min}} = 2000 \text{ m (6,567 ft.)} \]

Where; \( V \) is in \((\text{km/h})^2\)

\( R \) is in meters (m)
The radius of the vertical curve can be worked out based on the following relationship between speed of the vehicles, radius of the vertical curve and permissible values of vertical accelerations.

$$R_v \geq \frac{V_m^2}{a_m}$$

Where, $R_v$ = Radius of vertical curve in meter

$V_m$ = maximum permissible speed of the vehicle in m/sec

$a_m$ = permissible vertical acceleration in m/sec$^2$
European Design of Vertical Curve (cont.)

\[ T = \frac{\rho}{2} \frac{(i_2)}{1000} \]

\[ i_1 = 0 \% \]

\[ T = \frac{\rho}{2} \frac{(i_2 - i_1)}{1000} \text{ (sag curve)} \]

\[ i_1 \]

\[ i_2 - i_1 \]
European Design of Vertical Curve (cont.)

\[ T = \frac{\rho}{2} \frac{(i_1 - i_2)}{1000} \text{ (crest curve)} \]

\[ T = \frac{\rho}{2} \frac{(i_1 + i_2)}{1000} \text{ (crest curve)} \]

\[ T = \frac{\rho}{2} \frac{(i_1 + i_2)}{1000} \text{ (sag curve)} \]
Sweden Vertical Curve Design

\[ R_{v\,\text{min}} \geq 0.16 \times V^2 \]

\( V \) = permissible speed in km/h

\( R_v \) = Vertical curve radius in m (multiply by 3.28083 to convert to feet)

The recommended vertical curve radius is derived as follows:

\[ R_{v\,\text{rec}\,\text{min}} \geq 0.25 \times (1.3 \times V^2) \]

Where 1.3 is a speed factor applied with respect to ride comfort and future increased speed.

For tilt equipment, the minimum vertical curve radius is calculated using an overspeed of 25%:

\[ R_{v\,\text{min}\,\text{tilt}} \geq 0.25 \times V^2 \]
Vertical Curve Design in Germany

\[ V = \text{permissible speed in km/h} \]

\[ R_v = \text{Vertical curve radius in m (multiply by 3.28083 to convert to feet)} \]

\[ R_{v\text{rec min}} \geq 0.40 * V^2 \quad (\text{Recommended minimum value}) \]

\[ R_{v\text{limit}} \geq 0.25 * V^2 \quad (\text{Limit value}) \]

\[ R_{v\text{crest}} \geq 0.16 * V^2 \quad (\text{Vertical curve radius on a crest permission required}) \]

\[ R_{v\text{sag}} \geq 0.13 * V^2 \quad (\text{Vertical curve radius in a hallow or sag permission required}) \]

\[ R_{v\text{abs min}} \geq 2,000 \text{ m} \quad (\text{Absolute minimum vertical curve radius permission required}) \]
Table 17-3-2. Recommended Minimum Value for Vertical Curve Radius at 200 km/h

<table>
<thead>
<tr>
<th>Vertical Curve Radius</th>
<th>200 km/h (approx. 125 mph)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recommended minimum</td>
<td>16,000 m (52,493 feet)</td>
</tr>
<tr>
<td>Limit</td>
<td>10,000 m (32,808 feet)</td>
</tr>
<tr>
<td>Permission value on a crest</td>
<td>6,400 m (20,997 feet)</td>
</tr>
<tr>
<td>Permission value in a hallow or sag</td>
<td>5,200 m (17,060 feet)</td>
</tr>
</tbody>
</table>
Vertical Curve Design in Taiwan

• Vertical curve $Va < 0.20 \text{ m/s}$

<table>
<thead>
<tr>
<th>Vertical Curve Radius</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Recommended minimum</td>
<td>19,000 m (62,336) at 200 km/h (approx. 125 mph)</td>
</tr>
<tr>
<td>Limit</td>
<td>25,000 m (82,020) at 350 km/h (approx. 217 mph)</td>
</tr>
</tbody>
</table>
### Vertical Curve Design in Japan

<table>
<thead>
<tr>
<th></th>
<th>Tokaido Shinkansen</th>
<th>Sango Shinkansen</th>
<th>Tohoku-Joetsu Shinkansen</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum gradient, %°</td>
<td>20 %° (2%)</td>
<td>15 %° (1.5%)</td>
<td>15 %° (1.5%)</td>
</tr>
<tr>
<td>Minimum Vertical Curve Radius, m</td>
<td>10,000 m (32,808 feet)</td>
<td>15,000 m (49,212 feet)</td>
<td>15,000 m (49,212 feet)</td>
</tr>
</tbody>
</table>
Technical Specifications of Interoperability (TSI)

\[ R_v = \frac{V_{max}^2}{12.96} \times a_v \geq R_v, \text{limit value} \]

\[ V = \text{permissible speed in km/h} \]

\[ R_v = \text{Vertical curve radius in m (multiply by 3.28083 to convert to feet)} \]

\[ a_v = \text{vertical acceleration taking into consideration ride comfort where ther} \]
\[ (m/s^2). \]
Limiting Values of Vertical Acceleration, $a_v$

<table>
<thead>
<tr>
<th>Vertical Acceleration</th>
<th>Mixed traffic lines designed for passenger trains $200 &lt; V \leq 300$ (km/h)</th>
<th>Mixed traffic lines with passenger trains $V \leq 230$ (km/h)</th>
<th>High-speed lines with dedicated passenger traffic $200 &lt; V \leq 300$ (km/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recommended limiting values (m/s$^2$)</td>
<td>0.22</td>
<td>0.22</td>
<td>0.22</td>
</tr>
<tr>
<td>Maximum limiting values (m/s$^2$)</td>
<td>0.44</td>
<td>0.31</td>
<td>0.44</td>
</tr>
</tbody>
</table>
Limiting Values of Vertical Curve Radius, $R_v$

<table>
<thead>
<tr>
<th>Vertical Curve Radius</th>
<th>Mixed traffic lines designed for passenger trains $200 &lt; V \leq 300$ (km/h)</th>
<th>Mixed traffic lines with passenger trains $V \leq 230$ (km/h)</th>
<th>High-speed lines with dedicated passenger traffic $200 &lt; V \leq 300$ (km/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recommended limiting values (m)</td>
<td>$0.35 V^2 max$</td>
<td>$0.35 V^2 max$</td>
<td>$0.35 V^2 max$</td>
</tr>
<tr>
<td>Maximum limiting values (m)</td>
<td>$0.175 V^2 max$</td>
<td>$0.25 V^2 max$</td>
<td>$0.175 V^2 max$</td>
</tr>
</tbody>
</table>
**Limiting Values on Vertical Curve Radius (sample at 200 km/h)**

<table>
<thead>
<tr>
<th>Speed (km/h)</th>
<th>200 km/h (125 mph) Vertical Curve Radius (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recommended Value</td>
<td>14,100 m (46,260 feet)</td>
</tr>
<tr>
<td>Minimum value without tolerance</td>
<td>7,100 m (23,294 feet)</td>
</tr>
<tr>
<td>Minimum value on a crest</td>
<td>6,400 m (20,998 feet)</td>
</tr>
<tr>
<td>Minimum value in a hallow or sag</td>
<td>5,400 m (17,717 feet)</td>
</tr>
</tbody>
</table>
Practical Design of Profiles

- For the design of main lines, it is typical to use the flattest (lowest gradient) profile that the topography and other physical and operational constraints will permit, regardless of the intended operating speed.
- The maximum speeds desired will dictate the minimum lengths of vertical curves and conversely, if the desired profile cannot be used, the lengths of vertical curves will limit maximum speeds.
- Wherever, possible, the longest vertical curve should be used for future expansion.
- In areas where there is a shared corridor (high speed rail and freight), the reader should refer to AREMA
Other Considerations

• Turnouts, station platforms, bridges, and at-grade road crossings should not be placed in vertical curves.
• It is desirable to avoid placing vertical curves within the limits of horizontal curves.
• Undulating profiles consisting of many short vertical curves and tangents should be avoided.
• It is generally considered poor practice to design an erratic profile for the purposes of balancing earthwork or to “hit” a series of existing elevations along the track.
• Vertical clearance to overpasses and other overhead structures must be considered. Future electrification may have to be considered. It is recommended to allow 0.5 to 1.0 foot additional clearance to account for future track maintenance.
Geometric Design

-- Gradient and turnout
Factors determining gradients

• Power supply and energy consumption which increase with large gradients
• Some freight trains with friction-based traction locomotive power may have problem ascending and/or descending the gradients
• Braking distances increase in descending gradients
• Maximum speed achieved and/or permitted
• Train handling issues
• Ride quality
• Climate effects which reduce adhesion
Freight operation in North America

- A 1% maximum gradient is typically preferred
- Grades of 2% and slightly more are fairly common on many existing lines
- Consider the overall territory and not to add a steep grade so as to change the operational characteristics of the line
Freight operation in North America (cont.)

• Commuter or passenger service where trains are typically operated at greater horsepower per ton ratios than freight trains, the impact of gradients are considerably less.

• On lines with mixed traffic, gradients and curves must be selected that support the desired operation of all vehicle and trains types.
General guidelines

• 0% to 1.0% - generally considered acceptable for freight and passenger service
• 1.1% to 2.0% - acceptable for combined passenger and freight service if they are in compliance with maximum grades elsewhere on the line
• 2.1% to 3.0% - may be acceptable in passenger service and short ancillary freight service
• 3.1% to 4.0 – may be acceptable in passenger service, preferably only for short distances such as flyovers
• Grades above 4% are not recommended
• 0% to 0.2 % - preferred for maintenance and layover facilities
Compensated gradient

• A train on a grade that is on a horizontal tangent will encounter even greater resistance when moving into a horizontal curve
• To keep train resistance more uniform, the gradient can be slightly reduced in the horizontal curve to account for increased resistance of the horizontal curve
• Grade compensation should be considered in the areas of mixed traffic
Turnouts
Product

• Rail
• Switch rail
• Frog
• Guard rail
• Rail joints and joint bars
• Switch and frog plates and fasteners
• Switch and frog connections
• Switch ties
Clamp Lock (VCC)
It is an individual locking and switch rail control device. Both switch rails are locked and individually controlled in their final positions.

Swing nose clamp lock (VPM)
It locks the swing nose and is fixed to the cradle, working on the same principle as the VCC.

Paulvé detector,
It controls the application and opening of switch rails.

• www.vossloh-cogifer.com/media/downloads/.../BrochureVspeed-EN.pdf
AREMA recommendations for Rail ....

• Stock rail, closure rail and other turnout rails for high speed turnout should be new, fully heat treated or head hardened rail.
• Rails should be produced with a minimum Brinell Hardness Number (BHN) of 350 and a maximum as recommended by AREMA for premium rail
• Stock rail should be fabricated in compliance with AREMA recommendation
• Neither a joint or a weld lies on a tie nor within 3 in of the face of any tie
• Raised brands should be ground flush at joint bar locations
• Thermal restraint insert should not be used in the base of rail
Passenger comfort

– Lateral acceleration: 0.04-0.08
– Wheel impact
Intercity passenger rail service that is reasonably expected to reach speeds of at least 110 MPH.

- PRIIA § 26106
NOTE:
1. THE CDCR IS 60.1 mm/s (0.4 m/s²) IN 2ND SPIRAL.
2. PASSING TIMES OVER ANY TURNOUT SEGMENT IS OVER 1 SECOND.
Figure 3. Power Car Wheel L/V Ratio Time Histories, APTA 240 Wheel, Slab Track, Emerging Line Crossover, 120 mph (Black Line: S-C-S, Green Line: S-S, Red Line: Steer S-C-S)
Figure 5. Coach Car Wheel L/V Ratio Time Histories, APTA 240 Wheel, Slab Track, Emerging Line Crossover, 120 mph (Black Line: S-C-S, Green Line: S-S, Red Line: Steer S-C-S)
Figure 6. Carbody and Axle Lateral Displacement Time Histories, APTA 240 Wheel, Slab Track, Diverging Line Crossover, 120 mph (Black Line: S-C-S, Green Line: S-S, Red Line: Steer S-C-S)
High Speed Rail Aerial Structures
Outline

• TGV: Train a Grande Vitesse (France and Belgium)
• AVE: Alta Velocidad Espanola
• THSR: Taiwan High Speed Rail
• California HSR
• TGV: Train a Grande Vitesse (France and Belgium)
Figure 3-2: TGV High-Speed Railway Viaduct in Belgium

Source: [http://www.rail-be.net/Accessoires/Webs_Files/TUC_LGV.htm](http://www.rail-be.net/Accessoires/Webs_Files/TUC_LGV.htm)
Figure 3-3: Cheval Blanc Viaduct, France
TGV: Train a Grande Vitesse (cont.)

• Pros:
  – Noise and vibration is minimized due to use of ballast
  – Prefabrication allows for quick assembly and implementation
  – Independent structure may allow for rapid restoration of single track service following seismic events that damages a single guideway
TGV: Train a Grande Vitesse (cont.)

• Cons:
  – Potentially new construction technique in the U.S.
  – Superstructure limited to short span lengths
  – **Limited seismic performance** of superstructure
  – Designed for maximum speeds of 186 miles per hour
  – Design needs to accommodate the added weight of ballast
  – OCS poles located outside of walkway require stronger mast arms and supports
• AVE: Alta Velocidad Espanola (Spain)
Figure 3-6: AVE High Speed Rail Viaduct
AVE: Alta Velocidad Espanola (cont.)

• Pros:
  – Precast concrete box bridges allows for quick assembly and implementation
  – Designed for speeds up to 220 mph
  – Open box girder allows access for maintenance and inspection
  – Larger spans between pier – 80 to 200 feet (25 to 60 meters)
AVE: Alta Velocidad Espanola (cont.)

• Cons:
  – Two celled box girder restricts continuous maintenance access
  – Train loads not located directly over webs, instead loads are first carried by top slab and transferred to webs
  – Creating box girder to top of column moment continuity, if desired, is difficult requiring secondary closure pours and continuity tendons
THSR: Taiwan High Speed Rail

Figure 3-7: Section of Taiwan High-Speed Rail Viaduct
Figure 3-8: Taiwan High-Speed Rail Viaduct


Source: http://www.lusas.com/case/bridge/taiwan.html
THSR: Taiwan High Speed Rail

• Pros:
  – Designed to withstand seismic events similar to those expected in California
  – The shear key spring, foundation and bearing spring have been used effectively with stiff connections to withstand similar seismic events as those expected in California.
  – Single box girder allows for ease of access
  – Distances between columns allow for transverse access below the guideway
• Damage to shear key at intermediate support.
• https://www.researchgate.net/figure/269445386_fig9_Figure-9-Damage-to-shear-key-at-intermediate-support
THSR: Taiwan High Speed Rail (cont.)

• Cons:
  – OCS poles located outside walkway require stronger masts and supports
  – Open steel girders are difficult to maintain
California High Speed Rail Authority

- 100-foot-long typical span with a span to depth (S/D) ratio of 10
- The typical span could be longer (up to 130-foot-long) with a proportionally deeper cross section and thicker top deck, bottom soffit and web sections
- The cross section is also applicable to a direct fixation track structure
Figure 3-9: Viaduct Section from California High-Speed Train Program EIR/S
Figure 3-10: Basic High-Speed Train Aerial Structure Cross Section at Mid-span (100' span)
<table>
<thead>
<tr>
<th>Structural Performance</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Design Life</td>
<td>100 years as defined in TM 1.1.2: Design Life</td>
</tr>
<tr>
<td>Design Criteria Compliance</td>
<td>Rigid and stiff structure needs to comply with stringent project specific design parameters, including seismic resistance, passenger comfort, and train performance criteria</td>
</tr>
<tr>
<td>Load-Bearing Capacity</td>
<td>Carries self weight, ballast, dynamic live loads of high-speed trains</td>
</tr>
<tr>
<td>Damage Resistance</td>
<td>Ductile seismic design philosophy based upon project seismic design criteria</td>
</tr>
<tr>
<td>Fatigue Resistance</td>
<td>Structural design and routine maintenance will address and monitor fatigue</td>
</tr>
<tr>
<td>Reparability</td>
<td>Inelastic action directed to base of columns during severe seismic event, where observable and readily repairable. Standard bearings and ancillary parts allow for inventory to facilitate quick replacement</td>
</tr>
<tr>
<td>Functionality</td>
<td>Description</td>
</tr>
<tr>
<td>-------------------------------------</td>
<td>-------------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Tracks</td>
<td>Allow for double main tracks to be carried on a single structure</td>
</tr>
<tr>
<td>Track Support</td>
<td>Allow for both direct fixation and ballasted track</td>
</tr>
<tr>
<td>Sound Walls</td>
<td>Accommodate low sound walls, where required, to mitigate sound from wheel on rail connection while not obstructing passenger views</td>
</tr>
<tr>
<td>Drainage</td>
<td>Drainage is collected away from the tracks and the duct banks through the girder and directed to discharge location at columns</td>
</tr>
<tr>
<td>Overhead Contact System (OCS)</td>
<td>Provided based on electrical current requirements</td>
</tr>
<tr>
<td>Traction Power Supply System</td>
<td>Mount multiple, large diameter conduits on columns and route onto the guideway</td>
</tr>
<tr>
<td>Lighting</td>
<td>Permanent maintenance lighting is not required on aerial structures. Maintenance lighting will be provided as part of maintenance operations. Aerial structures are required to have lighting facilities for emergency access and egress</td>
</tr>
<tr>
<td>Walkways</td>
<td>Walkways are located outward of the OCS masts.</td>
</tr>
<tr>
<td>Railing/Parapet</td>
<td>Continuous railing or solid parapet is provided along outside of viaduct. May be solid parapet or open railing</td>
</tr>
<tr>
<td>Intermittent Access Stairs or ramps</td>
<td>Structurally independent; located to meet maintenance and operational requirements. Access control/detection is required at stair and ramp access locations</td>
</tr>
<tr>
<td>Maintenance Access</td>
<td>Structurally independent of high-speed train guideway. Access control/detection is required at maintenance access locations</td>
</tr>
<tr>
<td>Cable/Duct Banks</td>
<td>Provided on both sides, under walkways</td>
</tr>
<tr>
<td>Signal Heads</td>
<td>Space provided in the cross-section to accommodate panels</td>
</tr>
<tr>
<td>Safety</td>
<td></td>
</tr>
<tr>
<td>-------------------------------</td>
<td>-------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Passenger Evacuation</td>
<td>Walkways located outward of OCS poles with provision for emergency access and egress</td>
</tr>
<tr>
<td>Intrusion Protection / Detection</td>
<td>Continuous intrusion protection not required due to vertical separation. Fencing and detection systems to be installed where required</td>
</tr>
<tr>
<td>Serviceability</td>
<td></td>
</tr>
<tr>
<td>Allowance for Regular Inspections, Maintenance and Repairs</td>
<td>Access stairways, walkways, and, single cell concrete girder provided for inspection.</td>
</tr>
<tr>
<td>Economy</td>
<td></td>
</tr>
<tr>
<td>Materials &amp; Structure Type</td>
<td>Pre-stressed concrete box girders</td>
</tr>
<tr>
<td>Economy of Scale</td>
<td>Schedule efficiency and cost economy are based upon precast segmental production or cast in place production with reusable traveling shoring</td>
</tr>
<tr>
<td>Manufacturing and Delivery</td>
<td>Precasting segments, transporting and erecting the segments to be further investigated</td>
</tr>
<tr>
<td>On-Site Storage</td>
<td>Storage sites for segments to be determined</td>
</tr>
<tr>
<td>Trackside Environment</td>
<td></td>
</tr>
<tr>
<td>----------------------------</td>
<td>----------------------------------------------------------------</td>
</tr>
<tr>
<td>Ground Plane</td>
<td>Elevated structure minimizes permanent disturbances to existing ground surface</td>
</tr>
<tr>
<td>Noise Mitigation</td>
<td>Low sound walls mitigate sound from wheel on rail connection</td>
</tr>
<tr>
<td>Vibration Mitigation</td>
<td>Ballast (or ballastless tracks with lining) mitigates vibration</td>
</tr>
<tr>
<td>Property Access</td>
<td>Elevated structure maintains transverse access beneath the guideway</td>
</tr>
<tr>
<td>Color</td>
<td>Natural concrete color or pigmented concrete</td>
</tr>
<tr>
<td>Texture</td>
<td>Smooth or textured surfaces</td>
</tr>
<tr>
<td>Complementary/Contrasting Details</td>
<td>Architectural treatments as appropriate</td>
</tr>
<tr>
<td>Visual and Shadow Impacts</td>
<td>Standard structure promotes system identity, dimensions of box girder to minimize permanent shadows</td>
</tr>
</tbody>
</table>
Material Type

• Concrete
  – The most cost effective
  – Predominant use in CA
  – Reduced maintenance needs vs. steel
  – Reinforced and prestressed concrete design and construction technology advanced, particular in earthquake prone California
  – High-strength concrete vs. stiffness

• Steel
  – Cost
  – Maintenance
Constructability

• Cast-in-Place construction
  – Traditionally
    • Require temporary shoring, falsework, additional clearance provision
    • Slow, large labor effort
  – Recent advances
    • Travelling
    • Self launching shoring techniques
Figure 3-12: Example of Travelling Shoring System
Source: http://www.ibtengineers.com/Taiwan-High-Speed-Rail.html

Source: http://www.ibtengineers.com/Taiwan-High-Speed-Rail.html
Cast-in-Place construction (cont.)

• Pros:
  – Can be cast monolithically with the columns, result in superior structural performance for train operation, passenger comfort, and seismic response

• Cons:
  – The schedule impacts are greater vs. precast construction due to required closure pours coupled with the falsework set up and removal operations
Precast construction

- Each precast segment could extend over the entire 100 to 130 foot span
- The segment construction may be performed remotely in a construction yard and transported to the site
- https://www.youtube.com/watch?v=q9VYrrE_IUE
Figure 3-13: Example of Overhead Gantry
Source: http://www.launching-gantry-operator.com
Precast construction (cont.)

• Pros:
  – Fast method of construction for multi-span structures
  – The most cost effective

• Cons:
  – Segment lengths are short and requires more foundations and has a significant increase of the structure costs
  – Support bearings require routine maintenance and increase the life cycle costs
  – More challenging to meet the performance requirements (seismic, passenger comforts, etc.)
Span length and span to depth ratio

• 100 foot-long span, single cell box, the typical span length, popular in Taiwan
• Longer segments, weigh more, and difficult to transport in urban areas
• Longer segments, heavier, require fewer but significantly stouter foundations
• A longer span length may prove to be cost-effective if the project site is easy access and transportation dist is short
• Span to depth ratio: 10, i.e., 10 feet depth
Span articulation

• Continuous span system
  – Pros
    • Stiff, particularly vertically
    • Provide moment continuity with the column top
    • **No bearings** and no potential for the spans to become **unseated** during strong motion seismic events
    • Maintenance associated with the bearings is eliminated
  – Cons
    • Using a precast construction method and providing span to **column top continuity** complicates the construction process
    • Lengthens the construction cycle, and
    • Potentially more costly
    • Stress analysis is more complicated
The construction of the substructure

• Substructure: piles, pile caps, spread footings, columns and column caps
• Occurs separately and before the erection of the precast segmental superstructure
• Constructed by traditional pour-in-place concrete methods
• Typical foundations are conventional spread footing
• With marginal soils
  – Pile cap with cast-in-drilled-hole (CIDH) or cast-in-steel-shell (CISS) piles
The construction of the substructure (cont.)

- Columns
  - Constant cross section
  - Cross section increasing in area from bottom to top
  - Architectural concrete flares and treatments
  - Have a reinforced structural core with vertical, shear, and confinement reinforcement
Track Structure
Truck components

- Track type
- Rail
- Ballastless track
- Clip
- Tie
- Ballast
- Turnout
- Weld
- Smoothness management
Track type

- Ballast
- ballastless
Ballast Track

- **Pro:**
  - Construction cost low
  - Sound noise not far
  - Short time to construct
  - Quick to reconstruct
  - More automatic and mechanical maintenance
  - Geometry easy to fix

- **Con:**
  - Tend to settlement, track structure deteriorate fast, damage geometric features
  - Aerodynamic cause ballast flies
Ballast Track (cont.)

- No difference from the conventional ballast in structure
- High quality structural components and maintenance standard
- Heavier components
  - Reduce load at the bottom of tie: heavy and wide ties
  - Increase longitudinal continuous support: wide ties,
  - Increase rail elasticity: use plastic
Ballastless track

• Pros:
  – High stability
  – Smooth
  – Endurable
  – Lower weight center
  – Light weight
  – Less construction for tunnel
  – Less load to bridge
  – Cleaning and good looking
  – No ballast flying
  – Track deformation slow
  – Less maintenance

• Cons:
  – Capital cost high
  – Stiffness high
  – Elastic low
  – High vibration noise
• Widely used when speed is 300 km/h or higher
Rail

- High smoothness requirement
- Require high quality track base and strong track structure components
- High quality rail
  - Pure
  - Smooth surface
  - Geometric precision
  - Straight
Rail design

- Weight
- Rail base width
- Head height
- Base height
- Web width

- Increase rail height
- Increase base width
- Height/base width < 1.14-1.20
Ballastless track

• 30+ types
• Used on bridges and tunnel
  – Rheda 2000
  – Slab
RHEDA 2000®

- sleeper B 355 distance 650 mm
- rail fastening system Vossloh 300-1
- rail 60 E1
- hydraulically bonded layer (HBL)
- lateral reinforcement Ø 20
  a = 65
- frost protection layer (FPL)
- slab concrete C 30/37
- longitudinal reinforcement 18 x Ø 20
- subsoil

*) Depending on the sub-grade and the properties of the supporting layer

TOR = ± 0.00
-233 ... -253
-473 ... -493
-773 ... -793
• Unique manufacturing structure
• With same structure, it can be used in tunnel, rail track, bridge, turnout, and thermal adjustment areas
• Lower construction height
• Lower construction cost
Slab track

• Primarily in Japan
Floating slab track
Fastening

• Ballast track
  – Connect rail and tie
  – Sustain load

• Ballastless track
  – Most important element for track elastic and adjustment
Elastic fastening - Japan
Elastic fastening - Germany

Figure 8.25: Vossloh fastening system
Elastic fastening - British

Figure 8.23: Pandrol fastening system

Figure 8.24: Pandrol Fastclip
Tie

• Ballastless track is increasing
• Ballast track is still the majority
  – Concrete tie
  – Pros:
    • Lateral and longitudinal resistance is high
    • Stable
    • Materials for concrete is vast
    • Size is uniform, making elastic uniform
    • Not influenced by weather, fire, and insect
    • Endurable, long life

  – Cons:
    • Heavy
    • Elastic weak
    • Track bed required high quality
    • Thickness high
    • Absorbing layer
Tie Type

- Slab track (Japan and Germany)
- Concrete block tie
Concrete block ties

Twin block track form using a sleeper with two cast concrete blocks held to gauge by a steel bar. The system is favoured by the French and is also known by the names Sonneville block or Stedef track. It has the advantage of being lighter than standard concrete sleepers and the four faces of the two blocks resist movement better.
### Tie Comparison

#### Table 2.7 国外主要高速铁路混凝土轨枕结构形式及适用范围

<table>
<thead>
<tr>
<th>国别</th>
<th>轨枕形式</th>
<th>轨枕型号</th>
<th>长度 (mm)</th>
<th>轨下断面尺寸</th>
<th>中间断面尺寸</th>
<th>枕底面积 (cm²)</th>
<th>重量 (kg)</th>
<th>预应力筋</th>
<th>列车最高速度 (km/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>日本</td>
<td>整体式</td>
<td>3T</td>
<td>2 400</td>
<td>190</td>
<td>283</td>
<td>175</td>
<td>230</td>
<td>6 430</td>
<td>260</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3H</td>
<td>2 400</td>
<td>220</td>
<td>310.5</td>
<td>195</td>
<td>250</td>
<td>7 040</td>
<td>325</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4H</td>
<td>2 400</td>
<td>220</td>
<td>300</td>
<td>195</td>
<td>250</td>
<td>7 040</td>
<td>325</td>
</tr>
<tr>
<td>德国</td>
<td>整体式</td>
<td>B70W</td>
<td>2 600</td>
<td>210</td>
<td>300</td>
<td>175</td>
<td>220</td>
<td>5 930</td>
<td>304</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B90W</td>
<td>2 600</td>
<td>210</td>
<td>320</td>
<td>180</td>
<td>240</td>
<td>6 680</td>
<td>330</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B75</td>
<td>2 800</td>
<td>240</td>
<td>330</td>
<td>200</td>
<td>290</td>
<td>7 560</td>
<td>380</td>
</tr>
<tr>
<td>法国</td>
<td>双块式</td>
<td>U31</td>
<td>2 245</td>
<td>220</td>
<td>290</td>
<td></td>
<td></td>
<td>680</td>
<td>3 944</td>
</tr>
<tr>
<td></td>
<td></td>
<td>U41</td>
<td>2 415</td>
<td>220</td>
<td>290</td>
<td></td>
<td></td>
<td>840</td>
<td>4 872</td>
</tr>
</tbody>
</table>

- 表中数据单位为 mm、cm²、kg、根、kg, km/h。
Ballast track

• Ballast abrasion and pulverization
  – High grade
• Choose ballast to have high stiffness
• Aggregate size uniform
• Geotexture layer
Turnout

- Turnout with no high speed diverging
- Turnout with high speed diverging
Long Continuous Welded Rail through Stations

- Glued insulated rail joint
- Seamless Turnouts
- CWR on bridge
Glued insulated rail joint
Glued insulated rail joint

• Pro:
  – Integrated
  – High strength
  – High stiffness
  – Good insulation
  – Long life
  – Less maintenance

• Cons:
  – Not to take rapture
  – Lack of plasticity
  – Not for bending and collision
Seamless Turnouts
- Thermal impact
CWR on bridge

• Forces on surface
  – Dynamic force
  – Lateral force
  – Longitudinal force

• Interaction with bridge
  – Expansion and contraction of bridge
  – Bending
Force analysis

• Expansion/construction force
• Broken rail force
• Brake force
• Bending force
Seamless turnout on bridge
One time CWR vs two phase CWR

- Two phase CWR
  - Fully CWR after road bed is settled
- One time CWR requires high quality track
Track geometry irregularity management and information system

• Track geometry irregularity
  – Cross level
  – Elevation
  – Alignment and profile
  – Triangular dent
  – gauge

Figure 16.51: High speed track recording coach EM 250 of ÖBB
Track Geometry

- Gage
- Cross-level (tangent)
- Elevation (curve)
- Design centerline
- Alignment (horizontal)
- Profile (vertical)
Inspection

- Static inspection
- Dynamic inspection
Track geometry irregularity management - Japan

• Inspection once in 10 days
  – Over urgency standards, repair immediately
  – Over maintenance standards, repair in 10 days
  – Identify track weak sections, 20th each month, develop maintenance plan

• P value: number of inspection points that are over ±3 mm
Track geometry irregularity management - Japan

• Five categories of irregularity level
  – Acceptance target
  – Planned maintenance daily criteria
  – Comfort management target
  – Safety management target
  – Slow order target
  – 40m cord criteria
Track geometry irregularity management - France
Track geometry irregularity management - Germany
Track geometry irregularity management - China
Earthwork and Track Bed Design
General earthwork terms
Ballastless track

LEGEND
1. EMBANKMENT - FILL
2. CUTTING
3. TOPSOIL STRIPPING
4. DRAINAGE
5. UPPER PART OF EMBANKMENT
6. PREPARED SUBGRADE
7. SUBBALLAST LAYER
8. BALLAST
5 + 6. SUBGRADE
6 + 7 + 8. TRACK BED LAYERS
Ballast track

LEGEND

① EMBANKMENT - FILL
② CUTTING
③ TOPSOIL STRIPPING
④ DRAINAGE
⑤ UPPER PART OF EMBANKMENT
⑥ PREPARED SUBGRADE
⑦ SUBBALLAST LAYER
⑧ BALLAST
⑤ + ⑥ SUBGRADE
⑥ + ⑦ + ⑧ TRACK BED LAYERS
General Design Requirements

• Include ways to meet the environmental constraints
• To anticipate all possible difficulties
• To achieve balanced cut/fill volumes
• To produce optimized structures from the technical, financial, time and environmental point of view
General Design Requirements (cont.)

1. Evaluate the probable ground condition
2. Define the geometry of the structure and right-of-way
3. Assess the cost and time of execution of works
4. Ensure the reliability of the work
5. Achieve well-balanced cut/fill volumes
6. Assess the potential risks during construction and in operation
7. Define performance targets for construction sufficiently explicit
8. Limit the costs of maintenance during operations.
9. Maximize technical and financial considerations for the structure at each phase: design, construction and maintenance during operation.
Figure 18.2. Mass diagram fragment.
Specific Elements to Consider During Design

• Geological and Geotechnical Investigation and Design
• Meteorological Design
• Hydraulic and Drainage Design
• Hydrogeologic Design
Classification of Soils and Subgrades

- Geotechnical Classification of Soil
- Classification of Subgrade according to Bearing Capacity
- Frost Susceptibility of Soils
Soil type

• Mineral soils
  – Particle size
  – Plasticity
  – Sensitivity to water
  – Mineral content

• Organic soils

• Mixed soils
Mineral – by particle size

Figure 3-1 – Example of a particle size distribution curve (logarithmic scale of abscissas)
Figure 3-2 – Grain Size Classification (according to I.S.S.M.F.E recommendations of 1973)

<table>
<thead>
<tr>
<th>Particle Class</th>
<th>Grain Size (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clay</td>
<td>&lt; 0.002</td>
</tr>
<tr>
<td>Silt</td>
<td>0.002 – 0.06</td>
</tr>
<tr>
<td></td>
<td>0.002 – 0.006</td>
</tr>
<tr>
<td></td>
<td>0.006 – 0.02</td>
</tr>
<tr>
<td></td>
<td>0.02 – 0.06</td>
</tr>
<tr>
<td>Sand</td>
<td>0.06 – 2</td>
</tr>
<tr>
<td></td>
<td>0.06 – 0.2</td>
</tr>
<tr>
<td></td>
<td>0.2 – 0.6</td>
</tr>
<tr>
<td></td>
<td>0.6 – 2</td>
</tr>
<tr>
<td>Gravel</td>
<td>2 – 60</td>
</tr>
<tr>
<td></td>
<td>2 – 6</td>
</tr>
<tr>
<td></td>
<td>6 – 20</td>
</tr>
<tr>
<td></td>
<td>20 – 60</td>
</tr>
<tr>
<td>Cobbles</td>
<td>60 – 200</td>
</tr>
<tr>
<td>Boulders</td>
<td>&gt; 200</td>
</tr>
</tbody>
</table>
Uniformity and curvature coefficients

• Uniformity coefficient $\text{Cu}$
  – suitability for compaction
  – bearing capacity of the track bed layers closest to the underside of the sleepers
  – $\text{Cu}>6$, well graded

$$\text{Cu} = \frac{d_{60}}{d_{10}}$$

• Curvature coefficient $\text{Cc}$
  – Measure and symmetry and shape of the gradation curve
  – $1<\text{Cc}<3$, well graded

$$\text{Cc} = \frac{(d_{30})^2}{d_{60} + d_{10}}$$
Plasticity

- Fine cohesive soil
- Atterberg limits
  - Liquid (LL)
  - Plastic limit (PL)
  - Plasticity index (PI=LL-PL)
- Plasticity Chart for the Classification of Fine Grained Soils (After Casagrade)
Sensitivity to water

• The sensitivity of clay to water is characterized by the Methylene blue test (blue value Vb)
• The sensitivity of a soil to water is characterized by the clay content (Vbs)
• When Vbs<0.1, the soil is said to be insensitive to water
• When Vbs>0.2, the soil is sensitive to water
Mineral content

• Quartz sand
• Mica sand
• Olivine sand
• Fine marl, according to the CaCO3
Organic soils are the result mainly of the decomposition of vegetable or animal remain.

The main groups are: topsol, peat, organic soils (OH and OL).

Tested for: moisture content, liquid limit plasticity index, strength and compressibility.
Mixtures of mineral and organic soils

<table>
<thead>
<tr>
<th>Description of the soil</th>
<th>Percentage by dry weight of organic content</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mineral soils</td>
<td>≤ 1 %</td>
</tr>
<tr>
<td>Soils containing some organic matter</td>
<td>&gt; 1 % et ≤ 5 %</td>
</tr>
<tr>
<td>Mixed mineral/ organic soils</td>
<td>&gt; 5 % et &lt; 30 %</td>
</tr>
<tr>
<td>Organic oils</td>
<td>≥ 30 %</td>
</tr>
</tbody>
</table>

Note: Some railways use different values.
Classification of subgrade according to bearing capacity

- Determine the quality of each soil type contained in the subgrade
- Determine the bearing capacity of the whole system: subgrade + prepared subgrade + subsoil
General earthwork terms
Soil quality classes

• Geotechnical properties of the soil
• Local hydrogeological and hydrological conditions
  – The uppermost layer of soil is above the level of highest natural ground water
  – There is no harmful natural transverse, longitudinal or vertical water flow in the subgrade
  – Rainwater is correctly drained from the subgrade, and the longitudinal or transverse drainage system is in proper working order
<table>
<thead>
<tr>
<th>Soil Type</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>(Geotechnical Classification)</strong></td>
</tr>
<tr>
<td>---</td>
</tr>
<tr>
<td>0.1 Organic soils (OH and OL)</td>
</tr>
<tr>
<td>0.2 Soft soils containing more than 15% fines (^{(1)}), with a high moisture content therefore unsuitable for compaction.</td>
</tr>
<tr>
<td>0.3 Thixotropic soils (^{(2)}) (e.g. quick-clay)</td>
</tr>
<tr>
<td>0.4 Soils containing soluble material (e.g. rock salt or gypsum)</td>
</tr>
<tr>
<td>0.5 Contaminated ground (e.g. industrial waste)</td>
</tr>
<tr>
<td>0.6 Mixed material / organic soils (^{(2)})</td>
</tr>
<tr>
<td>1.1 Soils containing more than 40% of fines (^{(1)}) (except for soils classified under 0.2)</td>
</tr>
</tbody>
</table>
| 1.2 Rocks which are very susceptible to weathering, e.g.:  
  - Chalk with $\rho_d < (1.7 \text{ t/m}^3)$ 106 pcf and high friability  
  - Marl  
  - Weathered shale |  |
| 1.3 Soils containing 15 to 40% of fines \(^{(1)}\) (except for soils classified under 0.2) | SQ 1 \(^{(3)}\) |
| 1.4 Rocks which are moderately susceptible to weathering, e.g.:  
  - Chalk with $\rho_d < (1.7 \text{ t/m}^3)$ 106 pcf and low friability  
  - unweathered shale |  |
| 1.5 Soft Rocks, e.g. Microdeval wet (MDE) > 40 and  
  1.6 Los Angeles (LA) > 40 |  |
| 2.1 Soils containing from 5 to 15% of fines \(^{(1)}\) | SQ 2 \(^{(4)}\) |
| 2.2 Uniform soil containing less than 5% of fines \(^{(1)}\) (CU $\leq$ 6) |  |
| 2.3 Moderately hard rock, e.g. if $25 < \text{MDE} \leq 40$ and $30 < \text{LA} < 40$ |  |
| 3.1 Well graded soils containing less than 5% of fines \(^{(1)}\) | SQ 3 |
| 3.2 Hard rock, e.g.: if MDE $\leq 25$ and LA $\leq 30$ |  |
Bearing capacity of the subgrade

• Quality class of the soil which forms an embankment

• Quality and thickness of the prepared subgrade
  – P1: poor subgrade – deformation modulus ≤ 20 MPa (2.9 ksi)
  – P2: average subgrade – deformation modulus ≤ 50 MPa (7.25 ksi)
  – P3: good subgrade – deformation modulus ≤ 80 MPa (11.6 ksi)
Figure 9 – Determination of the Bearing Capacity of the Subgrade

<table>
<thead>
<tr>
<th>Quality Class of the Soil</th>
<th>Class of Bearing Required for the Prepared Subgrade</th>
<th>Requirement of Subballast Layer</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Quality Class</td>
</tr>
<tr>
<td>SQ 1</td>
<td>P1, P2, P3</td>
<td>SQ1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SQ2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SQ3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SQ3</td>
</tr>
<tr>
<td>SQ 2</td>
<td>P2, P3</td>
<td>SQ2</td>
</tr>
<tr>
<td>SQ 3</td>
<td>P3</td>
<td>SQ3</td>
</tr>
</tbody>
</table>
Frost susceptibility of soils

- Soil type based on frost susceptibility
  - Not susceptible to frost
  - Susceptible to frost
  - Very susceptible to frost

**Figure 10 – Frost Susceptibility of the various Soils Types**

<table>
<thead>
<tr>
<th>Degree of Frost Susceptibility</th>
<th>Soil Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Not susceptible to frost</td>
<td>Sand, Gravel</td>
</tr>
<tr>
<td>Susceptible to frost</td>
<td>Clay</td>
</tr>
<tr>
<td>Very susceptible to frost</td>
<td>Silt</td>
</tr>
</tbody>
</table>
Frost susceptibility of soils (cont.)

• A soil composed mainly of coarse particle will become frost-susceptible when the percentage of clay or silt rises above a certain critical level.

<table>
<thead>
<tr>
<th>Uniformity coefficient $C_U$ of the soil under consideration</th>
<th>Critical percentage (by Weight) of particles with a diameter $d &gt; 0.02$ mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>15</td>
<td>3</td>
</tr>
</tbody>
</table>
Frost susceptibility of soils (cont.)

• The degree of frost susceptibility can be estimated by the capillarity of the soil layer
• If the capillary rise of water is $> 0.7 \text{ m (23 in.)}$, the soil layer can be considered frost susceptible
• In track bed layers, the capillary rise of water shall be $< 0.3 \text{ m (12 in.)}$
Earthwork and Track Bed

- Suitability of soils for re-use
- Design and construction of earthwork
- Composition and thickness of the track bed layer
General earthwork terms
Stability Analysis of Earthwork

• Stability: resistance to slope failure must be demonstrated by calculation

• Settlement:
  – How fast construction can proceed
  – Demonstrate that any settlement after the line is open can be rectified by routine maintenance
  – If not, other alternative can be considered
Figure 19.3. Blasting to accelerate subsidence.
Figure 19.4. Slides due to failure in shear.
Stability Analysis of Earthwork (cont.)

- **Slope angle**
  - Embankment: 1.5H: 1V or 2H:1V (15% design)
  - Cuts
    - Intact rock not susceptible to weather and without unfavorable dip or cleavage: 45%-90%
    - Weathered rock subject to degradation and deterioration: special consideration
    - Granular soils: 1.5H:1V to 2H:1V
    - Cohesive soils: 1.5H:1V to 2H:1V
    - Pre-historic landslide areas: extensive evaluation

- **Freight rail**:
  - 1.5:1 commonly used
  - Sands or clay: 2:1 or 3:1
  - Solid rock cuts: ½:1 or ¼:1
  - Soil type is a determining factor
  - Cut widening or slope flattening
  - Terrace and setback
Stability Analysis of Earthwork (cont.)

- Sensitive soils or unfavorable hyrogeological conditions
  - Embankments
    - Replacement of the sensitive soil
    - Pre-loading for consolidation of the soil underlying the embankment
    - Installation of vertical drains or piles
  - Cuts
    - In ground which is sensitive to frost or water, cut slopes shall be protected by a coarse granular layer
    - ...
Stability Analysis of Earthwork (cont.)

• Embankment fills
  – $\rho_d \geq 90\%$ of the maximum dry density where embankment construction exceeds 5 ft in depth.
  – EV2 $d \geq 6.525$ for the fine soils, or 8.7 ksi for sandy and gravelly soils

• Prepared subgrade:
  – $\rho_d \geq 95\%$ of the maximum dry density as determined from ASTM D1557-07
  – EV2 $d \geq 11.6$ ksi (dynamic deformation modulus)
Blanket

• Blanket is a layer of coarse grained material between ballast and subgrade, spread over entire width.
  - Improving the bearing capacity
  - Reduction of induced stresses
  - To prevent mud pumping and fouling of ballast by upward migration of fine particles from the subgrade
  - To prevent damage of subgrade by ballast
  - Shedding surface water from the ballast and drain away from the subgrade
  - Protection of subgrade against erosion and climatic variations
Blanket (cont.)

• In its most complete form, consisting of:
  – A sandy gravel sub-ballast layer
  – A “foundation” layer of well graded sandy gravel
  – A filtering layer of sand to be used only with a subgrade of bearing capacity class P1
  – A geotextile filter used with prepared subgrade P1 and P2
Filter blankets and geotextiles
Determination of the thickness of the track bed layers

- The ballast thickness is constant
- The dimensions of the track bed layers for the sub-ballast layer and the eventual prepared subgrade are also constant
- For 15% design, it is proposed to use an 8 inch thick sub-ballast layer and a 20 inch thick prepared subgrade, which is used in France.
- The criteria and the optimization of the thickness of these layers will be developed at a later design stage.
HSR Station
HSR Station Characteristics

• Service characteristics
  – No freight
  – No postal service

• Design characteristics
  – Track side → on the track,
    • entrance upper, exit lower
    • Tall
  – Coordinate with other modes
HSR Station Characteristics (cont.)

• Operation characteristics: High density, short length
  – Passenger management
    • Automatic ticketing system
    • Traveler information system
    • Passenger guidance system: car position, platform...
  – Train operation: trains of different speed share track
    • By-pass station
Type of Stations

• Bypass
• Intermediate
• Terminal (departure and arrival)
Station Technical Characteristics

• Tracks and spacing
  – Track (#, length)
    • Mainline
    • Siding
    • ...
  – Track spacing
Station Technical Characteristics (cont.)

• Passenger service facilities
  – Waiting room
  – Platform (height...)
  – Shelter
  – Entrance and exits (bridge and tunnel)
  – Safety monitoring
Station Technical Characteristics (cont.)

- **Layout**
  - Two tracks
  - Two tracks two platforms
    - Symmetric
    - Island
  - With maintenance facilities
  - Two platforms four tracks
Station

Two Line Station

Station

Maintenance Base

Symmetric Station

Station

Maintenance Base

Island Station
Station Technical Characteristics (cont.)

• Layouts for different types of stations
  – Intermediate stations
  – Intermediate stations with trains returning
  – Stations with departure and terminal
Main Track on the side

HSR Station

Through Main Track
HSR hub

- Facility layouts
- Multimodal connectivity
Facilities in HSR hub

1. Rolling stock inspection and maintenance facilities
   - With different levels of facilities
2. System inspection and maintenance facilities
   - With different levels of facilities
3. Passenger stations
4. Train operation stations
5. Transfer facilities
HSR hub layout

• HSR mixed with existing railroads
  – Consider whole railroad network
  – Consider city development
  – Consider connecting other modes of transportation
HSR hub layout (cont.)

• The method to connect existing railroad
  – Connect at existing passenger station
    • Same level
      – Terminal station, same level
      – Passing through station, same level
    • Upper level
    • Lower level
  – Separate station
    • Connecting to existing passenger station
    • Not connecting to existing passenger station
1~5—Traditional Trains  6~8—HSR trains

1~6—Traditional Trains  7~9—HSR trains
Location of minor maintenance facilities

• At terminal stations
• At passing through stations
HSR Station

Car Stationing

Maint

HSR Station

Maint
Location of major maintenance facilities
Multimodal connection

• Capacity coordination
• Easy transfer
  – Subway, ...
  – Door to door transfer (shuttle)
  – One card for multiple modes
  – Bring multiple modes to the front of stations
Beijing South
Traction Power Supply and Propulsion
Outline

• Traction power supply system
• Overhead contact line
• Pantograph
• Engine
Figure 3.7 Power distribution system of a typical transit line
HIGH VOLTAGE POWER SUPPLY SYSTEM

RAILWAY SYSTEM

Transformers

Substation

Overhead catenary system

Pantograph (P)

Point of Common Coupling (CC)

Sketch of system boundaries
Figure 6: Feeding configuration between Los Angeles and Anaheim used for the traction power simulation
The system main components

- 2 x 25 kV Traction Power Supply Stations with a nominal output voltage of 50 kV.
- Paralleling Stations with 1 Autotransformer (2 autotransformers may be useful in special cases)
- Switching Stations (with Autotransformers)
- Phase break separation sections adjacent to traction power supply stations and switching stations.
Electricity consumption
Figure 3: 2 x 25 kV principle
substation
KEY: FIGURES 1-6
C1 - CATENARY FOR TRACK 1
C2 - CATENARY FOR TRACK 2
N - NORTH
S - SOUTH

2 POLE CIRCUIT BREAKER
SINGLE POLE CIRCUIT BREAKER
2 POLE DISCONNECT SWITCH
PHASE BREAK
INSULATOR

HV UTILITY CIRCUIT U1
HV TRANSFORMER
HV TRANSFORMER
C BUS N
C BUS S 25KV
C1N
C2N
C1S 25KV
C2S 25KV

RETURNS TRACKS 1 & 2

TRACTION POWER SUBSTATION WITH UTILITY SUPPLY - 1X25KV SYSTEM
C1 - Catenary for Track 1
C2 - Catenary for Track 2
F1 - Negative Feeder for Track 1
F2 - Negative Feeder for Track 2
N - North
S - South

HV Utility Circuit U1
HV Utility Circuit U2

HV Transformer with Center Tap
HV Transformer with Center Tap

C Bus N
F Bus N
C Bus S (+) 25kV
F Bus S (-) 25kV

50kV

F1N
C1N
C2N
F2N

Returns Tracks 1 & 2

F1S (-) 25kV
C1S (+) 25kV
C2S (+) 25kV
F2S (-) 25kV

Traction Power Substation with Utility Supply - 2x25kV Autotransformer Feed System
2x25KV Autotransformer Feed System:
Typical Proportional Current Distribution for Train Load of 200A
SIMPLIFIED COMPARISON OF EXTENT
OF ELECTROMAGNETIC FIELD FOR
1X25KV AND 2X25KV SYSTEMS
Overhead contact line

- https://www.youtube.com/watch?v=7ZiETnuidmc
- https://www.youtube.com/watch?v=kFPJ8eF9M2A
Tensioning

- auto-tensioning
- midpoint anchor

Breaks

• Section break
• Neutral section (phase break)
• Dead section
The Overhead Contact System for PDL Wuhan-Guangzhou $v = 350 \text{ km/h}$

Figure 4: The overhead contact line system on the Wuhan-Guangzhou line
Figure 5: Chinese high-speed overhead contact lines (concepts)
Figure 6: Elasticities in the high-speed overhead contact lines
Receiving Electricity

\[ c = \sqrt{\frac{T}{\rho}} \]

- C: wave speed, m/s
- T: wire tension, N
- ρ: wire density, kg/m
Pantograph

- http://en.wikipedia.org/wiki/Pantograph
• http://en.wikipedia.org/wiki/Pantograph_(rail)
• The (asymmetrical) 'Z'-shaped pantograph of the electrical pickup on the Berlin Straßenbahn. This pantograph uses a single-arm design
Pantograph (CRH DAS250)
Design requirement for HSR pantograph

• The sliding plate and wire have appropriate contact force
• Reduce the weight of the mobile of pantograph
• Reduce aerodynamics on the contact force between sliding plate and wire
• Sliding plate should be strong
• Reduce noise caused by pantograph
How does an ordinary DC motor work?

DC Motor

DC Motor, How it works?

https://www.youtube.com/watch?v=LAtPHANEfQo

dc motor

https://www.youtube.com/watch?v=fWyzPdyCAzU
DC Motor

- Easy to control the speed
- Hard to maintain the commutator and brush
How does an AC motor work?

AC Motor

Rotating Magnetic Field
https://www.youtube.com/watch?v=SiZ-mak4h4s

Rotating Magnetic Field & Synchronous Speed
https://www.youtube.com/watch?v=8XF-11MQGQ0

Working of Synchronous Motor
https://www.youtube.com/watch?v=Vk2jDXxZIhs
AC motor is better

- Structure is simple, no commutator, no brush, no part to deteriorate
- System modular based, more reliable, easy to maintain
- Easy to switch to electricity regeneration, no change on the circuit, no contact electronics
- Any changes can be made through software, not hardware
AC motor is better (cont.)

• Its rotation can be much higher
• Its rotation rate is: 7,000 per minute, or 116/s
• Light weight, small size
• It took 70 years to make AC motor widely used
• It requires both voltages and frequency to be adjustable, variable voltage variable frequency (VVVF)
• The development of electronic power equipment makes VVVF practical
VVVF
Key technologies

• High voltage
• 2*25 kv system
• Improved overhead contact line
• Improved pantograph
• Improved engine
Rolling Stock for HSR
Key technologies

- System integration
- Train body
- Truck
- Brake and control
Vehicle design

• Train shape
  – Surface air pressure when trains meet
    • Door, window sealing damage, window glass broken, ear uncomfortable
  – Surface air pressure in tunnel
    • Train speed, cross section area vs. tunnel cross section (congestion coefficient), train nose length vs. train body cross section area, friction between side of vehicle body and tunnel
  – train induced air flow
    • Hazard to worker along tracks
Vehicle design (cont.)

• Light weight design
  – Light weight materials
    • Stainless steel, aluminum alloy, atmospheric corrosion resisting steel
  – Vehicle body structural design
  – Vehicle body seal technology
    • Continuous welding, sealing glue
    • Fixed window
Vehicle design (cont.)

• Vehicle body sealing
  – Welding and sealing
  – Fixed widow
  – plug type door, rubber strip seal
  – Air condition air exchange pressure control
  – Toilet on high speed train
Vehicle design (cont.)

• Noise reduction
  – Noise from vehicle
    • Improve body stiffness, reduce vibration migration, increase thickness
    • Sound proof, anti-vibration, double layer window
    • Streamlined vehicle body
  – Interior design
    • Sound insulation, noise absorption materials
    • Room arrangement
    • Floor noise reduction
  – Equipment installation noise reduction
  – Window noise reduction
  – Developing new materials
Vehicle design (cont.)
Trucks (bogie)

- Traction Motor
- Gear
- Power Wheel
- Voltage transformer
- Current transformer
- Power Wheel
Truck (cont.)

• Concentrated power (France)
  – Easy for maintenance
  – Ventilation for cooling
  – Reduce car load
  – Reduce noise

• Distributed power (Japan)
  – Axial load small
  – Traction power big
  – Acceleration quick
  – Friction coefficient good
  – Higher speed
Basic parts of a three-piece freight car truck

Wheelset (wheel and axle)
Sideframe
Compression member
Tension member
Top member
Spring group (load coils)
Gib
Column
Roller bearing
Center plate
Center plate rim
Side bearing pad
Pedestal
Pedestal roof
Bearing adapter

American Steel Foundries illustration
Bogie weight reduction

- Welding structure than cast steel structure
- Hole-bored axle, small diameter wheel
- Journal box, gear box
Braking and its control

- Braking system requirements
  - Braking distance
    - Normal
    - Emergency braking: 3000-4000 m
  - Comfort
    - Jerk <0.6 m/s², no obvious uncomfortable
    - 0.6-0.75 m/s², acceptable
    - >1.0 ms², fail
  - Reliability
    - System component reliable
    - Fail safe
Braking technologies

- Disc brake
- Rheostatic brake, dynamic brake
- Regenerative brake
- Magnetic rail brake
- Electromagnetic rail brake (Eddy current brake)
- Rotary electromagnetic brake
- Wind resistance brake
Lorentz force

- dynamic brake
- electromagnetic rail brake
- electromagnetic rail brake
Braking technologies - type

• Friction braking
  – Disc brake
  – Magnetic rail brake
• Traction braking
  – Rheostatic brake, dynamic brake
  – Regenerative brake
  – Electromagnetic rail brake (Eddy current brake)
  – Rotary electromagnetic brake
• Wind resistance brake
Braking technologies - type

• Friction braking
  – Braking force does not change with speed
  – Braking force is limited
  – Limited by heat dissemination

• Traction braking
  – Change with speed
Braking technologies - type

• Adhesion braking
  – Disc brake
  – Rheostatic brake, dynamic brake
  – Regenerative brake
  – electromagnetic rail brake (Eddy current brake)
  – Rotary electromagnetic brake

• Non-adhesion braking
  – Magnetic rail brake
Integrated braking systems

• Japan, 270 mph, regen + disc
• ICE1, 300 mph, regen + disc + ElectMag Rail
• TGV-A, 300 mph,
  • veh w/ motor: regen + surface
  • Veh w/o motor: regen + surface, disc
<table>
<thead>
<tr>
<th>列车型号</th>
<th>运营时速（公里）</th>
<th>制动方式</th>
<th>拖车制动盘数/轴</th>
<th>标准制动距离（米）</th>
<th>不良状态制动距离（米）</th>
</tr>
</thead>
<tbody>
<tr>
<td>300系（日本）</td>
<td>270</td>
<td>再生+盘形</td>
<td>2</td>
<td>4000</td>
<td>4960</td>
</tr>
<tr>
<td>ICE1（德国）</td>
<td>300</td>
<td>再生+盘形+磁轨</td>
<td>4</td>
<td>3450</td>
<td>——</td>
</tr>
<tr>
<td>TGV-A（法国）</td>
<td>300</td>
<td>动车：电阻+踏面</td>
<td>4</td>
<td>3500</td>
<td>4500</td>
</tr>
<tr>
<td>TGV-PSE（法国）</td>
<td>270</td>
<td>动车：电阻+踏面</td>
<td>4</td>
<td>3000</td>
<td>3700</td>
</tr>
</tbody>
</table>
Braking control system

• Air braking control system – supplementary system for HSR
• Electronic braking control system
High speed rail traction network control system
High speed rail traction network control system

• Control
  – Coordination between vehicle with power
  – Traction control
  – Speed setting
  – Auxiliary system control
  – Phase control
  – Train operation and monitoring
  – Air and electrical braking

• Failure diagnostics and treatments

• Information display and setting
• Data storage
In-vehicle air environment control system

• Air environment control
  – Ventilation, cooling, heating, humidifier, automatic control

• Air pressure control
Tilting train

Tilting train (cont.)

• Trains with tilting by inertial forces (a few countries)
• Trains with active tilting with sensory information given by accelerometers (Bombardier)
• Trains with tilting controlled by a computer (many countries)
• Trains with active suspension (Japan)
CHR

CRH 1 BSP

CRH 3 唐山工厂

CRH 2 四方股份

CRH 5 长客股份
CRH1动车组组成

庞巴迪-四方-鲍尔（BSP）生产，原型是庞巴迪为瑞典AB提供的Regina

- 200 kmh
CRH2动车组组成及主要参数
HSR signal and control
HSR signal

• **Train operation control**
  – Train operation permit
  – Speed target
  – Monitoring and control

• **Station interlock**
  – In real-time setup routing of switching for entering, leaving and within station

• **Dispatching**
  – Develop operation plan and implement it

• **Diagnostics and service**

• **Monitoring system**

• **Hazard information treatment**

• **Communication network**
• http://www.cr.indianrailways.gov.in/view_section.jsp?lang=0&id=0,6,287,394,576
Train interval control and speed control

- Average block distance: 2,000-2,400 m
- Interval: 3 min
- Train distance gap: 13,500 m
Train interval at station

Figure 4.12 Time-distance elements of departure/arrival and headway between consecutive TUs at a station for $b_1 < \infty$
Figure 4.13 Minimum station headway with safety requirements typical for rapid transit systems
• Train interval between stations

Figure 4.4 Components of TU headway, spacing, and stopping distance
Key technologies

• Standardization: interaction between signal, communication, trackside
• Trackside-train data transmission
  – Continuous, point based; one direction, bi-direction,
    • Rail inductive loop, wireless mobile communication (GSM-R), Balise
• Train position system
  – GPS, Balise, rail inductive loop
• Speed measuring system
  – Radar
• Train integrity and occupancy
  – Train end GPS, rail inductive loop
• Interoperable
Balise
System components

• Trackside equipment
• Vehicle carried equipment
• Ground-vehicle communication
HSR train operation features

• Automatic train control
• Central train control, no station dispatching involved
• Train-ground information exchange equipment, verifying train location
• Computer controlled interlock
• Hot-box detection, clearance check
• Communication and signal integrated: primary digital
• No work zones
Train control type

• Automatic train protection (ATP) and automatic train control (ATC)
  – ATC is more advanced than ATP
  – ATC is widely used in Japan

• Equipment initiating (better) or driver initiating
  – Equipment initiating: Japan
  – Driver initiating: Germany and France

• Step or continuous speed control

• Point based (mature) and continuous train control (widely used)
ATP

• http://www.youtube.com/watch?v=Q4aWljbVpcg
Typical HSR train control systems in Europe

High speed signalling systems in EUROPE

- TVM
- LZB
- LZB+ASFA
- EBICAB
- ERTMS L1/L2+ASFA
- BACC
- ERTMS L2
The German signalling system for HS lines LZB (LinienZugBeeinflussung)

- Vital, computerized, continuous and centralized ATC (Automatic Train Control) system for speed up to 187.5 mph; 62/187=20 min
- A single centre manages about 62 miles of double track section line;
- The system is overlapped to the national light signalling system;
- The safe bidirectional link train/centre realized with a cable loop laid into the track for all the line length;

![Diagram of cable loop](image)
The German signalling system for HS lines LZB (LinienZugBeeinflussung)

- Each centre permanently connected to all interlockings and trains of its area as well as to adjacent centers for in and out relationships;
- The trackside vital computer sends cyclically, to every on board computer, data concerning the length of the available braking distance and the localization of braking initiation in respect of the braking train capacity.
The Spanish signalling systems for HS lines

- **Speed up to 187.5 mph**
  
  German LZB overlapped to the national light signalling system ASFA (Anuncio de Señales y Frenado Automatico). The latter is a system for on board repetition of trackside light signals used by conventional trains running the HS lines;

  OR

  ERTMS (European Rail Traffic Management System) level 1 and 2, overlapped to the national light signalling system ASFA.

- **Speed up to 137.5 mph**

  EBICAB (Électrique Bureau CABine) is a semi-continuous system based on wayside transponders which transmit to trains information for supervision of the braking curve (ATP = Automatic Train Protection).
The French signalling system for HS lines: TVM (Transmission Voie Machine)

- Vital ATP (Automatic Train Protection) system with distribute architecture for speed up to 200 mph;
- Single Trackside Control Centers (TCC) located every about 9 miles;
- The system operates without trackside signalling;
- Continuous track-to-train transmission through track circuits.
The French signalling system for HS lines: TVM (Transmission Voie Machine)

- Continuous speed control, calculated on board for each block section and based on data received from trackside (section length, speeds at the beginning and at the end of the block section, slope);
- Audio Frequency Track Circuits;
- Other auxiliary transmission media (balises) needed to manage track conditions (Power supply, Tunnels, etc.).

On line Paris-Strasbourg ERTMS L2 system has been implemented together with TVM national system.
The Italian signalling system for HS lines

- **Speed up to 156.0 mph**
  Italian BACC (Blocco Automatico a Correnti Codificate) national light signals block system, based on coded track circuits and on board repetition of trackside light signals. These HS lines are also used by conventional trains (to be soon upgraded to ERTMS);

- **Speed up to 187.5 mph**
  ERTMS (European Rail Traffic Management System) level 2. In the Italian application ERTMS operates without overlapping on other systems and without trackside signals.
  Only ERTMS equipped trains can run on such HS lines. The lack of a back-up system (ERTMS level 1 or similar) is balanced by a very high level of redundancy of subsystems involved.
Why ERTMS?

1. **Interoperability:** European Commission supports the development of operational and technical interoperability with unified signalling equipment in order to open railway markets to all train operators;

2. **Safety:** ERTMS equipments are designed and produced in compliance with CENELEC standards;

3. **Performance:** high speed can be reached using the lowest amount of time distance between the trains (in Italy only 2’30’’ between two trains running at 187.5 mph);

4. **Availability/Reliability:** due to the particular ERTMS architecture, there are less equipments along the lines, reducing fault probability and improving system reliability.
ERTMS levels

- ERTMS Level 1:
  Overlay using Eurobalises and track side signals;

- ERTMS Level 2:
  Fixed Block Authority is communicated directly from the Radio Block Center (RBC) to the train using GSM-R. Wayside track signals are optionally required;

- ERTMS Level 3:
  Introduction of “moving block”. Wayside track signals are not required.
Which ERTMS? ERTMS level 1

- Discontinuous system working on an underlying and already existing signalling system; provides a continuous speed supervision;
- Movement authorities and track description data are generated by electronic Lineside Equipment Unit (LEU), located by side of the tracks, on the basis of information received from external signalling systems and track circuits;
Which ERTMS? ERTMS level 1

- Movement authorities are transmitted to the train via wayside equipments called balises;
- The on-board sub-system calculates a dynamic speed profile taking into account the train braking characteristics and commands the brake application if necessary;
- Lineside signals are required. Loop (cable or radio) could be used in order to immediately refresh information related to the clear signal aspect (infill function).
Which ERTMS? ERTMS level 2

- Radio based Automatic Train Control (ATC) system (working on optional signalling system), which provides a continuous speed supervision toward fixed points of the line (end of block sections, speed restrictions, etc.);
- Movement Authorities, track description data, temporary speed restrictions and emergency messages are generated by Radio Block Centre (RBC) on the basis of information received from train itself, external interlocking system and track circuit. A RBC usually manages about 62 miles of double track section line.
Which ERTMS? ERTMS level 2

- Messages are transmitted/received to/from the train via GSMR system;
- Balises are used mainly for spot transmission of train location reference, to manage hand-over between RBCs and other particular situations;
- The on-board sub-system calculates a dynamic speed profile taking into account the train braking characteristics and commands the brake application if necessary;
- Lineside signals are optional.
Which ERTMS? ERTMS level 3

- Main features similar to ERTMS level 2, except for:
  - Functional difference: the target is the end of the preceding train (moving block);
  - Technical differences:
    - On-board equipment to check the train integrity is required (RBC needs this information to calculate movement authority);
    - Track Circuit for train detection are not required.

- Performances:
  - Increase line capacity (relevant for lines with intense traffic at low speed as subway)
ERTMS On Board MMI

The on board computer calculates the maximum permissible speed, monitors the real speed and controls the driver’s indicators.

Index of maximum speed permitted (300 km/h = 187.5 mph)
Distance to End of Autorithy
Instant Speed
Indication of On-Board Operation Mode (Full Supervision)
Indication of active link between train and RBC

Over speed detected by the system
Route Setting and Central Train Control
Outline

• Automatic Block Signaling
• Interlocking
• Traffic Control System
• Centralized Traffic Control
Automatic Block Signaling

- All switches in the block are properly aligned for the main track
- The block is free of other trains
- Restrictive signal aspects are displayed so that safe braking distances are ensured if two trains attempt to enter the same

http://www.lundsten.dk/us_signaling/signalbasics/
Double Track ABS

- On lines with 2 tracks, each track can be assigned a fixed direction of travel, the so called Current of Traffic.
- Each track will only be signaled for trains moving With the Current of Traffic
- A (rare) movement Against the Current of Traffic will have to have "manual" authorization.
Single Track ABS

• For opposing trains, however, the ABS must additionally provide a safety zone against head-on collisions
Interlocking

- An interlocking typically controls a number of power controlled switches, and allows trains to move from one main track to another, enter or exit sidings, yards etc.
Interlocking

- Signals cannot display a permissive aspect unless switches are aligned properly for the train move.
- Signals cannot simultaneously display proceed aspects for conflicting train moves.
Traffic Control System

• Traffic locking locks the direction of travel in a track when an interlocking clears a signal to that track
• It prevents the interlocking in the other end of the track from sending trains onto that track.
Centralized Traffic Control

• Allows remote control of a Traffic Control System
Interlocking in HSR

• Integrated interlocking and control
• Integrated station and block
  – Block used as unit
  – No separation between station interlocking and blocking
Characteristics of interlocking in HSR

- Integrated system
- Division based, not station based
- Hardware redundancy system for system reliability
- Automatic route setting and route storage
- Electronic interlocking
- Human-machine interface improvement based on multimedia
- Use maintenance management center
Interlocking - redundancy

• In computer science, there are four major forms of redundancy:
  – Hardware redundancy, such as DMR and TMR
  – Information redundancy, such as error detection and correction methods
  – Time redundancy, performing the same operation multiple times such as multiple executions of a program or multiple copies of data transmitted
  – Software redundancy such as N-version programming
Triple modular redundancy

• 2 out of 3 redundancy
• 3 out of 4 redundancy
Typical interlocking systems

• SIMIS (Siemens)
• TVM430 for TGV
  – https://www.youtube.com/watch?v=xRKC6N5MAjC
• SPAC-8 (Japan)
SIMIS-W Electronic Interlocking

Large-scale interlocking with decentralized controlled areas:
Extension of the IL bus by means of copper cables, fiber-optic cables or using public networks.

The number of ACCs depends on the size of the interlocking.

Advantages of decentralization:
> Centralized operation of large-scale (line and junction) interlockings
> Greater distance possible between the centralized interlocking and decentralized controlled area.
Optional operator control from a central location; operational dispatching

Input of operator actions; display of system and operating states; service and diagnostics

Processing of central functions; administration of the interlocking configuration and topographical data

Control of operational processes; control and monitoring of elements belonging to the outdoor equipment
Centralized traffic control for HSR

• Functions
  – Dispatching: display train status in real time, automatically send route setting command to station, run train adhering to schedule
  – Passenger service
  – Engine and car dispatching
  – Maintenance dispatching
  – Electricity power dispatching
  – Signal equipment monitoring
Centralized Traffic Control

Typical systems in the world

• Vicos OC 501 (Siemens)
• Alstom ICONIS ATS
• COSMOS (computerized, safety, maintenance and operation system, Japan)
Centralised operation of the interlocking, train operation control, and the display of all train operations on the operator consoles through a network of computers and automation functions

In addition to electronic interlockings, relay interlockings can also be incorporated into centralised operations control via a remote control system

Train identification, passenger information, and building services automation systems can also be connected

A modular operating control system: several computers are used for the various sub-tasks. This ensures that the large amount of data arriving from the various interlockings and other connected systems are processed on time.

Suitable for all types of railways ranging from light rail and metros to regional, industrial, and mainline networks

Make use of existing resources.
Vicos OC 501 (Siemens)

Planning

Dispatching and optimization

Operations control

Monitoring and control

Local monitoring and control

Automatic route setting
Automatic train tracking
Automatic train regulation
Integration of subsystems
Timetable
Local operator workstation & remote control
Remote control

Local operator workstation & remote control

Dispatching
Conflict detection / resolution
Train run forecasting / deviations
Automatic train regulation
Integration of subsystems
Timetable
Dispatching control center / dispatching center

Operations control center / dispatching center

Resources planning (lines, rolling stock, staff)
Work site planning / signaling systems
Timetable design and validation
Simulation
Owing to its modularity and flexibility, it is possible to tailor it to the individual needs of railway operators as well as the environmental conditions.
Рис. 5. Рабочее место диспетчера (фото: Siemens)
Alstom ICONIS ATS

FROM MONITORING TO FULL AUTOMATION

TRAIN COMPOSITION
TIMETABLES
STATES OF INFRASTRUCTURE
DISRUPTION

SCHEDULING
DETECT CONFLICT
SOLVE CONFLICT
AUTOMATIC CONTROL

OPERATOR DECISION SUPPORT
MONITOR
SIGNALING CONTROL
FIELD INFORMATION
COSMOS

Integrated Intelligent Transport Management System

COSMOS: Computerized Safety, Maintenance and Operation Systems of Shinkansen

- Facilities Control
- Transport Planning
- Operation Control
- Power System
- Station Yard Control
- CMS (Centralized Monitoring System)
- Maintenance Work Control
- Rolling Stock Control
Communications for HSR
Communications and Signals: Then and Now

- http://www.youtube.com/watch?v=3Sow8O1_ZNA
Communication Needs

• Dispatching command transmission
• Passenger service: real time information provision and offline statistics
• Maintenance and train service
Communication requirements

• Reliable
• Efficiency
• Integrated signal and communications
• Integrated computer and its network
• Multiple types of information to transmit: data, voice, image, monitoring signal, etc.
• Multiple media: wireline and wireless
Communications in Shinkansen

• Rail operation safety and efficiency
  – ATC: circuit and cable
  – CSC: substation remote control
  – Wind speed, rain fall monitoring
  – Track side telephone for maintenance
  – Train driver and dispatching operator wireless communications
  – CTC: dispatching center and 26 signal stations transmitting information to set routes
  – Fax from dispatching center to stations
  – Telephone from dispatching center to stations
  – Maintenance worker track side safety protection wireless device
  – Blocking telepone
Communications in Shinkansen (cont.)

• Communications for passenger service
  – Ticket booking
  – Station passenger information: arrival and dispatching time
  – Train operator communicating with dispatching
  – Passenger dispatchers
  – Fax into stations from dispatching center
  – Public telephone on train
Communications in Shinkansen (cont.)

• Communications for maintenance
  – Wireless mobile phone
  – Wireless call to maintenance crew from dispatching center
  – Direct phone between maintenance, power, and signal units
  – Track side phone
  – Fax
Communications - type

• Voice: direct phone, train phone, satellite (earthquake, etc.)
• Signal: blocking device, balise, highway and rail crossing, train dispatching, route setting
• Data: fax, ticketing
• Image
Communications - TGV

• Dispatching center to blocks
• Block warning
• Train to dispatching center
• Power facility maintenance to dispatching center
图 6-1-4 法国 TGV 专用通信简图
Wireline

• For mainline and interregional communication
• Telephone: cheap, track side maintenance
• Cable: short distance, power district, substation, ATC devices
• Composite cable: dispatching telephone, wireless station, and operators
• Fiber optical: data transmission,
Digital exchanger

- Exchange from analog to digital signal for transmission
Wireless

• **Fixed wireless communication:**
  – Multi-channel microwave telecommunication

• **Mobile wireless communications**
  – Train wireless communications
  – Protection
  – Blocking

• **Passenger mobile wireless communication**

• satellite
Wireless (cont.)

- Train mobile communications
  - Leaky cable (Japan)
  - Fixed stations with wireless between stations (TGV)
GSM-R, Global System for Mobile Communications – Railway

• It is used for communication between train and railway regulation control centres
• The system is based on GSM and EIRENE – MORANE specifications which guarantee performance at speeds up to 500 km/h (310 mph), without any communication loss.
• GSM is a standard developed by the European Telecommunications Standards Institute (ETSI) to describe protocols for second-generation (2G) digital cellular networks used by mobile phones

• http://en.wikipedia.org/wiki/GSM-R
GSM

Structure of a GSM network

GSM-R

- GSM-R = GSM + voice dispatching + railroad application
• GSM-R transmitter mast on the Nuremberg–Ingolstadt high-speed railway line
GSM-R (cont.)

- GSM-R to replace existing incompatible in-track cable and analogue railway radio networks.
- The standard is to achieve interoperability using a single communication platform.
- GSM-R is part of the European Rail Traffic Management System (ERTMS) standard.
- Carries the signaling information directly to the train driver, enabling higher train speeds and traffic density with a high level of safety.
GSM-R (cont.)

• GSM-R is a secure platform for voice and data communication between railway operational staff, including drivers, dispatchers, shunting team members, train engineers, and station controllers.
• It delivers features such as group calls (VGCS), voice broadcast (VBS), location-based connections, and call pre-emption in case of an emergency.
• This will support applications such as cargo tracking, video surveillance in trains and at stations, and passenger information services.
GSM-R (cont.)

• Automatic train control
• Synchronizing engine control
• Efficient dispatching command transmission
• Train number transmission and train stop information transmission
• Train end air pressure return transmission
GSM-R (cont.)

- GSM-R is typically implemented using dedicated base station towers close to the railway.
- The distance between the base stations is 7–15 km. This creates a high degree of redundancy and higher availability and reliability.
图 7.8 GSM-R 网络结构图
GSM-R (cont.)

- The train maintains a circuit switched digital modem connection to the train control center at all times.
- This modem operates with higher priority than normal users (eMLPP). If the modem connection is lost, the train will automatically stop.
GSM-R (cont.)

• It is used to transmit data between trains and railway regulation centers.

• When the train passes over a **Eurobalise**, it transmits its new position and its speed, then it receives back agreement (or disagreement) to enter the next track and its new maximum speed. In addition, trackside signals become redundant.
System components

- Base station subsystem
- Network and switching subsystem
- General packet radio service
- Intelligent network
- Operation maintenance subsystem
- Terminal computer
HSR Operation
Outline

• What is HSR operation?
• HSR capacity
• HSR CTC
Operation plan

- Satisfy different demand
- Make transfer convenient
- Consider the use of rolling stock (number, type, maintenance, etc.)
- Consider train service crew
- Consider stop requirement
- Consider maintenance (4-6 hours, track, signal, communication, power supply maintenance at the same time)
HSR passenger flow and train classification

• Passenger flows
  – Different speed
  – Different travel distance
  – Different stop pattern
  – Different operating sections
<table>
<thead>
<tr>
<th>Country</th>
<th>Model</th>
<th>Consist</th>
<th>KW</th>
<th>Max Speed</th>
<th>Power Distribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Japan</td>
<td>200 series</td>
<td>14M+2T</td>
<td>12,880</td>
<td>270 km/h</td>
<td>power distribution</td>
</tr>
<tr>
<td>France</td>
<td>TGV</td>
<td>2M+8T</td>
<td>8,800</td>
<td>260 km/h</td>
<td>power concentration</td>
</tr>
<tr>
<td>British</td>
<td>APT</td>
<td>2M+12T</td>
<td>6,000</td>
<td>tilt train</td>
<td>power concentration</td>
</tr>
<tr>
<td>Russia</td>
<td>ЭР200</td>
<td>14M+2(C)</td>
<td>11,520</td>
<td>200 km/h</td>
<td>power distribution</td>
</tr>
</tbody>
</table>
Scheduling for maintenance
Schedule for different trains
Schedule for different stop patterns
Schedule for rolling stock

High Speed Multiple Units Flexible Service Section Service Plan

- Layover time
- Between Station Cycle
- Turn around between multiple stations

High Speed Multiple Units Fixed Service Section Service Plan

- Window
- Connection time

Multiple Units

High Speed Multiple Units Flexible Service Section Service Plan
HSR capacity

• Influencing factors
  – Mixed use
  – Train type, proportion
  – Following time interval
  – Speeds
  – Station dwelling time
  – Distance between stations
  – Maintenance windows
  – Scheduling method
HSR capacity (cont.)

- Combination capacity: capacities for long distance trains and short distance trains
- By direction
- By section
- Day and time usage different
- Theoretical and practical capacities are significantly different
- Dwelling time and acceleration/deceleration have bigger impact
Capacity calculation method

- Influencing factor method
- Simulation

\[ n_h = \frac{1440 - (t_{\text{maint}} + t_{\text{misc}})}{I \varepsilon_h} \]

- \( T_{\text{maint}} \) – time for maintenance
- \( T_{\text{misc}} \) – time for miscellany activities
- \( I \) – time interval between trains
- \( \varepsilon \) – influencing factor
Train capacity

\[ C = \frac{365C_v\alpha}{K} \]

- \( C \) = capacity for a train (passengers)
- \( C_v \) = train capacity
- \( \alpha \) = loading factor
- \( K \) = seasonal factor
Centralized Traffic Control

- Highly planned, centralized control
- High safety
- High density
- High on-time performance
- Human centered passenger service
- Comprehensive maintenance
HST Passenger Service
HST Passenger Service

• Service
  – At station
  – On train

• Passenger information systems
Service at station

• Booking
• Loading and unloading
• Waiting
• Passenger information
• Special group of passenger service
• Extended service
Service at station (cont.)

• Booking
  – Windows at station
  – Wending machine
  – Internet
  – Telephone
  – Agents
Service at station (cont.)

• Pricing practices vary among different countries: France, Japan, Germany

• Pricing - France
  – Time varying
  – Priority consideration
    • Frequent public employee, 50% off
    • Pass for collaborating agencies like taxi
    • Point system
    • 12-25 year olds and 60+, 25-60% off
    • Veterans, etc.,
Service at station (cont.)

• Loading and unloading
  – Entering
  – Travel in station
  – Check in
  – Alight
Service at station (cont.)

• Waiting: any activities except booking and boarding and alighting
  – Shopping
  – Entertainment
  – Temporary storage
Service at station (cont.)

• Passenger information service
  – Passenger service: train status, transfer info, ticket price,
  – Announcement and travel guide: what about rail, travel guide, travel safety, service complaint, equipment usage
  – Social service: weather, hotel, hospital, fund, etc
Service at station (cont.)

• Special group of passenger service
  – Senior, child, veteran, etc.
  – VIP
  – Travel group
  – Students
Service at station (cont.)

- Extended service
  - Travel service
  - Connecting travel agencies
  - Taxi
  - Hotel booking
  - Umbrella renting
Service on trains

- Crews
- Broadcasting
- Information display
- Child care
- Service for handicapped
- Foods service
- Newspaper and magazine
- Phone on train
- Adjusted chair
Information systems

- Booking system
- Passenger service system
- Passenger marketing
- Customer service
Booking system
Booking system (cont.)

图 9.2 票务系统的功能构成
Passenger Service System

• Passenger information announcement
• Direction
• Displaying
• Monitoring
• Calling system
• Internet system
图 9.5 旅客服务系统的体系架构示意图
Passenger service system (cont.)

图 9.6 旅客服务系统的构成
Passenger marketing system

• Market survey, analysis and forecasting system
• Operation planning
• Analysis and assessment
Passenger marketing (cont.)
Customer service system
图 9.10 铁路客户服务中心功能构成图
Rolling stock and its maintenance
Onboard diagnosis

• Part diagnosis
• Vehicle diagnosis
• Train diagnosis
Vehicle part monitoring and diagnosis

- Monitor
- Monitor with input and output
- Monitor with control
Japan Shinkansen onboard monitoring and diagnosis system

<table>
<thead>
<tr>
<th>装置名称</th>
<th>机器监视装置</th>
<th>有传送功能的监视装置</th>
<th>有运行控制功能的监视装置</th>
</tr>
</thead>
<tbody>
<tr>
<td>概要</td>
<td>做出故障记录</td>
<td>监视列车上的机器，连结试验操作器，根据控制操作车上最少限度的检验</td>
<td>根据传送和接受的运行控制指令，可自动进行车检</td>
</tr>
<tr>
<td>记录故障</td>
<td>故障记录</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td></td>
<td>追踪功能</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>显</td>
<td>故障</td>
<td>○(发生故障,车辆项目,控制)</td>
<td>○(发生故障,车辆项目,控制)</td>
</tr>
<tr>
<td></td>
<td>装置开放状态</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td></td>
<td>出库检查</td>
<td>○(出库前有无异常)</td>
<td>○(出库前有无异常)</td>
</tr>
<tr>
<td></td>
<td>制动</td>
<td>○(指令级、制动缸压力)</td>
<td>○(指令级、制动缸压力)</td>
</tr>
<tr>
<td></td>
<td>牵引状态</td>
<td>○(指令级为,主回路电压电流)</td>
<td>○(指令级为,主回路电压电流)</td>
</tr>
<tr>
<td></td>
<td>车门信息</td>
<td>○(门的关闭状态,几号车)</td>
<td>○(门的关闭状态,几号车)</td>
</tr>
<tr>
<td></td>
<td>累计电力</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td></td>
<td>故障记录</td>
<td>○(有无故障记录,内容)</td>
<td>○(有无故障记录,内容)</td>
</tr>
<tr>
<td>收集试运行数据</td>
<td>○</td>
<td>○</td>
<td></td>
</tr>
<tr>
<td>车上试验</td>
<td>○(主控制器为手动操作)</td>
<td>○(除检查主控制器本身外,不操作主控制器,用显示器指令自动进行)</td>
<td></td>
</tr>
<tr>
<td>控制运行指令</td>
<td>○</td>
<td>○</td>
<td></td>
</tr>
<tr>
<td>补充控制指令</td>
<td>○</td>
<td>○</td>
<td></td>
</tr>
</tbody>
</table>
Maintenance idea and policy

• Maintenance idea
  – Preventive based, wear and tear theory based
  – Reliability based, reliability is time invarying

• Maintenance policy
  – Preventive
  – Status based
  – Emergency based, suit to system with many redundancy

• High speed rail use status based and preventive maintenance
HSR maintenance facilities

• Vehicle preparation
• Vehicle testing
• Wheel surface inspection
• Axle inspection
• Wheel and bogie replacement
• Vehicle cleaning and wash inside and outside
HSR maintenance characteristics

- Integration of operation, preparation, and maintenance
Japan Shinkansen

• Preventive, scheduled maintenance
• Consider the type of equipment and the operation schedule (6 am – 12 pm)
• Four level
  – Daily inspection and maintenance: pantagraph, brake, bogie
  – Weekly inspection and maintenance: under vehicle body check, ATC
  – Annual (450,000 km) inspection and maintenance: bogie, separate the train
  – 3 years (900,000 km) inspection and maintenance:
图 10.4 JR 东日本公司的新干线车辆基地
HSR Maintenance in Germany

• Scheduled and status based maintenance combined
• A,B,C maintenance level
• Maintenance facilities are distributed considering maintenance level
• Reliability based
图 10.5 列车运行的高峰低谷情况

安排维修计划

图 10.6 质量与检修周期的关系
### A: inspect, maintenance

- **L 级检修 (IS100)**
  - 走行里程 (km): 2000~4100
  - 检修时间: 1.5 h

- **N 级检修 (IS200)**
  - 走行里程 (km): 20000~24000
  - 检修时间: 2.5 h

### B: replace parts

- **IS510 级检修**
  - 走行里程 (km): 60000~72000
  - 检修时间: 9 h

- **IS520 级检修**
  - 走行里程 (km): 120000~144000
  - 检修时间: 9 h

### C: maintain entire trains

- **IS530 级检修**
  - 走行里程 (km): 240000~288000
  - 检修时间: 11 h

- **IS540 级检修**
  - 走行里程 (km): 480000~576000
  - 检修时间: 11 h

- **IS600 级大修**
  - 走行里程 (km): 1200000~1400000

- **IS700 级大修**
  - 走行里程 (km): 2400000+
图 10.7  ICE 动车段到主要设备的连接图

慕尼黑-勒母
ICE存车线

动力转向架
不落轮旋设备

ICE动车段

轮对诊断设备

动车组外部
清洁设备

慕尼黑车站
图 10.9 慕尼黑与汉堡动车段工作平台的比较
Track safety inspection and maintenance
Comprehensive inspection train
Comprehensive inspection train (cont.)

• Complete data collection: clearance, track, steel and wheel, pantograph, signal, telecommunication, environment monitoring
• Geographical location information
• The same size of train as the train in service
Track inspection technologies

1. Track limit and cross section inspection
2. Rail wear and tear
   - Gauge
   - Vertical smoothness
   - Longitudinal smoothness
   - Level
   - Triangle dent
   - Vibration acceleration
   - Track structure and parameters
3. Wheel and rail interaction
4. Pantograph inspection
5. Communications inspection
6. Signal inspection
7. Comprehensive analysis
LMS200/221/221/291 Laser Measurement Systems

- sicktoolbox.sourceforge.net/docs/sick-lms-technical-description.pdf
Track irregularities
(a) 高低不平顺

(b) 轨向不平顺

(c) 水平不平顺

(d) 轨距不平顺
Rail wear and tear

- One shot per 20-10 cm
Track Measurement Systems - ENSCO Inc.

- http://ensco.com/rail/track-measurement-systems
Gauge measurement
Profile irregularity - Measuring method

- Chord measuring method
- Inertia surveying system
Profile irregularity (cont.)

- Chord measuring method
  - Not influenced by speed
Profile irregularity (cont.)

- Inertia surveying system
  - Not good for low speed
Profile irregularity (cont.)

- Good for both speeds
Track orientation

• Combine gauge and inertia surveying system
Cross level irregularity
Twist
Vibration

- Vehicle body vertical and lateral acceleration
  - Assessing track irregularity and comfort
  - Vibration frequency small, range big

- Alex box acceleration
  - Steel wheel and noise
  - Frequency big, range small
Track structure parameters

- Flying ballast cause rail surface damage
- Track clip loose
- Tie damage
Steel wheel force measurement

- Assess vehicle running smoothness and safety
- Lateral force: Q
- Vertical force: P
Catenary and pantograph inspection

- Catenary wire wear and tear
- Catenary high
- Catenary height change rate
- Wire extension
- Hard point and impact point
- Contact force between catenary and pantograph
- Contactless time
- Horizontal distance between wire
- Vertical distance between wires
- Pantograph voltage
- Current to vehicle
- Position device slope
- Distance between pole
Wire extension

- http://www.tielu.cn/baike/91872.html
Catenary and pantograph measuring

- Triangular photograph measuring system
Sensors on pantograph

图 2 拉出值与硬点冲击超限检测传感器的安装位置

• http://www.doc88.com/p-5973045063865.html
Telecommunication inspections

- Wireless coverage along rail line
- GSM-R digital mobile communication system operation characteristics
- Train wireless dispatching information transmission characteristics
- Train operation control information transmission characteristics
- Wireless interruption along rail line
Telecommunication inspections

- Testing data collection, process and analysis
- Testing accessory system devices
Signal inspection

• Rail electricity return
• Rail track circuit
• Locomotive signal display
• Point information collection
• GSM-R information receiving
Comprehensive analysis

- Data collection from different units
- Share
- Real time
Other Maintenance
• Rail flaw detection
  – Ultrasonic detector
• Rail temperature monitoring

• Long bridge monitoring
  – Loading, column
  – Accelerometer,
Environment safety warning
content

- Wind
- Rain
- Earthquake
- Snow
### 表 10.8 京沪高速铁路强风管制建议

<table>
<thead>
<tr>
<th>风速 (m/s)</th>
<th>不设挡风墙</th>
<th>设置一定标准的挡风墙</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>向曲线外侧</td>
<td>向曲线内侧</td>
</tr>
<tr>
<td>&lt; 25</td>
<td>注意观察</td>
<td>列车限速 200 km/h</td>
</tr>
<tr>
<td>25 ≤ 风速 &lt; 30</td>
<td>列车限速 200 km/h</td>
<td>列车限速 80 km/h</td>
</tr>
<tr>
<td>30 ≤ 风速 &lt; 35</td>
<td>列车限速 80 km/h</td>
<td>停运</td>
</tr>
<tr>
<td>≥ 35</td>
<td>停运</td>
<td>停运</td>
</tr>
</tbody>
</table>
Rain

• Rain based monitoring system
• Three level operation regulation: vigilance, reduce speed and stop
• Sensors: camera, grade measuring, etc.
Earthquake

- Detect earthquake
- Cutoff power
- Stop train
- Strop train in contiguous sections
Snow

- Detect the snow fall, the depth of snow
- Impact the bottom of the train
- Impact the infrastructure next track
Maglev
• Maglev (derived from magnetic levitation) is a transport method that uses magnetic levitation to move vehicles without making contact with the ground
• The power needed for levitation is typically not a large percentage of its overall energy consumption; most goes to overcome drag
• maglev systems have been much more expensive to construct, offsetting lower maintenance costs.
Maglev is in operation in 3 countries

• German:
• Japan:
  – relatively low-speed HSST "Linimo" line in time for the 2005 World Expo
  – a new high speed maglev line, the Chuo Shinkansen is planned to become operational in 2027
• South Korea: Incheon Airport Maglev
• China: Transrapid in Shanghai was primarily based on German technology
Two notable types of maglev technology

• Electromagnetic suspension (EMS)
• Electrodynamic suspension (EDS)
• youtube
  https://www.youtube.com/watch?v=EbORQVt tbeU
Electromagnetic suspension (EMS)

- https://en.wikipedia.org/wiki/Maglev
Electromagnetic suspension (EMS) (cont.)

• Pros:
  – They work at all speeds

• Cons:
  – Magnetic attraction varies inversely with the cube of distance, requiring sophisticated feedback systems to maintain a constant distance from the track
Electrodynamic suspension (EDS)
Electrodynamic suspension (EDS) (cont.)

• Pros:
  – Dynamically stable – changes in distance between the track and the magnets creates strong forces to return the system to its original position.
  – The attractive force varies in the opposite manner, providing the same adjustment effects. No active feedback control is needed.

• Cons:
  – The train must have wheels or some other form of landing gear to support the train
Tracks

• The term "maglev" refers not only to the vehicles, but to the railway system as well, specifically designed for magnetic levitation and propulsion.

• All operational implementations of maglev technology make minimal use of wheeled train technology and are not compatible with conventional rail tracks.

• Because they cannot share existing infrastructure, maglev systems must be designed as standalone systems.
Propulsion

- EMS systems such as HSST/Linimo can provide both levitation and propulsion using an onboard linear motor.

- But EDS systems and some EMS systems such as Transrapid levitate but do not propel. Such systems need some other technology for propulsion. A linear motor (propulsion coils) mounted in the track is one solution. Over long distances coil costs could be prohibitive.
Stability

- Because maglev vehicles essentially fly, stabilization of pitch, roll and yaw is required
Guidance system

- When the vehicle is in the straight ahead position, no current flows, but any moves off-line create flux that generates a field that naturally pushes/pulls it back into line.
Energy use

• Most of the energy is needed to overcome "air drag". Some energy is used for air conditioning, heating, lighting and other miscellany.

• At low speeds the percentage of power used for levitation can be significant, consuming up to 15% more power than a subway or light rail service.

• For short distances the energy used for acceleration might be considerable.
Systems

• Test tracks
• Operational systems
• Maglevs under construction
• Proposed maglev systems
HSR Planning – Case studies
Two Case Studies

• UIUC and UIC (2013) conducted a preliminary feasibility study on the high speed rail in the Midwest area that connects Chicago, St. Louis, and Indianapolis

• The ridership for the California High Speed Rail was forecasted by Cambridge Systematics in 2005
220 Mph High Speed Rail Preliminary Feasibility Study
Travel Time Estimates (in minutes) between Chicago O’Hare International Airport and Lambert-St. Louis International Airport via Champaign

<table>
<thead>
<tr>
<th>Miles</th>
<th>Station</th>
<th>Exp.</th>
<th>Local</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>O'Hare International Airport</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>10</td>
<td></td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>28</td>
<td></td>
<td>28</td>
<td>28</td>
</tr>
<tr>
<td>55</td>
<td></td>
<td>55</td>
<td>65</td>
</tr>
<tr>
<td>84</td>
<td></td>
<td>84</td>
<td>84</td>
</tr>
<tr>
<td>88</td>
<td></td>
<td>88</td>
<td>102</td>
</tr>
<tr>
<td>127</td>
<td></td>
<td>127</td>
<td>141</td>
</tr>
<tr>
<td>140</td>
<td></td>
<td>140</td>
<td>154</td>
</tr>
<tr>
<td>154</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Miles</th>
<th>Station</th>
<th>Local</th>
<th>Exp.</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>O'Hare International Airport</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>16</td>
<td>Chicago Union Station</td>
<td>142</td>
<td>128</td>
</tr>
<tr>
<td>47</td>
<td>University Park</td>
<td>124</td>
<td>112</td>
</tr>
<tr>
<td>72</td>
<td>Kankakee</td>
<td>112</td>
<td>112</td>
</tr>
<tr>
<td>145</td>
<td>Champaign-Urbana</td>
<td>87</td>
<td>83</td>
</tr>
<tr>
<td>193</td>
<td>Decatur</td>
<td>68</td>
<td>68</td>
</tr>
<tr>
<td>233</td>
<td>Springfield</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>330</td>
<td>St. Louis Downtown</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>343</td>
<td>Lambert - St. Louis International Airport</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Southbound**

**Northbound**
Travel Time Estimates (in minutes) between Chicago O’Hare International Airport and Downtown Indianapolis via Champaign

<table>
<thead>
<tr>
<th>Southbound</th>
<th>Northbound</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Exp.</strong></td>
<td><strong>Local</strong></td>
</tr>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>28</td>
<td></td>
</tr>
<tr>
<td>40</td>
<td></td>
</tr>
<tr>
<td>55</td>
<td>65</td>
</tr>
<tr>
<td>84</td>
<td></td>
</tr>
<tr>
<td>117</td>
<td>131</td>
</tr>
<tr>
<td>127</td>
<td>140</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Ar</th>
<th>Dp</th>
</tr>
</thead>
<tbody>
<tr>
<td>140</td>
<td>127</td>
</tr>
<tr>
<td>130</td>
<td>125</td>
</tr>
<tr>
<td>111</td>
<td>108</td>
</tr>
<tr>
<td>98</td>
<td>95</td>
</tr>
<tr>
<td>73</td>
<td>70</td>
</tr>
<tr>
<td>55</td>
<td>52</td>
</tr>
<tr>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
Methodology

• UIUC and UIC (2013) conducted a preliminary feasibility study on the high speed rail in the Midwest area that connects Chicago, St. Louis, and Indianapolis.
• To estimate the ridership, this study developed an inter-regional trip model from which trips between stations in the Midwest high speed rail network can be estimated and forecasted.
• Surveys were conducted to travelers of different modes from which mode share models were developed.
• The station-to-station trips can be assigned to different modes of transportation including high speed rail.
Ridership Study Boundaries
Projected 2035 HSR Ridership – Driving Cost 50 Percent Higher

<table>
<thead>
<tr>
<th>2035 High Driving Cost Annual Riders (000s)</th>
<th>O'Hare</th>
<th>Union Station</th>
<th>University Park</th>
<th>Kankakee</th>
<th>Champaign</th>
<th>Indianapolis metro</th>
<th>Decatur</th>
<th>Springfield</th>
<th>St. Louis metro</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>O'Hare</td>
<td>560</td>
<td>9</td>
<td>11</td>
<td>362</td>
<td>948</td>
<td>239</td>
<td>459</td>
<td>954</td>
<td></td>
<td>3,541</td>
</tr>
<tr>
<td>Union Station</td>
<td>560</td>
<td>239</td>
<td>9</td>
<td>201</td>
<td>463</td>
<td>54</td>
<td>206</td>
<td>501</td>
<td></td>
<td>2,233</td>
</tr>
<tr>
<td>University Park</td>
<td>9</td>
<td>239</td>
<td>23</td>
<td>77</td>
<td>306</td>
<td>57</td>
<td>129</td>
<td>250</td>
<td></td>
<td>1,090</td>
</tr>
<tr>
<td>Kankakee</td>
<td>11</td>
<td>9</td>
<td>23</td>
<td>7</td>
<td>63</td>
<td>3</td>
<td>13</td>
<td>71</td>
<td></td>
<td>199</td>
</tr>
<tr>
<td>Champaign</td>
<td>362</td>
<td>201</td>
<td>77</td>
<td>7</td>
<td>91</td>
<td>5</td>
<td>23</td>
<td>117</td>
<td></td>
<td>882</td>
</tr>
<tr>
<td>Indianapolis metro</td>
<td>948</td>
<td>463</td>
<td>306</td>
<td>63</td>
<td>91</td>
<td>43</td>
<td>178</td>
<td>472</td>
<td></td>
<td>2,565</td>
</tr>
<tr>
<td>Decatur</td>
<td>239</td>
<td>54</td>
<td>57</td>
<td>3</td>
<td>5</td>
<td>43</td>
<td>3</td>
<td>43</td>
<td></td>
<td>447</td>
</tr>
<tr>
<td>Springfield</td>
<td>459</td>
<td>206</td>
<td>129</td>
<td>13</td>
<td>23</td>
<td>178</td>
<td>3</td>
<td>106</td>
<td></td>
<td>1,117</td>
</tr>
<tr>
<td>St. Louis metro</td>
<td>954</td>
<td>501</td>
<td>250</td>
<td>71</td>
<td>117</td>
<td>472</td>
<td>43</td>
<td>106</td>
<td></td>
<td>2,514</td>
</tr>
<tr>
<td>Total</td>
<td>3,541</td>
<td>2,233</td>
<td>1,090</td>
<td>199</td>
<td>882</td>
<td>2,565</td>
<td>447</td>
<td>1,117</td>
<td></td>
<td>14,588</td>
</tr>
</tbody>
</table>
Profit-and-Loss Estimates, Maximum Baseline Revenues

<table>
<thead>
<tr>
<th>YEAR</th>
<th>2025</th>
<th>2026</th>
<th>2027</th>
<th>2028</th>
<th>2029</th>
<th>2030</th>
<th>2031</th>
<th>2032</th>
<th>2033</th>
<th>2034</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Revenues</td>
<td>$536,287</td>
<td>$562,381</td>
<td>$589,825</td>
<td>$618,693</td>
<td>$649,063</td>
<td>$681,019</td>
<td>$714,648</td>
<td>$750,043</td>
<td>$787,301</td>
<td>$826,528</td>
</tr>
<tr>
<td>Total Operating Exp, Excl. Deprn</td>
<td>$162,748</td>
<td>$169,053</td>
<td>$173,842</td>
<td>$183,469</td>
<td>$192,634</td>
<td>$198,308</td>
<td>$209,606</td>
<td>$220,406</td>
<td>$227,198</td>
<td>$240,552</td>
</tr>
<tr>
<td>Net Income Excluding Deprn</td>
<td>$373,539</td>
<td>$393,328</td>
<td>$415,982</td>
<td>$435,223</td>
<td>$456,429</td>
<td>$482,711</td>
<td>$505,042</td>
<td>$529,637</td>
<td>$560,103</td>
<td>$585,975</td>
</tr>
</tbody>
</table>
Demand forecasting

- According to an Independent Peer Review (2011), the ridership for the California High Speed Rail was forecasted by Cambridge Systematics in 2005.
- Because the proposed California HSR is large in scale, models for intra-regional travel and inter-regional travel were developed.
- The model for intra-regional travel were adopted from the existing travel demand models for San Francisco, Los Angeles, and San Diego.
- The model for inter-regional travel consists of models for trip frequency, destination choice, mode choice, and assignment.
- The choice model was developed based on their stated and revealed preference surveys to travelers at airports, rail stations, on-board trains, and phone interview.
Survey

20. Which High Speed Rail station do you think you would use to start your trip?
   - Downtown San Francisco □
   - Millbrae (SFO) □
   - Palo Alto/Redwood City □
   - Downtown San Jose □
   - Gilroy □
   - Downtown Oakland □
   - Oakland Airport □
   - Fremont/Union City □
   - Pleasanton □
   - Sacramento □
   - Stockton □
   - Tracy □
   - Modesto □
   - Merced □
   - Fresno □

21. How do you think you would get to that station?
   - Drive and park □
   - Rental Car □
   - Get dropped off/picked up □
   - Bus □
   - Train □
   - Walk □
   - Other □
   - Taxi/shuttle □

22. About how long do you think it would take you to get to the station?
   __________ minutes
   I have no idea □

23. And about how much do you think it would cost to get to the station? (Please estimate costs including fares, gas, etc., but not including parking or rental car costs)
   $__________
   I have no idea □

24. At which station do you think you would get off the train?
   - LA (Union Station) □
   - Downtown Burbank □
   - Ontario Airport □
   - Riverside □
   - Temecula Valley □
   - Palmdale/Lancaster □
   - Sylmar/S. Fernando Vly □
   - Norwalk □
   - Anaheim □
   - Irvine □
   - E. San Gabriel Vly.. □
   - Escondido □
   - University City □
   - San Diego □
   - Bakersfield □

25. How do you think you would get from that station to your destination?
   - Drive and park □
   - Rental Car □
   - Get dropped off/picked up □
   - Bus □
   - Train □
   - Walk □
   - Other □
   - Taxi/shuttle □

26. About how long do you think it would take you to get from the station to your destination?
   __________ minutes
   I have no idea □

27. And about how much do you think it would cost to get from the station to your destination? (Please estimate costs including fares, gas, etc., but not including parking or rental car costs)
   $__________
   I have no idea □
Survey (cont.)

- Total number of completed retrieval surveys: 1,507.
- Retrievals by origin region: San Diego (158), Los Angeles (243), Bakersfield (144), Tulare/Visalia (98), Fresno (149), Merced (155), SF Bay (283), Modesto/Stockton (144), and Sacramento (133).
Exhibit 7-6. O&M cost ranges, IOS-North first through Full Phase 1 (2010 dollars in millions)
Exhibit 7-8. O&M cost ranges, IOS-South first through Full Phase 1 (2010 dollars in millions)
Exhibit 8-1. Capital costs IOS-North alignment—2010 dollars and year-of-expenditure dollars in millions

Total
$98.5 billion

$19,864
Phase 1 Full

$23,902
Phase 1 Blended

$24,011
Bay to Basin

$24,718
IOS-North

$19,400
2010 Dollars

$10,500
Phase 1 Full

$14,100
Phase 1 Blended

$16,100
Bay to Basin

$5,200
ICS

Year of Expenditure Dollars (millions)

2010 Dollars (millions)