Title: “Comparative Research on the Engineering and Economics of US and International High Speed Rail Standards”

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Abstract: As high speed passenger rail systems develop around the world, standardization of both vehicle technologies and infrastructure could bring about cost efficiencies for system operators. In 2013, the Federal Railroad Administration (FRA) published a report which compared FRA regulations to international High Speed Rail (HSR) standards with regards to operational safety. This paper builds on that work by comparing and contrasting international design standards and guidance with US HSR systems regulations, through comparison of the differing operating characteristics such as maximum train speed, vehicle weights, sizes, aerodynamic characteristics, infrastructure engineering considerations, etc. As part of the comparing and contrasting process, the forces and stresses involved in the interaction between a system’s vehicles and track infrastructure were studied. The paper reviewed information from the United States, the European Union, Japan, and China.

Key Words: High Speed Rail; Design Standards; Train/Track Dynamics; USA; European Union; China; Japan; Vehicles and Equipment; Track Infrastructure.

LIST OF TABLES
TABLE 1: Measures for comparison between system regulations
TABLE 2: Technical details of Chinese high speed rail trainsets
TABLE 3: Minimum radius of horizontal curvature by design speed class
TABLE 4: World-wide comparison of high speed rail construction costs per mile and per km
LIST OF FIGURES
FIGURE 1: HSR nose shapes from left to right – long & slender nose, long nose, duck nose, and sharp nose
FIGURE 2: Comparison of aerodynamic drag according to shape of train nose
FIGURE 3: World-wide HSR construction costs compared in Euros

INTRODUCTION
The idea for this research began when the Transportation Technology Center, inc. published comparative research on the subject of high speed rail (HSR) safety regulations. The purpose of that research was to identify gaps in the Federal Railroad Administration (FRA) “Code of Federal Regulation Title 49 CFR “Transportation”, pertaining to safety. By comparing and contrasting FRA regulations with Japanese, Chinese, and European Union rules, the research pointed to areas involving safety undefined by US Federal regulations, so that the deficiencies could be addressed. (1) That research sparked the insight that if comparative research of US and international high speed rail standards and regulations could identify where improvements in high speed rail safety standards could be made, perhaps comparative research of US and international high speed rail standards and regulations and the vehicles and infrastructure based upon them, could promote standardization of HSR infrastructure and vehicles, so that cost savings could be realized across the various US and international systems.

Objectives
The objectives of this research are to identify similarities and differences between US and international HSR standards and regulations, and also to identify any trends in HSR standards.

Approach
The approach of this research is to compare and contrast the US and international HSR standards and guidance as regards to eight measures significant to HSR system monetary costs. Where US and international HSR standards did not define inputs into the eight measures directly, an indirect manner of using data from HSR system components in operation was employed.

Scope
This research considered HSR operations only to be those with an operating speed of 125 mph or higher, or the closest international system’s equivalent speed rating. As the FRA regulations in Code of Federal Regulations Title 49, Subtitle B, Chapter II do not include track design requirements, such as weight of rail, types of ties, and fastening system, etc., the AMTRAK standards, APTA standards, AAR standards, CAHSR tech memos, and Chapter 17 of the AREMA Manual were studied for relevant topics not covered by the FRA’s regulations. These were then compared to the Japanese, European, and Chinese standards and regulations.

Summary of Substantial Findings
For high speed railway infrastructure many similarities exist across the various nations’ systems studied. Infrastructure guidelines and policies, therefore, do not present barriers to the creation of more uniform railway equipment and cost savings in procurement. Rather, the main source of differences in railway equipment and standards arises from the manner in which high speed rail system’s authorities view safety for shared passenger and freight operating environments. In the United States, although the Federal Railroad Administration defines a procedure for obtaining a non-compliant passenger equipment waiver in 49CFR Part 238.7, the regulations in 49CFR Part 238, Subpart C (Specific Requirements for Tier I Passenger Equipment) and Subpart E (Specific Requirements for Tier II Passenger Equipment) provide for a much higher level of crashworthiness and vehicle structural strength, than the European or Japanese Shinkansen systems. The tradeoff of lighter trains having lower structural strength in the other HSR systems was noted in the research. The maximum axle load of the US Acela equipment is approximately 23% heavier than the maximum allowed train equipment by TSI, and is roughly 44% heavier than the Model E7 Shinkansen train.

An additional, unexpected trend was noticed – a trend towards more qualitative and less quantitative regulations. The current version of the Technical Regulatory Standards on Japanese Railways and its immediate predecessor were studied. Many technical standards that had previously defined engineering limits numerically, now in the current version were replaced with qualitative statements referring to designing according to good engineering principles. The latest three versions of the UIC (European Union) Technical Standards for Interoperability (TSI’s) were studied. There too, the progression from defined numerical limits to conditional values for various other systems, such as
infrastructure, interactions, and further to qualitative statements such as used by the current Japanese regulatory standards, were noted.

**COMPARISON OF VEHICLES AND INFRASTRUCTURE**

**General Comments**

Eight measures were selected for comparing and contrasting the various high speed rail systems guidelines and regulations, as shown in Table 1.

**Table 1: Measures for comparison between system regulations**

<table>
<thead>
<tr>
<th>No.</th>
<th>HSR Item of Study</th>
<th>Measure Applicable</th>
<th>Result</th>
<th>Data Needed for Comparison</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Vertical (Bending) Stress</td>
<td>Weight</td>
<td>Rail Head Wear, Ballast Wear, Tie Wear</td>
<td>Maximum Axle Weight</td>
</tr>
<tr>
<td>2</td>
<td>Horizontal (Lateral) Forces</td>
<td>Centrifugal Force</td>
<td>Rail Gauge Face Wear</td>
<td>Trainset Gross Vehicular Weight, Max Speed Allowed,</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Maximum Degree of Horizontal Curvature</td>
</tr>
<tr>
<td>3</td>
<td>Shearing Stress</td>
<td>Wheel Load</td>
<td>Rail Head Wear, Tie Wear</td>
<td>Max Wheel (Vertical) Load, Wheel Radius</td>
</tr>
<tr>
<td>4</td>
<td>Acceleration and Braking Forces</td>
<td>Maximum Track Gradient</td>
<td>Train Maintenance</td>
<td>Maximum Track Gradient</td>
</tr>
<tr>
<td>5</td>
<td>Train Aerodynamic Shape</td>
<td>Air Resistance</td>
<td>High Energy Usage</td>
<td>Trainset Aerodynamic Drag</td>
</tr>
<tr>
<td>6</td>
<td>Train Nose Aerodynamic Shape</td>
<td>Air Resistance</td>
<td>High Energy Usage</td>
<td>Train Nose Shape</td>
</tr>
<tr>
<td>7</td>
<td>Train Crew Size</td>
<td>Crew Size Needed</td>
<td>Inefficient Labor Costs</td>
<td>Legislated Minimum Crew Size</td>
</tr>
<tr>
<td>8</td>
<td>Construction Costs</td>
<td>Generalized Construction Cost</td>
<td>Net Result of HSR Standards</td>
<td>Actual HSR Construction Costs for each of the HSR Systems</td>
</tr>
</tbody>
</table>

For each of the eight measures, where relevant government standards existed, they were examined, and then compared and contrasted. When government standards did not exist, characteristics of system vehicles in use were compared and contrasted. The fact that US regulations did not exist that are pertinent to all of the 8 measures used for comparison in this research should not be surprising. One of the main purposes of the Administration is to promulgate and enforce rail safety regulations. Therefore the regulations promulgated by the Federal Railroad Administration and codified in 49 CFR, Subtitle, Chapter II, do not mandate specific technical details of high speed railway equipment and structures, but rather provide numerical limits as needed to promote safe railway operations. This being said, the Part 213, Track Safety Standards, and Part 238, Passenger Car Safety Standards are important for high speed passenger rail vehicle design. (2)

The European Union has several different sources of governing railway standards and specifications. The Technical Specifications for Interoperability (TSI’s) specify mandatory requirements for all railways that are a part of the high speed rail system in Europe. Their purpose is “to ensure interoperability on the European high-speed rail network, thereby helping to open up transport services and equipment contracts and enhancing the competitiveness of the railway sector overall”. (3) In addition, there are the European Norms (EN), which are voluntary suggested standards, that detail technical solutions to HSR railway issues. After that, there is the International Union of Railways (UIC) Code, which is made up of a series of “leaflets”, that are railway professionals’ expert recommendations, but do not have to be followed. (1)

In Japan, all railways, Shinkansen (HSR) and conventional lines, are administered by the Ministry of Land, Infrastructure, Transport, and Tourism. (4) A “Shinkansen” is simply defined as “an artery railway that is capable of operating at the speed of 200 km/h (125 mph) or more in its predominating section.” (5) Direction for Japanese HSR lines is stated in three different sources – mandatory laws,
technical standards, and guidelines. Prior to a 2002 revision of the Nationwide Shinkansen Railway Development Act, laws and ordinances described standards in great detail, since the revision, laws and ordinances only describe principles of the rules. Currently, railways have to set their own criteria (Implementation Standards), based on the mandatory laws, technical standards, and guidelines. (6)

The development of Chinese high speed rail provisions over the past two decades has involved a combination of benchmarking practices from other HSR systems and incremental advancement. Chinese high speed railways had defined two different classes of high speed rail – one for 200-250 km/hour, shared freight and passenger traffic, and one for 300-350 km/hr, exclusive high-speed passenger service under the regulations “Temporary Provision for Passenger Railway Line of 200-250 km/hour” and “Temporary Provision for Passenger Railway Line of 300-350 km/hour”, respectively. The “Code for Design of High Speed Railway”, was released in 2009, and was largely based on the European UIC code. The document contains 22 chapters, including Alignment, Bridges and Culverts, Tunnels, Tracks, Stations, Traction and Power Supply, etc. (7)

Wear in Track Measures

“Wear in Track Measures” are those which contribute to the degradation of the condition of the track infrastructure. Considerable resources are allocated by railroads annually to maintain track in a state that allows the passage of high speed trains. Specific track components which need replacement are rail, crossties, and ballast. A variety of stresses cause wear to track components, such as vertical stress, lateral stresses, and shearing stress.

For a shared freight environment, rail in a track that experiences the passage of many heavy trains, such as a unit coal or iron ore train, each day, rail life may be used up in only a few years. In a track used exclusively for passenger trains, rails may not need replacement for decades. In either case, vertical bending stress, lateral stresses, shearing stress, and contact stress cause wear to rails.

Crossties in high speed rail environments are usually composed of concrete. Rail seat deterioration, the degradation of the concrete material beneath the rail, has been identified through surveys of North American Class I railroads as the most critical engineering challenge associated with concrete crossties. Likewise, shoulder/fastener wear or fatigue was identified through the same survey as the second most critical engineering challenge for concrete crossties. (8) Both of these issues are the result of vertical and lateral (horizontal) stresses.

Ballast degradation occurs through crushing and abrasion. Under the repetitively applied loadings of passing trains, ballast particles rub together. Softer ballast materials, such as some varieties of limestone, will abrade more quickly than harder materials, like granite. In both crushing and abrasion, the vertical stress and lateral stress impact the lifespan of the ballast.

Vertical Bending Stress

Vertical bending stress occurs as a train’s wheels transfer loads to the rail. The maximum bending stress in a rail is calculated with the following formula:

\[
S = \frac{M_0 c}{I}
\]

where,

- \(S\) = bending stress in pounds per square inch,
- \(M_0\) = maximum bending moment,
- \(I\) = moment of inertia of the rail, and
- \(c\) = distance in inches from the base of the rail to its neutral axis.

For comparison sake, if the same rail is assumed amongst all of the HSR systems, then the maximum bending moment is what differentiates. The formula for the maximum bending moment is,

\[
M_0 = P \sqrt{\frac{EI}{64u}}
\]

where,

- \(P\) = wheel load in Lbs,
- \(E\) = is the modulus of elasticity of rail steel,
- \(I\) = modulus of inertia of the rail steel, and
- \(u\) = modulus of elasticity of track support.
The FRA guidance regarding track stiffness in Part 213.359(a) states, “Track shall have a sufficient vertical strength to withstand the maximum vehicle loads generated at maximum permissible train speeds, cant deficiencies and surface defects”. Since quantitative limits for the modulus of elasticity of the rail steel and the modulus of elasticity of track support, is not defined, again, the rail and track typical section were assumed to be similar across HSR systems, and what differentiates is “IP”, the wheel load. However, for comparison in this research, the more common way of referencing weight according to axle load was used.

US Intuitively, one may expect to find guidance regarding system components that relate to vertical stress within the track system in the FRA’s CFR 49 Part 213 (Track Safety Standards), such as maximum allowable weight of trains. However, that is not found within Part 213. Nor are train weight guidelines found in Part 238, Passenger Equipment Safety Standards. While the FRA’s Passenger Rail Division does have responsibility for providing technical expertise and oversight of Passenger Rail Safety Programs to ensure safe operations, the Tier II (which cover high speed trains operating over 125 mph, but not exceeding 150 mph) and the Tier III (which cover high speed trains operating above 150 mph and up to 220 mph, and are due to be published later this year) Equipment Safety Standards, do not specifically address weight of trainsets or vehicle structural design in numerical terms. The responsibility for determining the maximum allowable weight of a rail vehicle allowed to travel over a section of track is left to each railroad, and they often base it on the state and quality of structures on the particular property. However, the most significant part of the Tier III standards is that Tier III vehicles will have to meet the crashworthy standards of the Tier I standards, which require trainsets to be interoperable with freight trains.

The issue of train weights in the passenger rail environment is a balance between a desire to run lighter-weight trains that use less energy, and a need for structural strength and crash survivability entailing more and heavier sections of materials. Where guidance is found pertaining to train weights is not in the FRA regulations, but in the American Public Transportation Association’s (APTA) Passenger Rail Equipment Safety Standards (PRESS), particularly in APTA PR-CS-S-034-99, Rev. 2 “Standard for the Design and Construction of Passenger Railroad Rolling Stock”. However, even in the APTA standards train weights are not defined per se, but are an indirect function of the materials and design of the car structure required.

Therefore, in order to find train gross vehicular weights for comparing different high speed rail systems characteristics, one needs to take an indirect approach that considers the GVW’s of actual ACELA trainsets in use by AMTRAK in the Northeast Corridor service. The ACELA trainset weighs a total of 1,171,000 lbs. over its eight total cars (6 passenger cars and 2 power cars – one at each end). The heaviest railcar in an Acela train is the “Power Car”, which weighs 200,244 lbs (90,829 Kg), and has an axle load of 25.03 tons (22.71 tonnes). (9)

European Union The European TSI 2002/735/EC “Rolling Stock Subsystem” in 4.1.2 had defined the maximum axle load for traffic under 250 km/h = 18 tonnes/axle, and the maximum of 17 tonnes/axle where traffic with a speed limit over 250 km/h. (10) This was superseded by TSI 2008/232/EC “Rolling Stock” 4.2.3.2 which expanded upon the previous requirements with a table that listed different limits for Class 1 and Class 2 rolling stock, with Class 1 rolling stock having a maximum speed equal to or greater than 250 km/h, and Class 2 rolling stock having a maximum speed of at least 190 km/h but less than 250 km/h. For Class 1 rolling stock the limit follows the same 18 tonnes / 17 tonnes formula for service speed up to 250 km/h and service speed over 250 km/h. However, the TSI notes that “if the maximum speed of this rolling stock is higher than 351 km/h, this TSI will apply, but additional specifications are necessary; these additional specifications are not detailed in this TSI and are an open point: national rules apply in such a case”. The most recent revision TSI 2013/1302/EC supersedes TSI 2008/232/EC, and in 4.2.3.2.1 addresses axle loads. The new rule does not give specific maximum axle loads, rather, it states, “The axle load is a performance parameter of the infrastructure specified in clause 4.2.1 of the INF TSI and depends on the traffic code of the line. It has to be considered in combination with the axle spacing, with the train length, and with the maximum allowed speed for the unit on the considered line.” Hence there is no longer a single simple axle weight limit, but the characteristics of the track needs to be considered as well. Looking to the TSI 2013/1299/EC “Infrastructure” 4.2.1 “Categories of Line”, for the track type “P1”, which allows speeds of between 250 and 350 km/h, the maximum allowable axle load is 17.0 tonnes.
**Shinkansen**  In Section 2 “Weight of Rolling Stock” of Chapter 8 “Rolling Stock” of the Technical Regulatory Standards on Japanese Railways, the current Ministerial Ordinance simply states, “Rolling stock shall not impose a load that exceeds the capacity of track and structure”, but prior to the March 2002 revision of “Technical Regulatory Standards on Japanese Railways” had been defined as 17 metric tonnes, and therefore provides no clarity for this research, and train rolling stock weights need to be determined from the actual HSR trains in service. (11) As of the year 2011, sixteen (16) different HSR trainsets were in service in Japan. Considering three different trainsets in use, the “E2-1000” has a maximum axle load of 13.2 metric tonnes (13.0 tons), the “E3” has a maximum axle load of 12.2 metric tonnes (12.0 tons), and the “E4” has a maximum axle load of 16 metric tonnes (15.7 tons). (12) The fastest of all of the Shinkansen is the N700 model, which has an operating speed of 330 km/h, and has the lightest maximum axle weight of any high speed train at 11.3 tonnes. (13) All models however, have a maximum axle load which is less than the previously defined maximum of 17 metric tonnes.

**Chinese HSR**  The “Code for Design of High Speed Railway” does not define a maximum axle weight. In China, four primary models of high speed train have been developed and used on railroad lines of differing design speeds. The design speeds of these trainsets vary between 200 km/h to 380 km/h. Their consists vary from 6 cars to 8 cars. The maximum axle weight for any of the Chinese high speed trainsets is 17.0 tonnes. The details of the Chinese HSR trainsets are provided in Table 2.

<table>
<thead>
<tr>
<th>Table 2: Technical details of Chinese high speed rail trainsets</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Consists</strong></td>
</tr>
<tr>
<td>Seating capacity</td>
</tr>
<tr>
<td>Weight (tonnes)</td>
</tr>
<tr>
<td>Length (m)</td>
</tr>
<tr>
<td>Max operating speed (km/h)</td>
</tr>
<tr>
<td>Max test speed (km/h)</td>
</tr>
<tr>
<td>Axle load (tonnes)</td>
</tr>
</tbody>
</table>

**Horizontal Forces**

When a train moves through a curved section of track, lateral forces are imparted on the rail by the train. The total lateral forces can be defined as the summation of the lateral force caused by the flanging of the rail wheel against the rail, the lateral force caused by non-compensated centrifugal force (or simply “centrifugal force”), force due to crosswinds, and a dynamic lateral force component. (15) For our research, for simplicity’s sake, we will consider only centrifugal force. Centrifugal force is transmitted between the train wheel and the outside rail in curves. The formula for centrifugal force is the following:

\[ F = \frac{(WV^2)}{(gr)} \]

where,

- \( F \) = centrifugal force
- \( W \) = weight
- \( V \) = velocity in ft/sec
- \( g \) = gravity (32.2 ft/sec²)
- \( r \) = radius of curvature in feet
As before, the maximum axle weights used for comparison were those of the actual Acela Express trainsets, which were stated earlier as 25.03 tons (22.7 metric tonnes). The minimum radius of curvature is not defined in the FRA standards directly as the FRA focuses on track safety and maintenance tolerances, through application of the formula for maximum track curvature, as it relates to speed limits and superelevation, found in Part 213.329 “Curves; elevation and speed limitations”, considering that this regulation defines the maximum actual superelevation to be 7 inches. (It should be noted, though, that FRA standards are about safety, and railways generally impose stricter standards to allow for track wear before proper maintenance can be performed. The formula is the following:

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

where,

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

In addition to the formula, in Part 213.307 “Classes of Track: Operating Speed Limits” the maximum speed limit for the highest class of track, Class 9, is stated as 220 mph. Looking for guidance from AREMA, in Chapter 17, High Speed Rail Systems, it states, “Degree of curvature shall be limited to provide civil speeds that are consistent with continuous high-speed operation. For conventional high-speed rail trains, curves of one degree or less are desirable. Desirable curvature for high-speed rail systems that use equipment with tilt systems will have higher maximum desirable curvature based on criteria for lateral acceleration, the amount of effective tilt, and the train’s suspension characteristics. Generally, desirable curves for high-speed tilt trains will be 1 degree-30’ or less. (16)

For high speed passenger trains, there is also guidance for lateral forces as related to vertical forces, or L/V ratio. FRA Part 213.345(a) “Vehicle/Track System Qualification” states, “All vehicle types intended to operate at track Class 6 speeds or above, or at any curving speed producing more than 5 inches of cant deficiency, shall be qualified for operation for their intended track classes in accordance with this subpart. A qualification program shall be used to demonstrate that the vehicle/track system will not exceed the wheel/rail force safety limits and the carbody and truck acceleration criteria specified in §213.333”.

European Union From before, the maximum allowable axle weight allowed by the UIC is 17.0 metric tonnes or 18.7 tons. The minimum allowable curve radius is defined in TSI 2002/732/EC “Infrastructure Subsystem” as 150 m. This was superseded by TSI 2008/217/EC “Infrastructure” which in 4.2.6 states, “when designing the lines for high-speed operation, the minimum radius of curvature selected shall be such that, for the cant set for the curve under consideration the cant deficiency does not exceed, when running at the maximum speed for which the line is planned, the values indicated in 4.2.8 of the present TSI”. So as with rolling stock, the revised TSI replaced this previously defined simple value with a performance-based criterion. The current revision, TSI 2013/1299/EC 4.2.3.4 states, “the minimum horizontal design curve radius for new lines shall not be less than 150 m.

The maximum operating speed is defined in TSI 2013/1302/EC “Rolling Stock” in which 2.3.3 states, “Considering the integrated railway system composed of several subsystems (in particular fixed installations; see Section 2.1), the maximum design speed of rolling stock is deemed to be lower or equal to 350 km/h”.

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**Shinkansen** From before the maximum axle weight allowed is 17 tonnes. The maximum speed allowed on Shinkansen routes is mentioned in the “Technical Regulatory Standards on Japanese Railways”, Chapter 10 “Train Operation”, Section 2 “Train Operation”, Article 2. However, all that this section actually states, is given in Article 103, and it states that “Train shall be operated at the safe speed, depending on the track and contact line conditions, vehicle performance, operational method, signal condition, train protection method”. (11) However, the code does state that the maximum speed shall be stipulated in the implementation standard.” With authority to set the speed limits devolved to each of the 6 Japanese passenger railway companies, one needs to look at the individual high speed rail lines. Currently the maximum operating speed in Japan is 186 mph (300 km/h) on the Tokaido, Sanyo, and Tohoku lines. Similarly, looking to the individual lines, the maximum cant (superelevation) of the track is 200 mm (7-7/8 in). The minimum horizontal curve radius for a line with a maximum speed of 300 km/h is 4,000m. (12)

**Chinese HSR** From before, the maximum axle weight is 17.0 tonnes. Chinese standards list minimum radii for each of several speed categories, as shown in Table 3. It can be seen that maximum horizontal curves are also specified for each design speed category.

### Table 3: Minimum radius of horizontal curvature by design speed class

<table>
<thead>
<tr>
<th>Design Speed</th>
<th>Ballast</th>
<th>Ballastless</th>
<th>Maximum curve</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ballast</td>
<td>Normal: 8,000-10,000; Min: 7,000; special: 6,000</td>
<td>Normal: 8,000-10,000; Min: 7,000; special: 5,500</td>
<td>12,000</td>
</tr>
<tr>
<td>Normal</td>
<td>350/250</td>
<td>300/200</td>
<td>250/200</td>
</tr>
<tr>
<td>Min</td>
<td>300/200</td>
<td>250/200</td>
<td>250/200</td>
</tr>
<tr>
<td>Special</td>
<td>250/200</td>
<td>250/200</td>
<td>250/200</td>
</tr>
<tr>
<td>Ballastless</td>
<td>Normal: 6,000-8,000; Min: 5,000; special: 4,500</td>
<td>Normal: 6,000-8,000; Min: 5,000; special: 4,000</td>
<td>12,000</td>
</tr>
<tr>
<td>Normal</td>
<td>300/200</td>
<td>250/200</td>
<td>250/200</td>
</tr>
<tr>
<td>Min</td>
<td>250/200</td>
<td>250/200</td>
<td>250/200</td>
</tr>
<tr>
<td>Special</td>
<td>250/200</td>
<td>250/200</td>
<td>250/200</td>
</tr>
<tr>
<td>Maximum curve</td>
<td>12,000</td>
<td>12,000</td>
<td>12,000</td>
</tr>
<tr>
<td>Ballast</td>
<td>Normal: 6,000-8,000; Min: 5,000; special: 4,500</td>
<td>Normal: 6,000-8,000; Min: 5,000; special: 4,000</td>
<td>12,000</td>
</tr>
<tr>
<td>Normal</td>
<td>300/200</td>
<td>250/200</td>
<td>250/200</td>
</tr>
<tr>
<td>Min</td>
<td>250/200</td>
<td>250/200</td>
<td>250/200</td>
</tr>
<tr>
<td>Special</td>
<td>250/200</td>
<td>250/200</td>
<td>250/200</td>
</tr>
<tr>
<td>Maximum curve</td>
<td>12,000</td>
<td>12,000</td>
<td>12,000</td>
</tr>
<tr>
<td>Ballast</td>
<td>Normal: 6,000-8,000; Min: 5,000; special: 4,500</td>
<td>Normal: 6,000-8,000; Min: 5,000; special: 4,000</td>
<td>12,000</td>
</tr>
<tr>
<td>Normal</td>
<td>300/200</td>
<td>250/200</td>
<td>250/200</td>
</tr>
<tr>
<td>Min</td>
<td>250/200</td>
<td>250/200</td>
<td>250/200</td>
</tr>
<tr>
<td>Special</td>
<td>250/200</td>
<td>250/200</td>
<td>250/200</td>
</tr>
<tr>
<td>Maximum curve</td>
<td>12,000</td>
<td>12,000</td>
<td>12,000</td>
</tr>
</tbody>
</table>

The maximum speed allowed is 350 km/h (217 mph), and at that speed the minimum radius of curvature for horizontal curves allowed is 7,000 m. Also noteworthy is that no compound curves are allowed on main line track. (14)

**Shearing Stress**

The concentration of loading at the contact point between a train wheel and the railhead creates a shear stress in the rail. This shear stress can lead to “shelling”, a railhead defect, and therefore is a concern for rail lifespan. Considering an even distribution of the wheel load over the wheel/rail contact area, the maximum shear stress in the rail would be:

\[
\tau_{\text{max}} = 412 \frac{Q}{r} \sqrt{r}
\]

where,

- \( \tau_{\text{max}} \) = maximum shear stress (in N/mm²)
- \( Q \) = wheel load (in kN)
- \( r \) = wheel radius (in mm)

(15)

**US** The wheel diameters are not defined in the FRA regulations, but are covered in the AAR’s “Manual of Standards and Recommended Practices, Specification M-107/M-208 - Wheels and Axles”. In that specification, three classes of rail wheel material composition are designated for high speed passenger rail use – Class L, Class A, and Class B. Additionally in the AAR’s Manual, the dimensions and tolerances are given for standard wheels. However, no specific diameters are defined for high speed rail trains. Therefore, the wheel diameters taken from AMTRAK Acela trains were used for comparison. Acela power cars have wheels of 40 inches (1.02 m) diameter. (17)

Wheel loads were derived from the car weights of the Acela trains. Acela cars use two (2) each two-axle trucks. For the heavier power cars, the wheel loads are the following:
Q = Wheel load = rail car weight / 8 wheels
Q = (power car wheel load) = (90,829 kg / 9.81 m/s²) / 8 wheels = (9.259 kN) / 8 wheels
Q = 1.157 kN/wheel

τ_max = \frac{1.157 kN}{510 \text{ mm}} = 19.62 \text{ N/mm}^2

European Union  TSI 1302/2013/EC “Rolling Stock” 5.3.4. states, “A wheel shall be designed and assessed for an area of use defined by: (1) Geometrical characteristics: nominal tread diameter. (2) Mechanical characteristics: maximum vertical static force and maximum speed. (3) Thermo-mechanical characteristics: maximum braking energy. (4) A wheel shall comply with the requirements on geometrical, mechanical and thermo mechanical characteristics defined in clause 4.2.3.5.2.2; these requirements shall be assessed at IC level”. However, it does not defines the wheel radius to use for high speed trains. Therefore the radius used for comparison was the actual radius of a TGV train wheel 460 mm (18 in).

Q = (max axle load / 2) = (8,500 kg / 9.81 m/s²) = 0.8665 kN/wheel

τ_max = \frac{0.8665 kN}{412 \text{ mm}} = 19.62 \text{ N/mm}^2

Shinkansen In the Technical Regulatory Standards on Japanese Railways, Chapter 8 “Rolling Stock”, Section 3 “Running Gear of Rolling Stock” the wheel radius for Shinkansen trains is defined to be “730 mm or more”.

Q = (max axle load / 2) = (8,500 kg / 9.81 m/s²) = 0.8665 kN/wheel

τ_max = \frac{0.8665 kN}{460 \text{ mm}} = 17.88 \text{ N/mm}^2

Chinese HSR From before, the maximum axle weight is defined as 17.0 tonnes. The wheel radius for Chinese HSR trains is defined as 445 mm in the China Code.

Q = (max axle load / 2) = (8,500 kg / 9.81 m/s²) = 0.8665 kN/wheel

τ_max = \frac{0.8665 kN}{365 \text{ mm}} = 20.07 \text{ N/mm}^2

Wear in Vehicles Measure

“Wear in Vehicles Measures” are those which contribute to the degradation of the condition of the rolling stock (trainsets). Earlier, the effects of wheel/rail interaction on the wearing of rail was examined. Although the contact produces stresses that result wear of the train wheels, it was considered to be redundant, and therefore not covered in again in this section.

High speed train mechanical systems experience wear through operation, and certain geographic conditions, such as steep gradients, cause the trains to work harder and wear more quickly than routes over level terrain. Therefore the maximum track gradients allowed were also compared.

Acceleration and Braking Forces (Gradients)

Unit grade resistance has been defined as 20 Lbs/ton per percent of grade. While considerably lighter than freight trains, high speed rail systems still limit the maximum gradient of track to minimize vehicle wear, and to avoid time delays that may occur due to speed loss in sustained steep grade areas. Vertical geometry and gradients are influenced by the type of corridor, whether dedicated HSR track or shared passenger and freight.

US The FRA regulations do not address the limits for maximum allowable track gradient. The AREMA Manual in Chapter 17 “High Speed Rail Systems”, Part 3.5.8.3 “Gradients”, suggests the following recommendations for maximum gradient of HSR track:

- 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

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**European Union** TSI 2014/1299/CE “Infrastructure” 4.2.3.3 states, “Gradients as steep as 35 mm/m are allowed for main tracks on new P1 lines dedicated to passenger traffic at the design phase provided the following ‘envelope’ requirements are observed: (a) the slope of the moving average profile over 10 km is less than or equal to 25 mm/m. (b) the maximum length of continuous 35 mm/m gradient does not exceed 6 km”.

Shinkansen The maximum track gradient is defined by the “Approved Model Specifications III-7, related to Article 18 (Gradient), which states, “(1) The maximum gradient in travelling areas for trains shall be as follows:

(A) 25/1000 (2.5%)  
(B) Where the above standard cannot be applied for topographic or other reasons, it may be 35/1000 (3.5%), taking the performance of the motive device, power transmission device, running gear and braking device into consideration.

(2) The maximum gradient in stopping areas for trains shall be 3/1000.”

**Chinese HSR** In China, the gradient on mainline running track is limited to 2.0%. In especially challenging terrain, gradients can be designed of up to 3.0% with Ministry of Railways permission. (14)

**Other Operating Factors**

**Train Aerodynamic Shape**

In high speed trains, up to 60% of the tractive effort is lost due to aerodynamic drag and friction. (21) More aerodynamic trains expend less energy to operate at the same speeds as less aerodynamic trains. In open air (not tunnels), train aerodynamic drag is a function of the shape of the fore and aft ends of the train, and the train length. The formula for aerodynamic drag is the following:

\[
D = \frac{1}{2} \rho A' V^2 \left( C_{dp} + \frac{\lambda'}{d'} l \right)
\]

where,  
\(D\) = drag  
\(\rho\) = density of the air  
\(V\) = train speed  
\(A'\) = cross-sectional area of the train  
\(C_{dp}\) = the coefficient of the pressure drag caused by the fore and aft bodies of the train  
\(d'\) = the hydraulic diameter of the train  
\(l\) = the train length  
\(\lambda'\) = the hydraulic friction coefficient caused by the couplers, pantographs, etc.

Through wind tunnel experiments the aerodynamic drag values for a TGV PSE train simulated to be travelling at 260 km/h was determined to be 3,873 N. (22) While direct values of aerodynamic drag were not obtained for the other HSR systems’ trains, a comparison of trainset cross-sectional area and length, reveals similarities in those measures that indicate that aerodynamic drag values for the other systems’ trains should be roughly similar:

- French TGV PSE, cross-sectional area of 11.40 m² (2.814 m x 4.050 m); length = 200 m
- German ICE-3, cross-sectional area of 11.75 m² (2.950 m x 3.890 m); length = 200 m
- Japanese N700, cross-sectional area of 12.10 m² (3.360 m x 3.600 m); length = 200 m
- China CRH5, cross-sectional area of 13.664 m² (3.200 m x 4.270 m); length = 211.5 m
- USA Acela, cross-sectional area of 13.71 m² (3.175 m x 4.318 m); length = 203 m  

(17)

**Train Nose Aerodynamic Shape**

A second basis for comparison was nose shape of the high speed rail train. A parametric study was carried out in 2002 on the influence of shape parameters of the head of high speed trains on the aerodynamic loads and moments of the leading vehicle. Extensive tests were therefore performed in a wind tunnel on 13 configurations of train models. The results indicated that drag can be significantly reduced with long and slender noses as well as low-rise car bodies. A recent study from 2013 also concluded that long, slender train noses produce the least aerodynamic drag for HSR trains. (23) For our purposes, then, the shape of the trainset nose was considered for comparison as a second aerodynamic
category. For this research four nose shapes were considered – “Long Nose”, “Long & Slender Nose”, “Duck Nose”, and “Sharp Nose”. While the study used hard geometric inputs for nose type definitions, the procedure used for assigning vehicles to the study’s categories was subjective, based on visual classification. However, it was determined that even the subjective method had merits for relative comparison, and the results follow.

![Figure 1: HSR nose shapes from left to right – long & slender nose, long nose, duck nose, and sharp nose (24)](image)

**US** The FRA regulations do not provide guidance regarding train aerodynamic shape. As relates to train noses, the FRA only defines structural strength and crashworthiness minimums in 49 CFR Part 238 “Passenger Equipment”. Therefore for comparison, the Acela Trainsets characteristics will be considered. From visual inspection, the Acela has a “short” nose shape.

**European Union** The shape of the nose of French HSR trains has evolved over time, and therefore several shapes are still in use, varying by route, but a newer model, the TGV Duplex has a “short-and-wide” nose. Likewise, the shape of a nose of German ICE trains has evolved with each new model, with successive train nose becoming narrower, but they are still “short”. The shape of a Spanish AVE 102 is “duckbill-shaped”. All of these trains systems are within the European Union, and show the latitude provided in train car design shape afford by the standards.

**Shinkansen** Government regulations do not define the shape of Shinkansen trains. A variety of nose shapes have been used by Shinkansen trains. The E5 series has a “Long” shape. The N700 has a “wide” nose. The H5 series has a “Long and Narrow” shape. As with the European standards, Shinkansen nose shapes are not limited by Japanese regulations.

**Chinese HSR** The Chinese Railway code does not limit the nose shape of HSR trains. The CHR1 has a “sharp nose”, while the CRH2 has a “long nose”, the CRH3 has a “long nose”, and the CRH5 has a “long and narrow” shape. As with the European and Japanese standards much variation in train noses is allowed.

**Nose Shape Results** The graph in Figure 2 compares aerodynamic drag of train noses according to shape.
Train Crew Size

Train crew size is a basis for comparison of labor costs to operate each high speed rail train. Therefore, trains which can operate with a smaller crew are more economical.

US While in CFR 49 Part 228 the FRA regulates hours of service for train crews, the FRA does not at this time mandate a minimum train crew size. However, on April 09, 2013, the FRA announced its intention to issue a proposed rule requiring two-person train crews on crude oil trains and establishing minimum crew size standards for most main line freight and passenger rail operations. However, at this time it is the decision of the passenger service operator (AMTRAK) to determine the train crew size.

European Union The UIC does not specify a minimum crew size.

Shinkansen While Chapter 2 “Staff”, Ministerial Ordinance Article 11 details “Duties of a Crew to Operate a Motive Power Unit”, it does not specify a minimum crew size.

Chinese HSR There is no government regulation stating a minimum crew size for Chinese HSR trains.

Infrastructure Construction Costs Comparison

Existing UIC databases summarize the average cost per kilometer of building high-speed rail systems based on 2005 prices in millions of euros and include infrastructure and superstructure costs but not planning or land costs. The average value of the projects is €17.5 million, but a comparison across countries is given in Figure 3. Based on the 2005 average of €1 = $1.26 conversion rate, the cost per mile is $22 million. Currently UIC lists the average cost of constructing 1 km of new high speed line in Europe between €12 – 30 M. (26)
Historically France and Spain have had lower building costs than Italy and Germany. This is attributed to similar geography, the existence of less populated areas outside major urban areas, and design criteria and construction procedures. For example, the cost of construction in France is lower than Germany because France permits steeper grades of up to 3.5%, reducing the number of viaducts and tunnels required. In Table 4, a comparison is shown of the cost of high speed rail construction on a “per mile” and “per km” basis, and includes recently bid sections of the California High Speed rail project.
Table 4: World-wide comparison of high speed rail construction costs per mile and per km

<table>
<thead>
<tr>
<th>Country</th>
<th>City Pairs</th>
<th>Cost/Mile</th>
<th>Cost/km</th>
</tr>
</thead>
<tbody>
<tr>
<td>China</td>
<td>Shijiazhuang - Zhengzhou</td>
<td>$31.9M</td>
<td>CNY123M</td>
</tr>
<tr>
<td>China</td>
<td>Guiyang - Guangzhou</td>
<td>$28.5M</td>
<td>CNY110M</td>
</tr>
<tr>
<td>China</td>
<td>Chongqing - Chengdu</td>
<td>$28.4M</td>
<td>CNY110M</td>
</tr>
<tr>
<td>China</td>
<td>Nanchong - Guangzhou</td>
<td>$27.6M</td>
<td>CNY110M</td>
</tr>
<tr>
<td>China</td>
<td>Beijing - Haian</td>
<td>$27.5M</td>
<td>CNY110M</td>
</tr>
<tr>
<td>Spain</td>
<td>Madrid - Albacete</td>
<td>$12.1M</td>
<td></td>
</tr>
<tr>
<td>USA</td>
<td>CA HSR CP 1</td>
<td>$32.9M</td>
<td></td>
</tr>
<tr>
<td>USA</td>
<td>CA HSR CP 2-3</td>
<td>$18.5M</td>
<td>does not include track or systems cost</td>
</tr>
<tr>
<td>Germany</td>
<td>Berlin - Frankfurt</td>
<td>$79.8M</td>
<td>€60M</td>
</tr>
<tr>
<td>Italy</td>
<td>Rome - Naples</td>
<td>$76.3M</td>
<td>€47.3M</td>
</tr>
<tr>
<td>Italy</td>
<td>Turin - Novara</td>
<td>$119.4M</td>
<td>€74.0M</td>
</tr>
<tr>
<td>Italy</td>
<td>Novara - Milano</td>
<td>$128.2M</td>
<td>€79.5M</td>
</tr>
<tr>
<td>Italy</td>
<td>Bologna - Florence</td>
<td>$155.5M</td>
<td>€96.4M</td>
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<tr>
<td>France</td>
<td>Bordeaux - Tours</td>
<td>$58.3M</td>
<td>€32.5M</td>
</tr>
<tr>
<td>France</td>
<td>Paris - Lyon</td>
<td>$16.5M</td>
<td>€10.2M</td>
</tr>
<tr>
<td>France</td>
<td>Paris - Strasbourg</td>
<td>$35.9M</td>
<td>€22M</td>
</tr>
<tr>
<td>Japan</td>
<td>Tokyo - Osaka</td>
<td>$15M</td>
<td>¥9.3M</td>
</tr>
<tr>
<td>Spain</td>
<td>Madrid - Seville</td>
<td>$15.8M</td>
<td>¥9.8M</td>
</tr>
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<td>Spain</td>
<td>Madrid - Levante</td>
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<td>¥15.7M</td>
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<td>Spain</td>
<td>A Coruna - Mondragón</td>
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<td>Spain</td>
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<td>€687M</td>
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<td>Spain</td>
<td>El Pinar Viaducts</td>
<td>$775M</td>
<td>€680M</td>
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<td>Taiwan</td>
<td></td>
<td>$84M</td>
<td></td>
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<td>UK</td>
<td>High Speed 1 (HST)</td>
<td>$130.4M</td>
<td>£80M</td>
</tr>
<tr>
<td>UK</td>
<td>High Speed 2 (HS2)</td>
<td>$197.2M</td>
<td>£121M</td>
</tr>
</tbody>
</table>

(1) IRI October 2014
(2) IRI March 4, 2015
(3) Eunews April 11, 2014

Conclusions

Within the sections for each of the measures of comparison, the details of each HSR system were listed for comparison. For the most part, differences among the characteristics across the systems were not noteworthy. Vehicles have similar dimensions, despite widely varying shape vehicles have similar aerodynamic profiles, and construction costs seem to be explained by differences in geography. The most noticeable difference between systems was found to exist for the Vertical Bending Stress measure, and that was a result of the Acela trainsets being substantially heavier than the other systems trains. From the comparisons of the HSR systems trains’ characteristics and the systems standards and regulations, the source of the discrepancy in vehicle weight appears to arise from the conservative approach of FRA regulations for passenger vehicles’ structural safety. If approaches to methodology of ensuring passenger safety continue to remain unchanged, a worldwide standard for high speed rail trainsets may develop with its inherent cost savings in procurement, while the USA proceeds alone with its own standards and vehicles.

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An additional point worthy of further research concerns the unexpected trend towards more qualitative regulations, as this has the potential to change the railway engineering environment. The change from government railway regulations having clearly defined numerical limits to government regulations that are qualitative in nature moves the burden of design safety from the government to the practicing railway engineer. What the result of this shift will be is not yet clear, but it may indicate that the demand internationally for highly experienced railway engineers should increase.

References


Comparative Research on Engineering & Economics of US & International HSR Standards

John Gregory Green, PhD, PE, Hatch Mott MacDonald
Francis J. Miller, PE, Jacobs
Hualiang Teng, PhD, University of Nevada Las Vegas
Outline

• Background & Need for research
• USA
• Japan
• European Union
• China
• Eight measures of comparison
• Conclusions

Background

• 2013 Federal Railroad Administration report compared safety regulations
• Why need for undertaking research
  – Possibilities for standardization of equipment
  – Potential for identifying best practices
• Evolving Standards

USA Standards

• Federal Railroad Administration (FRA) responsible for railroad safety
• Laws codified in Code of Federal Regulations in Title 49, Subtitle B, Chapter 2
• Other sources of guidance:
  – AREMA Manual
  – Association of American Railroads’ “Manual of Standards and Recommended Standards”
  – System operators internal standards
    • AMTRAK
    • California High Speed Rail

Japanese Shinkansen Standards

• All Lines administered by the Ministry of Land, Infrastructure, Transport, and Tourism
• “Shinkansen” means simply a railway capable of operations over 125 mph
• Direction given in three primary sources:
  – Mandatory Laws
  – Technical Standards
  – Guidelines

European Standards

• The European Union is the responsible governing authority
• Several sources of governing railway standards and specifications
  – Technical Standards for Interoperability (TSI)
  – European Norms (EN)
  – International Union of Railways (UIC) Code Leaflets

Chinese Standards

• Chinese standards were officially published in 2009
• Previously had temporary standards in China
• These standards are established based on the construction and operations of their HSR systems
• Some standards were developed based on adopting and improving technologies from other countries
Measure 1: Vertical Bending Stress

- A measure for track railhead vertical wear
  \[ S = \frac{M_0 c}{I} \]

  where,
  - \( S \) = bending stress in pounds per square inch,
  - \( M_0 \) = maximum bending moment,
  - \( c \) = moment of inertia of the rail, and
  - \( I \) = distance in inches from the base of the rail to its neutral axis.

Measure 2: Horizontal Force

- For an adhesion considered only on tractive force
  \[ F = \frac{W V}{g r} \]

  where,
  - \( F \) = centripetal force
  - \( W \) = weight (from previous slides)
  - \( V \) = velocity in ft/sec
  - \( g \) = gravity (32.2 ft/sec²)
  - \( r \) = radius of curvature in feet.

  Speed limits are defined by each system’s governments
  - USA – max speed = 384 km/hr, 220 mph
  - Japan – max speed = 300 km/hr (186.4 mph)
  - Europe – max speed = 300 km/hr (177.5 mph)
  - China – max speed = 360 km/hr (217.5 mph)

Measure 3: Shearing Stress

- Shearing stress can lead to “shalling” rail defects
  \[ \tau_{	ext{max}} = 412 \frac{N}{mm^2} \]

  where,
  - \( \tau_{	ext{max}} \) = maximum stress (in N/mm²)
  - \( f \) = frictional force (in N)

- US – AAR handling wheels but does not define sizes, radius from Aar power car wheel radius = 0.510 mm, \( \tau_{	ext{max}} = 16.6 \frac{N}{mm^2} \)
- Japan – 366 mm, \( \tau_{	ext{max}} = 20.07 \frac{N}{mm^2} \)
- Europe – 468 mm, \( \tau_{	ext{max}} = 17.88 \frac{N}{mm^2} \)
- China – 446 mm, \( \tau_{	ext{max}} = 18.18 \frac{N}{mm^2} \)

Measure 4: Acceleration and Braking Forces

- Acceleration and braking forces cause wear in vehicles
- Traversing gradients cause trains to expend more effort to accelerate and to brake
- US – undefined, AREMA Manual suggests max 4%
- Japan – 3.5% max
- Europe – 3.5% max
- China – 3.0% max

Measure 5: Train Aerodynamic Shape

- At high speeds, up to 60% of the tractive effort is lost due to aerodynamic drag and friction
  \[ D = \frac{1}{2} \rho V^2 \left( C_d + \frac{X^2}{A} \right) \]

  where,
  - \( D \) = aerodynamic drag
  - \( \rho \) = density of the air
  - \( V \) = train speed
  - \( A \) = cross-sectional area of the train
  - \( C_d \) = the coefficient of the pressure drag caused by the fore and aft bodies of the train
  - \( d \) = the hydraulic diameter of the train
  - \( l \) = the train length
  - \( \lambda \) = the hydraulic friction coefficient caused by the couplers, pantographs, etc.
Measure 5: Train Aerodynamic Shape
(continued)

<table>
<thead>
<tr>
<th>Train Model</th>
<th>Country</th>
<th>Cross-sectional Area (m²)</th>
<th>Length (m)</th>
<th>Cross-sectional Area (ft²)</th>
<th>Length (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACELA</td>
<td>USA</td>
<td>13.71</td>
<td>203.00</td>
<td>147.57</td>
<td>665.73</td>
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<tr>
<td>CRH5</td>
<td>China</td>
<td>13.66</td>
<td>211.50</td>
<td>147.03</td>
<td>693.72</td>
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<tr>
<td>TGV PSE</td>
<td>France</td>
<td>11.40</td>
<td>200.00</td>
<td>122.71</td>
<td>656.00</td>
</tr>
<tr>
<td>ICE 3</td>
<td>Germany</td>
<td>11.75</td>
<td>200.00</td>
<td>126.48</td>
<td>656.00</td>
</tr>
<tr>
<td>N700</td>
<td>Japan</td>
<td>12.10</td>
<td>200.00</td>
<td>130.24</td>
<td>656.00</td>
</tr>
</tbody>
</table>

Measure 6: Train Nose Aerodynamic Shape

- Shape of train head/nose is a significant aerodynamic drag factor
- Multiple designs currently in use by same agencies, no shape preferred by standards

Measure 7: Train Crew Size

- Crew size is basis for labor costs comparison
- US – No current minimum crew size
- Japan – No current minimum crew size
- Europe – No current minimum crew size
- China – No current minimum crew size

Measure 8: Construction Costs

- Currently UIC lists the average cost of constructing 1 km of new high speed line in Europe between €12 – 30M. ($19 – 53M/Mile)
- Historically France and Spain have had lower building costs than Italy and Germany.
- The cost of construction in France is minimized as they permit steeper grades up to 3.5% reducing the number of viaducts and tunnels.

Construction Cost Comparison

- Comparison of the cost of high speed rail construction on a “per mile” and “per km” basis

Cost Elements Data

Comparison of the cost elements of high speed rail construction

<table>
<thead>
<tr>
<th>Element</th>
<th>350 km/hr</th>
<th>250 km/hr</th>
<th>200 km/hr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Land Acquisition &amp; Resettlement</td>
<td>4%</td>
<td>4 – 8%</td>
<td>6 – 9%</td>
</tr>
<tr>
<td>Civil Works</td>
<td>48%</td>
<td>50 – 54%</td>
<td>44 – 51%</td>
</tr>
<tr>
<td>Track</td>
<td>9%</td>
<td>9 – 11%</td>
<td>6 – 7%</td>
</tr>
<tr>
<td>Signaling &amp; Communications</td>
<td>4%</td>
<td>3%</td>
<td>4%</td>
</tr>
<tr>
<td>Electrification</td>
<td>5%</td>
<td>4 – 5%</td>
<td>4 – 5%</td>
</tr>
<tr>
<td>Rolling Stock</td>
<td>15%</td>
<td>3 – 4%</td>
<td>5 – 7%</td>
</tr>
<tr>
<td>Buildings &amp; Stations</td>
<td>2%</td>
<td>2 – 4%</td>
<td>3 – 5%</td>
</tr>
<tr>
<td>Other Costs</td>
<td>Balance</td>
<td>Balance</td>
<td>Balance</td>
</tr>
</tbody>
</table>
Cost Data Spanish High Speed Rail

Real Costs of Spanish HSL Opened between 2003 and 2006

- Infrastructure: $9.6 - $26M/Mile
- Track: $3 - $5.5M/Mile
- Electrification: $1.5 - $2M/Mile
- Signaling & Telecom: $2 - $5.8M/Mile
- Total Cost: $16.6 - $37M/Mile

Unit Costs for Large & Medium-sized Stations
- Medium-Sized: $16.6 - $55M
- Large: $55 - $220M

[Source: APTA High Speed Practicum – “Infrastructure for High-Speed, Luis Lopez Diaz, March 30, 2010.”]

Maintenance Cost Data

- Maintenance of 1 km of new high speed line €70,000 ($111,000) per year and maintenance of a high speed train €1M ($1.58M) per year (Source UIC).
- For estimating maintenance costs, long term average (economic life or life cycle) for yearly percentages of investment.

Conclusions

- No significant differences among systems’ characteristics and costs, except for trainset weight
- USA trains are significantly heavier than European and Asian trains, so may end up with two standards – USA and rest of world
- Unexpected trend noticed away from quantitative regulations, and towards more qualitative ones