



American Railway Engineering and
Maintenance-of-Way Association

CHAPTER 17

HIGH SPEED RAIL SYSTEMS¹



FOREWORD

This Chapter contains AREMA recommended practice with respect to the planning, engineering, construction and maintenance of commuter, passenger and high-speed rail systems. It also includes recommendations relative to an incremental approach such as the upgrading of existing facilities for increased speeds, recognizing the possible joint use by freight and passenger services. These joint usage issues should be addressed at the preliminary planning stage. The manual, as it is now structured, is not stratified by speed ranges, but rather by the function of the facility or component. Where speeds are a factor of the element upper limits are not stressed. The purpose of this chapter is to identify the applicable speeds for the elements in the manual common to this chapter and use them as a base for developing high-speed criteria. The speed range stratification starts with that practical, given the limitations of existing facilities, to the super speeds of new facilities.

Chapter 17 considers present foreign high-speed rail technical capabilities and operating characteristics and extrapolates them to North American passenger and freight railroad experience to develop recommended practice for high-speed rail systems. Previous experience with imported technologies and practices has shown that modifications are often needed to successfully adapt them to the climatic, maintenance, operating, and regulatory environments found in North America.

System safety parameters, economics, and design philosophies must also be evaluated in the North American context.

The traditional manual material, for the most part, contains “stand-alone” recommended practices for the fixed plant of railways. This Chapter encompasses high-speed rail as a system; i.e., combining the planning, design, and construction of the facility with the specification and operating characteristics of the vehicle, including propulsion and control system considerations.

There are subparts of the Chapter that are the same as existing recommendations in the manual and where this occurs a reference is made to the existing Chapter and paragraph number. New and existing material that requires technical enhancement is presented based on existing high-speed rail systems and the expertise of committee members.

¹ The material in this and other chapters in the AREMA Manual for Railway Engineering is published as recommended practice to railroads and others concerned with the engineering, design and construction of railroad fixed properties (except signals and communications), and allied services and facilities. For the purpose of this Manual, RECOMMENDED PRACTICE is defined as a material, device, design, plan, specification, principle or practice recommended to the railways for use as required, either exactly as presented or with such modifications as may be necessary or desirable to meet the needs of individual railways, but in either event, with a view to promoting efficiency and economy in the location, construction, operation or maintenance of railways. It is not intended to imply that other practices may not be equally acceptable.

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INTRODUCTION

The Chapters of the AREMA Manual are divided into numbered Parts, each comprised of related documents (specifications, recommended practices, plans, etc.). Individual Parts are divided into Sections by centered headings set in capital letters and identified by a Section number. These Sections are subdivided into Articles designated by numbered side headings.

Page Numbers – In the page numbering of the Manual (17-2-1, for example) the first numeral designates the Chapter number, the second denotes the Part number in the Chapter, and the third numeral designates the page number in the Part. Thus, 17-2-1 means Chapter 17, Part 2, page 1.

In the Glossary and References, the Part number is replaced by either a “G” for Glossary or “R” for References.

Document Dates – The bold type date (Document Date) at the beginning of each document (Part) applies to the document as a whole and designates the year in which revisions were last made somewhere in the document, unless an attached footnote indicates that the document was adopted, reapproved, or rewritten in that year.

Article Dates – Each Article shows the date (in parenthesis) of the last time that Article was modified.

Revision Marks – All current year revisions (changes and additions) which have been incorporated into the document are identified by a vertical line along the outside margin of the page, directly beside the modified information.

Proceedings Footnote – The Proceedings footnote on the first page of each document gives references to all Association action with respect to the document.

Annual Updates – New manuals, as well as revision sets, will be printed and issued yearly.

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¹ References, Vol. 96, p. 77.

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¹ References, Vol. 97, p. 180.

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Part 3

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3.2.6 PASSENGER COMFORT (2009)

Passenger comfort is associated with car body translational acceleration in the vertical, lateral and longitudinal directions and rotational acceleration about these axes. These accelerations can be either a single event such as a sudden acceleration due to an isolated track geometry irregularity, or a series of accelerations over time due to continuous track irregularities. The waveform of single event accelerations must not exceed peak-to-peak safety limits established by FRA. The series of varying accelerations over time is a performance-based measurement represented by a root-mean square (rms) ride quality acceleration value. The ISO 2631 standard provides ride quality rms-type acceleration limits that are often used to judge the severity of the car body vibration over time.



The physiological response of the human body to vibration of various frequencies has been studied and found to be more sensitive to certain frequencies than others. For example, a well-known response is “sea-sickness” which results from cyclic motion at low frequencies typical of naval vessels and not commonly observed on a rail car. However, for the range of acceleration frequencies common to rail vehicles it is noted that some produce more physiological distress than others. Therefore the ISO standard recommends the use of certain filters to be used on the measured acceleration data which give larger weighting to some frequencies for which the human body is more sensitive, and less weighting for others.

Because the ride quality measurement averages car body acceleration over time, the contribution of a small number of sudden jolts from isolated track geometry irregularities is usually not a significant contributor to the ride quality value. The rms acceleration ride quality data is typically taken as a measure of car body response to track geometry over long distances.

3.2.7 VEHICLE/TRACK INTERACTION (2009)

The interaction between track and passenger rail vehicles is both a safety and a performance issue. Wheel-rail force safety limits are defined by FRA with criteria that relate to single wheel flange climb derailment, rail overturning, lateral track panel shift and vertical wheel lift off from the rail. Wheel-rail contact characteristics such as wheel flange angle and wheel-rail friction coefficient are critical to safety as they affect these force limits. Wheel-rail effective conicity is also safety critical because the speed at which truck hunting occurs is largely dependent upon it. Vehicle performance is mainly measured by ride quality which is also highly dependent upon vehicle-track interaction as described in the section above. In general, vehicle-track interaction is dependent upon the track geometry, wheel-rail characteristics, and the speed, mass, and suspension parameters of the vehicle.

In rail vehicle design there is a tradeoff between truck resistance to hunting in tangent track and truck curving ability. Although a truck with a relatively soft primary suspension may have good curving performance with low

wheel-rail forces and wear, it also may be less resistant to truck hunting in tangent track. Similarly a truck with a stiff suspension is better at resisting hunting but may curve poorly and provide large lateral wheel-rail forces and wear. Depending on the suspension parameters and other vehicle design factors chosen, a rail car may be designed to obtain a reasonable compromise between these two conditions.

To provide proper vehicle-track interaction, in addition to the track geometry being compliant with the FRA track class, a high speed track should also have rail that is free from corrugation and have rail profiles with at most only minor wear on the crown and rail gage face. Also, innovative track design methods such as improved spiral geometry have been shown to reduce the lateral wheel-rail forces and car body motions of high speed trains in curves compared to conventional spiral design.



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3.5.6 TRACK STRUCTURE¹ (2004)

High-speed traffic places different and possibly more severe demands on the track structure than slower, heavier freight traffic. Although dynamic loading considerations under freight traffic are important, they can become a predominant issue for high-speed passenger traffic, requiring the track engineer to consider dynamic properties of material, the effects of vibration, and the behavior and failure modes of track components associated with high frequency loads. Additionally, the more restrictive tolerances for track geometry associated with higher speeds places a greater value on the engineers' ability to design the track structure to withstand these forces. The challenge becomes even greater if the track has both freight and high-speed traffic.

Track structure of conventional construction can be divided into superstructure (rails, ties and fastenings) and substructure (ballast, sub ballast and sub grade). Superstructure components are usually more safety-critical and their performance more dependant upon their dynamic properties. The substructure primarily affects the longer-term track geometry performance because most of the permanent deformation under repetitive loading will occur in these layers. By using adequate design methods and maintenance procedures, substructure settlement can be kept tolerably small.

3.5.6.1 Structural Design Considerations

3.5.6.1.1 Superstructure

Chapters 5 and 30 in the AREMA Manual for Railway Engineering consider many aspects of track components from a static strength perspective. However, the higher frequency loads of high-speed traffic make it necessary to consider the effects of dynamic loads generated in the track structure by the vehicles. Due to the superstructure components' accessibility and their large effect on dynamic track performance, they are often designed to provide the desired dynamic response. The damping characteristics of tie pads and other resilient materials in the superstructure can be selected to minimize the forces and vibrations transmitted by high-speed vehicles.

3.5.6.1.2 Substructure

Chapter 1 of the Manual for Railway Engineering should be referenced for construction practices of new track, and for a wide variety of general maintenance practices on existing track related to the substructure. But whether the engineer is concerned with an existing track or new construction, a design-oriented approach is needed to address

¹ References

[1] Li, D., and Selig, E. T., "Method for Railroad Track Foundation Design," Journal of Geotechnical and Geoenvironmental Engineering, ASCE, April 1998, Vol. 124, No. 4.

[2] Selig, E. T., and Waters, J. M., Track Geotechnology and Substructure Management, Thomas Telford, Ltd., London 1994.

[3] Chrismer, S. M., and LoPresti, J., "Track Substructure Assessment with the Cone Penetrometer," Association of American Railroads Research and Test Department, February 1996, TD-96-002.



or prevent substructure instability. In recent decades track geotechnology research has provided new insight into substructure behavior allowing development of investigation tools and improved design methods. Additionally, the importance of dynamic properties of the substructure, particularly the subgrade, is becoming more apparent as vehicle speed is increased.



3.5.6.1.2.1 Ballast/Sub ballast Layer Thickness Design and Sub grade Strength Considerations



Because of the greater challenges posed by smaller geometry error tolerances for track with high-speed traffic, and the possible combination of freight with high-speed passenger traffic on the same track, an improved approach to substructure design is needed. The practice recommended in [Chapter 16, Article 10.3.2.1](#) of using 25 psi as the assumed sub grade strength in the calculation for the required ballast depth under tie, should only be used with caution for track with high-speed traffic because a lesser sub grade strength is quite common.



The methodology described in Ref [1] is recommended to design the granular layer (ballast and sub ballast) thickness over sub grade because it allows consideration of the distribution of load magnitudes and number of load repetitions for the actual traffic, the tonnage by MGT, the moduli of granular materials and sub grade soil, and soil type and soil compressive strength. The two most common types of sub grade failure are addressed; progressive shear, and excessive plastic settlement (ballast pockets). The method lends itself well to individual locations with sub grade instability where soil type and strength can be somewhat site-specific, but can apply equally well to granular layer thickness design over many miles. Also, the relative contribution of sub grade deformation due to heavy freight loading and lighter passenger loads can be assessed.



The amount of sub grade permanent deformation that contributes to track settlement decreases with depth into the soil, and this depth of influence varies with sub grade stiffness. For soils that are uniformly strong with depth this zone of influence may be only a few feet, or it may extend to 20 or 25 feet for softer soils [1]. For weaker soils it is important to characterize soil strength over the depth of influence to use a design approach to limit cumulative sub grade settlement. Much of this sub grade settlement will be differentially distributed along the track, and hence, will increase track geometry roughness.



There are a number of methods available to characterize sub grade over the depth of influence, as discussed in Ref [2]. In particular, the cone penetrometer has been shown [3] to be well suited to rapidly assess soil strength and type with depth, and the granular layer thickness. Such information is needed for a design approach to determining the existing strength of track substructure and alternatives to improve it.

3.5.6.1.2.2 Alternative Means to Improve the Substructure

As an alternative to using a thicker granular layer, a relatively stiff layer of hot-mix asphalt, concrete, geosynthetic-granular composite or other material placed over a soft sub grade can reduce loading stresses transmitted to the soil and reduce sub grade settlement. While asphalt and concrete are inherently stiff materials, the geosynthetic-granular composite attains stiffness due to lateral confinement of the granular material in the open cores of the geosynthetic. A given layer thickness of stiffer substructure material is better able to withstand imposed stresses without settlement and to reduce the stress passed along to the sub grade, compared to a granular layer of the same thickness. Also, concrete slab track can provide a stiffer track structure and reduce stresses on the underlying substructure layers compared to conventional tie-ballast track construction. The decision between using an increased granular layer thickness or a stiffer material, or between using a conventional tie-ballast track or slab track construction, to provide these benefits can be determined based on a cost analysis.

3.5.7 ALIGNMENT, HORIZONTAL (2005)

High-speed railway track alignment should provide for safe and comfortable operation. It should be designed to permit continuous operation at high speeds. Constant acceleration and deceleration of trains along an alignment is undesirable and therefore, track alignment design should endeavor to enable consistent train speeds along a high-speed rail route.

In order to achieve continuous operation at constant speeds greater than 90 miles per hour, curves with civil speeds less than the minimum desirable speed should be avoided wherever possible. For routes that have geographical constraints requiring curvature that will not allow conventional high-speed trains to travel at minimum desirable speeds, consideration of trains with tilting systems to counteract centrifugal forces in curves should be considered.

3.5.7.1 Design Speeds

Design speeds shall be based on Train Performance Runs (TPRs) that simulate actual train performance with respect to equipment acceleration and deceleration, grade, civil speed at curves, braking rates and other conditions that can affect train speed.

Consideration shall be given to providing an alignment that allows high-speed trains to run at consistent speeds over the alignment. Similarly, high-speed alignment design shall take into account areas where slower modes of railroad operation such as regional inter-city, commuter and freight trains may share tracks. Territories where high-speed trains will operate in congested or urban areas may not be desirable or practical for high-speed operation.

The desirable speeds for high-speed operation will vary with each system. Speeds will vary with respect to the type of high-speed equipment, the average distance between stations and the overall length of the high-speed route.

Desirable speeds for high-speed rail operations may also vary with respect to the type of system originally constructed. High-speed rail systems that are constructed through the incremental approach (that is the upgrade of an existing conventional railroad into a high-speed rail system) will likely have a lower desirable speed than new high-speed rail alignment.

The desirable design speeds for high-speed rail systems should be greater than 110 mph. In most cases, it will be desirable to achieve speeds 150 mph or greater. The Federal Railroad Administration has recognized that high-speed rail operation may achieve speeds up to 200 miles per hour by issuing Track Safety Standards for Track Classes of Six and higher.

3.5.7.2 Curvature

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 the 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.

3.5.7.3 Elevation

For high-speed rail systems with standard gauge, equilibrium elevation shall be defined by [EQ 14](#) in [Chapter 5, Part 3, Article 3.3.1](#), such that,

$$E = 0.0007V^2D$$

where E is equilibrium elevation in inches, V is speed in miles per hour and D is degree of curvature. The vehicle is said to be at balance speed if the track has a superelevation equal to the equilibrium elevation, E for the corresponding D and V values, meaning that the vehicle does not lean out or into the curve and the vertical wheel forces on both rails are equal. Equilibrium elevation is limited by the allowable amount of superelevation.

3.5.7.4 Actual Superelevation

The maximum achievable actual super-elevation on high-speed track is considered six inches. Where ballastless track construction is used, higher levels of actual super-elevation may be achievable.





Passengers, vehicles and track easily tolerate some unbalance when curves are traversed. Therefore, even if a curve can be raised to balancing elevation it is normally desirable to elevate it somewhat less so that passenger discomfort and vehicle-track forces will be reduced when trains stop on the curve or traverse it at lower speeds due to traffic or other causes. It is common practice to limit actual super-elevation of a curve to 75% of the equilibrium elevation.

In sections of track where trains are expected to operate at various speeds, actual super-elevation shall be designed to prevent lower speed trains from experiencing overbalanced elevation. However, for high-speed rail systems with a small amount of freight railroad traffic, curves may be super-elevated so that the actual amount of super-elevation is approximately equal to the equilibrium elevation for a speed that is 10 mph below the maximum authorized speed for freight traffic.

3.5.7.5 Lateral Acceleration (Quasi-Static)

Acceptable values of steady state lateral acceleration parallel to the floor of the car-body range from 0.04 to 0.1 g in North America. It should be noted that vehicle characteristics and track geometry affect this quasi-static lateral acceleration. The trip length should also be considered when deciding upon the maximum acceptable value of this lateral acceleration.

Current North American practice for HSR service is to limit lateral acceleration to 0.1 g. This is used for conventional trains operating at five inches of unbalance on the Northeast corridor, as well as both HSR train types that utilize tilt technology. In Europe, however, it is common practice to limit lateral acceleration to values as low as 0.05g. For HSR corridors where average trip lengths will be greater than 500 miles, it is desirable to limit lateral acceleration to a 0.05g.

3.5.7.6 Unbalanced Elevation

Unbalanced elevation is the difference between equilibrium and actual super-elevation. Mathematically, this is defined as,

$$E_u = E - E_a$$

where E_u is unbalanced elevation and E_a is actual super-elevation. When E_u is a positive value, it is considered underbalanced elevation providing a cant deficiency; when E_u is negative, it is considered overbalanced elevation providing a cant excess.

Underbalanced elevation is the amount that actual super-elevation is less than equilibrium elevation for any combination of speed and curvature. Overbalanced elevation is the amount that actual super-elevation is more than equilibrium elevation. Without consideration of tilt, when a train traveling around a curve experiences underbalanced elevation, the lateral acceleration is in the direction towards the outside of the curve; when the train experiences overbalanced elevation, the lateral acceleration will be towards the inside of the curve.

Underbalanced elevation is generally limited by the FRA Track Safety Standards to three inches. However, current Track Safety Standards allow unbalance up to four inches provided equipment meets certain FRA requirements. The FRA may also grant underbalanced elevation waivers for high-speed rail equipment. Waivers for up to five inches of underbalanced elevation have been granted for conventional passenger trains and passive high-speed tilt trains. Active tilt trains may be allowed to run at speeds with up to nine inches of underbalanced elevation.

The following process is required to obtain a waiver or variance from the established FRA Track Safety Standards.

- Petition for a waiver to conduct testing.
- Provide test conditions.
- Provide a test plan for approval.
- Report on the test results.

- Petition for a waiver to operate at high cant deficiency based on test results.
- Obtain a waiver with specific conditions from the FRA.

3.5.7.7 Clothoid Transition Spiral Lengths

The minimum length of clothoid spiral transition curves shall be determined based on runoff and jerk rate. For high-speed track alignments that will be used by high-speed trains with tilt active tilt mechanisms, minimum spiral length shall be sufficient for the trains tilt rate.

3.5.7.8 Runoff

A minimum rate of super-elevation should be provided uniformly throughout the length of a spiral to prevent racking and diagonal warp of the equipment. At least 1/2-inch runoff in 31 feet shall be provided such that,

$$L_s \geq 62E_a$$

where L_s is the length of clothoid transition spiral in feet and E_a is the actual super-elevation in inches.

The rate that actual super-elevation run-off occurs between tangent track and the beginning of the circular curve assists passenger comfort and the smoothness of the spiral operation. For speeds greater than 60 and less than or equal to 125 mph, at most a 3/8-inch runoff in 31 feet should be provided. For speeds greater than 125 mph, at most a 1/4-inch runoff in 31 feet should be provided. These runoff rates with respect to minimum spiral length may be defined mathematically as follows:

$$60 < V \leq 125 \text{ mph} \Rightarrow L_s \geq 82.7E_a$$

$$V > 125 \text{ mph} \Rightarrow L_s \geq 124E_a$$

where V is speed.

For dedicated high speed systems the maximum allowable value of track twist can be determined by considering wheel unloading due to twist (including dynamic unloading as modeled by simulation), vehicle torsional stress due to twist, vehicle roll mismatch at vehicle to vehicle passageways, effect of vehicle roll velocity at design speed on passenger comfort, and excitation of roll oscillation (and effect of such oscillation on passenger comfort) due to vehicle roll acceleration. Attention should also be paid to track twist limits of similar systems with successful operating history.

3.5.7.9 Jerk Rate

The change in lateral acceleration with respect to time is the jerk rate.

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. This is to ensure that passengers do not experience uncomfortable levels of jerk rate or jolts.

In general, conventional North American railroad practice is to limit jerk rate to 0.03 g per second where existing conditions permit. Where necessary, jerk rates of 0.04 g per second are allowable conventional practice where existing conditions warrant.

However, in high-speed operations, jerk rates may be increased when the change in lateral acceleration is low. In some instances, the change in lateral acceleration may be small enough where no transition is required-this is defined as jolt.

When the change in lateral acceleration is small enough, typically 0.01g or less, it is acceptable practice not to require transition spirals. In general, this will occur when the change in unbalance is 1/2-inch or less. Some high-speed train suspension systems may allow jolts at unbalanced elevation of up to one inch. Where the change in



lateral acceleration is 0.025g, jerk rates of 0.1g per second may be acceptable. It is recommended, however, the jerk rate not exceed 0.03g per second where the change in lateral acceleration is 0.05g or greater.

When the acceptable level of jerk rate is known, the minimum spiral length can be calculated such that,

$$L_s \geq vt = 1.46Vt$$

where L_s is the minimum clothoid transition spiral length in feet, v is speed in feet per second, V is speed in miles per hour and,

$$t = \frac{\text{LateralAcceleration}}{\text{MaximumAllowableJerkRate}} = \frac{a_L}{[(\Delta A_L)/(\Delta t)]_{\text{allowable}}}$$

The above equation for jerk rate provides the length of spiral for any value of lateral acceleration. Where the change in unbalanced elevation is directly proportional to the change in lateral acceleration, the equation can be redefined recognizing that when,

$$\frac{\Delta E_u}{E_u \text{ at maximum lateral acceleration}} = \frac{a_L}{A_L}$$

as,

$$L_s \geq 1.46V \left(\frac{A_L}{[(\Delta A_L)/(\Delta t)]_{\text{allowable}}} \right) \left(\frac{E_u}{E_u \text{ at } A_L} \right)$$

where L_s is the length of clothoid transition spiral in feet, V is speed in miles per hour, A_L is the maximum allowable lateral acceleration, $(\Delta A_L / \Delta t)$ is the maximum allowable jerk rate, E_u is the change in unbalance and $(E_u \text{ at } A_L)_{\text{allowable}}$ is the unbalance at the maximum allowable lateral acceleration.

3.5.7.10 Tilt Rate

For alignments that will support the operations of high-speed trains with tilt mechanisms, clothoid transition spiral lengths shall be long enough to allow the train to fully tilt to the required amount for the curve within the spiral. There are two conditions that should be satisfied:

- (1) Tilt rate of the car-body with respect to the truck, and
- (2) Tilt rate of the car-body with respect to the horizon.

The maximum tilt rate with respect to the truck or track level should be available from the manufacture of the equipment. As an example, a measured tilt rate for an active tilt system is 3.5° per second.

The time it takes to tilt is equal to:

$$t = \frac{\text{max tilt angle}}{\text{max tilt rate}}$$

The clothoid transition spiral must be long enough to allow the car-body to fully tilt to the degree required for the amount of lateral acceleration at the truck. The length of spiral can be defined with respect to speed and time such that,

$$L_s \geq vt = 1.46Vt$$

where L_s is the length of clothoid transition spiral in feet, v is the speed in feet per second, V is the speed in miles per hour and t is time required to tilt in seconds.

The above equation is only valid when car-bodies tilt throughout the entire curve. When the car-body partially tilts within the spiral (that is it tilts in one section of the spiral and does not tilt in another section), the spiral shall be long enough to ensure that the maximum allowable jerk rate is not exceeded in the section of the spiral where the car-body does not tilt.

It is also desirable to limit the amount the train tilts with respect to the horizon. This ensures sufficient passenger comfort when the train is subject to the rotation caused by super-elevation runoff and tilting.

3.5.7.11 Higher Order Spirals

3.5.7.11.1 Common Geometry

Higher order (S-shaped) transition spirals provide correct geometry that may be necessitated by high speeds and heavy axle loads, which will be prevalent in North American high-speed operations. Higher order spiral transition curves have been used throughout the world, but are currently not common practice for North American railroads, which have traditionally used the clothoid spiral in railroad construction.

Clothoid spirals are considered third order curves while circular curves are second order curves. Although acceptable at lower speeds associated with lower speeds, 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.

Clothoid spirals provide a straight ramp with respect to change degree of curvature, unbalanced elevation (and lateral acceleration), and actual super-elevation runoff.

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. The higher order curves provide a transition of the abrupt break caused at the beginning and end of the clothoid spiral ramp. This provides a smoother ride both horizontally and vertically as trains transition between tangent track and circular curve.

There are at least three higher order spiral transition curve geometries that are considered to be standard in railway alignment design practice. These curves are parabolic, sine and cosine, and are considered fourth and fifth order curves.



Figure 17-3-1 illustrates four common spiral transition curve geometries including the clothoid. Table 17-3-1 shows all the main features of the four different transition curves geometries. Two of the most important features are shift (f) and the increase in length, compared to the clothoid geometry with identical shifts.

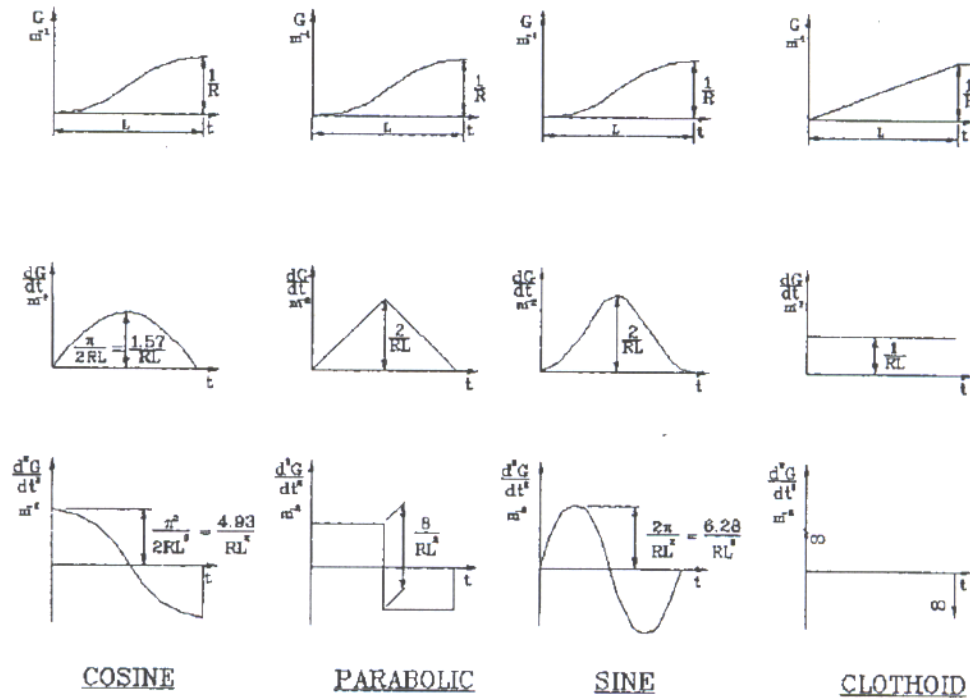


Figure 17-3-1. Common Spiral Transition Curve Geometries

The cosine based transition spiral also known as the Bloss spiral provides the most favorable condition. Although it offers the least improvement in shift and in increase in length, it still provides excellent conditions to speed increases with minimum lateral movement of the existing clothoid transitions that means minimum overall track shifts.

Table 17-3-1. Comparison of Cosine, Parabolic and Sine Spiral to Clothoid Geometry

Geometric Features	Cosine	Parabolic	Sine	Clothoid
	Transition Geometry			
$(dg/dt)_{\max}(m^2)$	$\frac{\pi}{2}RL$	$2/(RL)$	$2/(RL)$	Broken function ($1/RL$)
$(d^2G/dl^2)_{\max}(m^3)$	$4.93/(RL)$	$8/(RL^2)$	$6.28/(RL^2)$	Theoretically Indefinite
The approximate value of shift (f)	$L^2/(42.23R)$	$L^2/(48R)$	$L^2/(61.21R)$	$L^2/(24R)$
The approximate value of “y” end coordinate (m)	$0.149 (L^2/R)$	$0.146 (L^2/R)$	$0.141 (L^2/R)$	$0.16 (L^2/R)$
The angle of the end tangent (J)	$L/(2R)$	$L/(2R)$	$L/(2R)$	$L/(2R)$
Increase of length compared to the clothoid geometry with identical shift (%)	33	41	60	-
Maximum lateral displacement compared to the clothoid, with identical shift	$0.017f$	$0.025f$	$0.024f$	-

3.5.7.11.2 Minimum Spiral Lengths

For spirals of higher order than clothoids, minimum spiral lengths may be calculated for clothoid transition spirals in accordance with [Aeticle 3.5.7.8](#) and increased accordingly. This increase in spiral to allow for the additional length needed to transition the clothoid geometry break at the ends. The increase is provided assuming that maximum allowable jerk rate limits and actual super-elevation runoff gradients are the same as for clothoid transition spirals.

The minimum length of a cosine, parabolic and cosine transition curve may be defined as

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

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

$$L_r \geq 1.60L_s \quad \text{for cosine spiral}$$

where L_r is the length of the higher order spiral and L_s is the calculated minimum length of the clothoid spiral in feet.

Consideration can be given to reducing the lengths of the higher order spirals recognizing the S-shape spirals provide a more smooth ride through the transition curve, thus slightly higher jerk rates and superelevation runoff rates will be more tolerable in terms of comfort.



3.5.7.12 Effects of Tilt Trains



In order to maximize high-speed rail service, high-speed passenger trains can have a tilting system in order to compensate for centrifugal forces on curves. This will allow high-speed passenger trains to travel around existing curves at higher speeds than would be allowed for conventional (non-tilting) high-speed passenger equipment.



A passive tilt system is designed where the car body produces a positive tilt in response to centrifugal force acting on the car-bodies center of gravity. It suspends the car-body from the top of swinging bolsters above the wheels, and when the high-speed train rounds a curve at a higher than equilibrium speed, centrifugal force swings the bottom of the car-body outward like a pendulum. Talgo tilt trains utilized by Amtrak on the Pacific Northwest Corridor use a passive tilt system.



A tilt system that is actively controlled uses a design where the car-body tilt is actuated in response to controller transmitted commands. In this design, measurements are made of various system conditions such as the lateral acceleration, from which information is then processed by the Controller to activate the appropriate car-body tilt. A computerized hydraulic tilting system causes the trains to tilt. Sensors in the lead trucks are used to measure the amount of centrifugal forces in curves, and the computerized controller system tilts the car-bodies appropriately.

3.5.7.13 TOLERANCES



Track alignment tolerances are extremely important to the successful operation of high-speed service. Tolerances have implications to safety, system reliability, passenger comfort and maintenance economics.

Three types of tolerances should be considered for high-speed track alignment. These are:



- (1) **Safety Standards:** The absolute minimum tolerances where the train can operate safely. Safety standards may not be exceeded without a reduction of the speed limit (slow order) or suspension of service.
- (2) **Maintenance Tolerances** 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.
- (3) **Construction Tolerances** 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.

Tolerances for horizontal alignment should be based on allowable deviation from uniformity, where uniformity at any point along the track alignment is established by averaging the measured mid-chord offset values for nine consecutive points centered around that point and spaced according to the following:

Chord Length	Spacing
31'	7'-9"
62'	15'-6"
124'	31'-0"

In high-speed rail both single and multiple deviations should be considered.

For high-speed rail service, classes of track are designated based on the maximum permissible speed for each class. Maximum allowable speeds for high-speed passenger trains for each class of track are as follows:

Maximum Allowable	
Class of Track Passenger	Train Speed
Class 6	110
Class 7	125
Class 8	160
Class 9	200

For speeds greater than 200 mph, track alignment tolerances should be established based on current practices for establishing track safety, maintenance and construction tolerances including testing and economic analyses.

Construction tolerances are measured from the theoretical alignment and should be verified by deviations from uniformity. In other words, construction tolerances should meet two standards for ensuring that the track alignment as constructed conforms to the design.

3.5.7.14 Safety Standards

In the United States of America, the Federal Railroad Administration (FRA) has established Track Safety Standards for Classes of Track 6 through 9. These U.S. mandatory standards in the area issued as Subpart G of Part 213 of Code of Federal Regulations 49.

Subpart G applies to all track supporting passenger train speeds of 90 mph and greater and freight train speeds of 80 mph or greater. Freight trains or mixed use (passenger and freight) may operate at passenger speeds when they meet specific conditions of the FRA.

Maximum allowable deviations from uniformity of the mid-chord offset for 31, 62 and 124-foot chords for single and multiple deviations may be found in FRA Track Safety Standards § 213.327.

3.5.7.15 Maintenance Tolerances

Maintenance shall be performed when alignment values meet the following limits which were derived by using a slightly lesser allowable value than the safety FRA limits:

For Track Classes 6 through 9, alignment should not deviate for a single deviation from uniformity more than the amount prescribed in the following table:

Alignment Maintenance Limits-Single Deviation			
Class of Track	The Deviation from Uniformity of the Mid-Chord Offset for a 31' Chord should not be more than (inches):	The Deviation from Uniformity of the Mid-Chord Offset for a 62' Chord should not be more than (inches):	The Deviation from Uniformity of the Mid-Chord Offset for a 124' Chord should not be more than (inches):
6	3/8	1/2	1
7	3/8	3/8	7/8
8	3/8	3/8	1/2
9	3/8	3/8	1/2



For Track Classes 6 through 9, alignment should not deviate for multiple deviations from uniformity more than the amount prescribed in the following table for three or more non-overlapping deviations occurring within a distance equal to five times the specified chord length:

Alignment Maintenance Limits-Single Deviation			
Class of Track	The Deviation from Uniformity of the Mid-Chord Offset for a 31' Chord should not be more than (inches):	The Deviation from Uniformity of the Mid-Chord Offset for a 62' Chord should not be more than (inches):	The Deviation from Uniformity of the Mid-Chord Offset for a 124' Chord should not be more than (inches):
6	1/4	3/8	3/4
7	1/4	1/4	3/8
8	1/4	1/4	3/8
9	1/4	1/4	3/8

When the general alignment is to be corrected, such as the removal of long swings on tangents and the restoration of curves to circular curvature, laying out of spirals, etc., the throws or lining should be to present monuments. Surveying equipment, rail-mounted telescope or a long base automatic reference system should be used to determine the corrections required on tangents. The string line method should be used to determine the alignment of curves to and to calculate the required corrections or throws. For detailed corrections of an irregular line, the required throws may be determined by using surveying equipment, a line wire and indicator device or plotting a graph on curves with automatic lining equipment.

3.5.7.16 Construction Tolerances

The deviation of the designated mid-ordinate from a 62-foot chord should not be more than 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.

3.5.8 VERTICAL GEOMETRY (2008)

Various track conditions influence the gradients used in the design of vertical curves on high-speed rail (HSR) systems. These conditions include:

Track Usage

- Track used by all types of trains including heavy freight trains
- Track used by high-speed trains and light freight trains
- Track used by high-speed passenger trains

3.5.8.1 Design Considerations of Vertical Geometry

The design of vertical geometry of track for HSR systems is not similar to that of commuter, intercity and freight rail systems. The vertical alignment is subject to the constraints of the existing natural terrain and man-made infrastructure. This section describes various aspects of vertical geometry for HSR highlighting the differences between European systems designed and in use as compared to vertical geometry for commuter and intercity rail in the United States.