California High-Speed Train Project

TECHNICAL MEMORANDUM

Alignment Design Standards for High-Speed Train Operation TM 2.1.2

Prepared by: *Signed document on file*__________ __17 Mar 09_
George Harris Date

Checked by: *Signed document on file*__________ __23 Mar 09_
Dominique Rulens Date

Approved by: *Signed document on file*__________ __26 Mar 09_
Ken Jong, PE, Engineering Manager Date

Released by: *Signed document on file*__________ __4 April 09_
Anthony Daniels, Program Director Date

Revision	Date	Description
0	26 Mar 09	Initial Release

Prepared by PB

for the California High-Speed Rail Authority

System Level Technical and Integration Reviews

The purpose of the review is to ensure:

- Technical consistency and appropriateness
- Check for integration issues and conflicts

System level reviews are required for all technical memoranda. Technical Leads for each subsystem are responsible for completing the reviews in a timely manner and identifying appropriate senior staff to perform the review. Exemption to the System Level technical and integration review by any Subsystem must be approved by the Engineering Manager.

System Level Technical Reviews by Subsystem:

Systems: *Signed document on file*__________ 19 Feb 09 _
Eric Scotson Date

Infrastructure: *Signed document on file*__________ _17 Mar 09 _
John Chirco Date

Operations: *Signed document on file*__________ 05 Mar 09 _
Paul Mosier Date

Maintenance: *Signed document on file*__________ _05 Mar 09 _
Paul Mosier Date

Rolling Stock: *Signed document on file*__________ _03 Nov 08 _
Frank Banko Date

TABLE OF CONTENTS

ABSTRACT

This technical memorandum presents alignment design guidance for the segments of the proposed high-speed rail line in exclusive use operation. On these segments, speeds will be above 125 mph (200 km/h) up to a maximum operating speed of 220 mph (350 km/h) and will consider that faster operation up to not less than 250 mph (400 km/h) in the future will not be unnecessarily precluded. The technical memorandum defines the geometric design requirements for basic design in order to achieve a safe and reliable operating railway that meets regulatory and CHSTP functional; programmatic, operational and performance requirements.

The general basis of alignment design will be to follow best practices of the Japanese and European lines and also the guidance of UIC (International Union of Railways) for railway lines, while also taking into account common American practices and the guidance of the Manual for Railway Engineering of the American Railway Engineering and Maintenance of Way Association (AREMA Manual).

Guidance for the design of alignments in shared used corridors where train speeds will be equal to or less than 125 mph (200 km/h) are provided in the Technical Memorandum 1.1.6 – Alignment Standards for Shared Use Corridors (Specific to Los Angeles to Anaheim). Similar alignment guidance for the Caltrain corridor is under development.

Guidance for turnout geometry will be provided in a separate document.

Guidance for parking, maintenance and siding tracks will be provided in a separate document. However, some information on the location of passing tracks which are parallel to the main tracks is covered in this document.

1.0 INTRODUCTION

This technical memorandum presents the basis of design and alignment criteria for the segments of the California High-Speed Train Project (CHSTP) alignment where high-speed trains are operated on tracks exclusive of other railroads. On these exclusive-use segments, speeds will be above 125 mph with an initial maximum operating speed of 220 mph. The design shall not unnecessarily preclude operation at higher speeds up to at least 250 mph. This technical memorandum is intended to be used in developing the design for the track and alignment. It is anticipated that the design will be advanced consistent with applicable codes of practice, design guidelines and other information that defines the CHSTP programmatic, operational, and performance requirements.

Much of what applies to good railroad alignment at normal speeds of 60 mph to 100 mph applies in the same manner when the design speed is 200 mph, 250 mph, or higher so long as the effects of speed are considered. However, there are a number of “secondary” effects that are minor or unnoticeable at low speeds that do become important as speeds increase. Issues of this nature that affect the alignment will be noted and analyzed in this document.

1.1 PURPOSE OF TECHNICAL MEMORANDUM

The purpose of this Technical Memorandum is to define the geometric design requirements to be used in basic design in order to achieve a safe and reliable operating railway that meets applicable regulatory requirements and achieves CHSTP functional, programmatic, operational, and performance requirements. These standards are intended to promote consistency in the design of the overall CHSTP while recognizing the unique characteristics of the project’s multiple regions.

Conformance with applicable design standards, regulations and guidelines is critical to ensure that deliverables and supporting data will achieve timely acceptance by the CHSRA, FRA, state agencies and private rail railroad operators.

1.2 STATEMENT OF TECHNICAL ISSUE

The general basis of alignment design, as defined in this document, will follow best practices currently used on the design of high-speed railroad systems. Where specific guidance is not provided, the standards described in the Manual for Railway Engineering of the American Railway Engineering and Maintenance of Way Association (AREMA Manual) shall be followed. However, the material presented in the AREMA Manual is defined as “recommended practice” and varies considerably in level of detail and applicability.

The UIC (International Union of Railways) has issued, with the cooperation of Japan, Germany and France, documentation from which many technical issues can be derived. (The Association of American Railroads, Amtrak, and US Department of Transportation are members of the UIC. However, many US legal and customary practices differ significantly from those given in the UIC standards.) More recently, Technical Specifications for Interoperability (TSI) for high-speed railways have been developed by the European Union (EU) to be a set of required standards for all railroad systems in the European Union.

The alignment shall be developed to afford the highest practical speed that can be attained at a given location in accordance with the basis of design performance requirements concerning operating speed. In particular, low speed locations and the need for reduction in speed other than that imposed by the normal acceleration and braking curves into and out of stations shall be avoided.

1.2.1 Definition of Terms

The following technical terms and acronyms used in this document have specific connotations with regard to California HST system.

Attenuation Time — The time required for the vehicle motion to stabilize after crossing a point of change in the nature of the alignment

Degree of Curve — The central angle turned by a curve in 100 feet. It is closely approximated by Dc = 5730 feet / Radius. Railroad curves are defined by the Chord Definition, in which the length is described by a 100 foot long tangent between two points on the arc of the curve. The exact formula for chord definition curves is Dc = 2 * arcsin (50 / Radius)

Design Standard Classifications — The design standards presented in this document will normally be described using three terms:

- Desirable — The standard which shall be equaled or exceeded where there are no constraints on the alignment. Desirable horizontal and vertical standards may be used in any combination.
- Minimum/Maximum — The standard which shall be equaled or exceeded where constraints on alignment make use of Desirable standards impractical or significantly more expensive than if Minimum standards are used. Where Desirable standards are not obtainable, they shall be approached as nearly as practical. Certain combinations of Minimum horizontal and vertical standards shall not be used, or may be used as an Exceptional condition. These are described in this document. Approvals are required when Minimum / Maximum standards are not achieved.
- Exceptional — The standard which shall be achieved at the absolute minimum and only where Minimum standards are either unobtainable or exorbitantly expensive. Where Minimum standards are not obtainable, they shall be approached as nearly as practical. Certain combinations of exceptional horizontal and vertical standards shall not be used. These are described in this document.

Equilibrium Superelevation — The calculated superelevation that exactly balances the lateral force of the train on the curve at the defined speed. Normally called Balancing Cant or Equilibrium Cant in European publications

Exclusive Use Corridor — Segment along the CHSTP alignment where high-speed trains operate exclusive of other passenger railroads. Also, Dedicated Corridor.

Grade, Gradient — The slope of changes in elevation, defined in percentage, as feet of rise in 100 feet. Sometimes defined in European publication as millimeters of rise in one meter, in which case the symbol is normally written as $^{o}/_{oo}$.

Main Line Track — A track for the purpose of movement of high-speed train traffic at normal commercial speed. Scheduled stops of any kind, including station stops, are not normally permitted on Main Line Tracks.

Maintenance Siding — A dead end track dedicated to park maintenance trains and connected to a passing track, never to the main line.

Passing Track — A track connected to the main line on both ends for operating purposes, for example, to deal with delayed train or train with technical incident or to allow train overtaking.

Refuge Track — A dead end track connected to a station track primarily for the purpose of temporary storage of a disabled train.

Shared Track — Segment along the CHSTP alignment where rail operations are conducted by high-speed trains and another railroad on common track.

Design Speed — Maximum permissible speed along a segment of alignment based on the design specification of the track infrastructure, signaling system characteristics, and the maintenance specifications for that class of track.

Operating Speed — The highest in-service speed that is achievable by a trainset technology on a segment of alignment that conforms to all of the requirements specified for that class of track.

Maximum Authorized Speed — The highest speed that is permitted over a specific portion of the railroad. It may be authorized by special instructions of the current timetable, operating rules, or any other publication authorized by the chief operating officer.

Spiral — A curve of variable radius used to connect a straight section of track with the radius of the body of the curve. Sometimes call a Transition or a Transition Spiral in European publications.

- Constant Rate Spiral — The most common type of spiral. The radius increases at a linear rate over the length of the spiral. Commonly called a clothoid.
- Variable Rate Spiral — A spiral with a defined variation in the change of radius, usually in the form of a sine wave curve so as to reduce the entry and exit change in the rate of change. Desirable in high-speed operation, particularly if the track is on a concrete base.

Station Track / Platform Track — A track for the purpose of bringing a train alongside a station platform for a stop to embark / disembark passengers.

Superelevation — The difference in elevation between the outside rail of the curve and the inside rail of the curve measured between the highest point on each rail head. Normally called Cant in European publications.

Track Centerline — The line equidistant between the inside faces of the rail heads of a track.

Track Centers — Distance between adjacent track centerlines.

Unbalance, Unbalanced Superelevation - The difference between the Superelevation and Equilibrium Superelevation. In European publications, Unbalance is called Cant Deficiency if the actual Superelevation is less than the Equilibrium Superelevation and Excess Cant if the actual Superelevation is greater than the Equilibrium Superelevation.

Vertical Curves — The transition between grades are normally parabolic vertical curves in US and Asian practices and circular arc radii in European practices.

Yard Track — Track that is used for the storage, sorting or servicing of train cars.

Acronyms

AAR	Association of American Railroads
AREMA	American Railway Engineering and Maintenance of Way Association
Caltrans	California Department of Transportation
CHSTP	California High-Speed Train Project
CFR	Code of Federal Regulations
FRA	Federal Railroad Administration
GO	General Order
CPUC	Public Utilities Commission of the State of California
SNCF	Société Nationale des Chemins de fer Français (French National Railway Company)
TSI	The European Union’s Technical Specification for Interoperability
UIC	International Union of Railways

1.2.2 Units

The California High-Speed Train Project is based on U.S. Customary Units consistent with guidelines prepared by the California Department of Transportation and defined by the National Institute of Standards and Technology (NIST). U.S. Customary Units are officially used in the United States, and are also known in the US as “English” or “US Customary” units. In order to avoid any confusion, all formal references to units of measure should be made in terms of U.S. Customary Units.

Guidance for units of measure terminology, values, and conversions can be found in the Caltrans Metric Program Transitional Plan, Appendice B U.S. Customary General Primer *(http://www.dot.ca.gov/hq/oppd/metric/TransitionPlan/Appendice-B-US-Customary-General-Primer.pdf).* Caltrans Metric Program Transitional Plan, Appendice B can also be found as an attachment to the CHSTP Mapping and Survey Technical Memorandum.

2.0 DESIGN STANDARDS AND GUIDELINES

2.1 BASIS

The general basis for design standards will be the most applicable of the "recommended practice" described in the Manual for Railway Engineering of the American Railway Engineering and Maintenance of Way Association (AREMA Manual). The material presented in the AREMA Manual varies considerably in level of detail and obsolescence. Therefore, a reference to the AREMA Manual without a more specific designation of applicable chapter and section is not sufficient to describe any requirement.

Certain International Union of Railways documents and the recently developed European Technical Specifications for Interoperability provide guidance in areas where the AREMA Manual is either silent or inapplicable. In addition, there have been a number of previously developed project-specific documents and documents from other sources that are relevant to the alignment design.

2.1.1 Project-Specific Technical References

- California High-Speed Train Project Basis of Design (20 December 2007)
- California High-Speed Train Project Design Criteria (19 March 2007)
- California High-Speed Train Project – Draft Technical Memorandum Design Basis for Turnouts and Pocket Tracks (June 2007)
- California High-Speed Rail Project Working Paper, Japan Railway Technical Service (JARTS) 2007

2.1.2 AREMA Manual

The primary orientation of the AREMA Manual is to provide guidance in the engineering of railroads moving freight at speeds up to 70 mph and passenger trains at speeds up to 90 mph with the exception of the still incomplete Chapter 17, High-Speed Rail Systems.

When using the AREMA Manual, the statement at the beginning of each chapter will assist in understanding the scope, intent, and limitations of this document.

> "The material in this and other chapters in the AREMA *Manual for Railway Enginee*ring 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."

2.1.3 The European Union's (EU) Technical Specifications for Interoperability (TSI)

The Technical Specifications for Interoperability (TSI) are a set of standards required of all railroad systems in the European Union. For high-speed railway systems, they were first published as Council Directive 96/48/EC - Interoperability of the Trans-European High-Speed Rail System. In the countries that are part of the European Union these standards have the force of law. The TSI are defined and published by subject matter, described as "subsystems". Requirements of significance to a specific issue may require search of more than a single "subsystem" document, and much of the information is stated in general terms. Each document ends with a country by country description of specific issues relevant to each of the EU countries.

The various subsystems are classified as either "structural" or "functional" as follows:

Structural Subsystems:

- Rolling Stock
- Infrastructure
- Energy
- Control and command and signaling
- Traffic operations and management

Function Subsystems:

- Maintenance
- Telemantics applications for passenger and freight services.

The TSI that is primarily relevant to this TM is that for the Infrastructure Subsystem, current version dated 19 March 2008 based on a Commission Decision of 20 December 2007.

Application of the TSI requirements to the California High-Speed Train Project must be approached with caution as they are based on the historical and current conditions in Western Europe without consideration of practices prevailing in much of the rest of the world.

The Infrastructure TSI has limited information relative to alignment.

2.1.4 Other Technical References

Recognizing the limitations of the AREMA Manual and the existence of a number of other standards used around the world that have strong experience and theoretical basis in the alignment design of high-speed railroads, the source for some portions of the design requirements can be found in the following other documents:

- Comité Européen de Normalisation – European Committee for Standardization (CEN standard)
- UIC (International Union of Railways) Code 703 – Layout Characteristics of Lines Used by Fast Passenger Trains
- UIC – Design of new lines for speeds of 300 – 350 km/h – State of the art report (October 2001)
- Engineering studies in support of the development of high-speed track geometry specifications IEEE/ASME joint railroad conference (March 1997)
- Taiwan High-Speed Railway Design Manual (2000)
- SNCF – High-speed railway design standards (2007 edition)

2.2 LAWS AND CODES

There is no single law, code or design standard which will produce a high-speed railroad that fits the intended purpose and use anticipated. There are no laws or codes in the United States or the state of California specific to a railroad with operating speeds of over 200 mph. Reference is frequently made to FRA Track Safety Standards which currently "top out" at 200 mph. [It is understood that FRA may be in the process of revising the Track Safety Standards and may reduce the top speed to 150 mph.] These are not design standards in the normal sense. While they have some requirements that affect the design, their primary purpose is safety. In addition to the track condition requirements, there are FRA requirements that apply to the design and construction of a high-speed railroad. For the most part, the FRA requirements are no more restrictive than normal design standards for a high-speed railroad.

In case of differing accepted thresholds or conflicts in the various design requirements and guidelines, the standard followed shall be the one which results in the highest level of satisfaction of all requirements or the one that is deemed the most appropriate.

As much of the CHSTP is likely to be adjacent to or in the general vicinity of existing railroad lines operated by one of California's two major railroad companies, their standards can also affect the design of the CHSTP.

Applicable codes and standards include but are not necessarily limited to the following:

- Requirements of the Federal Railroad Administration (FRA), including:
  - CFR Part 213, Track Safety Standards, generally and in particular, Subpart G -Train Operations at Track Classes 6 and Higher
  - CFR Part 214, Railroad Workplace Safety
- California Public Utilities Commission (PUC) General Orders (GO), including:
  - GO 26: Clearances On Railroads And Street Railroads As To Side And Overhead Structures, Parallel Tracks And Crossings
  - GO 95: Overhead Electric Line Construction. Generally and in particular Section VII, Detailed Construction Requirements for Trolley and Electric Railway contact and Feeder Conductors and Their Supporting Messengers, Span Wires, etc. (Class T Circuits)
  - GO 118: Regulations Governing the Construction, Reconstruction, and Maintenance of Walkways Adjacent to Railroad Trackage and the Control of Vegetation Adjacent Thereto
  - GO 164: Rules And Regulations Governing State Safety Oversight Of Rail Fixed Guideway Systems

While much of the material in these PUC General Orders is not applicable to a high-speed passenger-carrying railroad, there is material that is either applicable by law or useful as guidelines in design.

<u>Other Design Guidelines:</u>

- The Manual for Railway Engineering of the American Railway Engineering and Maintenance of Way Association (AREMA Manual), in particular the following chapters:
  - Chapter 1: Roadway and Ballast
  - Chapter 5: Track
  - Chapter 17: High-Speed Rail Systems
  - Chapter 33: Electrical Energy Utilization
  - Chapter 28: Clearances
- BNSF Railway: Go to www.bnsf.com/tools/fieldengineering for contact information.

  Headquarters address:
  2650 Lou Menk Drive
  Fort Worth, TX 76131-2830
- Union Pacific Railroad: Go to www.uprr.com/aboutup/operations/specs/track/index.shtml for some of their engineering standards.

  See www.uprr.com/reus/roadxing/cross_cal.shtml for the Manager of Industry and Public Projects for guidance to further information.

  Headquarters address:
  1400 Douglas Street
  Omaha, NE 68179-1001

- Southern California Regional Rail Authority (SCRRA)

  700 South Flower Street, 26th Floor
  Los Angeles, CA 90017-4101

- Peninsula Corridor Joint Powers Board (Caltrain): For engineering standards, go to http://www.caltrain.com/engineeringstandards.html
- Caltrans Manuals and Standards, including but not necessarily limited to:
  - Highway Design Manual

The most recent applicable version of the above standards shall be used.

3.0 ASSESSMENT/ANALYSIS

3.1 ALIGNMENT CRITERIA

The alignment of the railroad shall be as smooth as practical with minimal changes in both the horizontal and vertical direction. Appearance, ease of maintenance, and ride quality are all enhanced by a smooth alignment with infrequent and gentle changes in direction. Over four changes in direction per mile shall constitute an Exceptional condition.

All alignment element segments (vertical curves, lengths of grade between vertical curves, horizontal curves, spirals) shall have a minimum length sufficient to attenuate changes in the motion of the rolling stock. This length is defined by the time elapsed over the segment, and therefore varies directly with design speed. Not all systems have the same time requirements. This attenuation time varies from 1.0 to 2.4 seconds, and on the SNCF, up to 3.1 seconds at higher speeds. Segment length requirements will govern only where design considerations for the various elements do not require longer segment lengths.

Vertical and horizontal alignment sections may overlap. Overlap of horizontal spirals and vertical curves shall be an Exceptional condition. Based on European high-speed rail standards, the Minimum distance between the end of a spiral and the beginning of a vertical curve or the end of a vertical curve and the beginning of a spiral is 50 meters (160 feet) with an Exceptional limit of 30 meters (100 feet).

3.1.1 Minimum Segment Length due to Attenuation Time

Attenuation time, based on the most conservative requirements, shall be:

- For V < 300 km/h (Under 186 mph)
  - Desirable attenuation time: not less than 2.4 seconds
  - Minimum attenuation time: not less than 1.8 seconds
  - Exceptional attenuation time: not less than 1.5 seconds
  - An attenuation time of 1.0 seconds on the diverging route in curves adjacent to or between turnouts
- For 300 km/h ≤ V (Over 186 mph)
  - Desirable attenuation time: not less than 3.1 seconds
  - Minimum attenuation time: not less than 2.4 seconds
  - Exceptional attenuation time: not less than 1.8 seconds

Minimum segment length is calculated by the formula: $L_{feet} = V_{mph} \times 44/30 \times t_{sec}$ and $L_m = V_{km/h} / 3.6 \times t_{sec}$. Sample minimum segment lengths are presented in Tables 3.1.1 and 3.1.2.

Table 3.1.1: Minimum Segment Lengths at Various Speeds of 300 km/h (186 mph) and higher

Design Speed		Minimum Segment Lengths for times of							
		3.1 seconds		2.4 seconds		1.8 seconds		1.5 seconds	
miles per hour	km/h	feet	meters	feet	meters	feet	meters	feet	meters
250	400	1137	346	880	268	660	201	550	168
220	355	1000	305	774	236	581	177	484	148
200	320	909	277	704	215	528	161	440	134
186	300	846	258	655	200	491	150	409	125
175	280	796	243	616	188	462	141	385	117
150	240	682	208	528	161	396	121	330	101

Table 3.1.2: Minimum Segment Lengths at Various Speeds of up to 300 km/h (186 mph)

Design Speed		Minimum Segment Lengths for times of							
		2.4 seconds		1.8 seconds		1.5 seconds		1.0 seconds	
miles per hour	km/h	feet	meters	feet	meters	feet	meters	feet	meters
186	300	655	200	491	150	409	125	273	83
175	280	616	188	462	141	385	117	257	78
150	240	528	161	396	121	330	101	220	67
125	200	440	134	330	101	275	84	183	56

Where alignment segments overlap, each change shall be treated as a separate alignment element for the purpose of calculating minimum segment lengths. For example, when there is a vertical curve within the body of a horizontal curve, the parts of the horizontal curve outside of the vertical curve will be treated as separate segments when calculating segment lengths.

3.2 HORIZONTAL ALIGNMENT

Curve radii will depend upon allowable limits in superelevation and unbalanced superelevation. Curves should be set to the largest practical radius and have the lowest practical superelevation and unbalance for the following reasons:

- Lower superelevation required to balance equipment speed
- Lower unbalanced superelevation
- Comfort over a wider range of speeds
- Lower wear on rails and forces on equipment

In locations where train speeds vary considerably, such as near stations, it is recommended that designers increase curve radii significantly above minimum values. This results in lower levels of unbalance, which are less perceptible to riders over ranges of train speed.

Alignments consisting of curves that are at or approaching minimum values of radius and maximum or near maximum values of superelevation and unbalanced superelevation are an indication of a poor quality design.

3.2.1 Superelevation

Design Considerations: The design value of superelevation will be influenced by:

- Maximum Speed Limit
- Calculated normal and maximum speeds of high-speed trains, including both through trains and stopping trains.
- Allowable limits of actual superelevation in track
- Allowable limits of unbalanced superelevation in track

Theoretical Basis: Balancing superelevation can be determined exactly by determining the angle of the plane across the top of rails that would equal the angle from vertical of the vector of centrifugal force and gravity.

Cross slope angle = arctan $(((V_{mph} \times 44/30)^2 / R_{ft}) / 32.174 \text{ ft/sec}^2)$

[32.174 ft/sec^2 being the gravitational constant]

When measuring curves in degrees and applying the center of rail head to center of rail head distance for standard gauge track, this formula becomes the familiar railroad formula of:

$SE = 0.0007 V^2 D$ (curvature in degrees, speed in mph and SE in inches)

Which when expressed with radius instead of degrees gives:

$SE = 4.0\ V^2 / R$ (radius in feet, speed in mph and SE in inches),

Or in metric system units:

$SE = 11.8\ V^2 / R$ (radius in meters, speed in km/h and SE in millimeter)

These formulae are approximate, but the level of approximation is insignificant.

Background Information: Traditionally, superelevation has been limited to 6 inches (152 mm) or less in the US and unbalanced superelevation has been limited to 3 inches (76 mm) However, in the past, higher values have been used by some railroads in order to allow higher passenger train speeds. Currently, superelevation limits are commonly set at 4 inches (101 mm) or less in lines that carry high center of gravity freight and up to 6 inches (152 mm) in lines carrying predominantly passenger traffic.

The highest known design value used in the US was 8 inches (203mm), by the New York Central. That was the value on the 7deg 24min (775 feet radius) curve on which the Lakeshore Limited derailed at a speed of 59 mph (speed limit was 45 mph) at Little Falls, New York in 1940. Seven inches (178 mm) was also used by some other eastern US railroads.

Maximum superelevation values of 160 mm (6¼ inches) to 180 mm (7 inches) are common in passenger carrying lines outside North America. Some systems only allow above 160 mm on slab track. The Shinkansen system maximum is 180 mm but with up to 200 mm ($7^7/_8$ inches) under limited circumstances without reference to type of track construction or train speed.

3.2.2 Unbalanced Superelevation

Practical limits of unbalanced superelevation are based on passenger comfort. Safe limits for unbalance for passenger equipment are significantly in excess of comfort limits. The FRA limits unbalance for US passenger carrying lines to 4 inches (100 mm) and requires a waiver for limits above 3 inches (75 mm). The TSI permits higher limits (varying between 180mm (7 inches) and 130mm (5.1 inches) at speeds under 300 km/h (186 mph). The Shinkansen system allows 110 mm ($4^3/_8$ inches) unbalance without reference to type of track construction or train speed.

Minimum Unbalance: It has been noted by many observations in various places that a train traversing a curve at the balancing speed tends to "hunt" or otherwise track poorly. Therefore, one inch of unbalance should be provided in relation to the normal **operating** speed (not the design speed). In curves where this would result in no actual superelevation, the unbalance and the actual superelevation shall be of approximately the same value. Excessive superelevation, resulting in negative unbalance shall not be used.

3.2.3 Limits for Superelevation and Unbalanced Superelevation

The first of the following tables provide the allowable upper limits for Superelevation plus Unbalanced Superelevation. Radii developed from these limits determine the smallest Desirable, Minimum, and Exceptional radius that is permissible for any given speed.

Table 3.2-1: Maximum Values, Superelevation plus Unbalanced Superelevation

Design Speed		Combined Superelevation and Unbalance					
		Desirable		Maximum		Exceptional	
miles per hour	km/h	inches	mm	inches	mm	inches	mm
<186	<300	6	150	9	230	11	280
≥186	≥300	6	150	9	230	10	250

Table 3.2-2: Maximum Values of Applied Superelevation

Design Speed		Applied Superelevation					
		Desirable		Maximum		Exceptional	
miles per hour	km/h	inches	mm	inches	mm	inches	mm
<186	<300	4	100	6	150	7	180
≥186	≥300	4	100	6	150	7	180

Table 3.2-3: Maximum Values of Unbalanced Superelevation

Design Speed		Unbalanced Superelevation					
		Desirable		Maximum		Exceptional	
miles per hour	km/h	inches	mm	inches	mm	inches	mm
<186	<300	2	50	3	75	4	100
≥186	≥300	2	50	3	75	3	75

Note the change in allowed Exceptional unbalance at 300 km/h. This change is a TSI standard and results in two values being given for radius limits at the speed of 186 mph in the tables in paragraph 3.2.5.

The Maximum Value of Unbalanced Superelevation is lower than the values permitted by TSI in order to achieve the passenger comfort lateral acceleration threshold value of 0.05g that has been established for the project. Note that the Exceptional Unbalanced Superelevation value does not achieve the passenger comfort lateral acceleration threshold value.

3.2.4 Determination of Applied Superelevation and Unbalanced Superelevation

Applied superelevation shall be set to provide the best practical ride quality to the majority of the passengers on the trains passing over the particular curve without violating criteria limits.

The speed to be used at the design stage of the alignment is the system design speed, not the maximum operating speed limit that is planned to be used at the time of start of operations. At the time of alignment design, the real purpose of determining superelevation is to determine the length of spiral to be applied to a particular curve. Thus, the highest anticipated speed, superelevation and unbalanced superelevation shall be used at this stage of the design.

However, in the construction of the track, the superelevation shall be based on the calculated speed on the curve as initially completed. Therefore, the initial superelevation applied to the track may be less than that used in the calculations for appropriate spiral length.

Normal operating practice is based on trains running at slightly less than maximum power and maximum speed so as to provide some allowance to recover lost time. For now, “Normal Speed” shall be considered to be 90% of the calculated maximum speed.

The design value of superelevation will be influenced by:

- Maximum Speed Limit
- Calculated normal and maximum speeds of high-speed trains in each direction
- Where applicable, calculated normal and maximum speeds of high-speed trains slowing for or accelerating from a station stop
- Calculated normal and maximum speeds of other passenger trains (where applicable)
- Minimum unbalance of 1.0 inch (25 mm) in relation to the normal train speed.

Design superelevation shall not exceed the allowable maximum superelevation. Design superelevation shall be calculated for each track. It is neither necessary nor in many locations desirable that both main tracks of the line have the same superelevation on a given curve. Where train speeds differ from the Design Speed, the unbalanced superelevation may be increased up to the Exceptional limit based on the Design Speed if necessary to provide a comfortable unbalance in relation to the actual train speed.

3.2.5 Curvature

Curves should be of a single arc radius. All main track, station track, and yard connection curves shall have spirals. Curves of larger than minimum radii require lower amounts of superelevation, therefore providing a comfortable ride over a wider range of speeds. Alignments consisting of curves that are all at or approaching minimum values are an indication of a poor quality design. In the cases where there will be significant variability in train speeds, larger radii are preferred to reduce the ride quality issues due to superelevation and unbalanced superelevation effects that occur with variation between design speed and actual speed of trains on the curve.

Curve radii standards provide “Desirable”, “Minimum”, and “Exceptional” values. However, even the desirable figures can be improved upon. A desirable radius is one that is larger than the standard radii if at all practical, for larger radii are better.

Curve radii are determined according to the superelevation limits given in Section 3.2.2. Tables 3.2.1 and 3.2.2 summarize Desirable, Minimum and Exceptional limits on superelevation that are used to develop the following minimum radius tables, Tables 3.2.4, 3.2.5, and 3.2.6. Two values for 186 mph (300 km/h) is a result of the break in allowable unbalance in the TSI requirements.

Table 3.2.4: Minimum Curve Radii

Design Speed		**Minimum Radii Based on Superelevation Limits**					
		Desirable		Minimum		Exceptional	
miles per hour	km/h	feet	meters (rounded)	feet	meters (rounded)	feet	meters (rounded)
250	400	45,000	13,700	28,000	8,500	25,000	7,600
220	355	35,000	10,700	22,000	6,700	19,500	6,000
200	320	30,000	9,200	18,000	5,500	16,000	4,900
186	300	25,000	7,600	16,600	4,700	14,000	4,250
<186	<300	25,000	7,600	16,600	4,700	12,600	3,850
175	280	22,000	6,700	14,000	4,200	11,200	3,400
150	240	16,000	4,900	10,000	3,100	8,200	2,500
125	200	10,500	3,200	7,000	2,100	5,700	1,750

For those used to working in degrees of curve (railroad definition), the following degrees of curvature may be used as substitute values for the radii given in Table 3.2.4. Please note that the values in Table 3.2.5 are not exact conversions of the radii given in Table 3.2.4, but are convenient values for degree of curve limits for the same speed standards.

Table 3.2.5: Minimum Degree of Curve

Design Speed		Minimum Curve in Degrees, degree, minutes, seconds		
miles per hour	km/h	Desirable	Minimum	Exceptional
250	400	0d 07m 30s	0d 12m 15s	0d 13m 30s
220	355	0d 09m 45s	0d 15m 30s	0d 17m 30s
200	320	0d 11m 15s	0d 19m 00s	0d 21m 15s
186	300	0d 13m 45s	0d 21m 30s	0d 24m 30s
<186	<300	0d 13m 45s	0d 21m 30s	0d 27m 15s
175	280	0d 15m 30s	0d 24m 30s	0d 30m 30s
150	240	0d 21m 15s	0d 34m 15s	0d 41m 45s
125	200	0d 32m 30s	0d 49m 00s	1d 00m 00s

Should values for other speeds be needed, they can be calculated using the information available in this Technical Memorandum. In the cases where there will be significant variability in train speeds, larger radii are preferred for any speed in order to reduce problems with ride quality due to superelevation and unbalanced superelevation effects.

Curves with Small Central Angles: For small central angles, the radius shall be sufficiently large to provide the time-based minimum arc and spiral segment lengths. There is no maximum radius requirement or desirable maximum for radius. In general, larger radii are preferable to smaller radii as the superelevation and unbalance values become smaller. A radius should be selected that results in the length of the simple curve portion being about equal to or longer than the length of spiral. Since each portion is an alignment segment, if each segment is equal in length, the entire curve with spirals should have a minimum length not less than three times the Minimum Segment Length given in Table 3.1.1 or 3.1.2, as appropriate for the design speed. Double spirals or curves with long spirals and short arc lengths shall not be used.

Low Speed Curves: Standards relating to minimum allowed curve radius and the relationship between curves in low speed tracks will be covered in other documents.

3.2.6 Spiral Types and Application to Curves

3.2.6.1 Background Discussion and Theory

Traditionally the spirals used on railroad curves have been designed with a linear rate of change in both radius and superelevation with length. For degree definition curves, the radius and superelevation both increase linearly from zero at the TS (tangent to spiral) point to full value at the SC (spiral to curve) point and decreases linearly between CS (curve to spiral) and ST (spiral to tangent) at the other end of the curve. When defining the curve by radius, the reciprocal of radius changes linearly, from R = infinity (1/R = 0) at the TS or ST points to the full radius at the SC or CS point.

In normal American practice, when spirals in track are laid out and maintained, the rate of change is reduced at their ends. This arrangement is seldom properly mathematized. An example of the normal situation may be seen in the discussion on String Lining of Curves in the AREMA Manual, Chapter 5, Part 3.2. In particular, note in Figure 3.2 - Platting Mid-Ordinates that in the final adjustment there is a curve in the plot of values of mid-ordinates at the transitions from straight to spiral and spiral to curve. In ballasted track, this non-mathematical feathering in and out is sufficient to provide good ride quality. Even in non-ballasted track, a limited amount of non-linearity occurs at spiral ends due to the stiffness of the rail.

As speeds increase, so does the need for a designed transition into and out of the spiral in order to reduce the entry and exit jerk. This “transition into the transition” is also described in UIC 703, in that allowable transition rates for linear spirals decrease with increasing speed. There are several types of these variable rate transition curves, the most common being either a sine wave form or a modification to the ends of a constant rate of change spiral.

The speed above which the change from straight rate of change to variable rate of change spirals should be made varies from system to system, generally in the 60 mph to 100 mph range.

Japanese Shinkansen lines require the use of variable rate spirals for all tracks having speeds above 100 km/h (62 mph). They use the "half-sine" Spiral for their variable rate spirals.

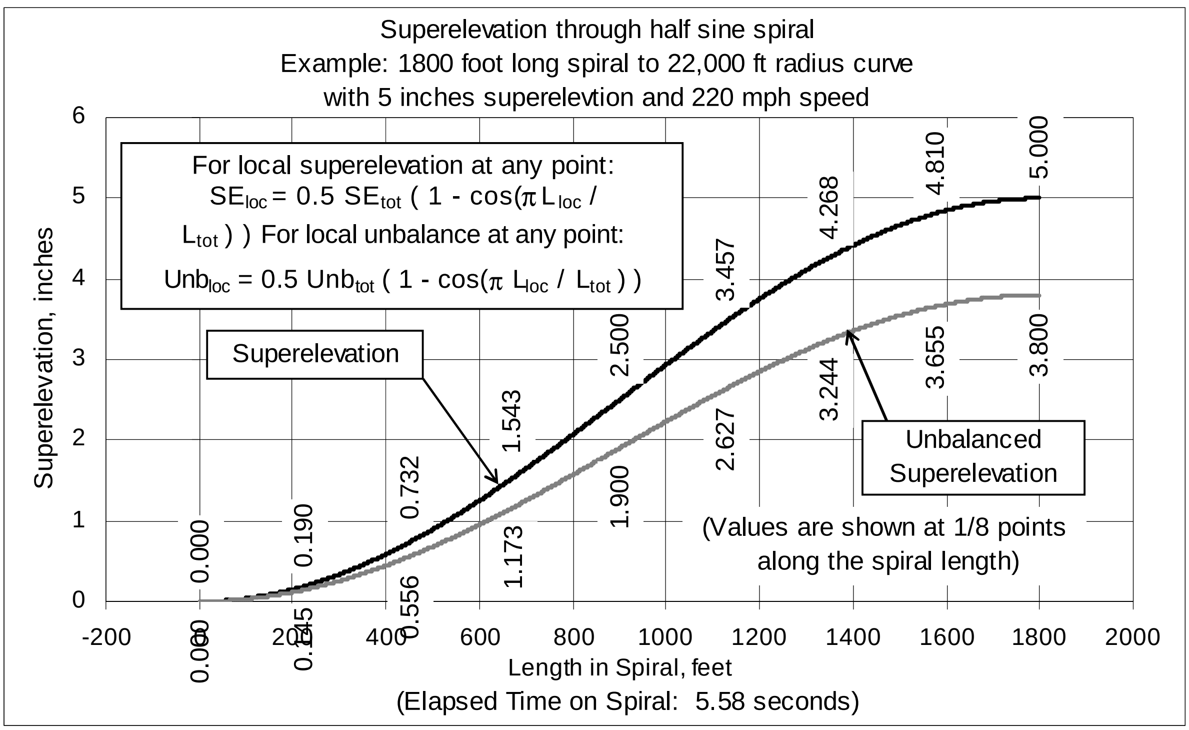
The French Railways (SNCF) uses constant rate of change clothoid spiral but applies a transition at the ends called a "doucine." The set length is 40 meters on TGV lines and 20 meters on lower speed lines. Doucines appear to be a high-speed version of the traditional American "stringline" method of reduction in rate of change of radius and superelevation at the ends of spirals.

Other systems using variable rate spirals have set higher minimum speeds for their use, up to as high as 160 km/h (100 mph).

Figures 3.2-1 through 3.2-6 illustrate the differing characteristics of the two types of spirals. For purposes of illustration, a 22,000 feet radius curve was selected and the appropriate desirable length spiral applied. The design is based on the initial operating speed of 220 mph, 5 inches of superelevation and a calculated 3.8 inches unbalanced superelevation.

First: Three charts illustrating the attributes of a half sine spiral.

Figure 3.2-1: Transition of Superelevation through the Half-Sine Spiral



Note: In Figure 3.2-1, the angle calculated by $\pi(L_{loc}/L_{tot})$ is in radians

Figure 3.2-2: Transition Rates with Time Through the Half-sine Spiral – Relative to Superelevation

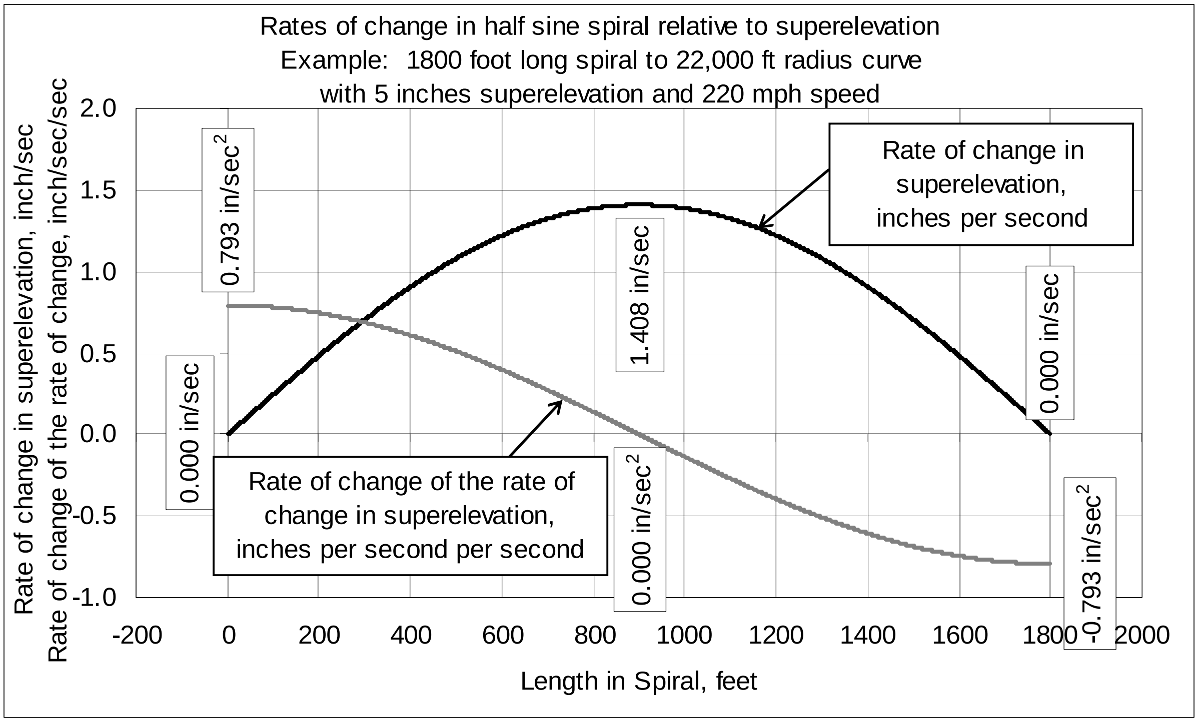
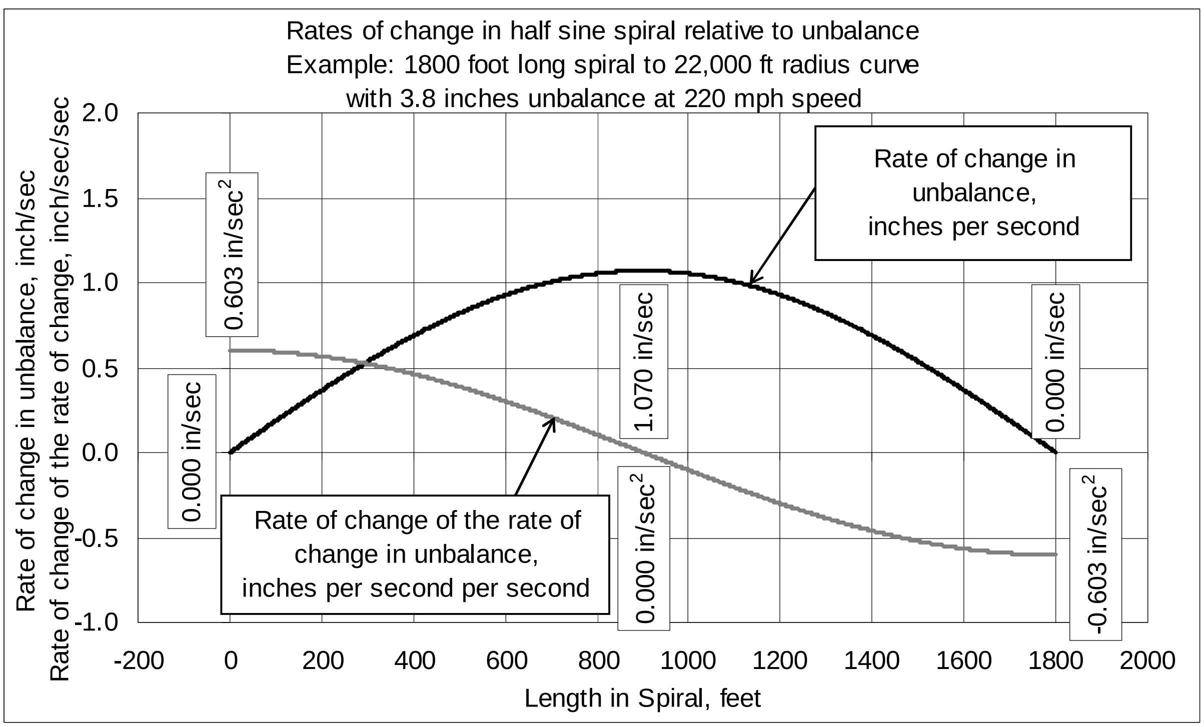


Figure 3.2-3: Transition Rates with Time Through the Half-sine Spiral – Relative to Unbalance



Next: Three charts illustrating the attributes of a clothoid (linear rate of change) spiral for the same curve conditions.

Figure 3.2-4: Transition of Superelevation through the Clothoid Spiral:

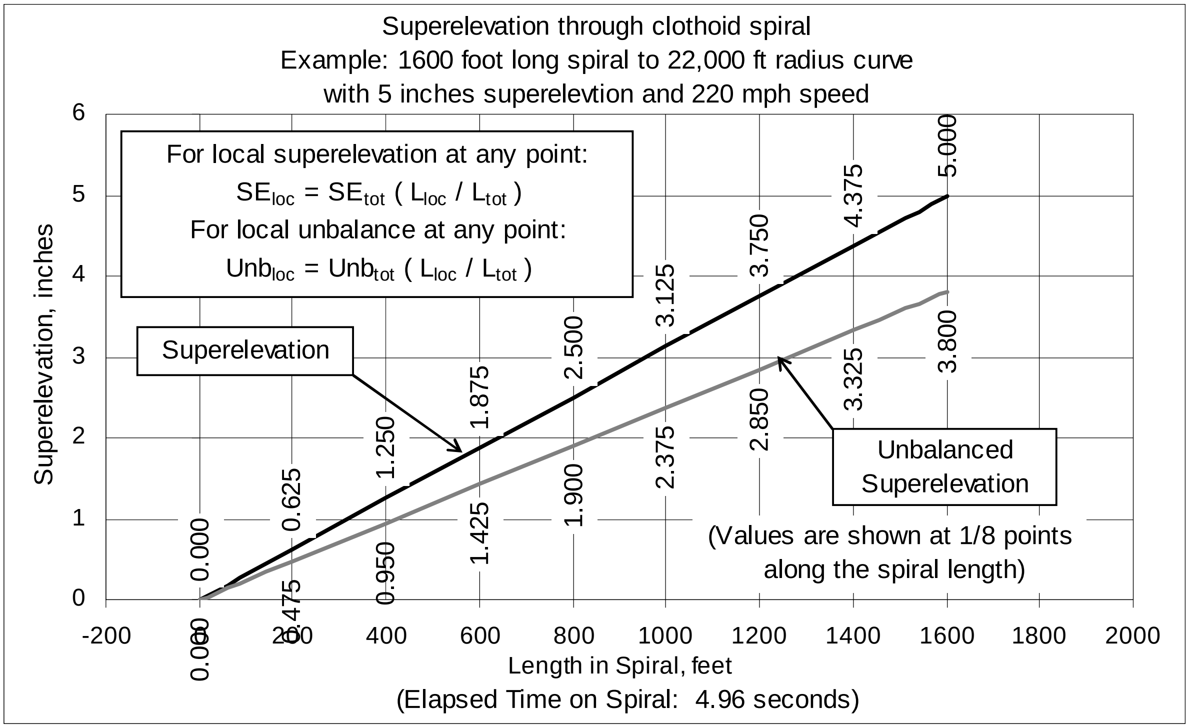


Figure 3.2-5: Transition Rates with Time Through the Clothoid Spiral – Relative to Superelevation

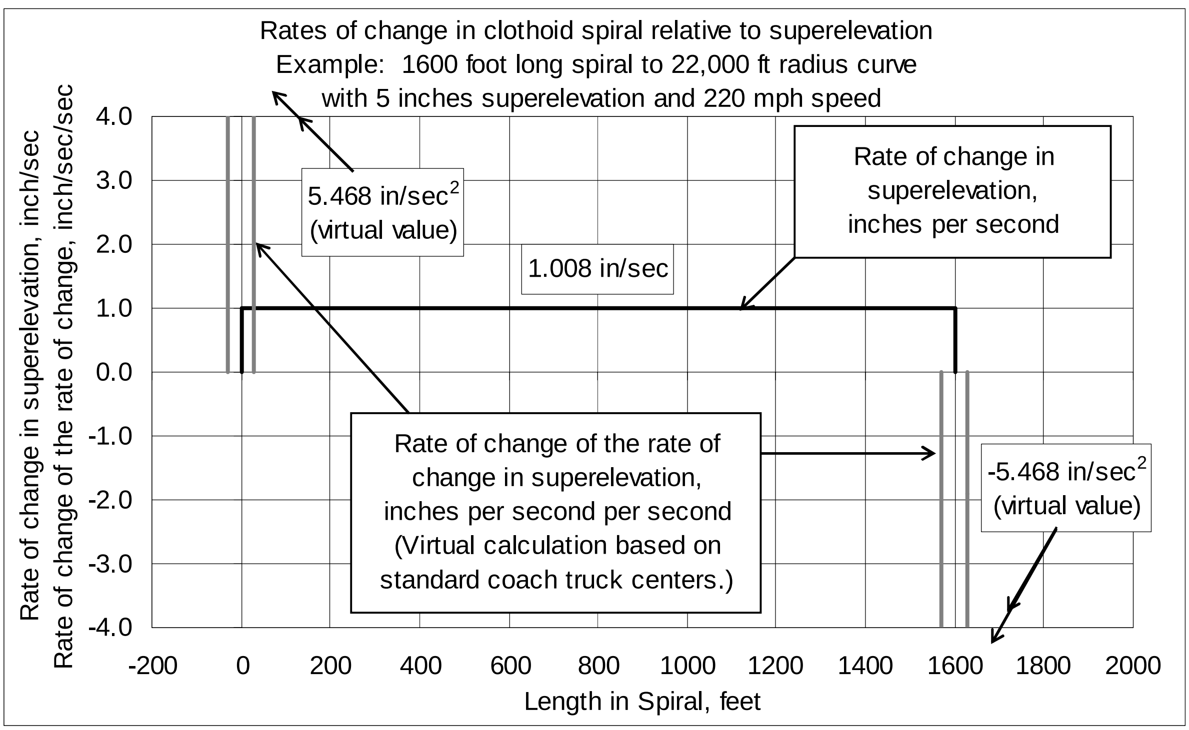
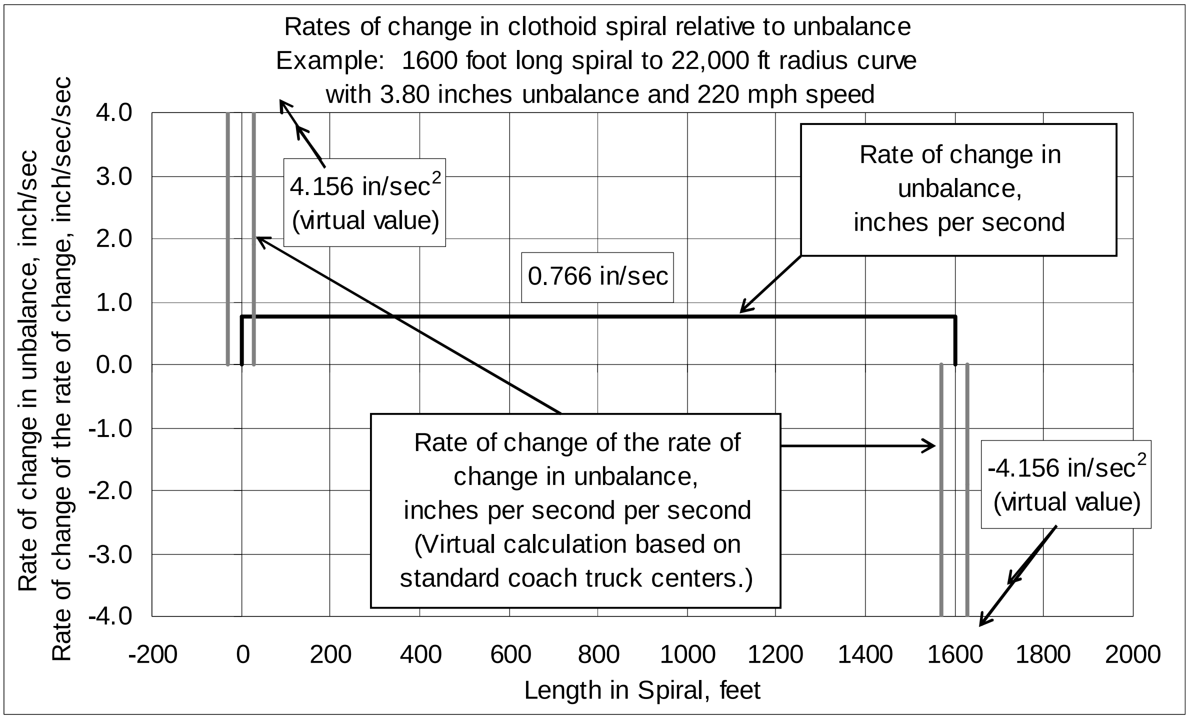


Figure 3.2-6: Transition Rates with Time Through the Clothoid Spiral – Relative to Unbalance



Note that the transition rate at the beginning and ending of the clothoid (constant rate of change) spiral becomes very high as speeds increase, as it occurs over a fixed length, which means that with increasing speed it must occur at a faster and faster rate with increasing speed.

Conclusion: In order to keep the "transition into the transition" to reasonable levels, Variable rate (Half-Sine) spirals shall be used on all high-speed curves, as defined in Section 3.2.6.2.

3.2.6.2 Application of the Two Types of Spirals and Spiral Formulae

In ballasted tracks a certain amount of "transition into the transition" naturally occurs with the normal maintenance processes. In concrete slab supported tracks this "transition into the transition" cannot occur. Therefore, it is desirable to change from constant rate spirals to variable rate spirals at a lower speed where using concrete base trackforms. For concrete base trackforms, the point of change will be set in accordance with Japanese Shinkansen practice. For ballasted track, a higher speed may be used.

Half-Sine Spirals (variable rate transitions) shall be used on all tracks designed for:

- Ballasted tracks: Curves having design maximum speeds of 80 mph or more
- Non-ballasted tracks: Curves having design maximum speeds of 60 mph or more
- Curves associated with turnouts having design maximum speeds of above 110 mph

Clothoid Spirals (constant rate transitions) shall be used on all lower speed tracks. Clothoid spirals may also be used on very large radius curves that require small amounts or no superelevation and have very small unbalanced superelevations, as described below under special situations.

Nature of the Internal Transitions in the Two Spiral Types:

Half Sine Spiral (Angles in these formulae are in radians.):

Local Radius through the Spiral:

$$R_{loc} = 2\,R_{curve} / (1 - \cos(\pi\ l_{loc} / L_{tot}))$$ **Local**

Superelevation through the Spiral:

$$SE_{loc} = 0.5\ SE_{curve}\ (1 - \cos(\pi\ L_{loc} / L_{tot}))$$

Clothoid Spiral:

Local Radius through the Spiral:

$$R_{loc} = R_{curve} / (L_{tot} / L_{loc})$$

Local Superelevation through the Spiral:

$$SE_{loc} = SE_{curve}\ (L_{loc} / L_{tot})$$

3.2.6.3 Determining Spiral Lengths

The length of the spiral shall be the longest length determined by calculating the various length requirements, which are:

- Length needed to achieve Attenuation Time
- Length determined by allowed rate of change in superelevation
- Length determined by allowed rate of change in unbalanced superelevation
- Length determined by limitation on twisting over vehicle and truck spacing length

The allowed rate of change in superelevation has a low speed floor determined by the allowed twist in the vehicle. Historically, this has been set at one inch in 62 feet in American track, which is a ratio of 1:744, which also appears to be within the operational capabilities of all known high-speed equipment. At higher speeds, the rate of rotation of the vehicle determines length of spiral in relation to actual superelevation. Generally this has been expressed in the change in superelevation per second of time at the design speed. Normal American practice for this element has been a rate of 1.25 inches per second. European practice usually allows faster rates of change, but Japanese practice is very close to American practice. Ride quality across the higher rate European-theory clothoid spirals indicates that a rate somewhat faster than 1.25 inches per second can still provide an acceptable ride quality.

Rate of change in unbalanced superelevation for passenger comfort is based on lateral acceleration. Passenger ride comfort studies done many years ago in the US recommended a rate of 0.03 g, with 0.04 g being considered permissible. Again, it is found that higher lateral accelerations up to 0.05 g have been used in European practice, but not in Japanese practice.

Spiral type selected shall be as described in the preceding section. Required Spiral Length shall be the greatest of the length determined by calculating the required length for each requirement using the formulae in Table 3.2.6.

Table 3.2.6: Minimum Length of Spiral

Clothoid (Linear Change) Spirals			
Spiral Design Factor	Desirable (0.03 g)	Minimum (0.04 g)	Exceptional (0.05 g)
Superelevation	1.47 Ea V	1.17 Ea V	0.98 Ea V
Unbalance	1.63 Eu V	1.22 Eu V	0.98 Eu V
Twist	90 Ea	75 Ea	62 Ea
Minimum Segment	2.64 V	2.20 V	1.47 V
Half-Sine (Variable Change) Spirals *			
Spiral Design Factor	Desirable	Minimum	Exceptional
Superelevation	1.63 Ea V	1.30 Ea V	1.09 Ea V
Unbalance	2.10 Eu V	1.57 Eu V	1.26 Eu V
Twist **	140 Ea	118 Ea	98 Ea
Minimum Segment	2.64 V	2.20 V	1.47 V

The length is given in feet with:

- Ea = Actual elevation in inches
- Eu = Unbalanced elevation in inches
- V = maximum speed of the train in mph

* Longer lengths of half-sine spirals are due to the variability in the ramp rate.

** Provides maximum twist rates identical to clothoids. As a practical matter, this limitation never governs as this type spiral is only on high-speed tracks.

After calculation and selection of length based on the governing requirement, the spiral length should be rounded to a convenient value for further calculation and use in the alignment. Rounding may be either up or down for "Desirable" values so long as the downward rounding does not reduce any of the required desirable lengths by more than 5.0%. Rounding may be either up or down for "Minimum" values so long as the downward rounding does not reduce any of the required minimum lengths by more than 1.0%. Rounding shall only be in the upward direction for "Exceptional" values.

Spirals on Large Radius Curves: Clothoid spirals may be used instead of half-sine spirals regardless of track type or design speed if the following conditions are met: The required superelevation and unbalanced superelevation are both under 1.0 inches at the maximum design speed; and the "Minimum Segment" length for the spiral is more than twice the length required by any other spiral design length factor. Spirals may be omitted if the following conditions are met: The required superelevation is zero (balancing superelevation for the maximum speed less than 0.75 inches); and the calculated offset of the curve due to application of the spiral is less than 0.05 feet in ballasted track or less than 0.02 feet in non-ballasted track. *(These values are subject to revision.)*

Reverse Curves: If there is insufficient distance between curves to provide the minimum required length tangent segment, the spirals shall be extended to provide a reversing curve. If beneficial to design and construction, a straight distance between curves that would be run in less than 0.2 seconds at the normal operating speed may be left between spiral ends.

3.2.6.4 Sample Calculation

Determine the spiral length for a 50,000 foot radius curve in the main line portion where the design speed will be 250 mph and the initial operating speed limit will be 220 mph, and located where it will not be affected by lower speeds of some or all trains due to acceleration, braking, or grades.

At 250 mph, balancing superelevation will be 5.00 inches. The 90% speed is 225 mph, which balances at 4.050 inches.

At 220 mph, balancing superelevation will be 3.872 inches. The 90% speed is 198 mph, which balances at 3.126 inches.

Spiral Length will be based on 3.00 inches superelevation and 2.00 inches unbalance for the 250 mph situation.

Since the initial maximum operating speed will be 220 mph, the actual installed superelevation upon opening will be 2.125 inches, giving an initial unbalance of 1.001 inches. Since it is impractical to change spiral length, the spiral length will not be based on this 220 mph design, but shall be determined based on the 250 mph design speed.

The Spiral type will be Half-Sine

Desirable Design Factors, based on 250 mph:

Superelevation: 1.63 Ea V = 1.63 x 3.00 x 250 = 1222.5 feet

Unbalance: 2.10 Eu V = 2.10 x 2.00 x 250 = 1050 feet

Obviously, neither twist nor minimum segment length need be considered for this spiral.

Select a Length of **1,200 feet** for this spiral. (less than 1.9% under the calculated length.)

3.3 VERTICAL ALIGNMENT

3.3.1 Grades

The railroad alignment shall be designed to have the smoothest practical profile while optimizing earthwork, structures, tunnels and drainage. Grades shall be as low as practical. Where grades do occur, they should be of the same slope from bottom to top where practical. Use of multiple short grades and multiple changes in grade within any particular change of elevation ("sawtooth profiles") are to be avoided to the greatest extent practical. In addition to increasing operational costs and difficulty by requiring frequent changes in power, a line with multiple changes in grade is aesthetically unappealing. As a check on the reasonableness of the profile developed, it shall be drawn up at a highly condensed horizontal scale so that the vertical changes are exaggerated. Otherwise, the alignment can appear deceptively smooth.

On the California High-Speed line, following grades are to be used:

- Desirable Grades shall be as low as reasonably practical, with a limit of 1.25%
- Maximum Grades: above 1.25% and shall be as low as practical up to 2.50
- Exceptional Grades: above 2.50% and shall be as low as practical up to 3.50%

Minimum Grade in Cut and Tunnel Sections: Low points and very flat grades should not be used in cuts or tunnels (including cut-and-cover) due to drainage considerations. Should a grade of at least 0.25% not be practical, a drainage system in addition to the normal track side facilities shall be provided. Drainage system requirements are described in a separate technical memorandum.

Limitations on Length of Grades: Where the terrain permits, long grades steeper than the following shall not be used due to limits of braking capability of some of the proposed train sets:

- The average grade for any 6 km (3.7 mile) long section of the line shall be under 3.5%
- The average grade for any 10 km (6.2 mile) long section of the line shall be under 2.5%.

Limitations of Grade at Power Supply Phase Breaks: In European practice, due to catenary and signaling constraints, it is desirable to limit grades to 0.60% for 600 m (2,000 feet) on each side of a phase break. The need for this constraint and its locations shall be confirmed in consultation with the development of design standards for the electrification system.

Limitations of Speed on Grades: In European practice, speed on downgrades is constrained by train set braking limitations. The restriction is based on the average grade over any continuous length of 5,200m (17,100ft) along the line. The following speed limits for different grades are as determined in accordance with French standards:

- Grade between 3.0% and 3.5%: Vmax = 230 km/h (143 mph)
- Grade between 2.2% and 3.0%: Vmax = 270 km/h (168 mph)
- Grade between 1.6% and 2.2%: Vmax = 300 km/h (186 mph)
- Grade between 0.0% and 1.6%: Vmax = 350 km/h (217 mph)

3.3.2 Vertical Curves

3.3.2.1 Normal US Practice

Normal US practice in both highway and railroad work is to use parabolic vertical curves. Hickerson's Route Surveying text, Route Location and Design, states simply, "Parabolic curves, owing to their easement qualities and adaptability to the method of offsets, are used exclusively for vertical curves connecting highway and railroad grade profile tangents." The AASHTO guide, A Policy on Geometric Design of Highways and Streets provides a little more detail, "For simplicity the parabolic curve with an equivalent vertical axis centered on the vertical point of intersection (VPI) is usually used in roadway profile design. The vertical offsets from the tangent vary as the square of the horizontal distance from the curve end (point of tangency)."

In railroad alignment, vertical curves are normally defined by the change in grade per 100 feet of length. This is the inverse of the usage in highway work, where the definition is the length required for a one percent change in grade, due to roadways normally having much shorter vertical curves.

3.3.2.2 Normal European and Japanese Practice

Normal European practice in both highway and railroad work is to use circular radius vertical curves. Consequently, European high-speed railways are normally designed and built with circular vertical curves.

The radius of the curve at the crest or sag is rounded to the nearest 100m (350 ft) and determined in accordance with the vertical acceleration permitted for passenger comfort and the maximum design speed of the line.. The formula in metric units is: **$R_{min} \geq (V/3.6)^2 / av$**, where R is in meters, V in km/h, Vertical acceleration (av) in m/s^2 and the 3.6 factor is necessary for the km/h to m/s conversion. The formula in US Customary units would be: **$R_{min} \geq (V*44/30)^2 / av$**, where R is in feet, V in mph, Vertical acceleration (av) in feet/sec^2 and the 44/30 is necessary for the mph to ft/sec conversion.

European high-speed lines reportedly do not use curves with radius over 40,000m (131,234 feet radius, or a rate of change 0.0762% per 100 feet) due to maintainability concerns.

In SNCF practice, it is unnecessary to provide a vertical curve between two gradients when the difference in gradient is less than or equal to 0.1% or 1mm/m, even for design speeds of 350 km/h (217 mph).

Normal practice in Japan and Taiwan is to use Parabolic Vertical Curves. Even though the vertical curves on the Taiwan High-Speed Railway were defined by radius, they were designed and constructed as parabolas, as the preliminary design was by European engineers and the final design and construction was by Taiwanese, Japanese, and American engineers.

3.3.2.3 Comparison between American, European, and Other Vertical Curve Design Practices

The difference in elevation between elevations calculated by the two types of curves as laid out is slight, usually under $^1/_8$ inch (3 mm) at any point on the curve.

Differences in maximum vertical curve radius requirements, or in US Customary railroad terminology, minimum rate of change requirements:

- It is reported that European measuring systems and maintenance practices are incapable of measuring vertical curves with radii of over 40,000 meters (0.0762% grade change per 100 feet), therefore vertical curves longer than this rate of change are prohibited.
- Rates of change down to 0.05 percent per 100 feet (Radius = 60,100 m) have been used in the US for many years without any maintainability issues ever being raised.
- The AREMA Manual states simply, "Vertical curves should be designed as long as physically and economically possible."
- The Taiwan High-Speed Railway has multiple vertical curves with radii of 100,000 meters to 300,000 meters (rate of change of 0.03 %/100ft to 0.01 %/100ft).
- It is anticipated that the high-speed tracks will be of some form of concrete slab-type construction with ballasted track used only in areas of potential ground instability. Therefore, even if the limitations of European maintenance machinery were of concern, they will not be an issue due to the predominance of slab track construction.
- **Conclusion on Length/Radius:** No upper limit needs to be set on vertical curve length/radius.

The relationship between vertical curves defined by radius and vertical curves defined by rate of change is as follows:

- Rate of change, %/100 feet = 3048% / Radius in meters
- Radius in meters = 3048% / (%/100 feet)
- Example: 40,000 meters: 3048% / 40,000 = 0.0762 percent per 100 feet
- Rounding: If a 40,000 m radius is desired, then a rate of change of 0.075 percent per 100 feet or less would be a reasonable value to use to determine the length of vertical curve.

Conclusion on type of Vertical Curve: Parabolic vertical curves shall be used in order to be in line with common US practice.

The speed-based formula for vertical curve length in the AREMA Manual provides a length of vertical curve that is equivalent to one based on change in grade and radius derived by using the vertical acceleration based formula.

In line with common US railroad practice, the length of vertical curves shall be rounded to the nearest 100 foot increment where practical.

3.3.2.4 Vertical Curve Design – Acceleration Rate and Curve Length

Vertical curves for passenger trains are set so as to provide a comfortable vertical acceleration rate. At low speeds, there is a minimum radius / maximum rate of change based on vertical angles at vehicle ends and undercar clearances. These factors do not apply to vertical curves designed for high-speed. The very low rate of change used in tracks carrying freight trains is due to the need to minimize in-train longitudinal forces.

Vertical acceleration limits have been set as low as 2.0% of gravity and as high as 6.0% of gravity. The SNCF standards are highest. However there have been complaints of noticeable ride quality issues with these higher values. Since crest vertical curves reduce the vertical component of the train load, high acceleration rates on vertical curves are to be avoided where horizontal curve will have high superelevation or high unbalanced superelevation.

Current AREMA recommendations for vertical curves are for a vertical acceleration of 0.6 ft/sec/sec for passenger service, which is 1.86% of gravity and a vertical acceleration of 0.1 ft/sec/sec for freight service, which is 0.31% of gravity. However, the continued use of a fixed rate of change of not greater than 0.05% per 100 feet in sags and 0.10% per 100 feet in summits is generally preferred along alignments that are located adjacent to where long freight trains are operated.

The acceleration values to be used for vertical curves shall be:

- Desirable: 0.60 ft/sec/sec (1.86 percent of gravity)
- Minimum: 0.90 ft/sec/sec (2.80 percent of gravity)
- Exceptional: 1.40 ft/sec/sec (4.35 percent of gravity)

The acceleration values are achieved by using the following AREMA Manual based formulae. The 2.15 factor is a constant necessary to unit conversions within the US Customary measuring system.

Vertical curve lengths on lines carrying high-speed trains only shall be:

- Desirable VC Length: The longer of $LVC_{feet} = 4.55\ V$ (for 3.1 seconds) or $LVC_{feet} = 2.15\ V^2\ (\Delta\% / 100) / 0.60\ ft/sec^2$, but not less than 400 Δ%
- Minimum VC Length: The longer of $LVC_{feet} = 3.52\ V$ (for 2.4 seconds) or $LVC_{feet} = 2.15\ V^2\ (\Delta\% / 100) / 0.90\ ft/sec^2$, but not less than 200 Δ %
- Exceptional VC Length: The longer of $LVC_{feet} = 2.64\ V$ (for 1.8 seconds) or $LVC_{feet} = 2.15\ V^2\ (\Delta\% / 100) / 1.40\ ft/sec^2$, but not less than 100 Δ %
- The speed used in the preceding formulae shall be no less than 250 mph, except where other alignment factors such as speed limiting curves exist. In those locations, a lower speed equal to or higher than the maximum anticipated achievable train speed may be used to calculate the required vertical curve lengths. At 250 mph, these formulae give:
  - Desirable VC Length: $LVC_{feet} = 2250\ \Delta\%$
  - Minimum VC Length: $LVC_{feet} = 1500\ \Delta\%$
  - Exceptional VC Length: $LVC_{feet} = 970\ \Delta\%$

The following tables illustrate the relationship between the various methods of calculating vertical curves. All values are rounded.

Table 3.3.2-1: Desirable Vertical Curves –
Rates of Change and Equivalent Radii (0.60 ft/s^2 = 1.86% g)

Speed mph	Speed km/h	% change per 100 feet	feet per % of change	Radius feet	Radius meters
300	480	0.030%	3250	325,000	100,000
250	400	0.045%	2250	225,000	70,000
220	355	0.060%	1750	175,000	53,000
200	320	0.070%	1450	145,000	44,000
175	280	0.090%	1100	110,000	33,000
150	240	0.120%	810	81,000	25,000
125	200	0.175%	560	56,000	17,000

Table 3.3.2-2: Minimum Vertical Curves – Rates of Change and Equivalent Radii (0.90 ft/s^2 = 2.80% g)

Speed mph	Speed km/h	% change per 100 feet	feet per % of change	Radius feet	Radius meters
300	480	0.045%	2150	215,000	66,000
250	400	0.065%	1500	150,000	46,000
220	355	0.085%	1160	116,000	36,000
200	320	0.100%	960	96,000	30,000
175	280	0.130%	740	74,000	22,500
150	240	0.180%	540	54,000	16,500
125	200	0.260%	375	37,500	11,500

Table 3.3.2-3: Exceptional Vertical Curves – Rates of Change and Equivalent Radii (1.4 ft/s^2 = 4.35% g)

Speed mph	Speed km/h	% change per 100 feet	feet per % of change	Radius feet	Radius meters
300	480	0.070%	1400	140,000	43,000
250	400	0.100%	970	97,000	30,000
220	355	0.130%	750	75,000	23,000
200	320	0.150%	620	62,000	19,000
175	280	0.200%	480	48,000	15,000
150	240	0.250%	350	35,000	11,000
125	200	0.400%	250	25,000	7,500

The lengths developed in the preceding tables and formulae are the shortest allowed lengths for each scenario. Vertical curve lengths shall always be rounded up, usually to an even 100 feet multiple. Rate of change and other parameters shall then be derived from that length.

Where the difference between gradients is small, the minimum segment length requirements described in Section 3.1.1 shall determine the minimum length of vertical curve. Rate of change, radius and other parameters of the vertical curve shall then be derived from the length.

3.3.3 Vertical Curve / Horizontal Curve Combinations

Vertical and horizontal curves can overlap. Crest vertical curves result in a downward acceleration of the vehicle, thereby reducing the gravitational effect. This reduction is small but not insignificant for the vertical curve rates of change permitted in this document. A reduction of 0.25 inches for limiting and 0.50 inches for exceptional unbalanced is sufficient to allow for this effect.

3.3.4 Other Vertical Curve Restrictions

It is neither practical nor possible to provide a set of rules that cover all situations. It is anticipated that the information in this document will be applied with good engineering judgment.

Vertical Curves in Spirals: Due to potential maintenance difficulties, it is desirable to avoid use of vertical curves in spirals. The desirable distance between end of spiral and beginning of vertical curve or end of vertical curve and beginning of spiral is 160 feet (50 m) with a minimum limit of 100 feet (30m). Overlap between vertical curves and spirals may be permitted as an Exceptional condition, but only where it can be shown that practical alternatives have been exhausted.

4.0 SUMMARY AND RECOMENDATIONS

The primary objective in setting alignment is to develop the smoothest practical alignment within the limitations imposed by location of stations, urban areas, mountain crossings and major stream crossings as well as environmental and political constraints. It is also important to consider the optimization of earthworks movement, tunnel length, drainage and structures. The radii of horizontal curves, in particular, should be larger than "Desirable" values wherever it is practical to do so. Going below "Desirable" values for the various portions of the alignment should not be treated lightly. Very seldom will an alignment as finally designed and built be better than that set out initially. Quite frequently points will be "locked in" very early in the study process. This is particularly true for the horizontal component of alignment.

Use of Minimum and Exceptional values should be held back to the greatest extent practical for use in the adjustments due to unanticipated constraints that will always occur.

It is very easy to get into a "can't see the forest for the trees" situation. At frequent intervals the designer should step back and look at things globally. This, in particular, means plotting condensed profiles, and looking at the layout over long segments. When transitioning from low speed areas to high-speed areas, consider the operating characteristics of both presently available trains and characteristics of trains with anticipated improvements in power, acceleration and braking. Sudden jumps in speed do not happen with trains.

There should be a relationship between horizontal and vertical alignment standards. For example, there is no point in using vertical curves designed for 250 mph which are adjacent to curves or other constraining elements that permanently restrict speeds to a much lower value. However, the speed used in developing vertical curves should never be lower than that possible under "Exceptional" conditions on adjacent horizontal curves.

It is not possible for this document to anticipate all eventualities, nor to be a textbook in alignment design practices, nor is it intended to be used as a substitute for good engineering judgment.

5.0 SOURCE INFORMATION AND REFERENCES

1. Manual for Railway Engineering of the American Railway Engineering and Maintenance of Way Association (AREMA Manual)
2. Federal Railroad Administration Code of Federal Regulations (CFR)
3. CFR Part 213, Track Safety Standards, generally and also in particular Subpart G—Train Operations at Track Classes 6 and Higher
4. CFR Part 214, Railroad Workplace Safety
5. California Department of Transportation, Manuals and Standards
6. Public Utilities Commission of the State of California General Orders
7. California High-Speed Train Project Basis of Design (20 December 2007)
8. California High-Speed Train Project Design Criteria (19 March 2007)
9. California High-Speed Train Project Technical Memorandum 1.1.18 – Design Variance Guidelines (June 2, 2008)
10. California High-Speed Train Project – Draft Technical Memorandum Design Basis for Turnouts and Pocket Tracks (June 2007)
11. California High-Speed Rail Project Working Paper, Japan Railway Technical Service (JARTS) 2007
12. Comité Européen de Normalisation – European Committee for Standardization (CEN standard)
13. UIC (International Union of Railways) Code 703 – Layout Characteristics of Lines Used by Fast Passenger Trains
14. UIC – Design of New lines for Speeds of 300 – 350 km/h – State of the Art Report (October 2001)
15. Engineering studies In Support of the Development of High-Speed Track Geometry Specifications IEEE/ASME Joint Railroad Conference (March 1997)
16. Taiwan High-Speed Railway Design Manual (2000)
17. SNCF – High-Speed Railway Design Standards (2007 edition)
18. Technical Specification for Interoperability, 'Infrastructure' Subsystem, EU Directive 96/48/EC as modified by the Commission Decision of 20 December 2007 (2008/217/EC)
19. "Speed and Gradient on High Speed Lines" technical memorandum by J. Rabouel (January 19, 2007)

6.0 DESIGN MANUAL CRITERIA

6.1 ALIGNMENT DESIGN

The following information applies to dedicated high-speed lines where the high-speed trainsets are the sole rolling stock in use. The Corridor shall be exclusively used by equipment designed and constructed for high-speed operation above 125 mph (200 km/h) and shall be designed to a set of criteria specific to that purpose.

The basic principle in alignment design is to provide the smoothest line as practical by minimizing frequency and severity of changes in direction and profile. Where changes in direction and profile occur, they should be as gentle as practical. Over four changes in direction per mile shall constitute an Exceptional condition.

6.1.1 Minimum Lengths of Alignment Segments

Attenuation time, based on the most conservative requirements, shall be:

- For V < 300 km/h (Under 186 mph)
  - Desirable attenuation time: not less than 2.4 seconds
  - Minimum attenuation time: not less than 1.8 seconds
  - Exceptional attenuation time: not less than 1.5 seconds
  - An attenuation time of 1.0 seconds on the diverging route in curves adjacent to or between turnouts
- For 300 km/h≤ V (Over 186 mph)
  - Desirable attenuation time: not less than 3.1 seconds
  - Minimum attenuation time: not less than 2.4 seconds
  - Exceptional attenuation time: not less than 1.8 seconds

Minimum segment length is calculated by the formula: $L_{feet} = V_{mph} \times 44/30 \times t_{sec}$ and $L_m = V_{km/h} / 3.6 \times t_{sec}$. Minimum segment lengths are presented in Tables 6.1.1 and 6.1.2.

Table 6.1.1: Minimum Segment Lengths at Various Speeds

Design Speed		Minimum Segment Lengths for times of							
		3.1 seconds		2.4 seconds		1.8 seconds		1.5 seconds	
miles per hour	km/h	feet	meters	feet	meters	feet	meters	feet	meters
250	400	1137	346	880	268	660	201	550	168
220	355	1000	305	774	236	581	177	484	148
200	320	909	277	704	215	528	161	440	134
186	300	846	258	655	200	491	150	409	125
175	280	796	243	616	188	462	141	385	117
150	240	682	208	528	161	396	121	330	101

Table 6.1.2: Minimum Segment Lengths at Various Speeds

Design Speed		Minimum Segment Lengths for times of							
		2.4 seconds		1.8 seconds		1.5 seconds		1.0 seconds	
miles per hour	km/h	feet	meters	feet	meters	feet	meters	feet	meters
186	300	655	200	491	150	409	125	273	83
175	280	616	188	462	141	385	117	257	78
150	240	528	161	396	121	330	101	220	67
125	200	440	134	330	101	275	84	183	56

Where alignment segments overlap, each change shall be treated as a separate alignment element for the purpose of calculating minimum segment lengths. For example, where there is a vertical curve within a horizontal curve, the parts of the horizontal curve outside of the vertical curve will be treated as separate segments when calculating segment lengths.

The segment length requirement will govern only where other design considerations for the various alignment elements do not require longer segment lengths.

6.1.2 Minimum Radii

As in segment lengths, curve radii standards will be provided for "Desirable", "Minimum", and "Exceptional" values. However, even the "Desirable" figures can be improved upon. A "Desirable" radius is one that is larger than this radius if at all practical, for larger radii are better. The radii provided in the table are based on superelevation calculation described in paragraph 6.1.4: The EU Technical Specification for Interoperability has a break in allowable unbalanced superelevation at 300 km/h (186 mph), thereby resulting in two values being given for the speed of 186 mph.

Table 6.1.3: Minimum Curve Radii

Design Speed		**Minimum radius, Based on Superelevation Limits**					
		Desirable		**Minimum**		**Exceptional**	
miles per hour	km/h	feet	meters (rounded)	feet	meters (rounded)	feet	meters (rounded)
250	400	45,000	13,700	28,000	8,500	25,000	7,600
220	355	35,000	10,700	22,000	6,700	19,500	6,000
200	320	30,000	9,200	18,000	5,500	16,000	4,900
186	300	25,000	7,600	16,600	4,700	14,000	4,250
<186	<300	25,000	7,600	16,600	4,700	12,600	3,850
175	280	22,000	6,700	14,000	4,200	11,200	3,400
150	240	16,000	4,900	10,000	3,100	8,200	2,500
125	200	10,500	3,200	7,000	2,100	5,700	1,750

For those used to working in degrees of curve (railroad definition), the following degrees of curvature may be used as substitute values for the radii given in Table 6.1.3. Please note that the values in Table 6.1.4 are not exact conversions of the radii given in Table 6.1.3, but are convenient values for degree of curve limits for the same speed standards.

Table 6.1.4: Minimum Degree of Curve

Design Speed		Minimum Curve in Degrees, degree, minutes, seconds		
miles per hour	km/h	Desirable	Minimum	Exceptional
250	400	0d 07m 30s	0d 12m 15s	0d 13m 30s
220	355	0d 09m 45s	0d 15m 30s	0d 17m 30s
200	320	0d 11m 15s	0d 19m 00s	0d 21m 15s
186	300	0d 13m 45s	0d 21m 30s	0d 24m 30s
<186	<300	0d 13m 45s	0d 21m 30s	0d 27m 15s
175	280	0d 15m 30s	0d 24m 30s	0d 30m 30s
150	240	0d 21m 15s	0d 34m 15s	0d 41m 45s
125	200	0d 32m 30s	0d 49m 00s	1d 00m 00s

At high speeds the distance between curves is determined by the minimum segment length. Guidance for low speed tracks is provided in California High-Speed Train Project Technical Memorandum 1.1.6 - Alignment Standards for Shared Use Corridors (Specific to Los Angeles to Anaheim).

Curves with Small Central Angles: For small central angles the radius shall be sufficiently large to provide the time-based minimum arc and spiral segment lengths. There is no maximum radius requirement or desirable maximum for radius. In general, larger radii are preferable to smaller radii as the superelevation and unbalance values become smaller. A radius should be selected that results in the length of the simple curve portion being about equal to or longer than the length of spiral. Since each portion is an alignment segment, if each segment is equal in length, the entire curve with spirals should have a minimum length not less than three times the Minimum Segment Length given in Table 6.1.1 or 6.1.2, as appropriate for the design speed. Double spirals or curves with long spirals and short arc lengths shall not be used.

6.1.3 Superelevation

Balancing superelevation shall be calculated by one of the following formulae, depending upon how the curve is defined:

$$SE = 0.0007\ V^2\ D$$ (curvature in degrees, speed in mph and SE in inches)

Which when expressed with radius instead of degrees gives:

$$SE = 4.0\ V^2 / R$$ (radius in feet, speed in mph and SE in inches) or

Or in metric system units:

$$SE = 11.8\ V^2 / R$$ (radius in meters, speed in km/h and SE in millimeters)

Curves shall not be superelevated to balance the design speed, calculated average speed, or maximum operating speed. A certain amount of unbalance, usually 1.0 inches at normal operating speed, is desirable for ride comfort and smooth running of the vehicles through the curve.

The design value of superelevation to be applied to the curve will be influenced by:

- Maximum Speed Limit
- Calculated normal and maximum speeds of high-speed trains
- Where applicable, calculated normal and maximum speeds of high-speed trains slowing for or accelerating from a station stop
- Calculated normal and maximum speeds of other passenger trains (where applicable)
- Minimum unbalance of 1.0 inch (25 mm) in relation to the normal train speed.

Design superelevation shall not exceed the allowable maximum superelevation. Design superelevation shall be calculated for each track. It is neither necessary nor in many locations desirable that both main tracks of the line have the same superelevation on a given curve. Where the normal operating speed of the trains differ from the Design Speed, the unbalanced superelevation may be increased up to the Exceptional level based on the Design Speed if it is necessary to provide a comfortable unbalance for trains moving at their normal operating speeds.

The first of the following tables provide the allowable upper limits for Superelevation plus Unbalanced Superelevation. Radii developed from these limits determine the Desirable, Minimum, and Exceptional radius that is permissible for any given speed.

Table 6.1.5: Maximum Values, Superelevation plus Unbalanced Superelevation

Design Speed		Combined Superelevation and Unbalance					
		Desirable		Maximum		Exceptional	
miles per hour	km/h	inches	mm	inches	mm	inches	mm
<186	<300	6	150	9	230	11	280
≥186	≥300	6	150	9	230	10	250

Table 6.1.6: Maximum Values of Applied Superelevation

Design Speed		Applied Superelevation					
		Desirable		Maximum		Exceptional	
miles per hour	km/h	inches	mm	inches	mm	inches	mm
<186	<300	4	101	6	150	7	180
≥186	≥300	4	100	6	150	7	180

Table 6.1.6: Maximum Values of Unbalanced Superelevation

Design Speed		Unbalanced Superelevation					
		Desirable		Maximum		Exceptional	
miles per hour	km/h	inches	mm	inches	mm	inches	mm
<186	<300	2	50	3	75	4	100
≥186	≥300	2	50	3	75	3	75

6.1.5 Spirals

6.1.5.1 Selection of Speed to be Used in Design

The speed to be used at the design stage of the alignment is the system design speed, not the operating speed planned to be used at the time of start of operations. During alignment design, the purpose of determining superelevation is to find the appropriate spiral length for a particular curve in the alignment design. Thus, the highest anticipated speed, superelevation and unbalanced superelevation shall be used at this stage of the design.

However, in construction of the track, the superelevation shall be based on the calculated speed on the curve on the time of initial operation. Therefore, the initial superelevation applied to the track may be less than that developed in the calculations for appropriate spiral length.

6.1.5.2 Selection of Spiral Type

In ballasted tracks a certain amount of “transition into the transition” naturally occurs with the normal maintenance processes. In concrete slab supported tracks this “transition into the transition” cannot occur. Therefore, it is desirable to change from constant rate spirals to variable rate spirals at a lower speed where using concrete base trackforms. For concrete base trackforms, the point of change will be set in accordance with Japanese Shinkansen practice. For ballasted track, a higher speed may be used.

Half-Sine Spirals (variable rate transitions) shall be used on all tracks designed for:

- Ballasted tracks: Curves having design maximum speeds of 80 mph or more
- Non-ballasted tracks: Curves having design maximum speeds of 60 mph or more
- Curves associated with turnouts having design maximum speeds of 110 mph or more

Clothoid Spirals (constant rate transitions) shall be used on all lower speed tracks. Clothoid spirals may also be used on very large radius curves that require small amounts or no superelevation and have very small unbalanced superelevations, as described below under special situations.

Nature of the Internal Transitions in the Two Spiral Types:

Half Sine Spiral (Angles in these formulae are in radians.):

Local Radius through the Spiral:

$$R_{loc} = 2\ R_{curve} / (1 - \cos(\pi\ L_{loc} / L_{tot}))$$

Local Superelevation through the Spiral:

$$SE_{loc} = 0.5\ SE_{curve}\ (1 - \cos(\pi\ L_{loc} / L_{tot}))$$

Clothoid Spiral:

Local Radius through the Spiral:

$$R_{loc} = R_{curve} / (L_{tot} / L_{loc})$$

Local Superelevation through the Spiral:

$$SE_{loc} = SE_{curve}\ (L_{loc} / L_{tot})$$

6.1.5.3 Determining Spiral Length

Spiral Lengths: The length of the spiral shall be the longest length determined by calculating the various length requirements, which are:

- Length needed to achieve Attenuation Time
- Length determined by allowed rate of change in superelevation
- Length determined by allowed rate of change in unbalanced superelevation
- Length determined by limitation on twisting over vehicle and truck spacing length

Table 6.1.7: Minimum Length of Spiral

Half-Sine (Variable Change) Spirals *			
Spiral Design Factor	Desirable	Minimum	Exceptional
Superelevation	1.63 Ea V	1.30 Ea V	1.09 Ea V
Unbalance	2.10 Eu V	1.57 Eu V	1.26 Eu V
Twist **	140 Ea	118 Ea	98 Ea
Minimum Segment	2.64 V	2.20 V	1.47 V
Clothoid (Linear Change) Spirals			
Spiral Design Factor	Desirable (0.03 g)	Minimum (0.04 g)	Exceptional (0.05 g)
Superelevation	1.47 Ea V	1.17 Ea V	0.98 Ea V
Unbalance	1.63 Eu V	1.22 Eu V	0.98 Eu V
Twist	90 Ea	75 Ea	62 Ea
Minimum Segment	2.64 V	2.20 V	1.47 V

The length is given in feet with:

- Ea=Actual elevation in inches
- Eu=Unbalanced elevation in inches
- V=maximum speed of the train in mph

* Longer lengths of half-sine spirals are due to the variability in the ramp rate.

** Provides maximum twist rates identical to clothoids. As a practical matter, this limitation never governs due to use of this type spiral only on high-speed tracks.

After calculation and selection of length, based on the governing requirement, the spiral length should then be rounded to a convenient value for further calculation and use in the alignment. Rounding may be either up or down for “Desirable” values so long as the downward rounding does not reduce any of the required desirable lengths by more than 5.0%. Rounding may be either up or down for “Minimum” values so long as the downward rounding does not reduce any of the required minimum lengths by more than 1.0%. Rounding shall only be in the upward direction for “Exceptional” values.

6.1.5.4 Special Situations

Spirals on Large Radius Curves: Clothoid spirals may be used instead of half-sine spirals regardless of track type or design speed if the following conditions are met: The required superelevation and unbalanced superelevation are both under 1.0 inches at the maximum design speed; and the “Minimum Segment” length for the spiral is more than twice the length required by any other factor. Spirals may be omitted if the following conditions are met: The required superelevation is zero (balancing superelevation for the maximum speed less than 0.75 inches); and the calculated offset of the curve due to application of the spiral is less than 0.05 feet in ballasted track or less than 0.02 feet in non-ballasted track. *(These values are subject to revision.)*

Reverse Curves: If there is insufficient distance between curves to provide the minimum required length tangent segment, the spirals shall be extended to provide a reversing curve. If beneficial to design and construction, a straight distance between curves that would be run in less than 0.2 seconds at the normal operating speed may be left between spiral ends.

6.1.5.5 Sample Calculation

Determine the spiral length for a 50,000 foot radius curve in the main line portion where the design speed will be 250 mph and the initial operating speed limit will be 220 mph, and located where it will not be affected by lower speeds of some or all trains due to acceleration, braking, or grades.

At 250 mph, balancing superelevation will be 5.00 inches. The 90% speed is 225 mph, which balances at 4.050 inches.

At 220 mph, balancing superelevation will be 3.872 inches. The 90% speed is 198 mph, which balances at 3.126 inches.

Spiral Length will be based on 3.00 inches superelevation and 2.00 inches unbalance for the 250 mph situation.

Since the initial maximum operating speed will be 220 mph, the actual installed superelevation upon opening will be 2.125 inches, giving an initial unbalance of 1.001 inches. Since it is impractical to change spiral length, the spiral length will not be based on this 220 mph design, but shall be determined based on the 250 mph design speed.

The Spiral type will be Half-Sine

Desirable Design Factors, based on 250 mph:

Superelevation: 1.63 Ea V = 1.63 x 3.00 x 250 = 1222.5 feet

Unbalance: 2.10 Eu V = 2.10 x 2.00 x 250 = 1050 feet

Obviously, neither twist nor minimum segment length need be considered for this spiral.

Select a Length of **1,200 feet** for this spiral. (less than 1.9% under the calculated length.)

6.1.6 Grades and Vertical Curves

The railroad alignment shall be designed to have the smoothest practical profile while optimizing earthwork, structures, tunnels and drainage. Grades shall be as low as practical. Where grades do occur, they should be of the same slope from bottom to top where practical. Use of multiple short grades and multiple changes in grade within any particular change of elevation (“sawtooth profiles”) are to be avoided to the greatest extent practical. In addition to increasing operational costs and difficulty by requiring frequent changes in power, a line with multiple changes in grade is aesthetically unappealing. As a check on the reasonableness of the profile developed, it shall be drawn up at a highly condensed horizontal scale so that the vertical changes are exaggerated. Otherwise, the alignment can appear deceptively smooth.

Low points and very flat grades should not be used in cuts or tunnels (including Cut and Cover) due to drainage considerations.

6.1.6.1 Limitations on Grades

Maximum Grade Limits:

- Desirable grades: as low as reasonably practical, with a limit of 1.25%
- Maximum grades: above 1.25% and shall be as low as practical up to 2.50%
- Exceptional grades: above 2.50% and shall be as low as practical up to 3.50%

Minimum Grades: Without a separate drainage system, grades in cuts or tunnels (included cut-and-cover) shall not be less than 0.25%.

Limitation on Length of Steep Grades: Where terrain permits, long grades steeper than the following shall not be used due to limits of breaking capability of some of the proposed train sets:

- The average grade for any 6 km (3.7 mi) long section of the line shall be under 3.5%
- The average grade for any 10 km (6.2 mi) long section of the line shall be under 2.5%

Limitations of Speed on Grades: In European practice, speed on downgrades is constrained by train set braking limitations. The restriction is based on the average grade over any continuous length of 5,200m (17,100ft) along the line. The following speed limits for different grades are as determined in accordance with French standards:

- Grade between 3.0% and 3.5%: Vmax = 230 km/h (143 mph)
- Grade between 2.2% and 3.0%: Vmax = 270 km/h (168 mph)
- Grade between 1.6% and 2.2%: Vmax = 300 km/h (186 mph)
- Grade between 0.0% and 1.6%: Vmax = 350 km/h (217 mph)

Limitations on Grade at power supply phase breaks: In European practice, due to this catenary and signaling constraints it is desirable to limit grades to 0.60% for 600 m (2,000 feet) on each side of a phase break. The need for this constraint and its locations shall be confirmed in consultation with the development of design standards for the electrification system.

6.1.6.2 Vertical Curves

Normal US Practice

In US railroad alignment, vertical curves are parabolic curves normally defined by the rate of change in grade per 100 feet of length. This is the inverse of the usage in highway work, which also uses parabolic curves, but defined by the length required for a one percent change in grade.

Normal Japanese and European Practice

Normal practice in Japan and Taiwan is also to use Parabolic Vertical Curves. Even though the vertical curves on the Taiwan High-Speed Railway were defined by radius, they were designed and constructed as parabolas.

Common European practice in both highway and railroad work is to use circular radius vertical curves. Consequently, European high-speed railways are normally designed and built with circular vertical curves.

The radius of the curve at the crest or sag is determined in accordance with the vertical acceleration permitted for passenger comfort and the maximum speed of the line. The formula in metric units is: **$R_{min} \geq (V/3.6)^2 / av$**, where R is in meters, V in km/h, Vertical acceleration (av) in m/s^2 and the 3.6 factor is necessary for the km/h to m/s conversion. The formula in US Customary units would be: **$R_{min} \geq (V*44/30)^2 / av$**, where R is in feet, V in mph, Vertical acceleration (av) in $feet/sec^2$ and the 44/30 is necessary for the mph to ft/sec conversion.

European high-speed lines do not use curves with radius over 40,000m (131,234 feet radius, or a rate of change 0.0762% per 100 feet) due to maintainability concerns.

In SNCF practice, it is unnecessary to provide a vertical curve between two gradients when the difference in gradient is less than or equal to 0.1% or 1mm/m, even for design speeds of 350 km/h (217 mph).

Comparison between American and European Vertical Curve Design Practices:

The difference between arc vertical curves and parabolic vertical curves as laid out is very slight, usually under $^1/_8$ inch (3 mm).

Differences in maximum vertical curve radius requirements, or in US Customary railroad terminology, minimum rate of change requirements:

- It is reported that European measuring systems and maintenance practices are incapable of measuring vertical curves with radii of over 40,000 meters (0.0762% grade change per 100 feet), therefore vertical curves longer than this rate of change are prohibited.
- Rates of change down to 0.05 percent per 100 feet (Radius = 60,100 m) have been used in the US for many years without any maintainability issues ever being raised.
- The AREMA Manual states simply, "Vertical curves should be designed as long as physically and economically possible."

- The Taiwan High-Speed Railway has multiple vertical curves with radii of 100,000 meters to 300,000 meters (rate of change of 0.03 %/100ft to 0.01 %/100ft).
- It is anticipated that the high-speed tracks will be of some form of concrete slab type construction. Therefore, even if the limitations of European maintenance machinery were of concern, they will not be an issue.
- Conclusion: No upper limit needs to be set on vertical curve length/radius.

The relationship between vertical curves defined by radius and vertical curves defined by rate of change is as follows:

- Rate of change, %/100 feet = 3048% / Radius in meters
- Radius in meters = 3048% / (%/100 feet)
- Example: 40,000 meters: 3048% / 40,000 = 0.0762 percent per 100 feet
- Rounding: If a 40,000 m radius is desired, then a rate of change of 0.075 percent per 100 feet or less would be a reasonable value to use to determine the length of vertical curve.

Vertical Curve Type Shall be Parabolic

Parabolic vertical curves shall be used in order to be in line with common US practice.

The speed-based formula for vertical curve length in the AREMA Manual provides a length of vertical curve that is equivalent to one based on change in grade and radius derived by using the vertical acceleration-based formula

In line with common US railroad practice, the length of vertical curves shall be rounded to nearest 100 foot increment where practical.

Vertical Curve Acceleration Rates:

The acceleration values to be used for vertical curves shall be:

- Desirable: 0.60 ft/sec/sec (1.86 percent of gravity) – AREMA recommended practice for passenger railroads.
- Minimum: 0.90 ft/sec/sec (2.80 percent of gravity)
- Exceptional: 1.40 ft/sec/sec (4.35 percent of gravity)

Vertical curve lengths on lines carrying high-speed trains only shall be:

- Desirable VC Length: The longer of $LVC_{feet} = 4.55\ V$ (for 3.1 seconds) or
  $LVC_{feet} = 2.15\ V^2\ (\Delta\% / 100) / 0.60\ ft/sec^2$, but not less than $400\ \Delta\ \%$
- Minimum VC Length: The longer of $LVC_{feet} = 3.52\ V$ (for 2.4 seconds) or
  $LVC_{feet} = 2.15\ V^2\ (\Delta\ \% / 100) / 0.80\ ft/\ sec^2$, but not less than $200\ \Delta\ \%$
- Exceptional VC Length: The longer of $LVC_{feet} = 2.64\ V$ (for 1.8 seconds) or
  $LVC_{feet} = 2.15\ V^2\ (\Delta\ \% / 100) / 1.20\ ft/\ sec^2$, but not less than $100\ \Delta\ \%$
- The speed used in the preceding formulae shall be no less than 250 mph, except where other alignment factors such as speed limiting curves exist. In those locations, a lower speed equal to or higher than the maximum anticipated achievable train speed may be used to calculate the required vertical curve lengths. At 250 mph, these formulae give:
  - Desirable VC Length: $LVC_{feet} = 2250\ \Delta\%$
  - Minimum VC Length: $LVC_{feet} = 1500\ \Delta\%$
  - Exceptional VC Length: $LVC_{feet} = 970\ \Delta\%$

The 2.15 factor is a constant necessary to unit conversions within the US Customary measuring system.

Tables 6.1.8-1 and 6.1.8-2 illustrate the relationship between the various methods of calculating vertical curves. All values are rounded.

Table 6.1.8-1: Desirable Vertical Curves – Rates of Change and Equivalent Radii (0.60 ft/s^2 = 1.86% g)

Speed mph	Speed km/h	% change per 100 feet	feet per % of change	Radius feet	Radius meters
300	480	0.030%	3250	325,000	100,000
250	400	0.045%	2250	225,000	70,000
220	355	0.060%	1750	175,000	53,000
200	320	0.070%	1450	145,000	44,000
175	280	0.090%	1100	110,000	33,000
150	240	0.120%	810	81,000	25,000
125	200	0.175%	560	56,000	17,000

Table 6.1.8-2: Minimum Vertical Curves – Rates of Change and Equivalent Radii (0.90 ft/s^2 = 2.80% g)

Speed mph	Speed km/h	% change per 100 feet	feet per % of change	Radius feet	Radius meters
300	480	0.045%	2150	215,000	66,000
250	400	0.065%	1500	150,000	46,000
220	355	0.085%	1160	116,000	36,000
200	320	0.100%	960	96,000	30,000
175	280	0.130%	740	74,000	22,500
150	240	0.180%	540	54,000	16,500
125	200	0.260%	375	37,500	11,500

Table 6.1.8-3: Exceptional Vertical Curves – Rates of Change and Equivalent Radii (1.4 ft/s^2 = 4.35% g

Speed mph	Speed km/h	% change per 100 feet	feet per % of change	Radius feet	Radius meters
300	480	0.070%	1400	140,000	43,000
250	400	0.100%	970	97,000	30,000
220	355	0.130%	750	75,000	23,000
200	320	0.150%	620	62,000	19,000
175	280	0.200%	480	48,000	15,000
150	240	0.250%	350	35,000	11,000
125	200	0.400%	250	25,000	7,500

The lengths developed in the preceding tables and formulae are the shortest allowed lengths in each scenario. Vertical curve lengths shall always be rounded up. Rate of Change, radius and other parameters of the vertical curve shall then be derived from this length.

Where the difference between gradients is small, the minimum segment length requirements described in Section 6.1.1 shall determine the minimum length of vertical curve. Rate of Change, radius and other parameters of the vertical curve shall then be derived from this length.

Where CHSTP lines closely parallel lines for other passenger or freight trains such that a common profile is desirable, the longest vertical curve length determined by the separate calculation for each type of traffic shall determine the vertical curve length to be used for all tracks.

6.1.7 Horizontal Curves in Vertical Curves

Unbalanced Superelevation Limits: Horizontal and vertical curves can overlap. Crest vertical curves result in a downward acceleration of the vehicle, thereby reducing the gravitational effect. This reduction is small but not insignificant for the vertical curve rates of change permitted in this document. A reduction of 0.25 inches for limiting and 0.50 inches for exceptional unbalanced superelevation is sufficient to allow for this effect.

Vertical Curves in Spirals: Due to potential maintenance difficulties, it is desirable to avoid use of vertical curves in spirals. The desirable distance between end of spiral and beginning of vertical curve or end of vertical curve and beginning of spiral is 160 feet (50 m) with a minimum limit of 100 feet (30m). Overlap between vertical curves and spirals may be permitted as an Exceptional condition, but only where it can be shown that practical alternatives have been exhausted.