California High-Speed Train Project

TECHNICAL MEMORANDUM

Alignment Standards for Shared Use Corridors (Specific to Los Angeles to Anaheim) TM 1.1.6

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Anthony Daniels, Program Director Date

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Prepared by PB 100 YEARS

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 memorandums. Technical Leads for each subsystem is 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*__________ __17 Dec 07_
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TABLE OF CONTENTS

ABSTRACT

The California High Speed Train System is being proposed as a high speed steel wheel on steel rail train operation that will provide service throughout the state of California with end terminals in Sacramento, San Francisco, Fresno, Bakersfield, Los Angeles, Anaheim and San Diego. There are several locations where the proposed California High-Speed Rail (CHSR) line will operate adjacent to or within a shared right-of-way with conventional passenger railroad lines and freight railroad lines. One such location is the rail corridor that serves freight and passenger customers between Los Angeles and San Diego referred to as the LOSSAN Corridor. Within this corridor, high-speed trains are expected to operate at speeds up to 125 mph.

This technical memorandum presents design guidance for the segment of the proposed High Speed Rail line between Los Angeles Union Station (LAUS) and Anaheim. It defines the geometric design requirements to be used in the basic design in order to achieve a safe and reliable operating railway that meet applicable regulatory requirements and achieve CHSTP functional, programmatic, operational, and performance requirements within the corridor. The general basis of alignment design will be to follow best practices as described in the Manual for Railway Engineering of the American Railway Engineering and Maintenance of Way Association (AREMA Manual) and the standards given in this document.

Guidance for the design of high speed train operations outside of the LOSSAN corridor will be provided in a separate 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 in shared use operation, specifically between Los Angeles Union Station and Anaheim. It is intended to be used by the Regional Engineering Consultants 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. Additional guidance on the alignment criteria to be used for dedicated high speed train operations will be transmitted in a separate document.

Following review, specific guidance in this technical memorandum will be excerpted for inclusion in the CHSTP Design Manual.

1.1 Purpose of Technical Memorandum

The purpose of this Technical Memorandum is to define the geometric design requirements to be used in the basic design in order to achieve a safe and reliable operating railway that meet applicable regulatory requirements and achieve 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. The standards in this Technical Memorandum are specifically applicable for the CHSTP operations up to 125 mph (max.) in the Los Angeles to Anaheim corridor.

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

1.3 GENERAL

The general basis of alignment design, in addition to the standards given in this document, will be to follow best practices as 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 is defined as "recommended practice" and varies considerably in level of detail and applicability. Where more specific guidance is not provided, the AREMA Manual shall be considered the primary source document.

The alignment shall be developed to afford the highest practical speed that can be attained at the given location. In particular low speed locations and the need for reduction in speed other than that imposed by the normal acceleration / braking curves into and out of stations shall be avoided.

To illustrate how significant the provision of higher speed track in currently slow areas is, please note the speed achievable when acceleration is not constrained by speed restrictions:

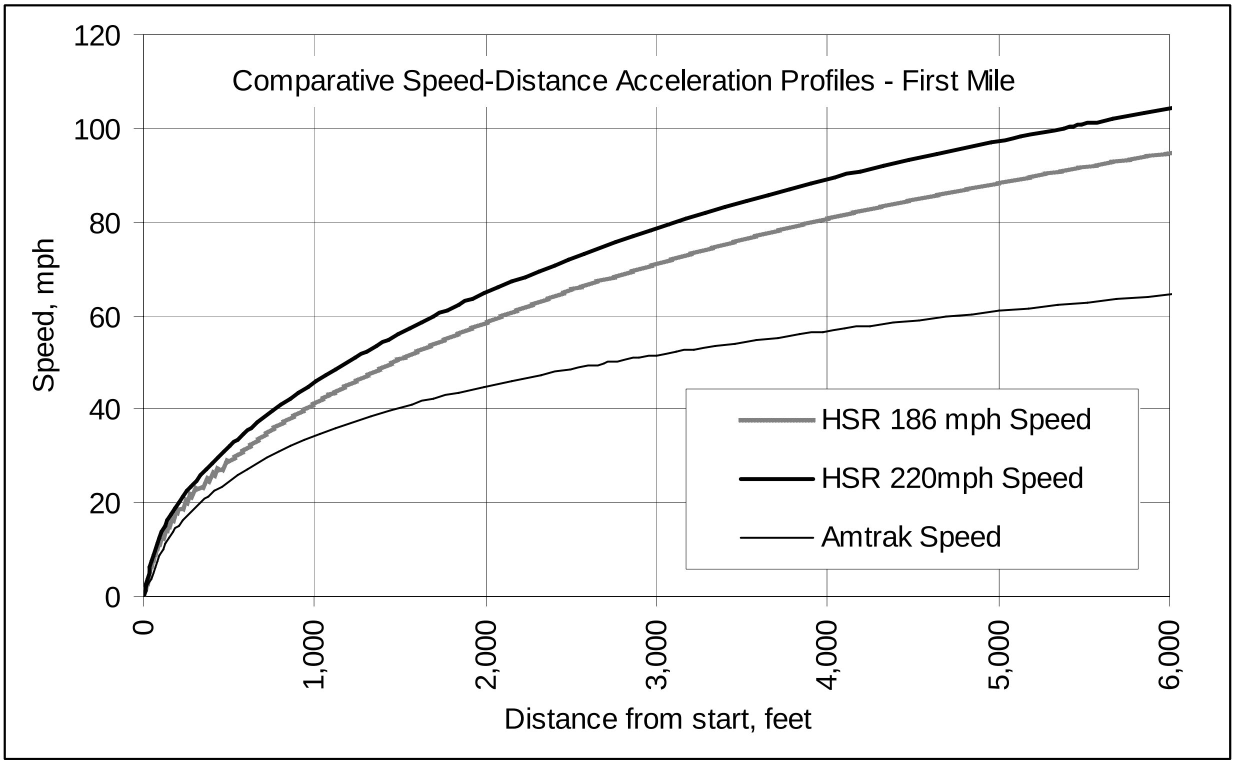
Table 1.3-1: Speeds after Unrestrained Acceleration for Various Distances

Distance from starting point	Speed at various distances from starting point for:		
	High Speed Train for 300 km/h (186 mph)	High Speed Train for 220 mph	Amtrak California Train
1000 feet *	42 mph	45 mph	34 mph
2500 feet	67 mph	74 mph	49 mph
1.0 Mile	89 mph	100 mph	62 mph
2.0 Miles	114 mph	126 mph	76 mph
5.0 Miles	151 mph	165 mph	95 mph **

* approximation for speed of end of train when clearing departing end of platform

** where speed limit above 79 mph is permissible

Figure 1.3-1: Speeds after Unrestrained Acceleration for Various Distances



Therefore, to provide a significantly faster entrance and exit from Los Angeles Union Station than either that currently existing or that previously proposed for the "Run Through Tracks" will be the most beneficial in saving time of any part of the Los Angeles to Anaheim improvement.

1.3.1 Definition of Terms

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

Shared Use Corridor - segment along the CHSTP alignment where high speed trains operate with other passenger railroads, i.e. Caltrain, Metro-Link, Amtrak

Dedicated Corridor - segment along the CHSTP alignment where high speed trains operate exclusive of other passenger railroads

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.

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.

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)

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.

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.

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.

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.

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 it is normally written as $^{o}/_{oo}$.

Vertical Curves - The transition between grades. Normally parabolic in US and Asian practices and circular arc radii in European practices.

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
PUC	Public Utilities Commission of the State of California
SNCF	Société Nationale des Chemins de fer Français (French National Railway Company)

1.3.2 Units

Federal Railroad Administration (FRA) encourages the use of metric as suppliers are likely to use metric. CHSTP information related to FRA regulatory approval will need to include soft conversion, imperial English units so that FRA can confirm CFR requirements and AREMA guidance.

Note that the draft version of this technical memorandum was prepared using imperial English units in order to allow the early release and review of the alignment information presented within. The final version of this document will be prepared using metric units.

2.0 DESIGN STANDARDS AND GUIDELINES

2.1 General

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.

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."

2.2 LAWS AND CODES

There is no one single law or code or design standard currently in existence that can be followed to produce a high speed railroad appropriate to the intended purpose and use anticipated. Reference is frequently made to FRA Track Safety Standards. However, these are not design standard in the normal sense. While they do have some requirements that could affect the design, their primary purpose is track safety. In addition to the track condition requirements, there are requirements that do apply to the design and construction of a high speed railroad, but for the most part the requirements in the FRA are no more restrictive than the equivalent standards that would be part of any normal design standards for a high speed railroad

In case of differing values or conflicts in the various requirements among the various design requirements and between any of them and the following design guidelines, the standard followed shall be that which results in the highest level of satisfaction of all requirements or that deemed the most appropriate shall be followed.

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

Certain requirements of the Federal Railroad Administration (FRA), among them:

- CFR Part 213, Track Safety Standards, generally and also in particular Subpart G -Train Operations at Track Classes 6 and Higher.
- CFR Part 214, Railroad Workplace Safety.

Certain California Public Utilities Commission (PUC) General Orders (GO), among them:

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

Other Design Guidelines:

- The Manual for Railway Engineering of the American Railway Engineering and Maintenance of Way Association (AREMA Manual), in particular the following chapters:
    - o Chapter 17: High Speed Rail Systems
    - o Chapter 33: Electrical Energy Utilization
    - o Chapter 1: Roadway and Ballast
    - o 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 certain 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
- Caltrans Manuals and Standards, including but not necessarily limited to:
    - o Highway Design Manual

The latest version of the above standards shall be the one applicable.

3.0 ALIGNMENT CRITERIA

3.1 GENERAL

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

Vertical and horizontal alignment sections may overlap. It is common in transit system standards and some European railroad standards to prohibit overlap of horizontal and vertical curves, particularly placing vertical curves in spirals. Prohibition against the practice is seldom if ever found in normal American mainline railroad design standards and overlap of horizontal and vertical alignment elements are common. The only apparent basis for this requirement is perhaps making some of the calculations slightly easier, and possibly simplification of some maintenance and checking of track, particularly in ballasted tracks. In transit systems where alignment elements are relatively short this requirement is not particularly onerous. High speed systems by their nature will have some very long alignment elements making the non-overlap requirement impractical. Worse is resolving the issue by using Limiting or Exceptional design requirements where Desirable requirements can be met with overlapping of elements.

- Desirable attenuation time: not less than 1.8 seconds.
- Minimum attenuation time: not less than 1.5 seconds.
- Exceptional attenuation time: not less than 1.0 seconds.
- An attenuation time of 1.0 seconds on the diverging route in curves adjacent to or between turnouts.

Minimum segment length is calculated by the formula: $L_{feet} = V_{mph} \times 44/30 \times t_{sec}$

Table 3.1-1: Minimum Segment Lengths at Various Speeds

Design Speed	Minimum Length, feet for times of		
	Desirable 1.8 seconds	Minimum 1.5 seconds	Exceptional 1.0 seconds
125 mph	330	275	184
100 mph	264	220	147
79 mph	209	174	116
60 mph	158	132	88
V mph	2.64 V	2.20 V	1.47 V

Where alignment segments overlap, each change shall be treated as a separate alignment element for the purpose of calculating minimum segment lengths. For example: Vertical curve within the body of a horizontal curve: Horizontal curve parts outside the vertical curve will be treated as separate segments from the part within the vertical curve to calculate segment lengths.

3.2 HORIZONTAL ALIGNMENT

3.2.1 Curvature

It appears that horizontal alignment adjustments will be highly constrained by the existing right of way. The greatest practical improvement to curve radius shall be implemented where practical.

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 is 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.

The maximum speed allowable with certain combinations of degree of curve or curve radius and superelevation and unbalance are shown in the following tables.

Table 3.2-1: Maximum Degree of Curve for Various Superelevations and Speeds

Super-elevation	Unbalance	Design Maximum Speeds			
		125 mph	100 mph	79 mph	60 mph
3	3	0d 32m 50s	0d 51m 20s	1d 22m 00s	2d 20m
4	3	0d 38m 20s	1d 00m 00s	1d 36m 00s	2d 45m
4	4	0d 43m 50s	1d 08m 30s	1d 49m 45s	3d 10m
5	3				
5	4	0d 49m 20s	1d 27m 00s	2d 03m 15s	3d 30m
6	3				
6	4	0d 54m 50s	1d 25m 30s	2d 17m 00s	3d 57m

Table 3.2-2: Minimum Radius of Curve for Various Superelevations and Speeds

Super-elevation	Unbalance	Design Maximum Speeds			
		125 mph	100 mph	79 mph	60 mph
3	3	10,500 ft	6,500 ft	4,000 ft	2,500 ft
4	3	9,000 ft	5,800 ft	3,600 ft	2,200 ft
4	4	8,000 ft	5,000 ft	3,200 ft	1,900 ft
5	3				
5	4	7,000 ft	4,500 ft	2,800 ft	1,700 ft
6	3				
6	4	6,500 ft	4,000 ft	2,500 ft	1,500 ft

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 can be low. A radius should be selected that results in the length of the simple curve portion being about equal to or longer than the spiral length. Since each portion is an alignment segment, if each segment is equal in length, the entire curve with spirals should have a minimum length requiring not less than 5.4 seconds travel time at the maximum design speed. Double spirals or curves with long spirals and short arc lengths shall not be used.

Minimum curve radius: The absolute minimum curve shall be 9 degrees. Curves shall be not less than 6 degrees where practical. In radius terms, the preferred minimum is 1,000 feet, and the absolute minimum is 650 feet. Curves of radii under about 650 feet are not used on any tracks currently hosting high speed railroad equipment. Further discussion on station fan tracks and yard tracks will be provided in a separate document.

Distances between small radius curves (where speed does not require greater lengths): When ends of curves are closer to each other than the length of the truck centers plus one end overhang beyond the trucks, the relationship between car ends is affected by both cars. As a consequence, the AREMA Manual recommends a minimum distance of 100 feet between curves where practical. Where space is highly constrained, smaller distances may be used. But, the minimum distance should be such that the combined effect of both curves is not worse than that of one curve of minimum radius. Minimum space between reverse curves shall be as follows:

- Desirable: 100 feet
- Minimum: 75 feet, but may be less, but not less than the following:
  - <u>For degree curves</u>: If both curves are the same: Tan = 1.5 D^2, or if the degree of curves are different: Tan = 0.75 D_1^2 + 0.75 D_2^2, but not less than 25 feet.
  - <u>For radius curves</u>: If both radii are the same: Tan = 48,000,000 / R^2, or if the radii are different: Tan = 24,000,000 / R_1^2 + 24,000,000 / R_2^2 but not less than 25 feet.
- Exceptional: 70 feet, but may be less, but not less than the following:
  - <u>For degree curves</u>: If both curves are the same: Tan = 0.92 Deg^2, or if the degree of curves are different, Tan = 0.46 D_1^2 + 0.46 D_2^2, but not less than 25 feet.
  - <u>For radius curves</u>: If both radii are the same: Tan = 30,000,000 / R^2, or if the radii are different: Tan = 15,000,000 / R_1^2 + 15,000,000 / R_2^2 but not less than 25 feet.
- Should either curve have a degree of 8 degrees 50 minutes or larger, or if using radius, 660 feet radius or smaller, 10 feet shall be added to the Minimum or Exceptional distance calculated, regardless of the radius of the other curve.
- If one of these curves is in a turnout, the end of the curve shall be defined as being at the point of frog for a curve on the frog end of the turnout and 20 feet ahead of the point of the switch for a curve on the switch end of a turnout for standard geometry Union Pacific or BNSF turnouts or 10 feet ahead of the point of switch for improved geometry turnouts.

If the curves have spirals, the ST (spiral to tangent) and TS (tangent to spiral) points may be set closer than these minimum distances down to a length of zero if there are spirals on both curves. The maximum length reduction shall be one-half of the length of each spiral.

For curves in the same direction, the distances between curves shall be the same as for reverse curves except that the Exceptional shall be either greater than 25 feet or it shall be zero. Combining spirals shall be used if either curve would require a spiral based on the paragraph on spirals on small radius curves.

Spirals on small radius curves: The end offset effects can be reduced or eliminated if a spiral of sufficient length is used with the curve. Spirals are not normally used in yard and depot curves where speeds are low. However, for all curves on main lines, station tracks, and yard lead tracks, spirals shall be applied regardless of how slow the speed is designed to be. Where practical, the spirals shall be long enough so that the vehicle end offsets do not exceed that on an unspiraled 7 degree (818 foot radius) curve.

3.2.2 Superelevation

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 nominating curves in degrees and constructing standard gauge track, this formula resolves itself into the very 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)

Both these formulae are slightly approximate. In general, they tend to slightly overstate the required superelevation. To use 0.000690 and 3.97 respectively would be more accurate, but the level of approximation can be regarded as insignificant. Recall that superelevation is measured, whether with a level board or by survey, by determining the relative difference between the highest point on the outside rail of the curve and the highest point on the inside rail of the curve. These points will be slightly further apart than the centerline to centerline separation of the railheads due to the rail inclination toward the track center, meaning that the distance between these points will be slightly greater than the sum of track gauge plus rail head width. Again, the error introduced is insignificant.

The design value of superelevation will be influenced by:

- Maximum Speed Limit
- Calculated normal and maximum speeds of high speed trains
- Calculated normal and maximum speeds of other passenger trains
- Calculated normal and maximum speeds of freight trains, if any. (There may need to be multiple values for freight train speeds, depending upon the nature of the freight traffic.)

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 all tracks of the line have the same superelevation on a given curve.

The AREMA Manual gives very little guidance on the selection of a maximum superelevation value. Traditionally, superelevation has been limited to six inches or less in the US. However, in the past higher values have been used by some railroads in order to allow higher passenger train speeds. The highest known value that has been used by design in the US is eight inches, by the New York Central. That was the value on the 7deg24min 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 was also known to have been used by some other eastern US railroads. Currently most railroad companies limit superelevation to either 5 inches or 4 inches, maximum. The use of six inches is still common on commuter and other primarily passenger carrying lines where freight traffic is either non-existent, low, or high cars cannot be handled.

Maximum values of 160 mm (6.30 inches) to 180 mm (7.09 inches) are common in passenger carrying lines outside North America. Some systems only allow above 160 mm on slab track. The Shinkansen system allows 180 mm maximum without reference to type of track construction.

High values of superelevation does increase discomfort in low speed trains and also add to the maintenance difficulties. Therefore, high values of superelevation should only be used if unavoidable.

The maximum superelevation shall be:

- On tracks which have both high speed and other passenger trains, but no freight trains:
  - Desirable: 4 inches (3 inches where actual speed of some trains will be or may likely be low)
  - Limiting: 5 inches (4 inches where actual speed of some trains will be or may likely be low)
  - Exceptional: 6 inches (4.5 inches where actual speed of some trains will be or may likely be low)
- On tracks which will have high speed trains only:
  - Desirable: 5 inches (3 inches where actual speed of some trains will be or may likely be low)
  - Limiting: 6 inches (4 inches where actual speed of some trains will be or may likely be low)
  - Exceptional: 7 inches (4.5 inches where actual speed of some trains will be or may likely be low)

Superelevation shall be applied by lifting the outer rail of each track. The top of rail profile line will be the top of rail of the low rail for the track.

3.2.3 Unbalanced Superelevation

Practical limits of unbalanced superelevation are based on passenger comfort.

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.

- Desirable minimum unbalance: 1.0 inch

Maximum unbalance:

- Desirable limit of unbalance: 3.0 inches
- Limiting unbalance: 4.0 inches (by FRA exemption only)
- Exceptional unbalance: 4.0 inches (by FRA exemption only)
- Limiting and Exceptional unbalance shall be reduced by 0.25 inches if any part of the curve is on a crest vertical curve that is shorter than Desirable values. (The use of shorter vertical curves than those in this document will require this value to be increased.)

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. Therefore, before determining applied superelevation the normal and maximum practical operating speeds must be calculated for each curve. The result of this analysis may result in the need for the use of different superelevation values on different tracks within the same alignment based on differing average speeds of trains. Due to the multiple factors that must be considered in determining what the applied superelevation, development of a set of rigid rules for determination of applied superelevation is not practical. Therefore, the following sets of rules and guidelines must be applied with use of good engineering judgment.

Normal good operating practice is based on trains running at slightly less than maximum power and maximum speeds so as to provide some allowance to recover lost time. Until such time as it is developed and defined differently, "Normal Speed" shall be considered to be 90% of the calculated maximum speed.

For the simplest of situations, which is a curve on a track carrying only type of traffic, the Applied Superelevation shall be developed using the following general guidelines:

- Applied superelevation shall be one inch less than that necessary to balance the normal speed. If the calculated balancing superelevation is less than three inches, then the applied superelevation shall be two-thirds of that necessary to balance the normal speed.
- In locations where multiple types of traffic operate, the appropriate applied superelevation shall first be calculated for each type of traffic. Then a value based on the proportions of each type of traffic shall be developed. This value should become the designated applied superelevation unless it results in violation of the Desirable limit of unbalance for the fastest train's Normal Speed or violation of the Limiting unbalance for the section Speed Limit. Should either violation occur, the applied superelevation should be increased sufficiently to meet these limits.
- While applied superelevation in excess of that required to balance any train being operated is undesirable, it may be necessary for this situation to occur to avoid restricting the speed of high speed trains.
- Where horizontal curves coincide with or contain crest vertical curves, some reduction in allowed unbalanced superelevation will apply if the vertical curves are at less than desirable rates of change.

3.2.5 Spiral Types and Application to Curves

3.2.5.1 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 decrease 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 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 Stringlining 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 and for the normal range of railroad speeds this non-mathematical feathering in and out is sufficient to provide good ride quality. Even in non-ballasted track a certain limited amount of non-linearity occurs at spiral ends simply due to the stiffness of the rail. However, as speeds increase, so does the need for a designed-in transition into and out of the spiral to reduce the entry and exit jerk. The speed above which this 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.

This need for a "transition into the transition" is also reflected in the information provided in UIC 703, in that, with the exception of SNCF, allowable transition rates for linear spirals decrease with increasing speed. Japanese Shinkansen lines require the use of variable rate spirals for all tracks having speeds above 100 km/h (62 mph). This is about the lowest value used. Other systems have used higher speed points, up to as high as 160 km/h (100 mph). The following figures illustrate the differing characteristics of the two types of spirals. For purposes of illustration, a curve of 0 degrees 45 minutes, radius 7,639.49 feet was selected and the appropriate desirable length spiral applied. For the half-sine the rounded up spiral length used is 1,100 feet. The rounded up length of clothoid spiral is 1,000 feet.

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

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

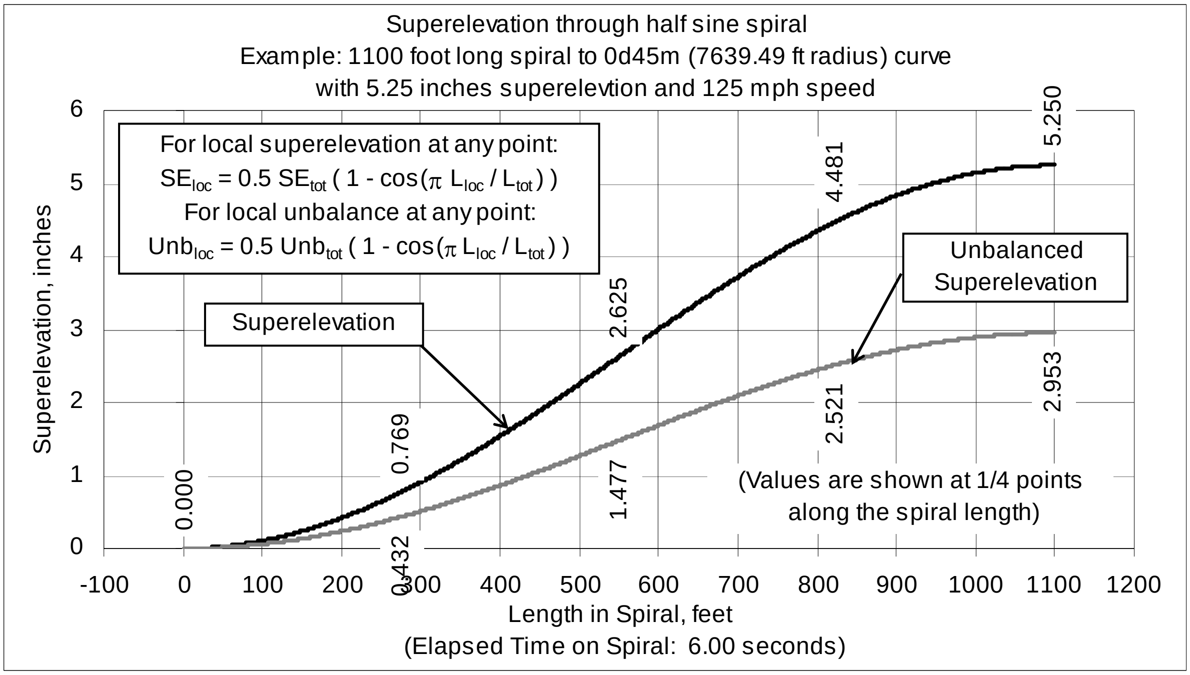


Figure 3.2-2: Transition Rates with Time Through the Half-sine Spiral – Relative to Superelevation

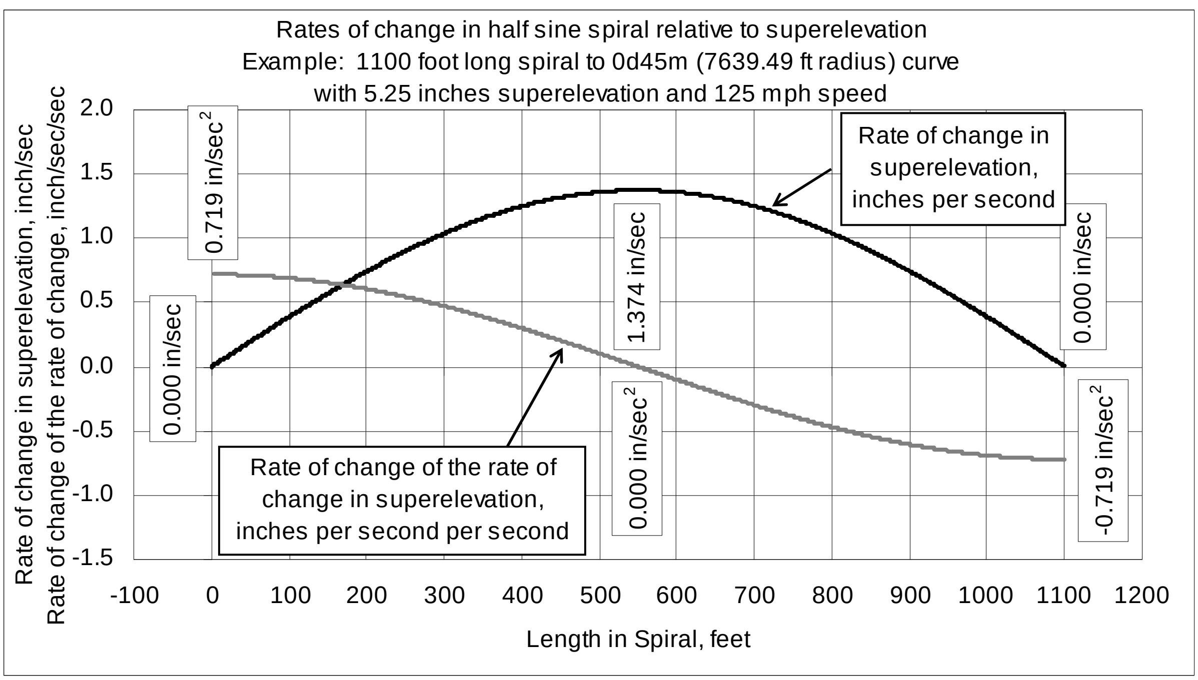
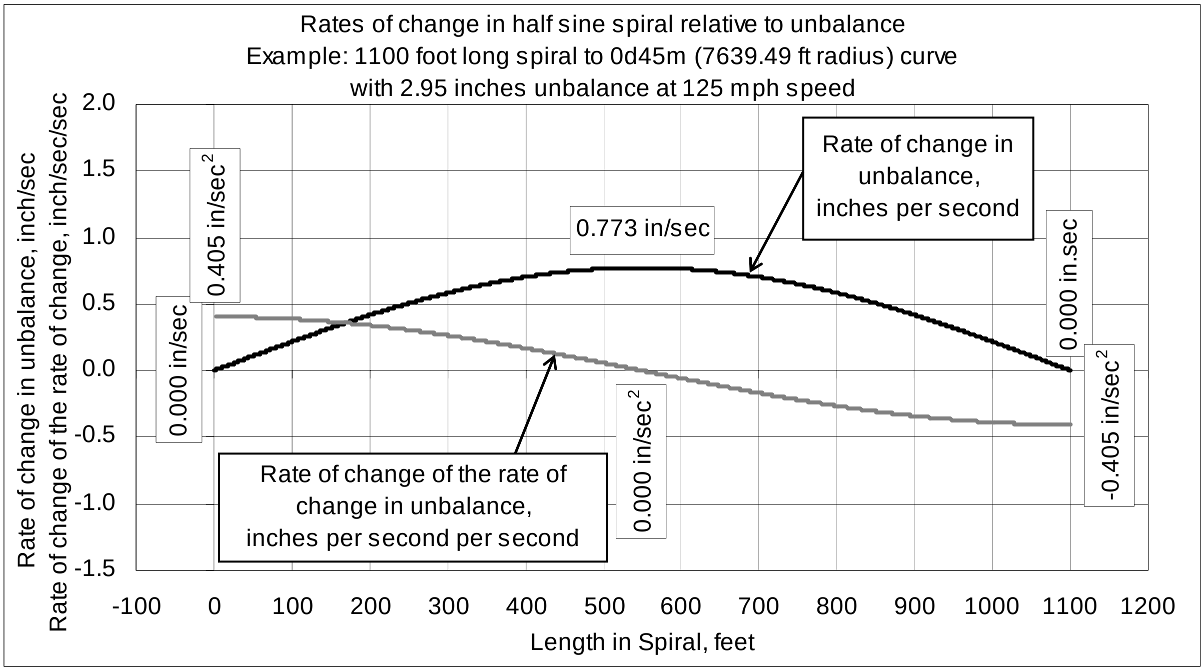


Figure 3.2-3: Transition Rates with Time Through the Half-sine Spiral – Relative to Unbalance



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:

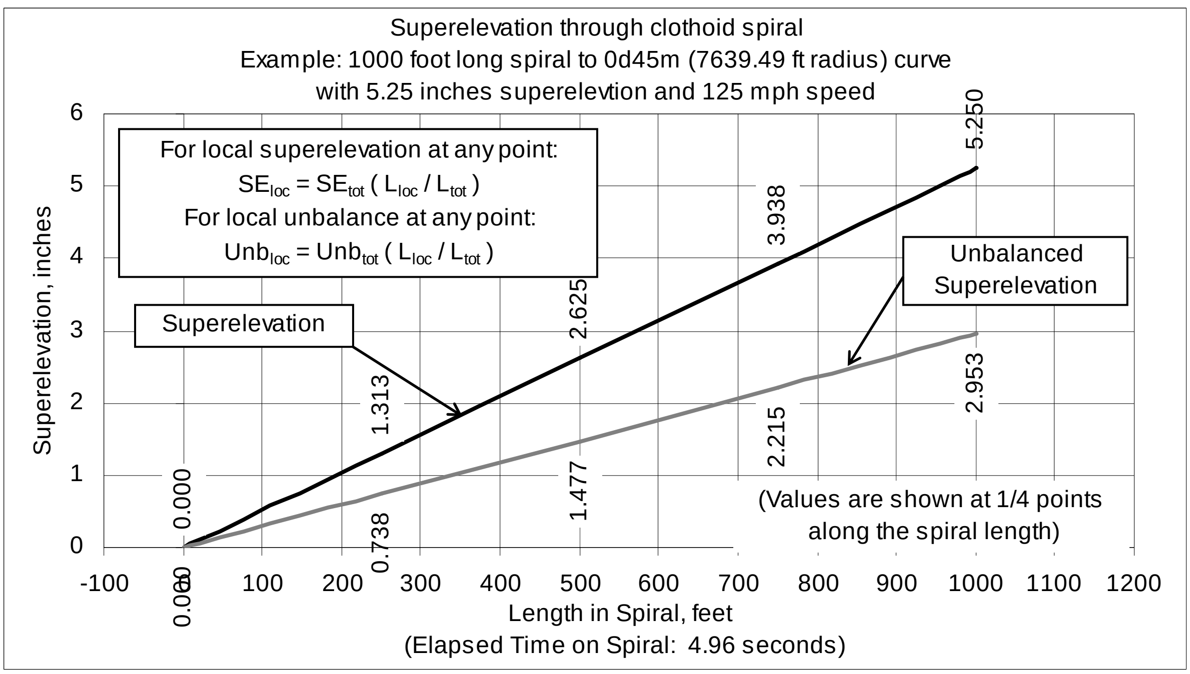


Figure 3.2-5: Transition Rates with Time Through the Clothoid Spiral – Relative to Superelevation

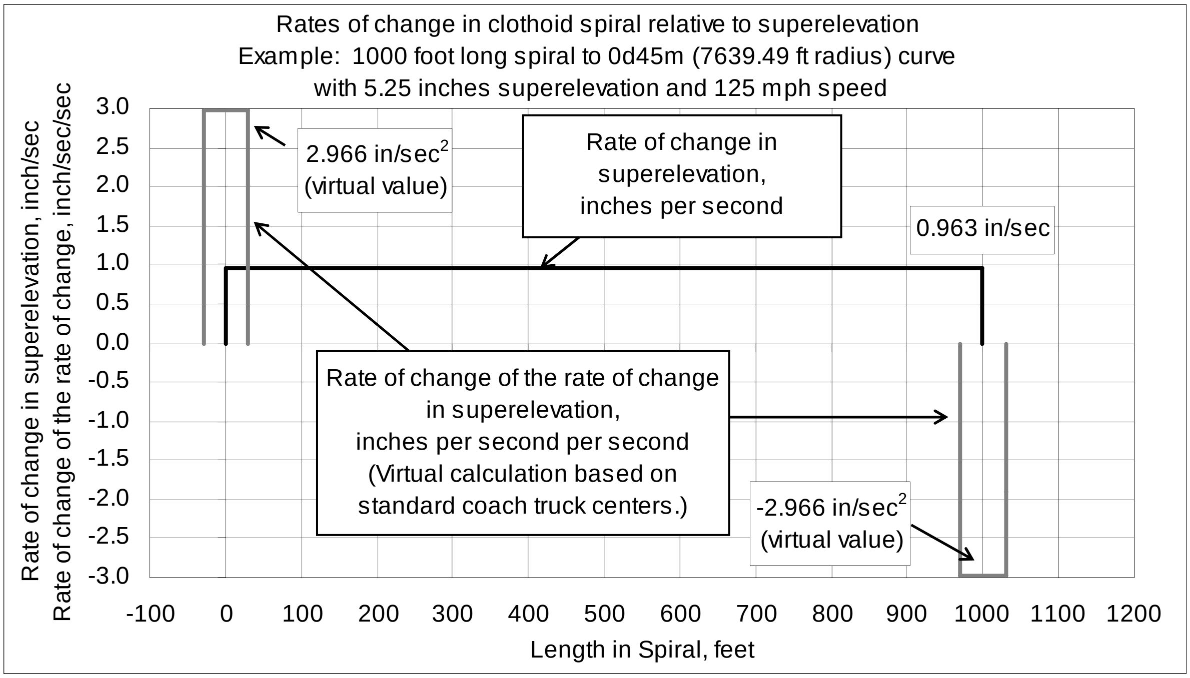
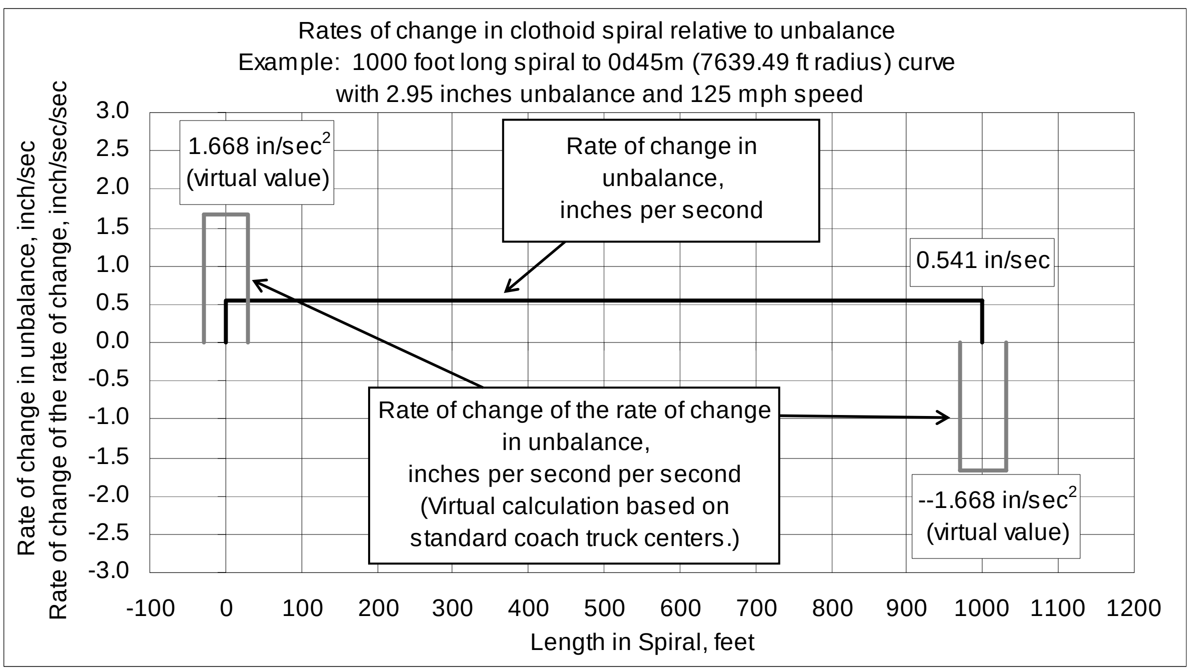


Figure 3.2-6: Transition Rates with Time Through the Clothoid Spiral – Relative to Unbalance



Variable rate (Half-Sine) spirals shall be used on all high speed curves, as defined below.

3.2.5.2 Application of the Two Types of Spirals and Spiral Formulae

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

Half Sine Spiral:

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:

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

Clothoid Spirals (constant rate transitions) will be used on all tracks having lower design speeds and under certain other conditions that will be defined where those conditions are discussed.

3.2.5.3 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.

Table 3.2-3: Minimum Length of Spiral

Clothoid (Linear Change) Spirals				
Spiral Design Factor	Desirable (0.3 g)	Minimum (0.4 g)	Exceptional (0.5 g)	Associated with turnouts
Superelevation	1.47 Ea V	1.17 Ea V	0.98 Ea V	0.75 Ea V
Unbalance	1.63 Eu V	1.22 Eu V	0.98 Eu V	0.75 Eu V
Twist	90 Ea	75 Ea	62 Ea	62 Ea
Minimum Segment	2.64 V	2.20 V	1.47 V	1.33 V
Half-Sine (Variable Change) Spirals *				
Spiral Design Factor	Desirable	Minimum	Exceptional	Associated with turnouts
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	- -

* 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 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" and "Associated with Turnouts" values.

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

Reverse Curves: Should there be insufficient distance between curves to provide a tangent segment of the minimum required length, the spirals shall be extended so as to provide a reversing curve. 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 if beneficial to design and construction.

3.3 VERTICAL ALIGNMENT

3.3.1 Grades

The railroad alignment shall be as near level as practical. 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 lines carrying passenger trains only:

- Desirable grades shall be as low as reasonably practical, with a limit of 1.00%
- Maximum Grades: above 1.00% and shall be as low as practical up to 1.70%
- Exceptional Grades: above 1.70% and shall be as low as practical up to 3.00%

On lines carrying or paralleling freight lines:

- Desirable grade: 0.60% or not more than 0.7 times the ruling grade, if less.
- Maximum grade: 0.90% or not more than 0.8 times the ruling grade, if less.
- Exceptional grade: the lesser of 1.50% or the current ruling grade for the particular freight line. (Exceptions may be found to exist, but shall have BNSF or Union Pacific approval, as appropriate.)

Compensation for curvature: Grades shall be reduced through curves on grades exceeding the desirable grades on lines carrying passenger trains or freight trains. Lesser grades on freight carrying lines may require compensation as necessary to meet the standards of the freight railroad. Compensation shall be at a rate of 0.04% per degree of curvature in the case of curves defined in degrees, or in the case of curves defined by radius: Compensation % = 230 / Radius where radius is measured in feet and the compensation is in percentage. Compensation need not be provided on curves of less than 0 degrees 30 minutes.

3.3.2 Vertical Curves

Vertical curves in normal US railroad and highway usage are parabolic in nature. In European practice they are normally described by radius and built as curves of constant vertical radius. With the small changes in slope and long vertical curve lengths prevailing, there is very little difference in the as-built curve, other than the layout complexity inherent in setting out a very large vertically oriented radius. Radius requirements determined by vertical acceleration are easily converted to rate of change requirements for the much easier to set out and more generally understood parabolic curve.

Vertical acceleration limits on high speed lines have been set as low as 2.0% of gravity and as high as 5.0% of gravity. All of these are higher than AREMA Recommended Practice (AREMA Manual Chapter 5) which is a vertical acceleration of 0.6 ft/sec/sec for passenger service (1.86% of gravity) and a vertical acceleration of 0.1 ft/sec/sec for freight service (0.31% of gravity). On lines that carry long heavy freight trains, use of the former fixed rate of change standard of 0.05% per 100 feet in sags and 0.10% per 100 feet in summits is preferred.

The calculated length should normally be rounded up to the nearest 100 feet of length, or 50 feet if the greater number is impractical. Desirable values may be rounded down, so long as the length is not reduced by more than 5.0%.

- Vertical curves shall be parabolic defined in accordance with standard US railroad practice.
- There is no upper limit on vertical curve length or radius. Provision of the minimum segment length for vertical curves connecting grades with small differences in grade can result in a vertical curve with a very large radius / small rate of change.
- Unless it is determined that the speeds can never be made to achieve these limits, the speed to use in the following formulae shall be no less than 125 mph or higher for passenger trains
- Vertical curve lengths on lines carrying passenger trains only shall be:
    - o Desirable VC Length: The longer of $LVC_{feet} = 2.64\ V$ or $LVC_{feet} = 2.15\ V^2\ (\Delta\% / 100\ ) / 0.40\ \text{ft/sec}^2$, but not less than $400\ \Delta\%$

 - Minimum VC Length: The longer of $LVC_{feet} = 2.20$ V or $LVC_{feet} = 2.15\ V^2\ (\Delta\ \%\ /\ 100\ )\ /\ 0.60$ ft/ sec^2, but not less than 200 Δ%
 - Exceptional VC Length: The longer of $LVC_{feet} = 1.47$ V or $LVC_{feet} = 2.15\ V^2\ (\Delta\ \%\ /\ 100\ )\ /\ 0.80$ ft/ sec^2, but not less than 100 Δ%
- For a 125 mph design speed, these formulae resolve to:
  - Desirable VC Length: The longer of $LVC_{feet} = 840\ \Delta\%$ or 350 feet
  - Minimum VC Length: The longer of $LVC_{feet} = 560\ \Delta\%$ or 300 feet
  - Exceptional VC Length: The longer of $LVC_{feet} = 420\ \Delta\%$ or 200 feet

Where lines carrying passenger trains and lines carrying freight trains closely parallel each other in profile 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.

Vertical curve lengths on lines closely paralleling freight lines shall be:

- Unless it is determined that the speeds can never be made to achieve these limits, the speed to use in the following formulae shall be no less than 75 mph or higher for freight trains
- Desirable VC Length: $LVC_{feet} = 2{,}000\ \Delta\%$ in sags and $1{,}000\ \Delta\%$ in summits, unless the formula $LVC_{feet} = 2.15\ V^2\ (\Delta\%\ /\ 100\ )\ /\ 0.08$ ft/sec^2 requires a longer VC.
- Minimum VC Length: $LVC_{feet} = 1{,}000\ \Delta\%$ in sags and $500\ \Delta\%$ in summits, unless the formula $LVC_{feet} = 2.15\ V^2\ (\Delta\%\ /\ 100\ )\ /\ 0.10$ ft/sec^2 requires a longer VC.
- Exceptional VC Length: $LVC_{feet} = 500\ \Delta\%$ in sags and $400\ \Delta\%$ in summits, unless the formula $LVC_{feet} = 2.15\ V^2\ (\Delta\%\ /\ 100\ )\ /\ 0.10$ ft/sec^2 requires a longer VC.
- Industrial trackage and other low-speed tracks which will not carry trains consisting of more than a few cars at a time may have shorter vertical curves, down to as short as 50 Δ% or 50 feet, whichever is longer.
- For a 75 mph freight train design speed, these formulae resolve to:
  - Desirable VC Length: $LVC_{feet} = 2{,}000\ \Delta\%$ in sags and $1{,}500\ \Delta\%$ in crests
  - Minimum and Exceptional VC Length: $LVC_{feet} = 1{,}200\ \Delta\%$

3.3.3 Vertical Curve / Horizontal Curve Combinations

Vertical curves defied by freight train requirements, “Desirable” crest vertical curves defined by passenger requirements and sag vertical curves, regardless of how short, may be used in horizontal curves without restriction. Vertical curves may be used in spirals where their avoidance would require than any design element to be at less than desirable values, would require an element that would otherwise be a “Minimum” value to become “Exceptional” or would result in excessive cost or other detrimental effects.

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 Exceptional Unbalanced superelevation is sufficient to allow for this effect.

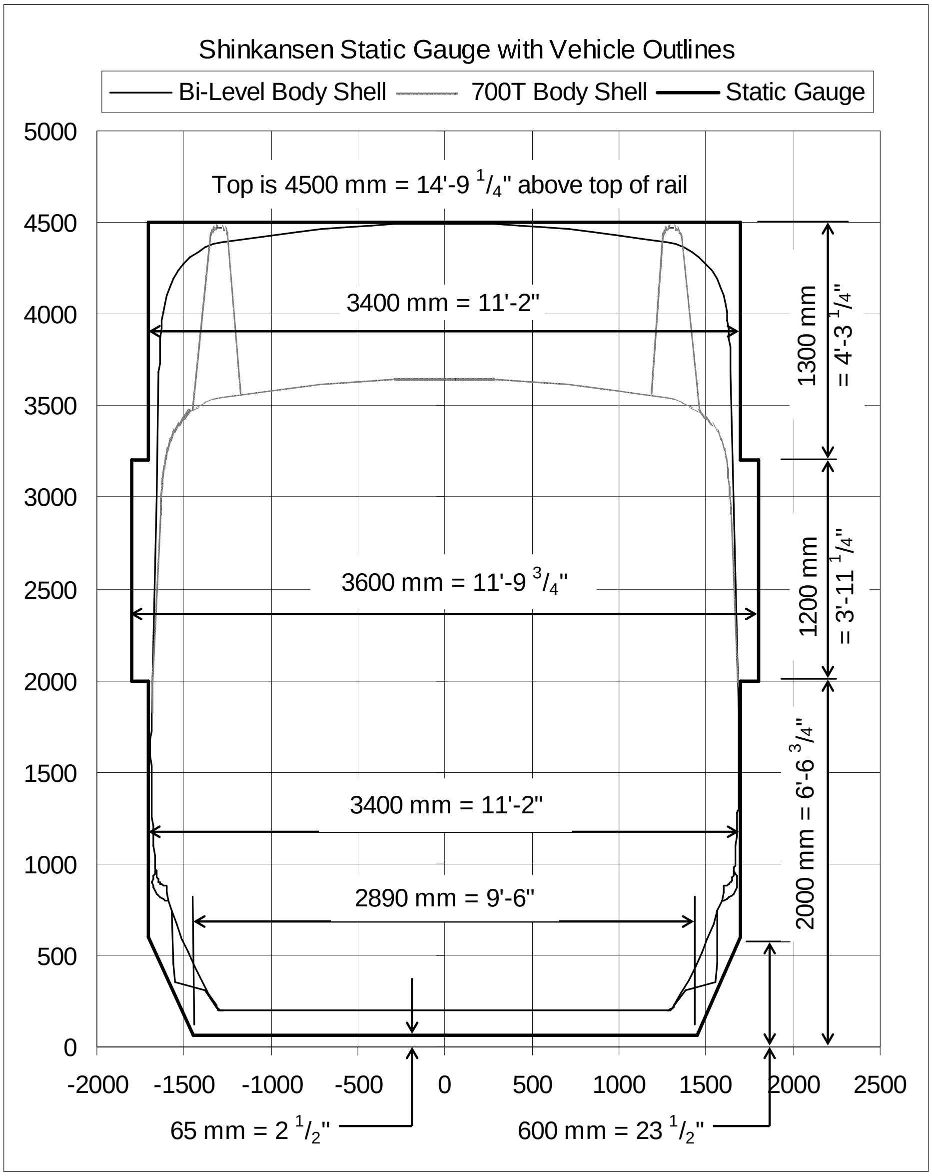
3.4 CLEARANCES

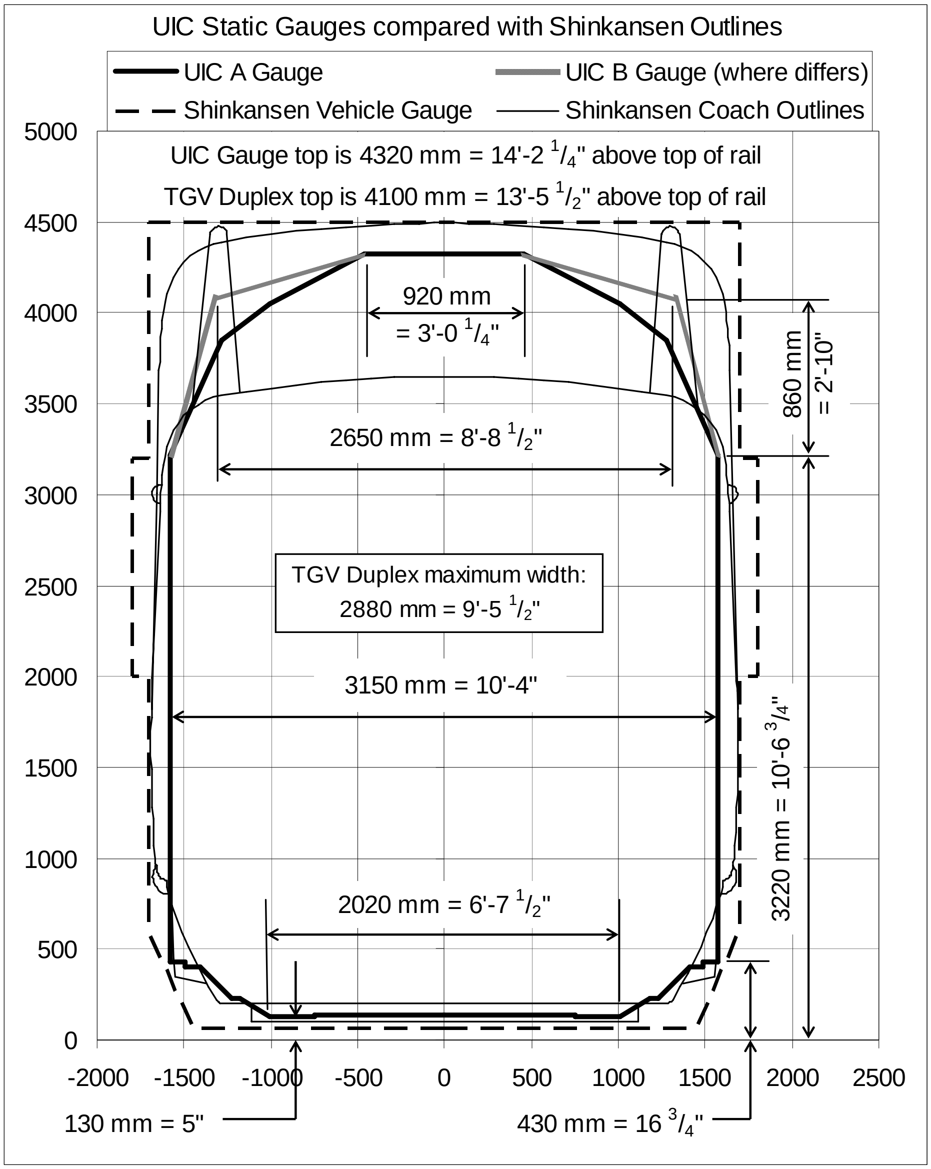
Further information on clearances will be provided in a separate document. The following is preliminary information provided for general guidance in developing preliminary alignments.

For information: Legal minimum clearances around railroad tracks in California are defined in PUC GO 26. The requirements of GO 26 shall govern regardless of lesser dimensions in other standards. However, in general the clearances required in GO 26 are less than those required in the AREMA Manual or in BNSF or Union Pacific standards. Where practical, not less than the full allowances shown in the AREMA Manual Chapter 28, Clearances, Figures 28-1-1, 28-1-2, 28-1-3 shall be provided. In addition, overhead clearances based on electrification with a 25,000 volt overhead wire at an elevation of 23’-6” shall be added. The AREMA Manual, Chapter 33, Electrical Energy Utilization, Part 2, Clearances may be referenced for guidance for additional space requirements, however, the requirements of the specific provider of the electrification technology may differ. An allowance of not less than 3 feet vertically above the nominal wire height to a space of not less than 4 feet each side of the track centerline shall be provided until such time as an electrification system design is selected.

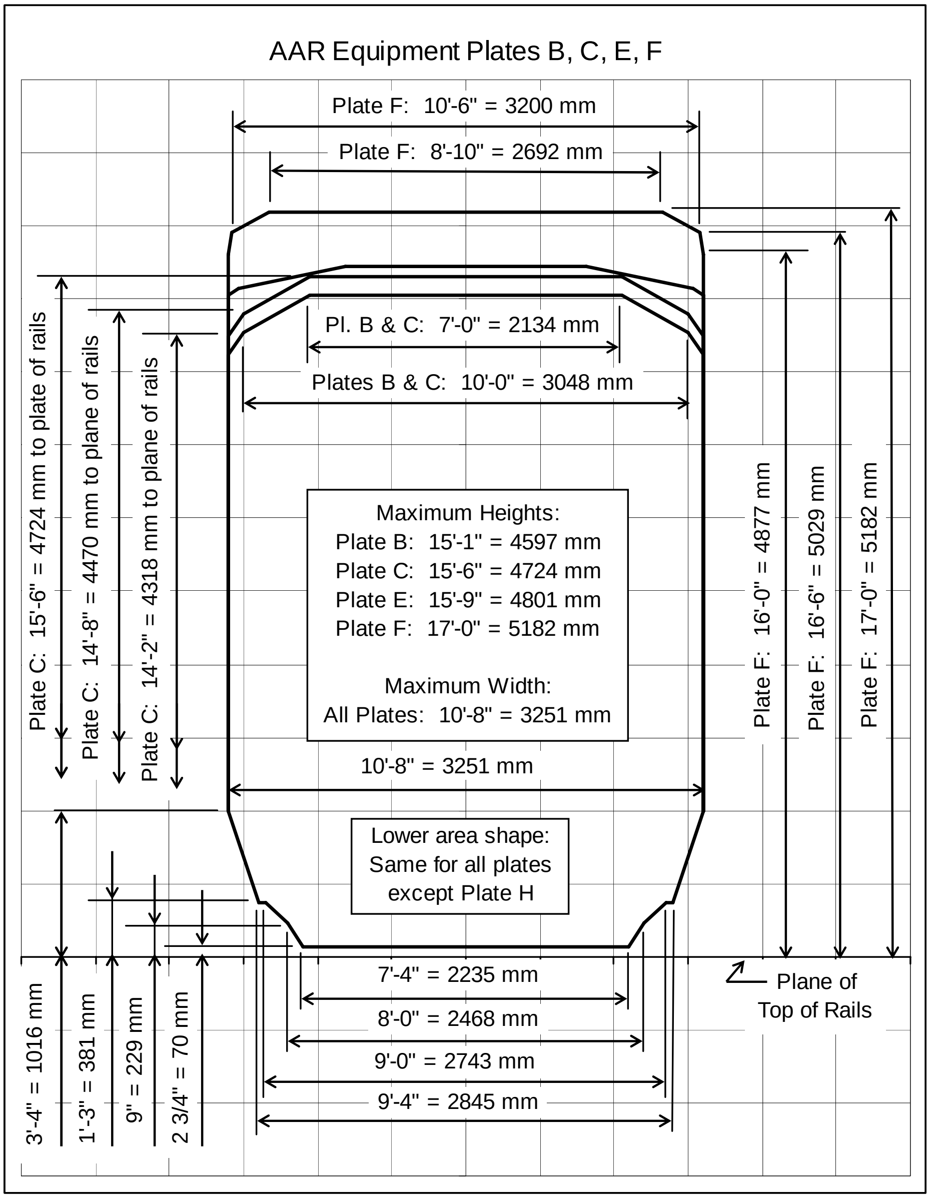
In areas where full AREMA clearances can not be provided, the clearances shall provide for passage of equipment up to the dimensions of AAR Plate F (17’-0” high). For these locations, the assumed overhead electrification allowances shall be based on a wire elevation of 19’-6”. The Amtrak Superliner cars and California Cars are sufficiently close to Plate F in dimensions that all tracks shall provide at least Plate F clearance dimensions.

Vehicles: At this point, the particular high speed rail vehicle has yet to be determined. For the American passenger equipment, all fits within Plate F. All the European equipment will fit within Plate B for height, with only the Japanese equipment being slightly wider.




UIC Static Gauges compared with Shinkansen Outlines
UIC A Gauge
UIC B Gauge (where differs)
Shinkansen Vehicle Gauge
Shinkansen Coach Outlines
UIC Gauge top is 4320 mm = 14'-2 1/4" above top of rail
TGV Duplex top is 4100 mm = 13'-5 1/2" above top of rail
920 mm = 3'-0 1/4"
860 mm = 2'-10"
2650 mm = 8'-8 1/2"
TGV Duplex maximum width: 2880 mm = 9'-5 1/2"
3150 mm = 10'-4"
3220 mm = 10'-6 3/4"
2020 mm = 6'-7 1/2"
130 mm = 5"
430 mm = 16 3/4"
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
-2000
-1500
-1000
-500
0
500
1000
1500
2000
2500

The limiting dimensions of equipment built for operation on the interconnected North American railroad system (Canada, United States and Mexico) are defined by one of several Equipment Diagrams defined by the Association of American Railroads. All these plates are 10'-8" wide, but the height varies, as seen in the diagram below:



Additional horizontal offset due to radius of curves: Additional clearances on curve shall be provided for curvature and superelevation as described in the AREMA Manual Chapter 28, Table 28-1-1, except that the additional offset required for objects more than 20 feet from the track centerline need not be provided. The offset shall be added on both sides of the track. The offset required in this table is 1.5 inches per degree of curve. In the case of curves defined by radius, the same offset is attained by using the formula: $O_{inch} = 8{,}600 / R_{feet}$. This additional offset is based on the need to pass long freight loads that exceed the length of any standard car. For lines that will be used by passenger equipment only, a lesser amount may be used. The additional offsets on curves for all high speed and Amtrak equipment may be accommodated by providing an addition offset of 1.0 inches per degree of curve or, in the case of radius defined curves, $O_{inch} = 5{,}750 / R_{feet}$. For large radius curves, the amount of widening is so small that it may be neglected. Therefore, there is no need to apply widening to curves with degrees of curve of 0 degrees 30 minutes or less, or radii of 10,000 feet or more. These additional offset requirements will not apply to station platforms that are on curves. Station platform offsets and additions for curvature shall be based on the actual equipment to be used so as to minimize the platform gap.

Additional vertical offsets due to superelevation: On curves, the top elevation of the clearance diagram shall increase by 7 inches unless the balancing superelevation for the design speed is less than 8 inches, in which case the top elevation shall be increased by one inch less the superelevation amount required to balance the design speed.

Additional horizontal offsets due to superelevation: On curves the offset toward the inside of the curve, including the width of the allowance for the electrification shall be increased by 35 inches toward the inside of the curve, or 5 inches less than 5 times the balancing superelevation for the design speed for the particular curve if it is less than 7 inches. For locations where the wire elevation will be 19'-6", the additional space toward the inside of the curve shall be 28 inches, or 4 inches less than 4 times the balancing superelevation for the design speed. There shall be no equivalent decrease in required lateral offset on the side toward the outside of the curve as the applied superelevation may vary downward to lesser amounts. These additional offsets shall be in addition to any additional offset due to the radius of the curve.

Clearances to bridge piers shall be in accordance with AREMA Manual Figure 28-1-6, including the additional offsets required on curves and for superelevation as described above.

Track centers shall be no less than 14'-0" (GO 26). Where practical, main track centers shall be not less than 15'-0" and the closest spacing between a main track and a track that is other than a main track, including a station platform track, shall be no less than 20'-0". Larger track centers are preferred. Track centers between passenger only tracks and adjacent freight track shall be no less than 25'-0" in accordance with BNSF and Union Pacific requirements.

Track centers of 14'-0" or greater normally do not need to be increased on curves. Under certain conditions of radius and superelevation widening may be necessary. Should the combined effect of radius and differences in superelevation on tracks at 14'-0" track centers result in effective track centers of less than 13'-6" the track centers shall be increased to the point that the effective track centers are 13'-6" or greater. Should the combined effect of radius and differences in superelevation on tracks at 15'-0" track centers result in effective track centers of less than 14'-0" the track centers shall be increased to the point that the effective track centers are 14'-0" or greater. Calculate the required additional offset due to radius and double it. The amount in excess of 6 inches shall be added to 14'-0" track centers. The amount in excess of 12 inches shall be added to 15'-0" track centers. If the superelevation is the same on both tracks or is greater on the track toward the inside of the curve, no superelevation based increase in track centers is required. If the superelevation on the outside track is greater, then four times the difference in superelevation shall be added to the track centers, in addition to any radius based increase in track centers.

Widening of Track Centers: Where track centers need to be increased for curves, the normal and preferred method is to use a longer spiral on the inside track. The outside track shall be given the spiral appropriate to the curve radius, speed and superelevation. The inside curve shall be given a longer spiral. The additional length shall be such that the spiral offset of the inside curve exceeds the spiral offset of the outside curve by the amount of the additional curve widening required.

Offsets to Catenary Poles: It is desirable that catenary poles be placed with their pole centers no less than 14'-0" from the track centerline. Poles set at this offset will not require the offset to be increased for curvature or superelevation under most circumstances. The exceptional offset shall be 8'-3" clear, which is the GO 26 minimum. Poles set with their centers at 9'-0" from centerline will meet this requirement. In addition GO 26 requires a clear distance from the widest part of the car body of no less than 24 inches. Increase of the 8'-3" distance is required due to superelevation and on small radius curves to meet the 24 inch requirement.

4.0 SUMMARY AND RECOMENDATIONS

The recommended Alignment Criteria for the Los Angeles Union Station to Anaheim Shared Use Corridors with 125 mph (max) operating speed is summarized in Section 6.0

As noted in the introduction, the primary objective in setting alignment is to develop as smooth an alignment as the various requirements for location in stations, mountain crossings, major stream crossings, environmental and political constraints permit. Horizontal curves, in particular, should be set larger than "Desirable" values where ever 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 means plotting condensed profiles and looking at the layout over long segments. When transitioning from low speed areas to high speed areas, the operating characteristics of both presently available trains and characteristics of trains with anticipated improvements in power, acceleration and braking. Remember, sudden jumps in speed simply do not happen with trains.

There should be a relationship between horizontal and vertical alignment standards. That is, there is not point in using vertical curves designed for 125 mph adjacent to curve or other constraining elements that will 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 a document such as this to anticipate all eventualities nor is it possible for it 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

Manual for Railway Engineering of the American Railway Engineering and Maintenance of Way Association (AREMA Manual)

Federal Railroad Administration Code of Federal Regulations (CFR)

- CFR Part 213, Track Safety Standards, generally and also in particular Subpart G -Train Operations at Track Classes 6 and Higher
- CFR Part 214, Railroad Workplace Safety

California Department of Transportation, Manuals and Standards

Public Utilities Commission of the State of California General Orders

6.0 DESIGN MANUAL CRITERIA

6.1 INFORMATION FOR INCLUSION IN DESIGN MANUAL

The following information applies to shared use Corridors where the shared use is other passenger train and does not include freight trains only. Corridors to be exclusively used by equipment designed and constructed for high speed operation above 125 mph shall be designed to a set of criteria specific to that purpose.

6.1.1 Track Centers

Main Track track centers without poles between them:

- Desirable: 16'-6" (where speeds are under 100 mph, may be 15'-0")

- Minimum: 15’-0”
- Exceptional: 14’-0”

Main Track track centers with catenary poles between them:

- Desirable: 30’-0”
- Minimum: 26’-0”
- Exceptional: 22’-0”

Main Track track center to nearest station or yard track track center without poles between them:

- Desirable: 25’-0”
- Minimum: 22’-0”
- Exceptional: 20’-0”

Main Track track center to nearest station or yard track track center with poles between them:

- Desirable: 30’-0”
- Minimum: 28’-0”
- Exceptional: 24’-0”

Station and Yard Track track centers without poles, walkways, or service roads between them:

- Desirable, Minimum and Exceptional: 14’-0”

Station and Yard Track track centers with catenary poles between them:

- Desirable: 24’-0”
- Minimum: 22’-0”
- Exceptional: 20’-0”

Station and Yard Track track centers with walkways between them:

- Desirable: 18’-0”
- Minimum: 16’-0”
- Exceptional: 15’-0”

Station and Yard Track track centers with “golf cart” service roads between them:

- Desirable: 22’-0”
- Minimum and Exceptional: 20’-0”

Desirable track centers on curves shall be increased on curve by twice the amount of increase required to an adjacent fixed structure, less 12 inches. Minimum and Exceptional track centers on curves shall be increased on curve by twice the amount of increase required to an adjacent fixed structure, less 6 inches.

6.1.2 Clearances

Clearance requirements will be described in greater detail in a separate document. The following is provided for insofar as it may affect the alignment design.

Offsets between main track or station track track centers and center of Catenary poles, based on an assumed pole diameter of not more than 18 inches.

- Desirable: 14’-0”
- Minimum: 12’-0”
- Exceptional: 11’-0”

Offsets between yard and other track track centers and center of Catenary poles, based on an assumed pole diameter of not more than 18 inches.

- Desirable: 12’-0”
- Minimum: 11’-0”

- Exceptional: 10’-0”

Clearances to walls, bridges, tunnels, etc., shall be as shown on typical sections. The Clearance requirement of the AREMA Manual Chapter 28, Figures 28-1-1 and associated discussion in Chapter 28 shall govern where more specific guidance is not provided.

6.1.3 General Alignment Requirements:

The basic principle in alignment design is to provide as smooth a line as practical with the minimum number of changes in direction and profile. Where changes in direction and profile occur, they should be as gentle as practical.

Minimum segment length: $L_{feet} = V_{mph} \times 44/30 \times t_{sec}$

Table 6.1-1: Minimum Segment Lengths at Various Speeds

Design Speed	Minimum Length, feet for times of		
	Desirable 1.8 seconds	Minimum 1.5 seconds	Exceptional 1.0 seconds
125 mph	330	275	184
100 mph	264	220	147
79 mph	209	174	116
60 mph	158	132	88
V mph	2.64 V	2.20 V	1.47 V

Segment length requirement will govern only where other design considerations for the various elements does not require longer segment lengths.

6.1.4 Minimum Radii

The maximum speed allowable with certain combinations of degree of curve or curve radius and superelevation and unbalance are shown in the following tables.

Table 6.1-2: Maximum <u>Degree</u> of Curve for Various Superelevations and Speeds

<table>
<tr><th rowspan="2">Super-elevation</th><th rowspan="2">Unbalance</th><th colspan="4">Design Maximum Speeds</th></tr>
<tr><th>125 mph</th><th>100 mph</th><th>79 mph</th><th>60 mph</th></tr>
<tr><td>3</td><td>3</td><td>0d 32m 50s</td><td>0d 51m 20s</td><td>1d 22m 00s</td><td>2d 20m</td></tr>
<tr><td>4</td><td>3</td><td>0d 38m 20s</td><td>1d 00m 00s</td><td>1d 36m 00s</td><td>2d 45m</td></tr>
<tr><td>4</td><td>4</td><td rowspan="2">0d 43m 50s</td><td rowspan="2">1d 08m 30s</td><td rowspan="2">1d 49m 45s</td><td rowspan="2">3d 10m</td></tr>
<tr><td>5</td><td>3</td></tr>
<tr><td>5</td><td>4</td><td rowspan="2">0d 49m 20s</td><td rowspan="2">1d 27m 00s</td><td rowspan="2">2d 03m 15s</td><td rowspan="2">3d 30m</td></tr>
<tr><td>6</td><td>3</td></tr>
<tr><td>6</td><td>4</td><td>0d 54m 50s</td><td>1d 25m 30s</td><td>2d 17m 00s</td><td>3d 57m</td></tr>
</table>

Table 6.1-3: Minimum <u>Radius</u> of Curve for Various Superelevations and Speeds

<table>
<tr><th rowspan="2">Super-elevation</th><th rowspan="2">Unbalance</th><th colspan="4">Design Maximum Speeds</th></tr>
<tr><th>125 mph</th><th>100 mph</th><th>79 mph</th><th>60 mph</th></tr>
<tr><td>3</td><td>3</td><td>10,500 ft</td><td>6,500 ft</td><td>4,000 ft</td><td>2,500 ft</td></tr>
<tr><td>4</td><td>3</td><td>9,000 ft</td><td>5,800 ft</td><td>3,600 ft</td><td>2,200 ft</td></tr>
<tr><td>4</td><td>4</td><td rowspan="2">8,000 ft</td><td rowspan="2">5,000 ft</td><td rowspan="2">3,200 ft</td><td rowspan="2">1,900 ft</td></tr>
<tr><td>5</td><td>3</td></tr>
<tr><td>5</td><td>4</td><td rowspan="2">7,000 ft</td><td rowspan="2">4,500 ft</td><td rowspan="2">2,800 ft</td><td rowspan="2">1,700 ft</td></tr>
<tr><td>6</td><td>3</td></tr>
<tr><td>6</td><td>4</td><td>6,500 ft</td><td>4,000 ft</td><td>2,500 ft</td><td>1,500 ft</td></tr>
</table>

At high speeds the distance between curves shall be that required by the minimum segment length. At low speeds, vehicle end offsets and angles between ends determines how close together reversing curves can be placed.

Minimum space between reverse curves is as follows:

- Desirable: 100 feet
- Minimum: 75 feet, but may be less, but not less than the following:
  - o <u>For degree curves</u>: If both curves are the same: Tan = 1.5 D^2, or if the degree of curves are different: Tan = 0.75 D_1^2 + 0.75 D_2^2, but not less than 25 feet.
  - o <u>For radius curves</u>: If both radii are the same: Tan = 48,000,000 / R^2, or if the radii are different: Tan = 24,000,000 / R_1^2 + 24,000,000 / R_2^2 but not less than 25 feet.
- Exceptional: 70 feet, but may be less, but not less than the following:
  - o <u>For degree curves</u>: If both curves are the same: Tan = 0.92 Deg^2, or if the degree of curves are different, Tan = 0.46 D_1^2 + 0.46 D_2^2, but not less than 25 feet.
  - o <u>For radius curves</u>: If both radii are the same: Tan = 30,000,000 / R^2, or if the radii are different: Tan = 15,000,000 / R_1^2 + 15,000,000 / R_2^2 but not less than 25 feet.
- Should either curve have a degree of 8 degrees 50 minutes or larger, or if using radius, 660 feet radius or smaller, 10 feet shall be added to the Minimum or Exceptional distance calculated, regardless of the radius of the other curve.
- If one of these curves is in a turnout, the end of the curve shall be defined as being at the point of frog for a curve on the frog end of the turnout and 20 feet ahead of the point of the switch for a curve on the switch end of a turnout for standard geometry Union Pacific or BNSF turnouts or 10 feet ahead of the point of switch for improved geometry turnouts.

If the curves have spirals, the ST (spiral to tangent) and TS (tangent to spiral) points may be set closer than these minimum distances down to a length of zero if there are spirals on both curves. The maximum length reduction shall be one-half of the length of each spiral.

For curves in the same direction, the distances between curves shall be the same as for reverse curves except that the Exceptional shall be either greater than 25 feet or it shall be zero. Combining spirals shall be used if either curve would require a spiral based on the paragraph on spirals on small radius curves.

6.1.5 Superelevation

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

- Degree Curves: SE = 0.0007 V^2 D (curve in degrees, speed in mph and SE in inches)
- Radius Curves: SE = 4.0 V^2 / R (radius in feet, speed in mph and SE in inches)

Curves shall not be superelevated to balance the design speed or even the calculated average or maximum operating speed. A certain amount of unbalance, usually considered to be 1.0 inches for the normal operating speed of trains, not the speed limit, 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
- Calculated normal and maximum speeds of other passenger trains

Design superelevation shall be calculated for each track. It is neither necessary nor in many locations desirable that all tracks of the line have the same superelevation on a given curve.

The maximum superelevation shall be:

- On tracks which have both high speed and other passenger trains, but no freight trains:

- o Desirable: 4 inches (3 inches where actual speed of some trains will be or may likely be low)
- o Limiting: 5 inches (4 inches where actual speed of some trains will be or may likely be low)
- o Exceptional: 6 inches (4.5 inches where actual speed of some trains will be or may likely be low)

- On tracks which will have high speed trains only:
  - o Desirable: 5 inches (3 inches where actual speed of some trains will be or may likely be low)
  - o Limiting: 6 inches (4 inches where actual speed of some trains will be or may likely be low)
  - o Exceptional: 7 inches (4.5 inches where actual speed of some trains will be or may likely be low)

Superelevation shall be applied by lifting the outer rail of each track. The top of rail profile line will be the top of rail of the low rail for the track.

Unbalance:

- Preferred minimum unbalance: 1.0 inch
- Desirable limit of unbalance: 3.0 inches
- Limiting unbalance: 4.0 inches (by FRA exemption only)
- Exceptional unbalance: 4.0 inches (by FRA exemption only)
- Limiting and Exceptional unbalance shall be reduced by 0.25 inches if any part of the curve is on a crest vertical curve that is shorter than Desirable values. (The use of shorter vertical curves than those in this document will require this value to be increased.)

6.1.6 Spirals:

Two types of spirals shall be used. Clothoid (straight rate of change) spiral for low and medium speed curves and Half-sine (variable rate of change) spirals for high speed curves.

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

Half Sine Spiral:

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:

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

Clothoid Spirals (constant rate transitions) will be used on all tracks having lower design speeds

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 6.1-4: Minimum Length of Spiral

Clothoid (Linear Change) Spirals				
Spiral Design Factor	Desirable (0.3 g)	Minimum (0.4 g)	Exceptional (0.5 g)	Associated with turnouts
Superelevation	1.47 Ea V	1.17 Ea V	0.98 Ea V	0.75 Ea V
Unbalance	1.63 Eu V	1.22 Eu V	0.98 Eu V	0.75 Eu V
Twist	90 Ea	75 Ea	62 Ea	62 Ea
Minimum Segment	2.64 V	2.20 V	1.47 V	1.33 V
Half-Sine (Variable Change) Spirals *				
Spiral Design Factor	Desirable	Minimum	Exceptional	Associated with turnouts
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	- -

* 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%. 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” and “Associated with Turnouts” values.

Spirals on Large Radius Curves: Should the radius be such that for the maximum design speed the required superelevation and unbalanced superelevation both be under 1.0 inches and the “Minimum Segment” length for the spiral is more than twice the length required for any other factor, clothoid spirals may be used instead of half-sine spirals regardless of track type or design speed. Should the required superelevation be zero (balancing superelevation for the maximum speed be less than 0.75 inches) and the calculated offset of the curve due to application of the spiral be less than 0.05 feet in ballasted track or less than 0.02 feet in non-ballasted track, spirals may be omitted. (these values subject to revision)

Reverse Curves: Should there be insufficient distance between curves to provide a tangent segment of the minimum required length, the spirals shall be extended so as to provide a reversing curve. 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 if beneficial to design and construction.

6.1.7 Grades and Vertical Curves:

Grade Limits:

- Desirable grades shall be as low as reasonably practical, with a limit of 1.00%
- Maximum Grades: above 1.00% and shall be as low as practical up to 1.70%

- Exceptional Grades: above 1.70% and shall be as low as practical up to 3.00%

Vertical Curves: The calculated length should normally be rounded up to the nearest 100 feet of length, or 50 feet if the greater number is impractical. Desirable values may be rounded down, so long as the length is not reduced by more than 5.0%.

- Vertical curves shall be parabolic defined in accordance with standard US railroad practice.
- There is no upper limit on vertical curve length or radius. Provision of the minimum segment length for vertical curves connecting grades with small differences in grade can result in a vertical curve with a very large radius / small rate of change.
- Unless it is determined that the speeds can never be made to achieve these limits, the speed to use in the following formulae shall be no less than 125 mph or higher for passenger trains
- Vertical curve lengths on lines carrying passenger trains only shall be:
  - Desirable VC Length: The longer of LVC_{feet} = 2.64 V or $LVC_{feet} = 2.15 V^2 (\Delta\% / 100) / 0.40$ ft/sec^2, but not less than 400 $\Delta\%$
  - Minimum VC Length: The longer of LVC_{feet} = 2.20 V or $LVC_{feet} = 2.15 V^2 (\Delta\% / 100) / 0.60$ ft/ sec^2, but not less than 200 $\Delta\%$
  - Exceptional VC Length: The longer of LVC_{feet} = 1.47 V or $LVC_{feet} = 2.15 V^2 (\Delta\% / 100) / 0.80$ ft/ sec^2, but not less than 100 $\Delta\%$
- For a 125 mph design speed, these formulae resolve to:
  - Desirable VC Length: The longer of LVC_{feet} = 840 $\Delta\%$ or 350 feet
  - Minimum VC Length: The longer of LVC_{feet} = 560 $\Delta\%$ or 300 feet
  - Exceptional VC Length: The longer of LVC_{feet} = 420 $\Delta\%$ or 200 feet

Where lines carrying passenger trains and lines carrying freight trains closely parallel each other in profile 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.

Vertical curve lengths on lines closely paralleling freight lines shall be:

- Unless it is determined that the speeds can never be made to achieve these limits, the speed to use in the following formulae shall be no less than 75 mph or higher for freight trains
- Desirable VC Length: LVC_{feet} = 2,000 $\Delta\%$ in sags and 1,000 $\Delta\%$ in summits, unless the formula $LVC_{feet} = 2.15 V^2 (\Delta\% / 100) / 0.08$ ft/sec^2 requires a longer VC.
- Minimum VC Length: LVC_{feet} = 1,000 $\Delta\%$ in sags and 500 $\Delta\%$ in summits, unless the formula $LVC_{feet} = 2.15 V^2 (\Delta\% / 100) / 0.10$ ft/sec^2 requires a longer VC.
- Exceptional VC Length: LVC_{feet} = 500 $\Delta\%$ in sags and 400 $\Delta\%$ in summits, unless the formula $LVC_{feet} = 2.15 V^2 (\Delta\% / 100) / 0.10$ ft/sec^2 requires a longer VC.
- Industrial trackage and other low-speed tracks which will not carry trains consisting of more than a few cars at a time may have shorter vertical curves, down to as short as 50 $\Delta\%$ or 50 feet, whichever is longer.
- For a 75 mph freight train design speed, these formulae resolve to:
  - Desirable VC Length: LVC_{feet} = 2,000 $\Delta\%$ in sags and 1,500 $\Delta\%$ in crests
  - Minimum and Exceptional VC Length: LVC_{feet} = 1,200 $\Delta\%$

X.1 APPENDIX: DISCUSSION OF SOURCE OF STANDARDS

Table 1.3-1 and Figure 1.3-1: Speeds After Unrestrained Acceleration for Various Distances: By calculation using the following: High speed trains based on Shinkansen 700T train resistance. Power for 700T for the 300 km/h case and higher power and acceleration from Shinkansen information found on the web for the 220 mph case. Amtrak acceleration based on a standard train and train resistance based on modified Davis formula.

FRA track standards and the California PUC GOs can be found on the internet.

Certain BNSF and UPRR information is available on their respective web sites. However, as work progresses more information will be needed which will have to be obtained from their respective engineering departments.

3.1 General: Alignment segment length requirements are from the Taiwan High Speed Rail Corporation Design Specification, and are presumably from either SNCF or DB. The 1.0 second standard is “reverse engineered” from DB high speed turnout designs, was the actual design practice in THSRC, and has proven to provide a high quality ride on station entries and exits.

3.2.1 Curvature: Curvature tables are by calculation.

Curves with small central angles: based on run time requirements and known practices.

Minimum curve radius: Based on use of no less than 190 m radius in Europe and 200 m radius in Japan, and the use of 190 m radius in Taiwan with Japanese equipment, and Japanese concerns that were not backed by any technical analysis that anything under 200 m would cause difficulties with the equipment.

Distances between small radius curves: Formulae based on information provided in AREMA Manual, Chapter 5, Part 3.5.1 and similar information in DB AG standards, and calculation based on the position of both Shinkansen and American coach ends on small radius curves not adjacent to other curves.

3.2.2 Superelevation: In addition to calculations based on basic mechanics and information in the AREMA Manual Chapter 5, Part 3.1., the Half Sine Spiral is explained in the Northeast Corridor High-Speed Rail Passenger Service Improvement Program (NECIP) Task 19.2, Review of Lengths and Comfort Criteria for Spirals, and Japanese publications, also some information on variable rate spirals is UIC 703, also notes on common practice in AREMA Manual Chapter 5, Part 3.2.1, particularly Figure 5-3-2.

3.2.3 Unbalanced Superelevation: Minimum desired unbalance on curves based on discussions with Kowloon Canton Railways operations and engineering personnel, direct observation of the ride quality at various speeds on certain curves in the Taiwan High Speed Railway, know practices in other systems. 4.0 inch maximum is from the FRA.

3.2.5.2 Application of the Two Types of Spirals and Spiral Formulae: Half Sine Formulae from the Taiwan High Speed Rail Design Specification. Break point between Clothoid and Half-Sine spirals based on Japanese Shinkansen practice for non-ballasted track and a compromise between Japanese and Taiwan standards for ballasted track.

3.2.5.2 Determination of Spirals Lengths: For clothoid spirals: Desirable and Minimum values based on AREMA Chapter 5, Part 3.1, and the NECIP report, and Japanese preferred twist rates. Exceptional and With Turnouts based on European values and AREMA twist rates. For Half-Sine Spirals, standards based on Japanese information.

Half Sine Formulae from the Taiwan High Speed Rail Design Specification. Break point between Clothoid and Half-Sine spirals based on Japanese Shinkansen practice for non-ballasted track and a compromise between Japanese and Taiwan standards for ballasted track.

3.2.5.2 Grades: Limits based on normal American practices. Use of 3.00% instead of 2.50% or 2.20% for the Exceptional given the presence of Amtrak and Metrolink trains is based on the realities of California mountain railroading and known grades on the Redondo Junction Flyover, but is beyond the limit of normal practice for locomotive hauled trains. Compensation for grades is based on AREMA Manual Chapter 5, Part 3.7.1. The radius formula is a rounded mathematical conversion of the degree formula. Application of compensation has considerable variation in practice. That included here appears to be appropriate for the situation.

3.3.2 Vertical Curves: Vertical Curve practices are based on AREMA Manual, Chapter 5, Part 3.6. Selected values for vertical acceleration are based on Part 3.6.g, and for the higher exceptional value, knowledge of practice. It is inadvisable to go much beyond the current acceleration limit in the AREMA recommendations for passenger service without strong evidence that it raises no issues with American passenger equipment. The current AREMA already results in much shorter vertical curves than the recommendations that prevailed in the Manual for many years. The designated fixed change values for freight vertical curves were formerly the AREMA Recommended Practice and are still used by many railroad companies. Variations of these fixed rate freight values are also in line with US railroad company practices, either current or in the recent past. (Recall that many companies have disappeared in mergers, and with that their practices.)