AREMA®
American Railway Engineering and
Maintenance-of-Way Association

Part 8

Embedded Track

— 2023 —

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SECTION 8.1 INTRODUCTION

8.1.1 GENERAL (2010)

This section of Chapter 12 deals specifically with the planning, design, construction and maintenance of facilities and tracks used for what is commonly called “street running,” where the tracks are embedded in pavement or other road surface, and generally the paving surface is even with the top of rail. Embedded Track is founded on a concrete slab, similar to non-ballasted track (covered elsewhere), and the paving infill is usually concrete or asphalt, but can also be pavers, paving stones, grass, etc.. Embedded track may be used by a wide variety of steel wheeled vehicles including light rail vehicles, streetcars, trolleys or trams (the name depending on local preference), and sometimes shared use with freight trains, and the track structure must accommodate the types of traffic anticipated, including heavy- axle load rubber-tired traffic.

As the variety of vehicles that might use the tracks covered in this Section of Chapter 12 of the *Manual for Railway Engineering* are myriad, the following verbiage will be used to describe the typical vehicles:

- Light Rail Vehicle (LRV): a vehicle of modern design, sometimes with four axles but frequently articulated and having six or more axles or pairs of independently rotating wheels, used in street running but primarily intended for relatively high-speed travel between fairly widely spaced stations, often operated coupled in trains, top operating speed in the 55-65 mph range, and usually limited to minimum curve radii of 82 ft (25 m).

- Streetcar: a vehicle of either heritage or modern design, frequently having four axles, but sometimes articulated and having six or more axles, used primarily in mixed traffic, street running in downtown circulator operations, top operating speed in the 30-45 mph range.Vintage streetcars are sometimes capable of negotiating curve radii down to 35 ft (11 m) but modern low-floor streetcars are usually limited to minimum radii of 66 ft to 82 ft (20m to 25m).

As all recommendations in this Section are related to hypothetical vehicles, not specific ones, it is absolutely essential that the designer and specifier be fully conversant with the operating and tracking capabilities of the vehicle(s) that will actually use the tracks, and to verify suitable track geometric and alignment criteria that will interact and work properly. It is equally essential that the track designer be constantly aware that there may be characteristics of the shared street civil or architectural design that may be detrimental to the design of good and safe track alignment, and that any conflicts should be resolved as early as possible in the planning.

Embedded track requires special planning and design approaches to integrate the rail facilities into the urban streetscape successfully and to have the rail vehicles interact efficiently and safely with the rubber-tired traffic in the shared roadway, while maintaining the appropriate balance between the needs of the rail transit system and other stakeholders in the busy urban environment. This starts with careful planning to be sure there are no glaring safety issues caused by the track alignment or facilities and that the rail vehicles will mesh well with the overall traffic plan and signaling. Further, that the installation in the streets will not significantly degrade the operation of the rail vehicles, such as excessive street surface drainage crossfall and curves without spirals. The planning should also include considerations of ancillary facilities such as locations and designs of overhead contact wire system poles, stations, stops, traction power substations, pedestrian crosswalks, safety zones, etc.

The design involves developing a comprehensive alignment plan and construction details that cover the unique requirements of street running, generally described as:

- Types of rail traffic; vehicle loadings and geometric requirements, wayside clearances, safety issues.
- Locations and details for special trackwork, with particular attention to inspection and maintenance, as well as the interfaces and potential hazards associated with placement of special trackwork in areas shared with motor vehicles and/or pedestrians.
- Traction power, TP wayside facilities, stray current and corrosion control.
- Integration of the track into the street design physically, operationally and esthetically.
- Special considerations such as bridges, tunnels, viaducts, especially passenger/pedestrian safety issues.
- Track maintenance inspection, access and repair considerations.
- Traffic and rail signal integration; vehicle and pedestrian grade crossings, parking lanes and safety zones.
- Station, stops and their amenities, including safe pedestrian access and protection from auto and rail traffic.
- Maintenance and repair management considerations; life-cycle costs.

The planning and the design items listed above are covered in detail in the sections following, and with references to other Chapters of the *Manual for Railway Engineering* and other authoritative sources, such as AASHTO, State PUCs, and local ordinances. These may dictate design features, especially those related to truck and bus pavements, bridge design, street utilities and drainage provisions, and the like. These recommendations are based not only on theory but also on documented experience from both successful and unsuccessful embedded and paved track and facilities projects and rail transit properties operating extensive embedded and paved track operations. Where criteria or plans are quoting a specific Agency’s standards, it will be noted, and the reader should be aware that such standards tend to be property-specific and should be thoroughly investigated as to their appropriateness for any other project. The following excerpt from the 1923 issue of the American Transit Engineering Association Engineering Manual, Way and Structures Division “W”, recognized the limitations of that Manual. Part 8 of Chapter 12 will be developed with this in mind and recognizing that such limitations remain valid today.

> *"This specification is intended to cover the construction of electric railway track in paved city streets. It is obvious that no general specification can be prepared for such work to cover all special types of track construction, or to meet special conditions. The scope of this specification has therefore been limited to an expression of the fundamental principles which should be followed out in constructing track in paved streets."*

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SECTION 8.2 EMBEDDED TRACK ALIGNMENT

8.2.1 GENERAL (2010)

Alignments for embedded track in streets are frequently more constrained than for other light rail transit (LRT) track types (ballasted and direct fixation.) Embedded tracks follow streets within traffic lanes and curb offsets, make tight turns within street intersections and follow pavement cross sections and profiles.

The primary objectives of any track alignment are cost effectiveness, operating efficiency and passenger safety and comfort. The alignment recommendations in this section include worst case criteria for application to embedded track alignment. Like all alignments, the absolute maximum/minimum alignment criteria herein are to be avoided in favor of longer tangents, flatter curves, and longer spirals wherever possible. Where the costs of street modifications are minor, they should be incorporated if they will improve the alignment. Extensive use of absolute maximum/minimum values results in slower operations and higher maintenance costs.

It is recommended that these worst case criteria be combined with more conservative criteria into a single criteria document for any specific project. Alignment criteria may be found in Chapter 3 of Transit Cooperative Research Project (TCRP) Report No. 155, Transit Design Handbook for Light Rail Transit, and in both Chapter 5, Part 3, and Section 3.5 of this Chapter of the AREMA *Manual for Railway Engineering*. Developing a general criteria that includes worst case allowable criteria will reduce the time consuming effort required to grant variances from the general criteria that are often needed otherwise. As stated above, these worst case criteria should be applied only when general criteria will not produce a feasible design. Even with comprehensive criteria containing desired values, minimum/maximum values, and absolute minimum/maximum values, field conditions will occur requiring engineering analysis of alternatives, judgment and compromise to arrive at a safe, efficient solution.

The criteria in Section 8.2 are based on a typical light rail vehicle (LRV). If possible, during preliminary design, the vehicle parameters affecting alignment criteria should be established. For final design, it is imperative that the vehicle parameters affecting alignment criteria be established and the project alignment criteria adjusted accordingly. For streetcars (both modern and vintage) due to their greater variance of vehicle parameters compared with LRV's, the advice in this paragraph is of even greater importance.

Street running embedded track speeds are usually limited to the legal speed of the roadway traffic which is seldom over 35mph. For embedded track in open running territory where the typical LRT vehicle is capable of a sustained operating speed of 55mph or higher, more conservative (lower maximum and higher minimum) values should be considered for alignment criteria.

Combinations of any of maximum grade, maximum unbalanced superelevation, minimum horizontal curve radius and minimum vertical curve radius should be avoided. Track designers must consult with vehicle designers to ensure that proposed combinations will not damage vehicles or present a risk of vehicle derailment. Furthermore, any proposed equipment being used for maintaining the tracks (MOW equipment) should also be considered as this equipment may be unable to negotiate proposed alignment geometry. Rail grinders and some high-rail equipment cannot negotiate tight curves so if these geometries cannot be avoided, then maintenance restrictions will likely be required. Steep grades also pose problems for MOW equipment as these vehicles sometimes slip trying to climb or descend the grade especially in areas where the tracks become slippery due to fallen leaves, water or ice.

These criteria assume standard gauge track (56.5 inches.) plus or

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minus small adjustments for tight gauge and gauge widening.

Many of the criteria stated herein are excerpted from or derived from information in TCRP Report No. 155 which is available from the US Transportation Research Board (TRB).

8.2.2 VEHICLE INTERFACE (2010)

These embedded track alignment criteria reflect the operating limitations of typical modern LRT vehicles. Circulator system vehicles (streetcar and trolley car are used synonymously herein) are often capable of tighter radius horizontal and vertical curves than an LRV.

Most modern LRVs and streetcars utilize a low-floor design which allows for level boarding of passengers in compliance with the Americans with Disabilities Act (ADA). In contrast, most vintage streetcars utilize high floors and narrow aisles which generally do not comply with the ADA so these vehicles usually require significant modifications or waivers before they can operate. Refer to Section 8.8 – Stations, Stops, Passenger Access and Safety of this Chapter for more information.

Individual vehicles may be significantly different in one or more operating characteristics than the typical values given here. This is known to be specifically true for vehicles with trucks having independently turning wheels.

These criteria, based on typical values for an LRV, may be considered useful for preliminary design but they should be adjusted as the actual operating characteristics are established. It is imperative for an efficient final design that the vehicle specification (or consultant or manufacturer) be consulted as to vehicle limiting operating characteristics. Alignment criteria for final design must be compatible with the selected vehicle.

Vehicle characteristics should be based on worst case of new or deteriorated condition. For example, minimum clearance under the vehicle which affects allowable crest vertical curve radius may be reduced for worn or collapsed suspension compared with new conditions.

For an average, modern, bi-directional, coupled, fully loaded, articulated LRV, typical limiting operating characteristics are:

Maximum vehicle operating speed	55mph
Maximum allowable grade	7%
Minimum horizontal curve radius (25m)	82 feet
Minimum vertical curve radius (250m), sag: 1150ft (350m)	crest: 820ft
Maximum allowable rate of twist 25ft	1 inch in
Maximum vehicle roll angle (stabilized suspension)	< 1.5 degrees
Typical vehicle width (2650 mm)	8.7 feet
Typical truck spacing	22 to 30 ft

For comparison, typical vintage streetcar limitations are:

Maximum vehicle operating speed	35mph
Maximum allowable grade	9%

Minimum horizontal curve radius

35 feet

Minimum vertical curve radius crest:	310 ft; sag: 560 ft.
Maximum allowable rate of twist	1 inch in 12.5 ft
Maximum vehicle roll angle	Varies
Typical vehicle width	8.1 feet (2460 mm) and narrower
Typical truck spacing	22 ft

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All vehicle dimensions and clearances should be established before the design commences. If the precise vehicle has not been determined, appropriate design values should be agreed upon so that both the track and vehicle designers know what values have been assumed. If any of these values need to be altered, further discussion and coordination between the track and vehicle designers should be conducted

8.2.3 HORIZONTAL ALIGNMENT (2010)

Horizontal alignment consists of tangents, circular curves and spirals in various combinations.

8.2.3.1 Tangents

- The desirable minimum tangent between curves should be the truck spacing plus axle spacing of a truck (overall wheelbase) so that a vehicle will have adjacent trucks exit one curve before entering another. No portion of the tangent should be superelevated.
- The absolute minimum tangent between curves is zero so long as the resultant geometry does not exceed the vehicle coupler maximum angle, the speed does not exceed 20 mph and the adjoining curves are unsuperelevated.
- If adjoining curves are superelevated, they must have spirals or intervening tangent of sufficient length to meet superelevation runoff requirements.
- The foregoing criteria apply to reverse curves. For curves in the same direction, a smoother ride results from a compound curve rather than a short tangent between the two curves. Compound curves should have spirals connecting the different radius portions of the curve. The spiral shall begin with the radius of one curve and uniformly increase/decrease to the radius of the other adjacent curve and not be back to back spirals meeting at a common tangent.

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8.2.3.2 Curves

- The desirable minimum curve radius is 1.5 times the absolute minimum radius.
- The absolute minimum radius is that radius at which a coupled vehicle will negotiate the curve.
- For superelevated curves, the desirable minimum length of circular curve (in feet) is three times the normal operating speed (in mph) of the curve. For spiraled curves this is the length of the circular curve plus one half the sum of the lengths of the spirals.
- There is no desired minimum length for unsuperelevated curves, ie back-to-back spirals can be used.

8.2.3.3 Superelevation

Street running track does not often allow for design of actual superelevation (E_a) based solely on operating speeds. While actual superelevation is not precluded on street running track, it is likely that the superelevation will have to accommodate the cross slope of the street as well as the desired superelevation. Negative superelevation can occur and speed should be adjusted accordingly.

Since street running requires frequent speed reductions and stops to accommodate street traffic, the maximum E_a should not exceed 3 inches. Exceptions to this maximum, such as roadway curves with larger than 3 inches of cross slope in the roadway and where frequent stopping of trains is unlikely offer opportunities to use higher actual superelevation. On tangents the maximum cross slope should not exceed one inch. On tangents and curves, the differential between the street cross slope and track cross slope/superelevation should not be greater than one inch.

8.2.3.4 Allowable Speed on Curves

Based on ride comfort for short trips and assuming well maintained alignment on LRT embedded track systems, the recommended maximum lateral acceleration is 0.1g (6 inches of unbalance). This limit may be increased, on a case by case evaluation of critical locations, to a lateral acceleration of 0.15g (9 inches of unbalance superelevation). The Commentary at Appendix A of Part 8 provides further considerations for a case by case evaluation.

Allowable speed on a curve is:

$$\mathbf{V = \sqrt{E / 0.0007\,D}}$$

Where V = speed in mph

E = total superelevation in inches, the sum of $E_u + E_a - E_r$

Where E_r = equivalent car body roll allowance which for a stabilized vehicle is 1.5 inches and for unstabilized suspensions is 3 inches. See Section 8.10, Appendix A - Commentary on Analysis of Lateral Acceleration and Jerk Rate for Establishing Superelevation and Spiral Length for further analysis of E_r.

E_u = design unbalance: up to 6 inches (0.1g) with up to 9 inches (0.15g) for approved specific locations E_a =

actual superelevation in inches.

D = degree of curvature (5730/radius in feet)

8.2.3.5 Spirals

Spirals should be used on all mainline (passenger carrying) embedded track curves unless the calculated spiral length is less than one percent of the curve radius. Constructing short spirals on large radius curves is not practical as the spiral offsets are not noticeably different from the adjoining simple curve offsets. For zero actual superelevation on embedded track curves, spiral length is determined based on the rate at which lateral acceleration (unbalance) is introduced. This topic is discussed in Appendix A. The maximum rate of change of lateral acceleration for embedded track (jerk rate) is 0.1g/s. This value is much greater than the jerk rate allowed in section 3.5.7. The absolute minimum length spiral L_s is therefore:

$$\mathbf{L_s = 0.29\,V\,E_u}$$

Where Ls = length of spiral in feet

V = velocity in miles per hour

E_u = unbalance from the curve computation in inches

When curves have superelevation in them, the rate of attainment should not exceed a vertical acceleration rate of change of 0.1g/s. The equivalent formula is:

$$Ls = 0.29\,V\,E_a$$

The ability of the vehicle to withstand twist must also be considered when E_a is used. For a typical LRV with an allowable rate of twist of 1 inch in 25 ft, the formula is:

$Ls = 25E_a$

The longest spiral computed using these three formulae determines the actual spiral length to be used. The more conservative formulae given in Section 3.5 of this Chapter should be used where they do not cause excessive cost to implement.

There are many different methods for computing spiral parameters. The notations and formulae in Chapter 5, Part 3 are recommended for spiral layout computations.

Many different philosophies have been used to proportion E_a and E_u on curves. See TCRP Report No. 155 for applicable formulae.

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8.2.4 VERTICAL ALIGNMENT (2010)

Vertical alignment is comprised of tangential gradients joined together by parabolic vertical curves.

8.2.4.1 Tangent Grades

- Maximum gradient must be based on vehicle braking and tractive effort. Typically for LRVs this requires that sustained grades over 2500 ft long not exceed 6% and shorter sustained grade not exceed 7%.
- Minimum tangent length between vertical curves; desired 100ft; minimum is truck spacing plus axle spacing on a truck (overall wheel base), usually about 40 ft. Absolute minimum is zero.
- Desirable grade at stations is 0% to 0.35% and in the United States the grade is typically limited to no more than 2% in order to comply with Americans with Disabilities Act (ADA) provisions. The ADA does provide exceptions where existing street grades exceed 2% but using steeper grades at stations should be carefully considered as it will impact the accessibility of the system.

8.2.4.2 Vertical Curves

Vertical alignment must follow street grades unless the streets will be re- graded as part of the track construction. The critical vertical curve length is governed by either physical vehicle requirements or passenger comfort. in both sag and crest curves. For physical vehicle requirements, the minimum vertical curve must allow for coupler connections, articulation limits and appropriate clearance of the underside of the vehicle adjusted for wear and collapsed suspensions. Typically, physical vehicle requirements will govern minimum vertical curve lengths at speeds of 15mph and less. Passenger comfort usually dictates the minimum vertical curve lengths for speeds above 15mph. Where autos are also sharing the same lane as the LRV or Streetcar, roadway design criteria must also be met so the track designer must ensure that vertical curve designs also meet roadway design requirements for autos and these requirements are generally set by the local transportation department.

A typical LRV's vertical curve radius limit is usually around 820 ft for crests and 1150 ft for sags. Using these values, the equivalent minimum curve length (LVC) for physical vehicle requirements can be determined from:

$LVC = 0.01AR$

Where A = algebraic difference (using the percent grade as whole numbers, i.e. 2.0 % = 2, -2.0% = -2 and 0.35% = 0.35) of gradients connected by the curve, and

R = Limiting radius in ft

For example, crossing a street with a 2% crown (1:50 cross slopes) the minimum LVC = 0.01 x (2 minus -2) x 820 = 32.8 ft. This length LVC would fit a 40 ft wide street.

For passenger comfort, the

minimum crest LVC is LVC =

$AV^2/25$

Where V = design speed in mph

The minimum sag LVC is LVC

$=AV^2/45$

Using the above sample curve, the speed for the 32.8 ft long crest LVC should not exceed $32.8 = 4V^2/25$. V = 14.3 mph.

Back to back reverse curves are acceptable as long as the above minimums are met by each curve.

SECTION 8.3 WHEEL RAIL INTERFACE

An improper wheel/rail interface can lead to derailments. TCRP Report 155 contains in-depth descriptions on how to perform a thorough wheel-rail analysis and track designers should consult this resource for further guidance prior to designing embedded track. It should be noted that freight and transit practices differ in this area so simply checking transit wheel-rail interfaces may not be adequate if non-transit vehicles (rail grinding equipment and catenary bucket trucks for example) are allowed to operate on the system as well. All equipment that uses the track must be checked or must be modified to match the configurations that have been checked.

SECTION 8.4 RAIL

8.4.1 RAIL CONSIDERATIONS (2010)

This section discusses rail sections and provides information and recommendations for their application in embedded track. Both tee rails and grooved rails are used in constructing embedded tracks. Grooved rails have the advantage of a built-in flangeway and are the preferred rail section in areas where both trains and autos share the same guideway. Traditional tee rails are satisfactory for systems that are designed for exclusive transit operations and these rails are easier to obtain in North America because they meet Buy America requirements.

8. Rail Selection Criteria

When considering the specifications for a rail section or sections for use in embedded track the following six most important considerations should be used to evaluate tee and grooved rails sections:

a. Suitability for the application:

(1) Beam strength.

(2) Head profile to match wheel profiles and have recommended gauge face angle.

(3) Projected wear life of plain and premium rails.

(4) Height of section which impinges on excavation and paving depth details.

(5) Applicability to the project paving and rail mounting details, and providing a suitable, ADA-compliant flangeway that is architecturally pleasing and maintainable.

(6) Requirement for guarding, either curves or fully guarding all tracks.

(7) Matching prior rail usage on the property.

(8) Adequate cross section area and conductivity for negative return without excessive voltage drop.

b. Cost factors:

(1) First cost.

(2) Premium feature first cost.

(3) Projected life-cycle cost.

(4) Projected future cost for repair or extensions.

(5) Added cost for guarding devices where needed.

c. Availability:

(1) Rolling frequency.

(2) Projected long-term availability.

(3) Multiple sources preferred.

(4) Availability of premium features and long lengths.

(5) Compliance with Buy America provisions, if applicable.

d. Metallurgy & maintenance

(1) Weldability, electric flash-butt and thermite.

(2) Requirements for special treatment of welds such as post-weld hardening.

(3) Ease of compromise welding to rails of different metallurgy.

(4) Running surface hardness achieved by alloying or heat-treating, or both.

(5) Subject to brittle fracture (especially in cold climates).

(6) Grinding – are grinders available to be used for corrugation removal and re-profiling.

e. Adaptability to special trackwork

(1) Availability of matching cast and/or built-up components.

(2) Adaptability to machining and pre-curving.

(3) Section height suitable for use of asymmetric switch tongues/points.

(4) Suitability for laying in plates or DF Fastenings.

f. Quality Assurance

(1) Availability of industry recognized quality standards & inspection techniques.

(2) QC requirements that lend themselves to normal field inspection methods.

(3) Availability of trained inspectors and suitable equipment to verify the QC requirements.

8.4.1.2 Use of Tee or Grooved Running Rails

Based on the criteria above, many properties in North America have selected the 115RE tee rail section for use in embedded track. The selection was based on the following considerations:

a. Suitable for most applications regarding strength, head profile, wear life, height, etc.

b. Interfaces well with the AAR 1B wheel profile; reasonably well with ATEA-type wheel profiles.

c. Readily available from several producers; Buy America compliant.

d. Initial cost; reasonable delivery times.

e. Available head-hardened and in long lengths; some mills furnish CWR.

f. Easy to weld, both flash-butt and thermite.

g. Some matching special trackwork appliances available.

h. Adequate current capacity for most operations.

i. Dimensions, properties and quality are controlled by AREMA *Manual for Railway Engineering* Chapter 4 specifications, which are well respected and understood in the industry

It is recommended that the designer or specifier give proper consideration to all the factors listed above, and apply proper weighting of those factors based on project-specific criteria, including the historical or aesthetic concerns. The 115RE rail section is normally more cost-effective than grooved rail, and can be used where practical. Alternatively, other tee rail sections can also be used, such as 85 ASCE, 90 ARA-A, or 100 ARA-B, if available, either new or Class I condition relay. However, there are situations where grooved rails are preferred, and may have attributes that offset some or all of the additional cost of the rails, such as:

a. The integral flange guard provides built in protection against wheel-climb derailments, especially on sharp curves and in special trackwork.

b. Having the infill paving, especially asphalt, flush with top of rail on each side reduces the potential for raveling or chipping and spalling of the pavement.

c. The relatively small flangeway opening reduces the tripping hazard for pedestrians and bicycles vs a large, tooled flangeway.

d. Grooved rail is much easier to lay in elastomeric grout embedment, as it doesn't need a separate flangeway formed in the grout.

e. Concrete placement/finishing with modified paving machinery is easier with grooved rail.

It should be noted that using tee rail in embedded track requires a means to maintain a suitable flangeway opening in the infill paving, such as:

a. In Portland cement concrete, a blocked-out, troweled or screeded flangeway of appropriate dimensions and shape can be easily formed in the concrete.

b. In less rigid paving infills, such as hot-mix asphalt, pavers, brick, crushed stone, a flangeway guarding device will be required such as shown in Article 8.4.1.3 or a rubber or plastic flangeway former.

c. In rails mounted in polyurethane or similar resilient polymers, a flangeway must be formed in the polymer, by pouring the polymer low on the gauge side, by use of a flangeway forming blockout, or a flangeway forming device as shown in Article 8.4.1.3.

8.4.1.3 Typical Flangeway Guarding Methods & Appliances

When tee rail is used, a flangeway can be tooled into the concrete; however, this is not always acceptable. Therefore, other methods of forming the flangeway are shown in the figures below. These are only two of many possible methods, some proprietary, which will produce a satisfactory flange guard. Where curves are to be guarded, a restraining guard rail device must be added to the tee rail. Flange guard must not be confused with restraining guard rail as rubber and concrete are not recommended materials for the latter..

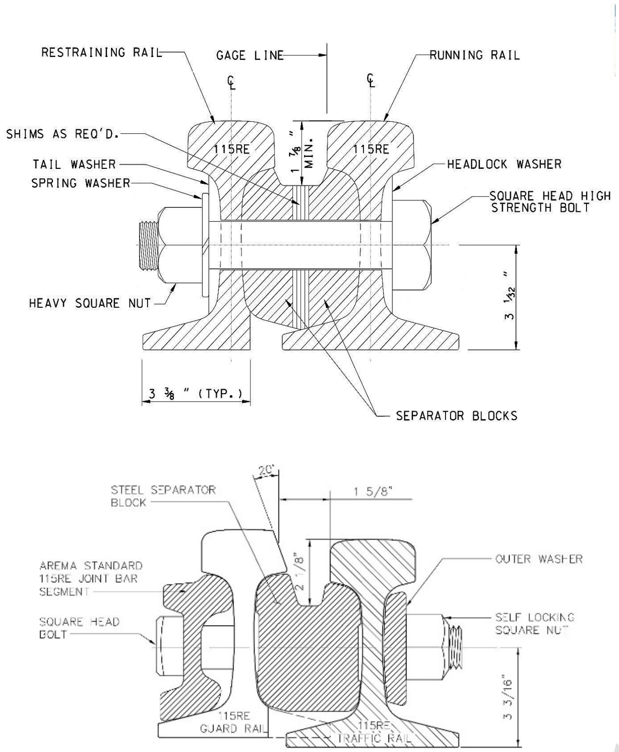

Figure 12-8-1. Typical Flangeway Guarding

Note: There are other methods, as noted above, available to provide a flangeway, some proprietary. See additional details including electrical isolation techniques in Section 8.5, Rail Fixation (Fastening).

8.4.1.4 European Grooved Rails and Special Trackwork Rail Profiles

The grooved rails produced primarily by European rolling mills are not currently covered by the AREMA MRE; they are covered by several European standards organizations, which control both the design and manufacture. Article 8.4.2 will provide information on the standards organizations and their respective specifications and recent changes in those organizations' responsibilities. This is furnished as information only,

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not an AREMA recommended practice. It is the responsibility of the designers and users to familiarize themselves with the appropriate, current specifications for rails and special rail sections contemplated for use in North American projects that will be rolled in non-domestic mills, and with the terminology used. This section will cover the topics listed below:

a. Information on the standards organizations controlling the specifications applicable to grooved rails and special rail sections produced primarily in non-domestic mills and to which AREMA recommended practices do not presently apply, and limited details of those specifications and/or recommended practices.

b. The changes in nomenclature applicable to certain rails and special sections produced to European or other standards that are frequently used in North America.

Typical manufacturing specifications, tolerances and testing of the rails noted in a., and b., above

a. Drawings and physical characteristics of certain rails and special sections produced to European or other standards that are frequently used in North America.

b. General recommendations for selection of appropriate rails and special sections.

c. Special considerations related to handling, welding (both field and shop), laying and de-stressing of embedded rails.

5 Block Rails

In addition to tee rails and grooved rails, there exists a third category of rails called block rails which do not have a rail web. While grooved rails are no longer manufactured in North America, one North American rail mill is rolling lengths of 112TRAM block rail. 112TRAM block rail has a rail head profile similar to 59R2/51R1 grooved rails. The block rail height is very low since the rail web is omitted which makes this a desirable section to use on bridges where space available for adding rails may be more severely limited. However, the missing rail web significantly reduces the beam strength of the rail and complicates the use of many rail accessories such as rail alignment jigs, bolted insulated joints and rail bonds that historically have used the rail web for attachment. Transitions between block rails and other rail sections can also be problematic and expensive. All of the criteria listed in Section 8.4.1.1 – Rail Selection Criteria, should be carefully evaluated before choosing to proceed with a block rail section.

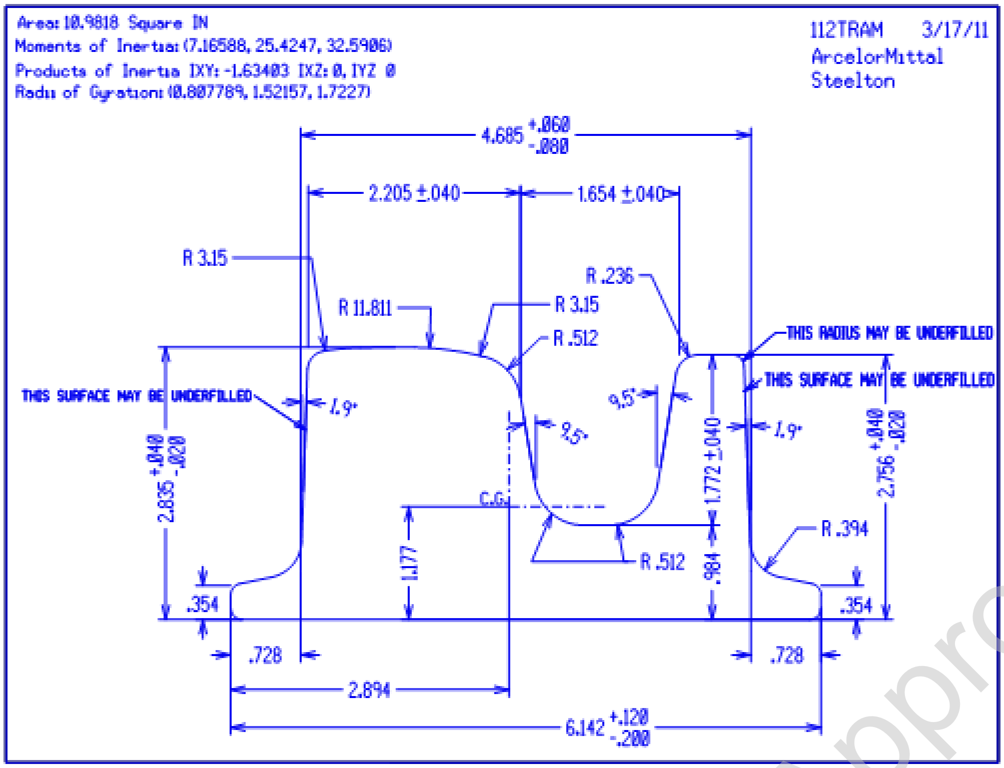

Figure 12-8-2. Block Rail Section

8.4.2 STANDARDS ORGANIZATIONS AND RELEVANT STANDARDS OR RECOMMENDED PRACTICES (2011)

8.4.2.1 Standards Organizations

a. UIC - The International Union of Railways (UIC is a French acronym for, “L’Union Internationale des Chemins de fer“) is an international organization based in France whose purpose is to promote the interests of railway transport on a worldwide basis, including technical cooperation. Prior to the creation of the European Union, many rail standards were controlled by the UIC, and rail sections were named with UIC in the nomenclature, such as UIC-60 and UIC-33. That role is now filled by the CEN (see below). The UIC is similar to the AAR combined with the focus on passenger transport of APTA.

b. VDV – The Association of German Transport Undertakings (in German = “Verband Deutscher Verkehrsunternehmen“; formerly “VöV”) is an organization of German-speaking public transit and freight rail groups to provide cooperative technical guidance similar to AREMA; the specifications they publish are recommended practices, not standards. Grooved rails were, and in some cases still are, supplied per VDV specifications, and tramway special trackwork is still controlled by VDV.

c. CEN – The European Committee for Standardization (languages: English, German, French) is based in Brussels, Belgium, and publishes standards for a multiplicity of technical endeavors, including rails controlled by the steel committee. The CEN is like ASTM, ACI, ASME, IEEE, SAE, AAR, AREMA, etc. rolled into one standards organization. The signatory countries, now more than thirty, are required to accept the “European Norm” standards as their own without alteration. These standards have “EN” plus an identification number and date of approval in the name; in the case of grooved rails and special “construction” sections, the CEN standard is EN 14811, which replaced both UIC and VDV specifications in most cases. If the standard has “pr” before the name, such as prEN 14811, that indicates a “provisional” status; the provisional standard has been approved by the sponsoring committee, but has not been approved by all the signatory countries. However, it is generally considered to be in effect as approved standards drafted by the designated controlling committee(s) are seldom rejected by the signatories. The information following is based primarily on the CEN EN 14811 standard with some additional information from CEN standard EN 13674 which covers tee

(Vignole, also called flat bottom) rails and special sections of interest such as restraining guard rails, STW construction rails, and asymmetric switch point sections.

d. For domestically produced tee rails the relevant standards are controlled by:

(1) American Railway Engineering and Maintenance-of-Way Association (AREMA) – domestic tee rails only.

(2) American Society of Civil Engineers (ASCE) – lighter tee rail sections, mainly 85 AS, primarily an industrial section, but rolled regularly.

8.4.2.2 Applicable European CEN Standards EN 14811, EN 13674, and VDV

The nomenclature of grooved rails and certain special construction rail sections have been standardized and harmonized per Table 12-8-1, below. All drawings, plans, specifications and procurement documents should reflect the proper CEN Standard nomenclature, where applicable, to avoid confusion and errors. If the profiles are per VDV standards, the same information noted should appear in all documents.

Table 12-8-1. Revised Standard Nomenclature of Grooved Rails and Construction Rails per CEN Standards EN-14811 and EN-13674 (Partial List)

CEN Standard Profile Designation	Prior Profile Designations (VDV, UIC, etc.)	Generally Applicable To	Fig.
51R1	Ri 52-R13, Ri 52	Running rails, H = 130 mm	1
53R1	R1 53-R13, Ri 53	Running rails, H = 130 mm	2
55G1	35 GP	Running rails, H = 152.5 mm	3
56R1	Ri Ic	Running guard rails, H = 160 mm	4
59R1	Ri 59-R10, Ri 59	Running rails, small g.c. radius[3], H = 180 mm	na
59R2	Ri 59-R13, Ri 59N	Running rails, large g.c. radius[3], H = 180 mm	5
60R1	Ri 60-R10, Ri 60	Running rails, small g.c. radius[3], H = 180 mm	na
60R2	Ri 60-R13, Ri 60 N	Running rails, large g.c. radius[3], H = 180 mm	6
62R1	NP4aMod	Running guard rails, H = 180 mm	7
67R1	Ph 37a	Running rails, large flangeway, H = 180 mm	8
49E1A1	Zu2-49	Switch tongue profile, H = 116 mm	9
61C1	Ri Ii	STW const. grooved rail, flange-bearing, H = 160 mm	10
75C1	BA 75	STW const. grooved stock rail, H = 180 mm	11
76C1	VK Ri 60	STW const. blind groove guard rail, H = 180 mm	12
33C1	U69, UIC33, RI 1-60	Frog guard & restraining rails, H = 93 mm	13
Fz 36[1]	Fz 36, Zu 36	Switch tongue profile, H = 75 mm	14
GGR-118[2]	GGR-118	Running grooved guard rails, H = 168,3mm (6.625-in)	na

Footnotes:1) Section is not controlled by standards; produced per producing mills' and/or users' designs & specs.

2) Section is no longer rolled but is in track on several NA properties, as info only; not a CEN standard.

3) g.c. is gauge corner.

General notes:

a. The rail sections listed above either are being or have been used in North America with some regularity.

b. Not all sections listed in Table 12-8-1 are illustrated on the following pages. In addition, many more rail sections (profiles) not listed here are available from some manufacturers. Those have not been included here because they have either not been adopted as CEN standards or have seen little or no use in North America. For other sections available, refer to mill catalogues and to the referenced CEN standards, or other standards if not covered by CEN.

c. Sections including the letter “R” in their designation are grooved rails; in German, “Rillenschiene”. Grooved rails, commonly known in North America as “girder rails”, are rolled with an integral flangeway in the head of the rail, and used in the construction of ordinary embedded track. Sections including the letter “C” in their designation are known as “construction rails” and used in the fabrication of special trackwork. When fabricating STW using construction rails, the flangeways and head contours are machined (see Fig. 12). Additional details of embedded special trackwork construction are in Section 8.7, presently under development, which also covers designs outside the scope of CEN and VDV standards.

d. For a more detailed discussion of the application of grooved rails in LRT construction, especially as relates to wheel profile/rail groove matching, please see Transit Cooperative Research Program (TCRP) Report No. 155 “Light Rail Track Design Handbook”.

8.4.2.3 Rail Profile Drawings with Properties of the Sections/Profiles

Figures 1 through 14 shown below have the principal dimensions called out, along with basic section properties. Some sections are not shown where they are almost identical to another section, with the key differences noted. For complete dimensions and properties, please refer to the appropriate CEN or VDV Standard, or the producing mill’s drawings or catalog.

Chap TOC
VOL 1
VOL 2
VOL 3
VOL 4

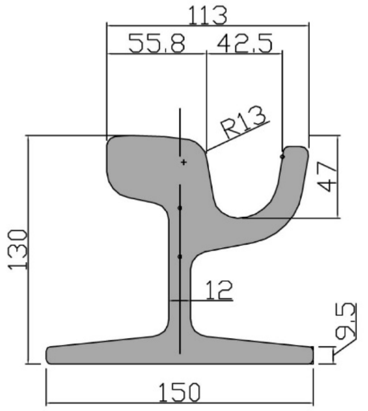

Fig 1 - CEN Profile 51R1

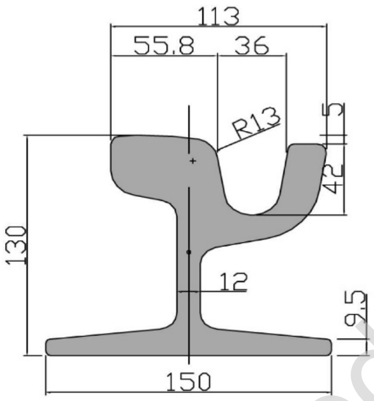

Fig 2 - CEN Profile 53R1

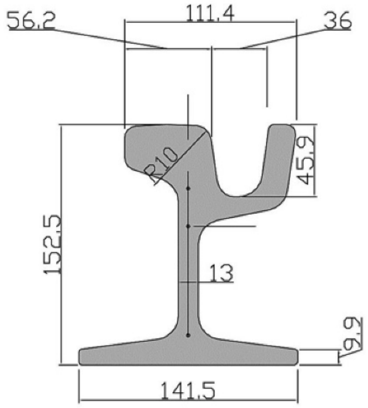

Fig 3 - CEN Profile 55G1

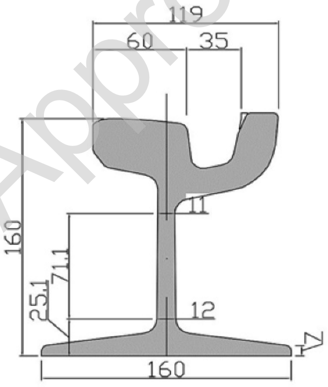

Fig 4 - CEN Profile 56R1

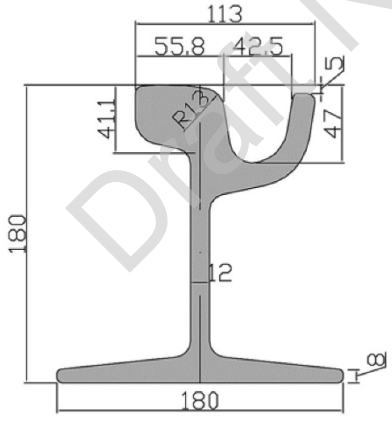

Fig 5 - CEN Profile 59R2

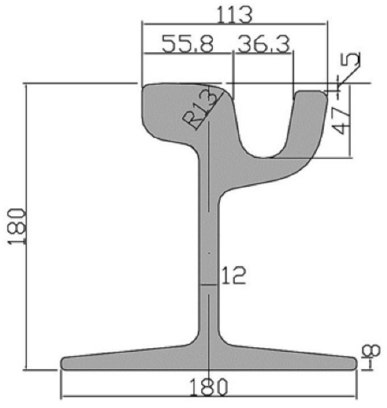

Fig 6 - CEN Profile 60R2

Figure 12-8-3. Rail Profiles

Chap TOC
VOL 1
VOL 2
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VOL 4

Note: Profiles 59R1 and 60R1 are similar to 59R2 and 60R2, respectively, except that the gauge corner radius is 10mm (0.394-in), rather than 13mm, and the flangeway is approximately 3-5mm narrower

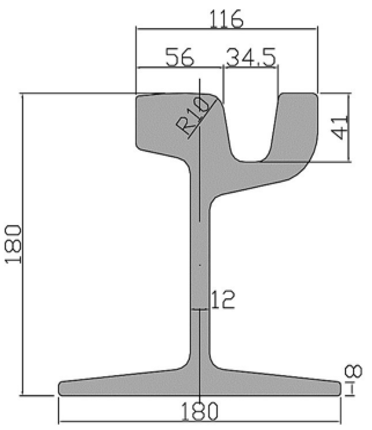

Fig 7 - CEN Profile 62R1

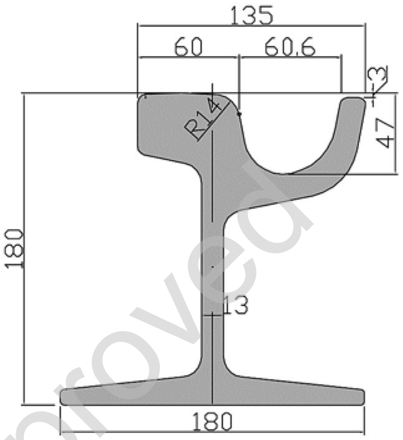

Fig 8 - CEN Profile 67R1

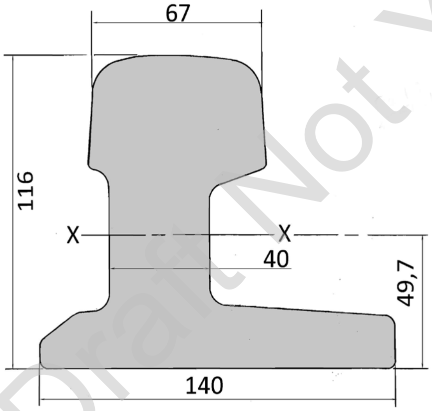

Fig 9 - CEN Profile 49E1A1

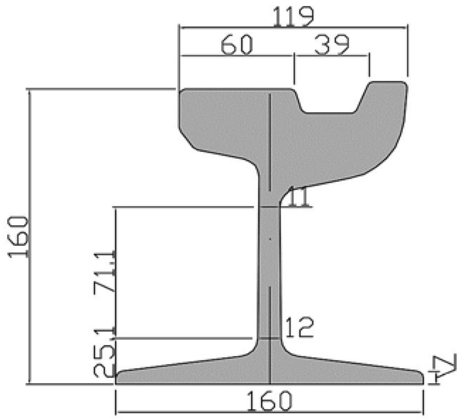

Fig 10 - CEN Profile 61C1

Figure 12-8-3. Rail Profiles (Continued)

Chap TOC
VOL 1
VOL 2
VOL 3
VOL 4

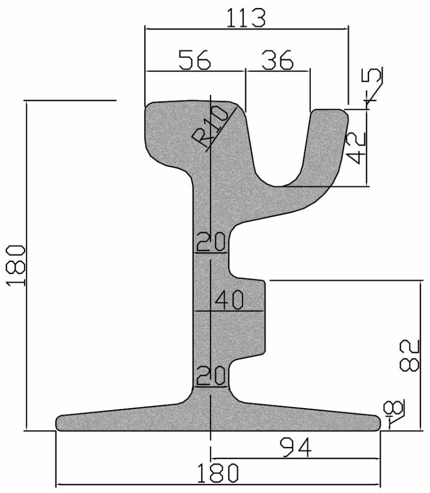

Fig 11 - CEN Profile 75C1

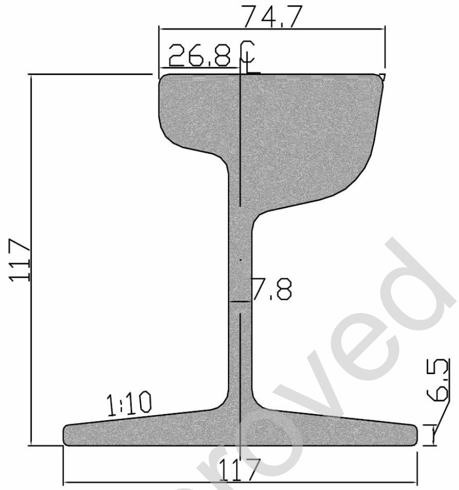

Fig 12 - CEN Profile 76C1

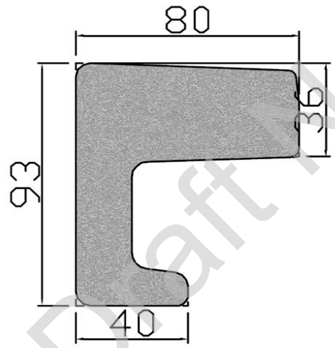

Fig 13 - CEN Profile 33C1

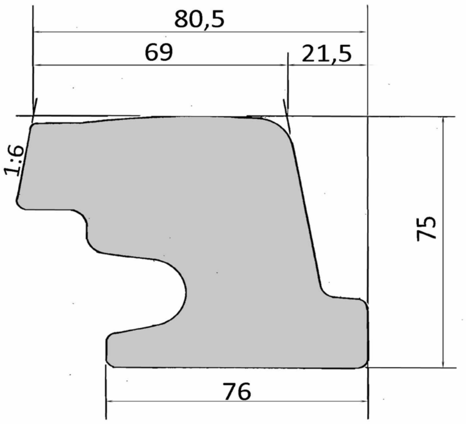

Fig 14 - Fz 36

Figure 12-8-3. Rail Profiles (Continued)

8.4.2.4 Properties of Grooved and Construction Rail Profiles/Sections

Table 12-8-2. Table of Properties - Grooved Rails and Construction Rails per CEN Standards EN-14811 and EN-13674 & Some Proprietary Items (Partial List)

CEN	**Linear Mass**		**Area**		**I xx (Note 2)**		**I yy**		**S head**		**S base**		**Rail Lg/Unit Wt**	
Profile	**kg/m**	**lb/yd**	**cm^2**	**in^2**	**cm^4**	**in^4**	**cm^4**	**in^4**	**cm^3**	**in^3**	**cm^3**	**in^3**	**m/tonne**	**ft/gr ton**
51R1	51.37	103.6	65.44	10.14	1289	30.93	695.6	16.69	198.4	12.10	198.1	12.08	19.47	64.86
53R1	52.98	106.8	67.49	10.46	1326	31.82	738.4	17.72	208.3	12.71	199.9	12.19	18.87	62.92
55G1	54.77	110.4	69.78	10.82	2076	49.82	681.5	16.36	285	17.39	260.5	15.89	18.26	60.87
56R1	55.98	112.9	71.31	11.05	2477	59.45	802	19.25	349	21.29	278	16.96	17.86	59.52
59R1	58.97	118.9	75.12	11.64	3267	78.41	886.2	21.27	373.8	22.80	352.8	21.52	16.96	56.52
59R2	58.14	117.2	74.07	11.48	3211	77.06	757	18.17	363.1	22.15	350.5	21.38	17.2	57.32
60R1	60.59	122.2	77.19	11.96	3353	80.47	928.6	22.29	391.4	23.88	355.4	21.68	16.5	54.99
60R2	59.75	120.5	76.11	11.80	3298	79.15	920.1	22.08	380.6	23.22	353.3	21.55	16.73	55.76
62R1	62.37	125.8	79.45	12.31	3535	84.84	1042	25.01	427.6	26.08	363.3	22.16	16.03	53.42
67R1	66.76	134.6	85.04	13.18	3554	85.30	1250	30.00	436	26.60	360.8	22.01	14.98	49.92
49E1A	63.14	127.3	80.43	12.47	1098	26.35	681.9	16.37	165.3	10.08	221.7	13.52	15.83	52.76
61C1	60.79	122.6	77.44	12.00	2631	63.14	834	20.02	394	24.03	283	17.26	16.45	54.82
75C1	75.23	151.7	95.84	14.86	3596	86.30	967.5	23.22	398.3	24.30	400.8	24.45	13.29	44.29
76C1	72.73	146.6	92.65	14.36	3949	94.78	1049	25.18	529.6	32.31	374.6	22.85	13.75	45.82
33C1	32.99	66.52	42.02	6.51	297	7.13	218.8	5.25	83.7	5.11	51.8	3.16	30.31	101.01
Fz36	*33.99*	68.53	*46.8*	7.25	*933.7*	22.41	*1190*	28.56	*NA*	#####	*NA*	####	*29.42*	98.05
GGR-118	58.3	117.6	74.3	11.52	2640	63.43	777	18.65	321.5	19.61	283.2	17.3	17.15	57.16

Note 1: values are valid to only three significant figures at this writing; they should be verified prior to performing stress calculations and writing firm procurement or construction specifications.

Note 2: Some sections show the Moment of Inertia to the IX-X axis (the base), not the Ix Neutral Axis; see appropriate producer's drawing to verify the geometric properties of the section/profile of interest.

8.4.2.5 Manufacturing Methods, Tolerances and Testing

All European specifications for grooved rails and construction rails require the use of steel produced by the continuous casting process, with vacuum-degassed steel specified for rails to be head-hardened; however, there are some substantial differences in the philosophy behind the specifications:

a. Manufacture:

   (1) EN 14811 is performance-based, rather than prescriptive, wherever possible.

   (2) The six grades of non-alloyed rail steels are classified by hardness, not tensile strength; three grades are as-rolled, three grades are heat-treated.

   (3) The hardnesses specified range from 200-240 HBN to 340-390 HB.

(4) The allowable mass of included hydrogen is specified for each grade in PPM, and is controlled by testing the blooms.

(5) Alloyed rails are covered by agreement between customer and producer.

(6) EN 14811 references other CEN standards to specify steel grade nomenclature, and tensile and hardness testing.

(7) Quality management is based on the producer adhering to the requirements of EN ISO 9001.

b. Tolerances:

(1) Rails are produced to two different tolerance levels, analogous to railroad vs. industrial quality.

(2) Many more measurement points on the profile are required in EN 14811 than prior standards.

(3) The profile and straightness tolerances are generally greater in EN 14811 than in AREMA *Manual for Railway Engineering*, Chapter 4, Table 4-2-2 (i.e. in EN 14811, height of rail ±0.059-in [±1,5mm] vs. Chapter 4 + 0.030-in. [0,76mm]/- 0.015-in [0,38mm] based on the premise that the traffic is relatively low speed.

(4) Construction rails used in making special trackwork have tighter tolerances than running rails.

(5) Both minor upsweep and downsweep are acceptable.

(6) Rail length tolerance is much tighter than Chapter 4.

c. Testing:

(1) Testing procedures are generally similar to AREMA practice.

(2) For the as-rolled profiles, hardness testing is required on the running surface only; for heat-treated, both running surface and internal hardness testing is required.

(3) Purpose-designed gauges are used for profile checking.

(4) No tests are specified to determine residual stresses.

8.4.2.6 Additional Considerations for Grooved Rail Selection

a. The selection criteria listed in Article 8.4.1.1 are equally applicable to grooved rails of non-domestic manufacture.

b. Investigate the popularity of a candidate profile/section regarding how often it is rolled, by how many producers, etc., as this has important implications regarding long-term availability and cost.

c. Determine the chemical composition and hardness of a candidate section to make sure that welding will not be difficult or require special procedures, such as post-hardening; if special procedures are required, make sure they are covered in the construction specifications.

d. Obtain proper handling information from the producer regarding slinging long rails with spreaders and put this information in the specs.

e. Determine compatibility of candidate section with the wheel profile(s) to be used; note, for instance, that 59R1 and 59R2 have different gauge corner radii and slightly different groove widths, important considerations in sharp curves.

f. Determine that shipment of a candidate section will be done so as to protect the rails from salt-spray corrosion during transit, and that an appropriate spreader is available to unload the rails without damage.

8.4.2.7 Special Considerations Regarding Handling, Welding, Laying and De-stressing Rails

a. The recommendations in Chapters 4 and 5 should be followed faithfully, plus some special considerations listed below.

b. Handling: special care should be taken when lifting or moving grooved rails, as the thin web and base flanges make it easy to cripple the base or web if the rails are overbent in handling (see 8.4.2.6.c and 8.4.2.7.d), or to twist it beyond the yield point.

c. Welding: care should be exercised in both flash-butt and thermite welding to make sure the web and base are not overheated, or base droop and/or web curling may occur.

d. Laying: welded strings should not be dragged around sharp corners or otherwise mishandled as noted in 8.4.2.7.b to prevent kinking or twisting the rails.

e. De-stressing: there is no common agreement at this time whether embedded rails need de-stressing in the conventional sense specified for open track, as sun-kinks are not likely; however, it is prudent to lay the rails at something near the average ambient temperature to reduce any tendency to have pull-aparts.

This practice is also recommended for all running rails in embedded tracks.

SECTION 8.5 RAIL FIXATION (FASTENING)

There are three common types of rail fixation in embedded track. The first method employs the use of an insulating material wrapped around the rails (often referred to as a “rail boot”), supporting the wrapped rails on temporary ties or jigs and then casting the rails into the surrounding embedment material (typically concrete or asphalt cement). The second method employs suspending rails in troughs and then filling the troughs with a pourable elastomeric material to secure the rails in position. The third method employs typical ballasted track construction with a surfacing layer of asphalt or concrete placed on top of the ties. Refer to TCRP Report No. 155 for additional discussion of embedded track rail fixation.

SECTION 8.6 SUPPORT STRUCTURE

Embedded tracks are almost always supported on a concrete slab. This section covers considerations in the design of concrete support for embedded track. If embedded track will be supported on concrete or timber ties, then standard ballasted track design techniques should be used. If the track system utilizes direct fixation fasteners, then the design procedures described in Chapter 8 for Concrete Slab Track can be employed but the designer should be aware that the vast majority of concrete pavements are now constructed as either unreinforced or conventionally reinforced pavements so designing for CRC would be an atypical pavement construction method in most locations.

Embedded tracks are most similar to conventional concrete roadways designed as a rigid slab on a flexible support (subgrade). It is therefore recommended that local roadway design and construction techniques be followed as these techniques are typically based on local conditions and decades of experience in constructing long-lasting concrete support slabs. Some critical components of concrete roadways that should be included in concrete slabs for embedded tracks are:

- Use of local roadway jurisdiction specifications for concrete mix designs. The local specifications should account for unique weather conditions and should help avoid custom mixes that cost more and are unfamiliar to local producers and installers.
- Use of a concrete mix design with a minimum compressive strength of 4000 psi
- Use of surface finish consistent with local roadways to ensure adequate traction for rubber-tired vehicles and to avoid excessive noise.
- Use of standard joint designs for contraction, construction, and isolation joints. Note that expansion joints are not recommended in embedded track slabs and designers are encouraged to review

Track slab can be unreinforced or designed with reinforcement steel and the designer is urged to follow pavement design techniques rather than bridge design techniques when designing the concrete track slab unless there are special circumstances that will require the tracks to span trenches or other unusual obstacles. The designer should also consult corrosion control engineers to determine if any special details are required in the slab to control and/or monitor stray electrical currents.

The following parameters must be determined prior to design of the support structure:

- Anticipated loads from rail and road vehicles including any maintenance vehicles that may be allowed on the tracks
- Maximum anticipated train speeds
- Anticipated track modulus
- Impact Factor for rail joints and wheel flats
- Subgrade support. Note that AREMA recommends designs utilize a subgrade support value of at least 20 pounds per square inch so if the subgrade support is anticipated to be lower than this, then subgrade improvements should be included in the design

SECTION 8.7 SPECIAL TRACKWORK

Locating special trackwork in embedded track areas should be avoided if possible since this trackwork requires more regular maintenance which will become more difficult once it gets embedded. If the trackwork can be located in areas where direct fixation is permissible (no shared traffic), that is recommended. If the trackwork must be located in embedded track, then the trackwork must be specifically designed to be embedded in pavement. One critical consideration in embedded track will be the type of switch machine that will be employed as most switch machines are not designed for embedment so the transit agency must determine whether switches will be manually operated or power operated and what machines will be acceptable. The dimensions of the switch machines and their respective housings often require more depth than the typical trackwork and designing appropriate drainage systems for these areas is crucial as dirt and debris can quickly render switches inoperable. For areas with snow and ice, special consideration should be taken for how roadway sanding, salting or other deicing methods will impact the performance of switch machines.

SECTION 8.8 STATIONS, STOPS, PASSENGER ACCESS & SAFETY

Wherever possible, AREMA recommends utilizing level boarding for rail transit service as this facilitates the most efficient passenger loading/unloading, provides the greatest access for all passengers (including those with limited mobility), and generally reduces impacts to existing infrastructure due to the lower platform heights that are typically employed. In some instances where vintage streetcar systems are in use and it is not feasible to convert to level boarding, special considerations should be given to improving access to vehicles for riders with disabilities. This may involve retrofitting streetcars and/or designing stops in a manner to facilitate passenger loading and unloading without stairs. For systems with relatively low use, this may involve a boarding ramp/plate being placed between the vehicle and platform but for most systems an automated lift, ramp or bridge plate system should be utilized.

In areas where rail vehicles and autos share the same lane alongside a platform, the designer must consider carefully how the platform will encroach into that lane as the platform edge will generally be much closer to the tracks than a typical curb. This may require more roadway width adjacent to the platform so that autos do not strike the platform edge or it may require the tracks to gently swerve toward the platform side of the lane so that the platform edge can be located at the typical curb line location. Another consideration for shared lanes is that when rail vehicles stop at the platform, autos may want to attempt to go around the stopped vehicle. Many transit agencies are familiar with this phenomenon as it happens quite frequently with buses so there are likely solutions being employed for bus stops that may be a viable solution for the rail transit stop as well. The actual stop location (near-side, far-side or mid-block) will usually have the biggest impact to autos but traffic control devices, the number of travel lanes, heavy turning movements and other issues may drive the design as well so it is important for the track designer to work closely with traffic engineers to make sure the layout of all stops along shared lanes has been coordinated to facilitate the most efficient flow of traffic through the corridor.

Another consideration for areas with shared lanes between rail/autos is the impact of rail flangeways on bicycles and other vehicles with narrow wheels. The grooves created by rail flangeways are safe to cross at a perpendicular angle but when vehicles travel parallel to the rails, narrow tires could become trapped in the flangeway groove and the direction of the tire/vehicle could be abruptly shifted to parallel the track which may result in loss of vehicle control. AREMA recommends that separate bicycle lanes be provided rather than allowing cyclists to share lanes with rail vehicles. The location of these bike facilities may interfere with rail transit stops so resolution of any conflicts should be discussed early in the design process so appropriate solutions can be found to serve all roadway users. The National Association of City Transportation Officials (NACTO) has developed guidelines for transit streets and urban bikeways which track designers are encouraged to review so they are aware of the various techniques that can be employed to address these issues.

SECTION 8.9 OTHER

Embedded tracks are typically designed along urban streets which allows for fairly easy access to the tracks for maintenance and emergencies. The designer should also review National Fire Protection Association (NFPA) 130 “Standard for Fixed Guideway Transit and Passenger Rail Systems” for additional requirements related to the design of emergency access.

The Federal Transit Administration (FTA) requires most rail transit agencies to comply with safety oversight by State Safety Oversight agencies (SSOs). In most cases this involves preparing documents to identify hazards and threats that may be present when the transit system operates. The designer will be required to mitigate identified hazards and threats so it is important to get access to these documents so that the designer is aware of them and includes appropriate mitigation (ideally the designer is involved when these threats and hazards are identified). Designs must typically be certified as safe and appropriate certification/documentation must be submitted to the relevant SSO. Track designers are encouraged to review State Safety Oversight Program requirements as published by the Federal Transit Administration as well as the local SSO agency.

SECTION 8.10 APPENDIX A - COMMENTARY ON ANALYSIS OF LATERAL ACCELERATION AND JERK RATE FOR ESTABLISHING SUPERELEVATION AND SPIRAL LENGTH

a. Introduction

The US rail industry standard for lateral acceleration and jerk for a long time has been 0.1g (g = force of gravity) and 0.03g/s respectively. The standard used by railroads and transit properties in the US is based on research conducted 50 years ago and was applicable to all types of cars including dining cars where a smooth ride was essential. Today, several European countries allow higher rates. SNCF (French National Railways) uses 0.15g for lateral acceleration and 0.1g/s for jerk for its railroads including the high speed TGV system. Some higher values for jerk rate have been suggested by research on high speed rides but do not seem to have been put into practice. Subjective experiments of ride comfort on curves were judged as "noticeable lateral acceleration" at 0.1g and "strongly noticeable but not uncomfortable" at 0.15g. For short LRT rides, strongly noticeable lateral acceleration now and then would seem to be an acceptable ride condition. While the data is less conclusive for jerk, several studies support a higher rate with some research suggesting it is not a factor in ride comfort at all. It therefore seems reasonable to consider a somewhat higher jerk rate as well.

Increasing maximum allowable lateral acceleration equals use of a higher limit for unbalanced superelevation (E_u, cant deficiency) on curves and correspondingly higher speeds regardless of actual superelevation.

Jerk rate is one of three parameters (jerk, twist, and rate of twist) used to establish minimum spiral length. Allowing a maximum higher jerk rate will allow shorter spirals. In unsuperelevated curves common to embedded track, jerk is the only parameter used to determine spiral length.

Various researchers from Hirshfeld (1932) and Code (1955) to more recent studies for high speed rail travel in the US, France, Germany and Japan (1989 to 2004) have examined ride comfort versus unbalanced superelevation on curves and jerk rates for spirals. The results of those studies produced recommended rates that range from less than 0.1 g to 0.16g for lateral acceleration. For jerk rate, the studies recommendations range from 0.03 g/s to 0.25g/s with additional other limitations for the higher jerk rates. Analyses of ride comfort relative automobile and airplane performance under situations somewhat analogous to railroad curving have been made. Analyses of ride comfort versus vibration levels and uneven ride conditions (lateral jolt due to track irregularities) have also been made and comparisons made to ride comfort on railroad curves. The overall conclusion of these studies is that severe jolts and long term vibrations have more to do with rider comfort than reasonable lateral acceleration levels and spiral jerk rates. Safety (rather than comfort) limits were examined in one report which suggest that as jolt rates (and spiral jerk rate) increase, the lateral acceleration must be decreased so that the two in combination do not produce an unsafe ride. Unsafe meaning some standing riders would loose their footing.

Ride comfort is a subjective parameter, and while for the sake of analysis, it is equated with precise values of acceleration (g) it is not really a precise parameter. Ride comfort is affected by the vehicle characteristics as well as the track design. Vehicle characteristics vary significantly from one design to another. Code used a wide variety of passenger cars in his ride comfort studies and in the end, simplified the varying performance of the cars into just two classes, those with loose suspensions and those with stabilized suspensions. These two factors – the subjective nature of ride comfort evaluation and the variability of the cars to affect ride comfort - make research to establish values for all systems problematic. A better approach is to evaluate ride comfort for a given system by operating its vehicles at varying speeds around a number of curves to decide, for the specific system what constitutes a comfortable ride.

b. Lateral Acceleration Discussion

Ride comfort on the body of a curve is determined from a combination of vehicle roll and unbalance of the curve. A 0.1g value is equivalent to 6 inches total unbalance. For a loosely sprung vehicle, up to 3 of those 6 inches is consumed by vehicle roll leaving 3 inches E_u as a maximum design value for alignment criteria. For more stable cars (ie those with suspensions that limit roll to 1.5 degrees or less per AREMA Chapter 5 test procedure), the E_u max for design rises to 4.5 inches since the vehicle roll uses 1.5 inches or less of the total of 6 inches allowable unbalance.

SNCF uses 0.15g for lateral acceleration. This has been a suggested acceptable level by others in the US but does not appear to have been implemented. SNCF also commits to maintaining track alignment to limit lateral jolts due to misalignment to less than 0.025g/s. A USDOT Federal Railroad Administration (FRA) sponsored 1991 ride safety (not comfort) study indicates that it is safe to operate at speeds equal to 0.15g lateral acceleration if track alignment is well maintained so as not to introduce excessive jolts due to misalignment into the ride. It concluded up to 0.183 g/s jolt with 0.15g lateral acceleration as safe. The safety study was based on analysis of ride quality on many curves at various speeds.

Using the higher 0.15g value for lateral acceleration allows increasing the allowable maximum unbalance from 6 to 9 inches. The formula $E = 0.0007V^2D$ is used to compute velocity (V, in miles per hour) for a given value of E (total superelevation in inches). See note at end of this section on D (degree of curve) vs R (radius of curve in feet). A clearer presentation of the formula should include E_r (for roll)
when computing V. By including the E_r value, the design formula becomes $E_a+(E_u - E_r)= 0.0007V^2D$.
This is in effect the same relationship described by Code but in clear mathematical terms. The ride comfort is a limited to a combination of maximum unbalance based on a maximum lateral acceleration reduced by unbalance value for the roll angle. As roll angle increases the maximum unbalance decreases for any given degree of ride comfort. Code's simplified solution was to reduce the 6 inch E_u (0.1g) value by 3 inches for unstabilized car suspensions and 1.5 inches E_u for stabilized suspension cars. Modern air suspension systems may result in a roll angle value for unbalance approaching zero depending on the air suspension performance. As stated earlier, the optimal means of establishing the relationship of ride comfort to speed is to test the specific cars on a variety of curves and then use the formulae given herein to extrapolate that ride comfort level to all curves.

The matter of whether or not increasing allowable lateral acceleration increases the risk of wheel climb derailment or overturning has been considered. Wheel climb is caused by wheel/rail angle, angle of attack, and suspension stiffness. Lateral acceleration due to speed (unbalance) if increased indefinitely leads to vehicle overturning not wheel climb. This is so because the higher lateral force on the wheel due to higher lateral acceleration is offset by more of the vehicle weight transferring to the vertical component on the wheel. TCRP Report No. 155 has formulae for analyzing overturning which may be used for comparison with the proposed lateral acceleration/Eu values. Using the TCRP formula, the overturning speed for an 82ft radius, unsuperelevated curve is 26 mph or about twice the proposed maximum operating speed of 14mph. Furthermore, safe speed is defined in TCRP Report No. 155 as the speed at which the vehicle becomes unstable and in danger of derailment upon introduction of any anomaly in the track which momentarily increases angle of attack. The maximum safe Eu value, using the TCRP formula for safe speed is 9.6 inches E_u which is greater than the proposed maximum of 9 inches. A 2008 Transportation Technology Center, Inc. (TTCI) research effort demonstrated that wheel climb derailment potential is virtually unaffected by unbalance whereas lower rail angle and track perturbations are the principle causes of wheel climb. Embedded track, once built to accurate alignment, should retain the accuracy of that alignment indefinitely.

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For example, increasing the allowable lateral acceleration from 0.1g to 0.15g and, where appropriate, using a roll angle value of zero for optimum air suspension vehicles for the E_r value in the speed computation will result in an allowable *safe* increase in speed from 10 to 14 mph for an 82 ft radius unsuperelevated curve. Based on observations by trackwork engineers riding on various LRT systems, this modest adjustment to the design criteria will do no more than reflect actual operating conditions on systems where operators frequently increase speed before a train has cleared a curve.

(Note: The standard formula $E = 0.0007 V^2 D$ uses D based on $D = 5730/R$. This formula was derived when curves were surveyed with transit and tape methods and defining a curve by “Degree of Curve” was useful in the field for staking curves. As noted in surveying texts this method of staking a curve becomes progressively more inaccurate as radius of curve decreases. It is accurate, however for converting R in feet to D for use in the above formula for computing speed (V) or total superelevation (E) even at the small radii anticipated for LRVs and trolley cars. In other words, D should not be used to “define” the radius of a curve of less than 300 feet but may be used to convert R to D in the above formula.)

c. Jerk Rate Discussion

The jerk rate establishes the time needed to introduce the lateral acceleration or unbalance of a curve at the beginning and end of a circular curve. A constantly increasing amount of lateral acceleration beginning at zero and ending at the desired lateral acceleration value for a curve is achieved through the passage, at a constant speed, of a vehicle traveling along a constantly increasing degree of curvature, ie a spiral.

The length of the spiral determines the time required to go from zero lateral acceleration to the lateral acceleration of the circular curve. It has been demonstrated that the amount of lateral acceleration (E_u) is more important to ride comfort than the rate at which it is introduced (spiral length). Never the less, an unreasonably high rate of introduction of lateral acceleration (jerk rate) is undesirable, especially for high levels of E_u. If no spirals are used, the jerk rate is theoretically infinite. In reality, the play between the wheels and track gage along with dynamic response of the vehicle reduces this infinite rate to a jerk rate that is measurable though high.

The current US standard of 0.1g lateral acceleration, coupled with an 0.03g/s jerk rate dictates the introduction of E_u over 3.33 seconds. This, for a typical maximum E_u of 4.5 inches transforms into the familiar formula for determining spiral length: $L_s = 1.09VE_u$.

In the US, just as with lateral acceleration, a conservative low jerk rate of 0.03 g/s was adopted as standard. However, numerous studies, beginning with Hirshfeld, concluded that higher jerk rates were acceptable with respect to ride comfort. The FRA Ride Safety Study of 1989 concluded that jerk rate was not significant to ride comfort and that rates (either jolt or jerk) as high as 0.183 g/s were safe for lateral acceleration values up to 0.15g. The 1978 North East Corridor study of ride comfort endorsed the SNCF’s values of 0.15g and 0.10 g/s with a limit on jolt of 0.025 g/s. The 2004 FRA Study for high speed rail between Richmond and Charlotte endorsed the same SNCF values and noted that a jerk rate as high

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as 0.25 g/s would be acceptable so long as no track irregularities were to occur that would momentarily raise the jerk rate to a higher level.

The conclusion from these studies is that a jerk rate of 0.10 g/s would not produce an unacceptable ride on embedded track which, once properly constructed to a smooth alignment, would preclude any unusual jolt values from occurring. In fact, a jerk rate of 0.10 g/s is conservative compared with some recommendations.

For a lateral acceleration maximum of 0.15g, a jerk rate of 0.1g/s means the spirals need to be long enough to introduce the E_u over 1.5 seconds. The spiral formula for a 0.15 g lateral acceleration and 0.10 g/s jerk rate becomes $L_s = 0.29VE_u$.

To put this in perspective an 82 ft radius unsuperelevated curve could have the following designs:

(1) Existing standard of 0.1g and 0.03g/s: E = 4.5 inches (stabilized suspension vehicle) E =

$0.0007\ V^2\ D$ V = 9.6 mph

$L_s = 1.09VE_u$ $L_s = 47.1$ ft

Spiral Offset: 1.12 ft

(2) Proposed rates of 0.15g and 0.10g/s Total E, adjusted for roll, of 7.5 inches (stabilized suspension vehicle)

$E = 0.0007\ V^2\ D$ V = 12.4 mph

$L_s = 0.29VE_uL_s = 26.9$ ft.

Spiral Offset: 0.37 ft.

(3) Proposed rates of 0.15g and 0.10g/s and with E of 9 inches (vehicle with no roll), the results are: E =

$0.0007V^2DV = 13.6$ mph

$L_s = 0.29\ VE_uL_s = 29.9$ ft

Spiral Offset: 0.45 ft

d. Summary

Based on the foregoing analysis the following should be considered when selecting an allowable lateral acceleration and jerk rate.

(1) Operating needs should be evaluated to determine if there are benefits from using a higher lateral acceleration value.

(2) The allowable usual lateral acceleration of 0.1g may be safely increased to 0.15g which corresponds to 9 inches of allowable unbalance.

(3) For computing speed, E should be computed as $E_a + E_u - E_r$ in the formula $E = 0.0007\ V^2\ D$, that is, $V = \sqrt{}$

$(E_a+E_u-E_r)/0.0007D$

(4) Vehicle roll angle should be determined for a homogeneous fleet and E_r value determined from the roll angle. (Lacking field measured roll angle, the conservative values proposed by Code should be used, that is E_r = 3 inches for loosely suspended vehicles whose roll angle is probably greater than 1.5 degrees and 1.5 inches for stabilized vehicles whose roll angle is probably less than 1.5 degrees.)

(5) The allowable jerk rate for spiral design may be increased from 0.03 g/s to 0.10 g/s and the spiral length based on not less than 1.5 seconds to traverse the spiral where shorter spirals would have benefits.

(6) Application of these higher values for lateral acceleration and jerk imply a commitment to high quality construction and maintenance of track alignment.

(7) These considerations apply only to standard gauge embedded track.