Chapter 4—Track Structure Design

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CHAPTER 4—TRACK STRUCTURE DESIGN

4.1 INTRODUCTION

The design standards for contemporary light rail transit (LRT) track structures, whether in an aerial, at-grade, or tunnel environment, differ considerably from the principles for either "heavy" rail transit or railroad service. The varied guideway environments in which an LRT system can be constructed result in horizontal and vertical track geometry that often affects light rail vehicle (LRV) design and performance. Consequently, the light rail track designer must consider not only the track geometry, but also the characteristics of the LRV and how it responds to the guideway geometry This is particularly true in embedded track located in streets. Embedded track construction constitutes the greatest challenge to the light rail track designer.

4.2 TRACK AND WHEEL GAUGES AND FLANGEWAYS

The determination of the correct dimensions to be used for track and wheel gauges and for the widths of the flangeways through special trackwork and other guarded portions of the track structure is the most critical activity to be undertaken during track design. If these dimensions are not carefully selected to be compatible with the rail vehicle(s) that will operate over the track, unsatisfactory performance and excessive wear of both the track structure and the vehicle wheels will occur.

4.2.1 Vehicle Truck Factors

New, state-of-the-art LRV designs, particularly "low-floor" LRVs, incorporate many features radically different from heavy rail metros and railroads. These may include smaller diameter wheels, short stub single wheel axles, and a wide variety of truck axle spacings and truck centers—all of which affect the vehicle's interface with the track structure. In some cases, multiple variations of these factors can occur on a single car. A common situation involves smaller diameter wheels and a shorter truck wheelbase on the center truck of a partial low-floor light rail vehicle. If these parameters are not carefully considered in track design, the vehicle's tracking pattern can be susceptible to hunting, truck skewing in curves, and unpredictability at special trackwork. The track gauge-to-wheel gauge relationship is especially important in controlling these operational performance features.

In general, reducing the lateral clearance between the wheel flange and rail head, either through increasing the wheel gauge or decreasing the track gauge, improves wheel tracking of the rail by keeping the truck square to the rails. This reduces hunting, skewing, and flange attack and results in improved performance through curved track and special trackwork. Vehicle wheel gauge will generally not vary within a given LRV fleet although cases have occurred where the wheel gauge and wheel contour of a new vehicle procurement have not matched that of the transit agency's existing fleet. The track designer should take steps to ensure that the vehicle designer does not select wheel parameters independent of track design.

If, as is common, there are several series of vehicles in use on a rail transit line, each with a different combination of truck characteristics, the track designers must consider the worst-case requirements of each car series and optimize the track gauge parameters accordingly.

4.2.2 Standard Track and Wheel Gauges

The majority of contemporary rail transit systems nominally utilize "standard" track gauge of 1435 mm (56-1/2 inches). This track gauge stems from 18th century horse drawn railways used by English collieries, where track gauge was dictated by the common wheel-to-wheel "gauge" of the wagons used to haul the coal. This wagon gauge can be traced back to ancient times, where it was used on Roman chariots because it approximately matched the center-to-center distance of a pair of war horses. This made it easier for the horses to follow the wagon ruts in the roads. While many different track gauges were adopted over the years, none have proven to be either as popular or practical as standard gauge.

Track that is nominally constructed to standard gauge can actually be tighter or wider than 1435 mm depending on a variety of circumstances. The track gauge can be adjusted along the route so as to optimize vehicle-to-track interaction. Conditions that can require gauge adjustments include track curvature, the presence or lack of curve guard rails, rail cant, and several vehicle design factors. Vehicle factors include wheel diameter; wheel tread taper and width; wheel flange shape including both height and thickness; the distance between axles; and the wheel gauge or distance between wheels mounted on a common axle.

While nominal standard gauge is nearly universal for both electric rail transit and "steam" railroads, different requirements of these modes resulted in appreciably different details, such as where the track gauge is measured, under what conditions it is varied, and the amount of freeplay that is required between the wheel flanges and the sides of the rails

4.2.2.1 Railroad Gauge Practice

North American railroads set track and wheel mounting gauges in accordance with criteria established by the Mechanical Division of the Association of American Railroads (AAR) and the American Railway Engineering and Maintenance-of-Way Association (AREMA). AAR standard wheel gauge is defined as 55-11/16 inches (equivalent to 1,414 millimeters) and is measured 5/8 of an inch (15.9 millimeters) below the wheel tread surface. The AREMA definition of track gauge is measured at the same distance below the top of rail. These gauge standards have been incorporated in many contemporary LRT track designs to accommodate possible joint railroad and LRT operations.

If wheels using the current AAR-1B wheel profile are mounted at standard AAR wheel gauge, and the wheel and axle assembly is centered between the rails at standard track gauge, the horizontal clearance between the wheel and the rail at the gauge line elevation is 13/32 inch or 10.3 millimeters as shown in **Figure 4.2.1**. This results in total freeplay between correctly mounted and unworn wheelsets and exactly gauged rails of 13/16 inch or almost 21 millimeters.

It is important to recognize that railroad gauge practices generally evolved in a different environment than transit operations. Particularly in curved tracks, railroad criteria is predicated on the use of equipment that generally has much larger diameter wheels than those used on transit vehicles. In addition, both the maximum wheelbase and the number of axles that might be mounted on a rigid truck frame are usually much greater. Steam locomotives in particular could have wheels over 1800 millimeters (6 feet) in diameter, with up to five such sets of wheels on a rigid frame. Even contemporary diesel

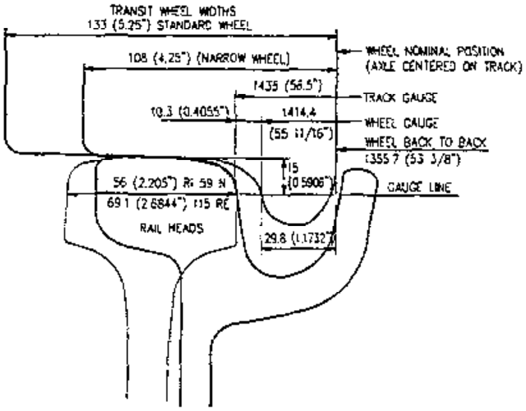


Figure 4.2.1 Standard Wheel Gauge—AAR (Railroad)

locomotives can have wheels that are over 1 meter (3.2 feet) in diameter, with three wheel and axle sets on trucks that can have an overall wheelbase of nearly 4 meters (13 feet). By contrast, contemporary rail transit vehicles rarely have wheels over 711 mm (28 inches) in diameter, never have more than two axles per truck, and generally have maximum wheelbase distances no longer than about 2200 millimeters (7 feet). (Refer to Table 2.1.) The much larger truck features associated with railroad equipment dictate wheel gauge-to-track gauge relationships that are far less stringent than those required for transit equipment. Hence, railroad gauge and flangeway criteria should not be adopted unless both transit and freight railroad equipment will operate jointly on a common track.

4.2.2.2 Transit Gauge Practice

Traditional street railway/tramway systems developed guidelines for wheel gauge that differ considerably from those used by railroads. In the United States, the most common standards for track and wheel mounting gauges were those promulgated by the American Electric Railway Engineering Association (later renamed the American Transit Engineering Association or ATEA) The metric equivalents of the ATEA standard track and wheel gauges were 1,435 and 1,428 millimeters (56-1/2 inches and 56-1/4 inches), respectively, and were measured 6 millimeters (1/4 inch) below tread height. In addition, some transit systems tightened the track gauge in tangent track, taking advantage of a compound curve gauge corner radius that was rolled into the head of some ATEA girder rails. ATEA standards are generally followed by those North American light rail systems that predate the renaissance of light rail transit that began in the late 1970s. European tramways developed similar standards although it is important to note that, in general, European street railways use wheel flanges that are even smaller than those promulgated by ATEA.

The transit type standards for wheel gauge have several advantages:

- With a tighter gauge relationship, truck "hunting"—the lateral oscillation of a truck from one rail to the other as it seeks a consistent rolling radius on all wheels—is more easily controlled. Hunting typically is a tangent track phenomenon and is more prevalent at higher vehicle speeds. The threshold for vehicle hunting is controlled by the stiffness of the primary suspension.
- Trucks cannot become as greatly skewed to the track, thereby reducing flange bite in curving.
- Flangeways can be appreciably narrower; a significant consideration for embedded tracks areas with significant pedestrian activity.

Generally tight wheel gauge-to-track gauge relationships can only be employed when the transit operator does not have to share its tracks with a railroad Many contemporary LRT systems fall into that category and, as a result, feature a wide variety of vehicle wheel gauges while all generally employing standard track gauge of 1,435 millimeters (56-1/2 inches). Table 2.1 in this handbook provides selected track and wheel gauge standards of 17 light rail transit systems currently operating in North America.

As a guideline, **Figure 4.2.2** illustrates a recommended wheel gauge of 1421 millimeters (56 inches) for transit use with standard track gauge. The free play between one wheel and rail is 7 millimeters (0.3 inch).

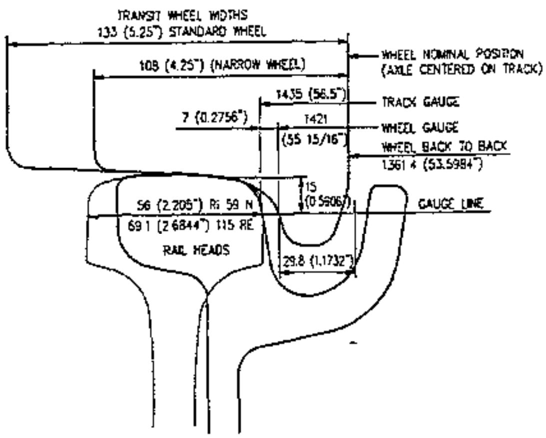


Figure 4.2.2 (Recommended) Standard Wheel Gauge—Transit System

4.2.2.3 Gauge Issues for Joint LRT and Railroad and Mixed Fleet Operations

For a system with a mixed fleet, compromises may be required to accommodate a variety of truck and wheel parameters. This problem is not new—early 20th century electric street railway track designers frequently had to adapt their systems to handle not only city streetcars with short wheel base trucks and relatively small diameter wheels, but also "interurban" trolleys that typically had longer wheel base trucks and larger diameter wheels. Some trolley companies even offered freight service and routinely handled "steam" railroad engines and freight cars over portions of their lines. Today, if the light rail system shares any portion of its route with a freight railroad, or if future extensions either will or might share freight railroad tracks, then conformance with freight railroad gauge and other freight geometry constraints will control the track design.

When a new light rail system shares track with a freight railroad, freight operations normally occur only along ballasted track segments. It is unusual for freight trains to share aerial structure or embedded track segments of a system. Nevertheless, the mixing of rail freight and LRT operations on any portion of a system will govern track and wheel gauge design decisions for the entire system. Even if the system's "starter line" does not include joint operation areas, consideration should be given to whether future extensions of the system might share tracks with a freight railroad.

The key issues to consider in accommodating mixed operations are the setting of the back-to-back wheel dimension, guard check gauge, and guard face gauge criteria that result from a particular wheel setting. Track design parameters that will be most affected by these decisions include:

- The practicality of using available girder groove and guard rails that are rolled with a specific flangeway width.
- The flangeway width and track gauge required for effective restraining rail or guard rail applications.
- Details for guarding of frog points in special trackwork locations.

Transit systems that do not share tracks with a freight railroad may still have a track connection at the maintenance facility yard for delivery of freight cars loaded with track materials or the system's new light rail vehicles. If the system's maintenance program contemplates movement of railroad rolling stock (such as hopper cars full of ballast) over portions of the system, it may be necessary to compromise the track design to accommodate the railroad equipment. This does not mean wholesale adoption of railroad standards. Provided that the guard check gauge at turnout frogs allows sufficient space for AAR back-to-back wheel gauge, freight cars can usually be moved over open track portions of an LRT system at low speeds. It may be necessary to prohibit any railroad equipment whose wheels are not precisely mounted, as AAR has tolerances for wheel settings that are considerably more liberal than those applied to rail transit fleets.

Embedded track areas that utilize narrow flangeway girder rails typically cannot accommodate movements of railroad rolling stock through curves with radii less than about 100 meters, regardless of rail section. Other restrictions on railroad equipment movements involve the structural capacity of bridges designed for LRT loads and clearances to trackside obstructions such as catenary poles and station platforms.

Another category of joint operations is where it is proposed to extend an existing "heavy" rail transit operation using light rail technology. The existing system will already have track gauge, wheel gauge, and wheel contour standards in place that must be considered in the design of the light rail tracks and vehicles for the new system. If the truck parameters of the existing rolling stock, such as truck wheelbase or wheel diameter, are appreciably different from typical LRV designs, compromises will be necessary to achieve compatible operations.

Even if neither railroad rolling stock nor mixed transit car fleets are a consideration, the trackwork designer should consider the ramifications that track and wheel gauge variations might have for on-track maintenance-of-way equipment. It is imperative that specific notification be given that the transit system's gauge standards differ from AAR and AREMA standards so that construction and maintenance equipment do not damage the track.

4.2.2.4 Gauge Issues for Embedded Track

The appropriate track gauge to use in embedded track is highly dependent on the rail section (either tee rail or girder groove rail) and the vehicle wheel gauge. In this regard it is very important to note that standard railroad wheel contours (e.g. AAR-1B) and railroad wheel mounting gauges are not compatible with narrow flangeway girder rails presently available from European mills if the track is built to 1435-millimeter (56-1/2 inch) gauge. The backs of the wheels will bind with the tram or guarding lip of the girder rail causing one flange to ride up out of the flangeway. If narrow flangeway girder rails are selected, such as Ri 59N or Ri 60N, it will be necessary to adopt either a wide wheel gauge or an equivalent narrow track gauge.

If railroad standard wheel gauge must be employed on an LRV because some portion of the route shares track with a freight railroad, wheel clearance to the embedded girder rail track can alternatively be achieved by reducing the track gauge only in those areas where the girder rail is installed. This will reduce the wheel-rail clearance at the gauge line and may result in unsatisfactory interaction with railroad equipment. Embedded track is typically separated from joint use track. Railroad equipment movements, limited to occasional maintenance work trains at low speed, may be acceptable.

If routine joint operation with railroad freight equipment along an embedded track area is expected, use of narrow flangeway girder rails will not be possible. Wide flangeway girder rails for freight railroad use are provided by some European rolling mills, but presently available designs of this type are so wide that the tram does not provide any guarding action for curves or special trackwork. Freight railroad girder rail flangeways are also generally wider than desirable for pedestrian areas. Such was not the case with girder rails made in North America until the mid-1980s; however they can no longer be obtained A near match of the head and flangeway contours of North American designs can be achieved by milling the head of the 105/180 structural section available from European mills; however this is an expensive solution that requires careful investigation and justification.

More latitude for joint operations in embedded track can be achieved using tee rails rather than girder rails; however a separate flangeway must be constructed and maintained in the pavement surface. Refer to Section 5.2.2.3 of this handbook for additional discussion concerning the possible application of tee rails to embedded track.

4.2.2.5 Non-Standard Track Gauges

In addition to standard 1,435-millimeter (56-1/2 inch) track gauge, several other gauges have been used on light rail transit systems in North America and overseas. Narrow gauge systems, typically 1,000 millimeters (39-1/3 inches), are relatively common in Europe, particularly in older cities where narrow streets restrict vehicle sizes. There were once many narrow gauge street railways in North America; however the only known survivors are the Detroit street car and the San Francisco cable car system. Broad gauge trolley systems were more common Four traditional trolley operations in North America use broad gauges. These range from 1,496 millimeters (58-7/8 inches) in Toronto to 1,581 millimeters (62-1/4 inches) on the Philadelphia City system to 1,588 millimeters (62-1/2 inches) on the Pittsburgh, New Orleans, and Philadelphia Suburban systems. Such gauges were typically dictated by the municipal ordinances that granted the streetcar companies their "franchise" to operate within the city streets. In such legislation it was typically specified that the rails should be laid at a distance apart that conformed with local wagon gauge, thereby providing horse drawn wagons and carriages with a smoother running surface than the primitive pavements of the era. The only new start transit operation in North America to adopt a non-standard gauge in recent years was San Francisco's BART "heavy" rail system at 1,676 millimeters (66 inches). This gauge was intended to provide increased vehicle stability against crosswinds for a proposed bridge crossing.

Those systems that employ unusual gauges typically rue the fact because it complicates many facets of track design, construction, and maintenance. Contracting for services such as track surfacing and rail grinding becomes more difficult and expensive since contractors do not have broad gauge equipment and converting and subsequently reverting standard gauge equipment for a short-term assignment is time consuming and expensive. Vehicle procurement is also complicated since off-the-shelf truck designs must be modified and potential savings from joint vehicle procurements cannot be realized. Wide gauges also preclude joint operation of a rail transit line on a railroad route since dual gauge special trackwork and train control systems necessary to operate it are both extremely complex and expensive. Accordingly, non-standard gauges are not recommended for new start projects. Systems that presently have broad gauge tracks most likely need to perpetuate that practice for future extensions so as to maintain internal compatibility in both track and rolling stock design.

4.2.3 Gauge Measurement Location

Track gauge is measured a specific distance below top of rail because of the gauge corner radii of the rail and the flange-to-tread fillet radius of the wheel. The location where gauge is measured frequently differs between railroad and transit systems. The customary gauge elevation point on North American railroads is 15.9 millimeters (0.625 inches) below top of rail. Track gauge on traditional street railways systems was, and in some instances still is, measured at either 6.4 millimeters (0.25 inches) or 9.5 millimeters (0.375 inches) below top of rail.

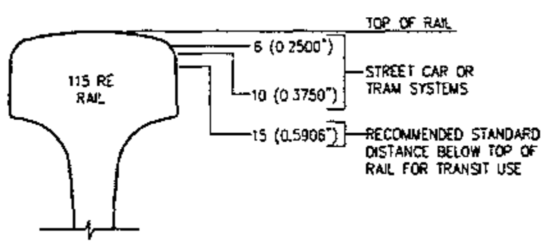


Figure 4.2.3 Gauge Line Locations on 115 RE Rail Head

Rail sections with compound gauge corner radii, such as 115 RE section (**Figure 4.2.3**), do not have a nominally vertical tangent section for gauge measurement at the 6.4- (0.25-inch) or 9.5-millimeter (0.375-inch) height, hence the designation of a lower elevation. Older rail sections that were prevalent when the ATEA promulgated its standards, such as ASCE and ARA rails, had gauge corner radii that were smaller and thus more conducive to gauge measurement closer to top of rail. Except for the 100 ARA-B section, such rail is no longer commonly rolled in North America. Since measurement of gauge within the curved portion of the rail head is difficult at best and misleading at worst, it is recommended that gauge elevation be defined consistent with railroad practice. For a transit system that is being designed in metric dimensions, designation of gauge elevation at 15.9 millimeters (0.625 inches) below top of rail is awkward.

As a guideline for metric transit track design, it is recommended that track gauge be defined at 15 millimeters (0.591 inches) below top of rail. Wheel gauge will be measured at a location to suit the height of wheel flange.

4.2.4 Rail Cant and Wheel Taper—Implications for Track Gauge

Rail cant is a significant factor in wheel-to-rail interface. Cant describes the rotation of the rail head toward the track centerline. It is intended to complement conical wheel treads in promoting self-steering of wheelsets through curves. The cant also moves the vertical wheel loading away from the gauge corner of the rail and toward the center of the ball of the rail. Rails are generally installed at 1:40 cant in both tangent and curved track. Zero cant is usually specified through special trackwork so as to simplify the design and fabrication of trackwork components. Canted special trackwork is now often specified for high-speed operations over 140 km/hr (90 mph).

4.2.4.1 Tapered Wheel Tread Rationale

Railway wheel treads are typically tapered to be shaped like a truncated cone. A cone that is lying on a flat surface will not roll straight forward but one that is supported on a single edge—such as a rail—can be made to follow a straight path if its axis is held rigidly at right angles (i.e., by an axle) to the direction of travel. Railway design takes advantage of this geometric relationship to facilitate self-steering of railway trucks through gentle curves without requiring interaction between the side of the rail head and the wheel flanges.

The usual conicity of the wheel tread is a ratio of 1:20. This results in a wheel that has a greater circumference close to the flange than it has on the outer edge of the wheel tread. In curved track, this differential moderately compensates for the fact that the outer rail of a curve is longer than the inner rail over the same central angle. The wheel flange on the outer wheel of the axle shifts toward the outer rail when negotiating a curve and hence rolls on a greater circumference while the inner wheel flange shifts away from that rail and rolls on a smaller circumference. Thus, the outer wheel will travel forward a greater distance than the wheel on the inner rail even though they are both rigidly attached to a common axle and hence have the same angular velocity. As a result, the axle assembly steers itself around the curve just as a cone rolls in a circle on a table top.

Railroad wheelsets, mounted at AAR standard wheel gauge and tapered at 1:20, theoretically eliminate flanging on curves with radii over 580 meters (1900 feet). Below that radius, contact between the wheel flange and the gauge side of the rail provides a portion of the steering action. Nevertheless, tapered wheels still provide a significant degree of truck self-steering that reduces flanging on curves with radii as small as 100 meters (328 feet) For sharper curves, flanging is the primary steering mechanism. Transit wheels self-steer only on relatively large radii curves, due to the fact that the minimal 6 millimeters (0.2 inches) of freeplay between wheel gauge and track gauge allows only very limited differential rolling radii on a conical wheel before the wheel begins flange contact with the rail. A transit wheelset, mounted at standard transit wheel gauge and tapered at 1:20, theoretically will begin flanging on curves of radii less than 1350 meters (4,429 feet).

Wheel profiles that have either a cylindrical tread surface or only a slight taper, such as 1:40, do not self-steer through curves; hence flanging is the primary steering mechanism. Conical wheels that are not re-trued regularly also lose their steering characteristics because the contact patch becomes excessively wide as a significant portion of the wheel tread matches the contour of the rail head. Hollow worn wheels develop a "false flange" on the outer portion of the tread and can actually attempt to steer the wrong way as the rolling radius on the tip of the false flange can be equal or greater than on the flange to tread fillet. The importance of a regular wheel truing program cannot be overstated and track designers should insist vehicle maintenance manuals require wheel truing on a frequent basis.

Note that rolling radius differential is maximized when the wheel and axle set is free to shift laterally an appreciable amount. An actual cone has a fixed slope ratio; hence it can smoothly follow only one horizontal radius. A wheel and axle set with tapered wheels, on the other hand, can assume the form of a cone with a variable side slope by shifting the free play left and right between the wheel flanges and the rails. Hence larger values of track gauge-to-wheel gauge freeplay can be beneficial in that regard.

4.2.4.2 Asymmetrical Rail Grinding

Rail grinding to remove surface imperfections has been performed for decades, but a recent trend has been rail grinding designed to alter the location of the rail contact patch. By grinding an asymmetrical profile on the rail head, and having distinctly different contact patch locations on the high and low rails of a given curve, the location of the contact patch on the tapered wheel tread can be optimized, thereby changing the rolling radius. In theory, a special grinding pattern could be created for each curve radius, thereby optimizing the ability of a truck to steer through that curve.

4.2.4.3 Variation of Rail Cant as a Tool for Enhancing Truck Steering

Rail cant variation can improve the rolling radius differential on standard rail head profiles in a manner similar to that achieved by asymmetrical rail grinding. Aside from the structural implications of loading the rail closer to or further from its vertical axis, greater or lesser amounts of cant can be beneficial by altering the point on the tapered wheel tread that contacts the rail. Rails installed with no cant create a contact zone or wear strip that is close to the gauge corner of the rail. In rails installed with 1:40 or 1:20 cant, the contact patch progresses further from the gauge corner of the rail. Note that the greater the rail cant, the smaller the rolling radius of a tapered wheel, which reduces the self-steering effect.

Figure 4.2.4 illustrates the theoretical contact patch locations measured from the vertical centerline of the rail. The lateral distance between the contact patches for 1:40 and 1:20 cants is 6.32 millimeters (0.249 inch) for a rail head radius of 245 millimeters (10 inches). This results in a decrease in circumference at the contact point of 2.0 millimeters (0.8 inches) for a wheel with a 1:20 taper and a nominal diameter of 711 millimeters (28 inches). While this may appear to be insignificant, if the steeper cant is applied to the inside rail, it will increase the amount of curvature the wheelset can negotiate without flanging by a significant amount. For example, a trolley wheelset will flange at a 1,350-meter (4,429-foot) curve radius if both rails are at 1:40 cant. If the low rail is canted at 1.20 while the high rail remains at 1:40, then the threshold radius for flanging drops to about 750 meters (29.5 feet).

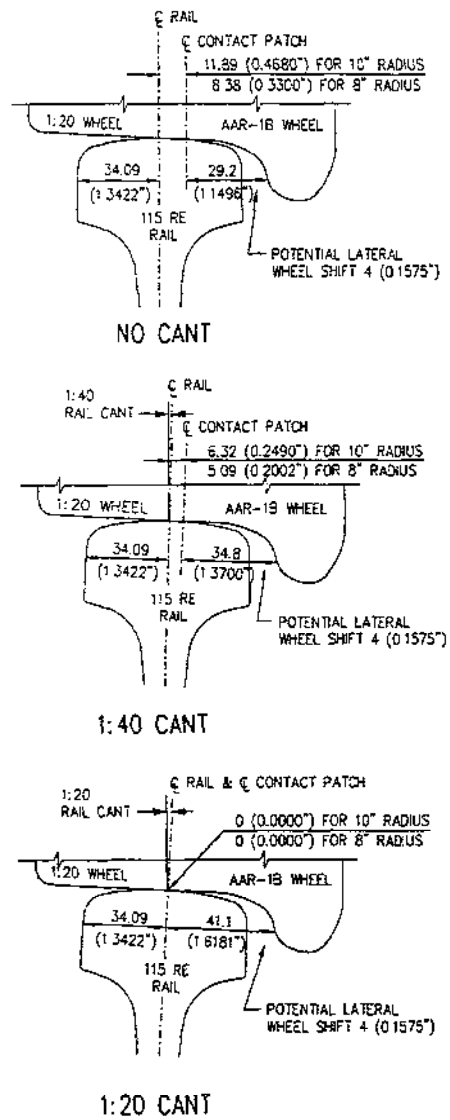


Figure 4.2.4 Rail Cant Design and Wheel Contact

Cant differential, in effect, mimics asymmetrical rail profile grinding. However, the application of 1:20 low rail cant in curved track can be considered even if asymmetrical rail grinding is practiced.

The drawback of differential cant is that it requires that curved track employ different concrete ties than tangent track. Further, the curve ties would have right and left hand orientations that would have to be carefully monitored during track construction In direct fixation and timber tie ballasted track at least two types of rail fasteners—1:40 cant and 1:20 cant—would be required.

The benefits of differential cant, like those of asymmetric rail grinding, decline as the wheels and rail wear. As wheel treads wear toward a flat or hollow profile and rails wear to conform with the wheel profile, self-steering capabilities decline. Once the rail has worn, the contact patch must be restored to its as-designed location by asymmetric rail profile grinding, as it is not practical to modify rail cant after installation.

4.2.5 Track Gauge Variation

On an ideal light rail system, there would be no need for any variations of the track gauge, thereby producing a completely uniform environment for the wheel-rail interface. This is seldom practical, particularly on systems that have tight radius curves or employ narrow flangeway girder rails. When mixed track gauges are employed, the designer should consider rail grinding operations and the adjustment capabilities of state-of-the-art rail grinding machines as a means of maintaining a reasonably consistent wheel-rail interface pattern.

4.2.6 Considerations for Determination of Appropriate Gauge

Determination of appropriate track gauge is the heart of this section. The sections that follow detail some of the design conditions that must be accounted for in gauge design. A recommended analytical procedure for this work is defined in Section 4.2 9 herein.

4.2.6.1 Gauge for Tangent Track

Light rail transit tracks that are constructed with conventional tee rails can use standard 1,435-millimeter (56-1/2-inch) track gauge in both tangent track and through moderate radius curves without regard to whether railroad (1,415-millimeters or 55.7087 inches) or transit design standards are used for wheel gauge. As noted in Section 4.2.2, transit wheel gauge varies considerably between different LRT operations although 1,421 millimeters (55.9449 inches) is recommended.

Operations that use the tighter freeplay standard generally have fewer problems with truck hunting. This can be achieved either through widening the wheel gauge or narrowing the track gauge. The former approach is generally recommended. Non-standard track gauge impacts several aspects of trackwork design and maintenance including concrete crosstie design, as well as maintenance operations (such as tamping and grinding) undertaken by on-track vehicles.

4.2.6.2 Gauge for Curved Track

The threshold radius at which it may be appropriate to alter the gauge in curved tracks will vary based on a number of factors related to the vehicles that operate over the track. Track gauge on moderately curved track can normally be set at the standard 1,435 millimeters (56-1/2 inches) to accommodate common wheel gauges. As curves become sharper, more consideration should be given to ensure that sufficient freeplay is provided to prevent wheelset binding. Factors involved in this analysis are the radius of curve under consideration and wheel diameter, shape of the wheel flange, wheel gauge, and wheel set (axle) spacing on the light rail vehicle truck. Systems with mixed fleets and a variety of wheel and axle configurations must consider the ramifications associated with each and develop a compromise among the various requirements.

Conventional wisdom suggests that track gauge must be widened in curved track; however this axiom is largely based on railroad experience with large diameter wheels and long wheelbases. By contrast, transit vehicles with small diameter wheels, short and narrow flanges, and short wheelbase trucks will often require no track gauge widening in moderately to sharply curved track. Transit equipment may, therefore, require track gauge widening on any severely curved track segments. For trucks with wheel diameters less than 711 millimeters (28 inches) and axle spacings less than 1980 millimeters (6.5 feet), gauge increase will rarely exceed 3 to 6 millimeters (1/8 to 1/4 inches) even if AAR wheel flanges are used. Conversely, large diameter wheels, large flanges, and long wheelbases will require gauge widening at appreciably greater curve radii than for smaller trucks which may be incompatible with satisfactory operation on extremely sharp radius curves. As an example, light rail vehicles with axle spacings of 1828 millimeters (72 inches), wheel diameters around 650 millimeters (25.5 inches) and wheel flange heights less than 20 millimeters (0.8 inches) typically do not require any gauge widening for curves with radii greater than above 35 meters. They can also negotiate extremely small radius curves as low as 11 meters (36 feet). Vehicles with larger trucks are typically limited to curve radii of at least 25 meters (82 feet) and may require gauge widening on curves with radii less than 60 meters (197 feet).

As a guideline, it is recommended that systems that have numerous sharp curves select vehicles with smaller trucks. While curves with radii less than 25 meters are not recommended and less than 50 meters are generally discouraged, sharp curves cannot always be avoided.

Even small gauge increases are usually not possible if railroad contour flanges are used in combination with narrow flangeway girder rails because the gauge widening exacerbates the problem of back-to-back wheel binding.

The appropriate gauge to be used through curved track must be determined through an analytical process. One such method is the development of "Filkens-Wharton Diagrams," a graphical method developed about 100 years ago by Wm. Wharton, Jr. & Co., Inc. of Philadelphia. Details of this method are described in Section 4.2.9.

Reduction rather than widening of track gauge in curved track has been considered on several systems in Europe and at one agency in North America as a way to improve vehicle-tracking performance when passing through reduced radius curves. It is thought that this could also reduce wheel squeal by limiting lateral wheel slip, which is believed to be a main source of such noise. This is an interesting concept that requires further research and development to generate actual performance values. Designers should refer to current professional journals and papers for information on this topic that may have been published subsequent to printing of this handbook.

4.2.7 Flangeways

Once track gauge and wheel gauge have been selected, flangeway widths must be designed that permit free passage of the wheel flange at both special trackwork (e g., frog and frog guard rail flangeways) and on restraining rails in sharply curved track sections that require track guarding.

The following method of checking track gauge with vehicle truck and wheel profile and determining the minimum flangeway widths is derived from a 1909 report by the Committee on Way Matters of the American Electric Railway Engineering Association (AEREA).

The primary concern was to establish flangeway widths to suit the wheel flange on various curves due to the extensive use of girder rails on the street railways. The method used was a series of wheel-axle-track gauge plots. Similar procedures utilizing computer-aided drafting will be used in contemporary design considering the various tight radius curves and the various wheel gauges and wheel profiles available.

In addition to track gauge, flangeway widths in guarded curves must be considered. Where adjustable restraining rail is employed, this is dealt with fairly easily. However, girder groove or girder guard rails cannot be readily adjusted and will require special consideration.

4.2.8 Guarded Curves and Restraining Rails

It is customary in light rail track design to provide a continuous guard rail or restraining rail through sharp radius curves. The restraining rail provides additional steering action using the flange of the wheel that is riding on the inside rail of the curve. By doing so, the lateral over vertical (L/V) ratio at the outer wheel can be reduced, which will both reduce wheel and rail wear and deter possible derailment.

In a typical LRT installation, the restraining rail is installed inside the gauge line of the curve's low rail to provide a uniform flangeway, typically 35 to 50 millimeters (1-3/8 to 2 inches) wide. The working face of the restraining rail bears against the back side of the inside wheel, guiding it toward the curve's center and reducing the lateral contact force of the opposite outside wheel's flange against the high rail of the curve This essentially divides the lateral force between two contact surfaces and greatly reduces the rate of lateral wear on the high rail. It also reduces the tendency of the truck to assume the shape of a parallelogram, thereby reducing the angle of attack between the wheel flange and the rail. In all cases, the use of restraining rail in a curve will reduce the tendency of the leading outside wheel to climb the high rail, thereby preventing possible derailments.

The radius threshold for employing guarded track varies between light rail transit agencies. Some transit agencies guard any track curves with radii less than 365 meters (1,200 feet), while others do not guard track in curves with radii larger than 91 meters (300 feet). Other operations relate the need for guard rails to vehicle speed and the amount of unbalanced superelevation, hence considering the lateral portion of the L/V ratio before deciding that the expense of guarding is warranted. A system with short tramway type wheel flanges will have a greater need for guarding than one that uses railroad type wheels, since the lateral wheel loading will be distributed over a narrower contact band along the side of the rail head thereby increasing contact stresses. In theory, a system whose vehicles are equipped with a self-steering radial truck design will not need guarded track.

Curve guarding does not usually terminate at the point of tangency of a curve; it extends some distance into the adjacent tangent track. This distance depends on a number of factors including the resistance to yaw of the vehicle's suspension system. The conservative designer will extend the restraining rail a distance equivalent to one truck center into the tangent track, typically about 10 meters (33 feet). When the curve is spiraled, the need for guarding typically ends long before the spiral-to-tangent location In such cases, curve guarding can usually be terminated a distance equivalent to one truck center beyond the point on the spiral where the instantaneous radius matches the curve guarding threshold.

The criteria for beginning curve guarding on the entry end of the curve is typically the same as for the exit end, accounting for the possibility of occasional reverse running train operation. As a guideline, the minimum guarding should begin at the tangent-to-spiral location of a spiraled curve so that the vehicle trucks are straight prior to entering the guarding threshold spiral curve.

For additional information on curve guarding and vehicle steering, refer to Section 4.2.9.1.

4.2.8.1 Curve Double Guarding

Some transit agencies "double guard" extremely sharp curves, placing a guard or restraining rail adjacent to the high rail as well as the low rail. These installations are designed to counter the tendency of the second axle on a truck to drift toward the center of the curve, exacerbating the angle of attack of the outside wheel on the leading axle. In a double restraining rail installation, the restraining rail alongside the inner rail shifts the leading axle of the truck toward the center of the curve. The outer restraining rail then guides the trailing axle away from center, helping to ensure that the truck is reasonably square to the track, that both axles are in a nearly radial orientation, and that the truck frame is rectilinear rather than parallelogrammed. In superelevated, sharp radius track curves where the vehicle speed is reduced, the vehicle truck may tend to hug and climb the low rail. The outer restraining rail reduces this derailment potential.

As a guideline, a typical threshold for consideration of double guarded track is for curves with radii of 30 to 38 meters (100 to 125 feet).

4.2.8.2 Restraining Rail Design

Curve guarding on traditional street railway systems was most frequently achieved using a girder guard rail section similar to that illustrated in Figure 5.2.1 of this Handbook, particularly for track embedded in pavement. For open track design, such as ballasted or direct fixation track, a separate restraining rail mounted alongside the running rail is commonly used. The restraining rail itself can be a machined section of standard tee rail, which can be mounted either vertically or horizontally, or a specially rolled steel shape.

For additional information on various types of restraining rail designs, refer to Section 5.3 of this Handbook.

4.2.9 Gauge Determination Analysis

Requisite track gauge and flangeway dimensions in curved track must be determined analytically for each combination of vehicle truck factors. To visualize the positions that the wheel flanges assume with the rail, a simple and effective graphical technique was developed known as the Filkins-Wharton diagram.

A modified version of the Filkins-Wharton diagram, referred to herein as the Nytram Plot, has been developed for this Handbook taking advantage of the power of computer aided design and drafting as an analytical tool. The Nytram Plot illustrations, beginning with **Figure 4.2.5**, show horizontal sections of a selected wheel profile that have been derived at the gauge line elevation, at the top of rail, and, where appropriate, at a restraining rail height 19 millimeters (0.75 inches) above the top of rail. Figure 4.2.5 illustrates the method of establishing the Nytram Plot.

The plot is derived by sectionalizing both the side view of a wheel of specific diameter with designated flange height and the wheel profile in the flange area. Projecting points 0 to 9 from both sections as shown, a horizontal section or "footprint" of the wheel can be developed at various heights above or below the top of rail elevation. Using these wheel sections, the actual vehicle truck axle and wheel positions can be superimposed on a section of curved track to simulate the truck in a radial and skewed position to determine the "attack angle" and wheel clearances.

4.2.9.1 Nytram Plot—Truck-Axle-Wheel Positioning on Track

Filkins-Wharton diagrams produced manually were forced to graphically shrink track gauge and wheelbase in order to depict an entire truck assembly on a reasonably sized drafting sheet. CADD provides the track designer with the ability to develop a full-sized picture of the entire vehicle truck positioned on a curved track. These can then either be plotted at reduced scale or selected portions of the diagram can be printed at full size.

To illustrate the methods involved, a series of figures have been developed that illustrate the fundamentals of adapting track gauge to wheel gauge and wheel contour and positioning of a truck on a segment of curved track. To understand the impacts of tight curvature, and the ramifications of different wheel gauge standards and axle spacings, the figures include the following parameters:

Wheel Profile	Modified 133-millimeter (5.2-inch) AAR-1B* width
Wheel Diameter	711 millimeters (28 inches)
Wheel Gauge	Transit: 1428 millimeters (56.25 inches) AAR: 1415 millimeters (55.7087 inches)
Axle Spacings	1828 millimeters (72.00 inches) 2300 millimeters (90.55 inches)
Curve Radii	25 meters (82.0 feet) 150 meters (492.1 feet) 228 meters (748.0 feet)

* The AAR-1B wheel profile has been used in the example for convenience. Transit profile wheels with alternate flanges may be considered.

Figure 4.2.6 illustrates a vehicle truck with transit wheel gauge, 1828-millimeter (72-inch) axle spacing on a 25-meter (82-foot) radius track curve positioned on the centerline of track perpendicular to the radius line. The vehicle wheel plots are taken from Figure 4.2.5. To establish the gauge lines of the track a circle is drawn with a 1435 millimeter (56.5-inch) diameter centered at the midpoint of the axle. The track gauge lines (inside and outside) are drawn tangent to the diameter of the circle. The clearance distances from the wheels to the gauge line of the rails have been derived using CADD software and represent the closest point of the wheel plot to the gauge face of the rail. Note that these clearances differ (are less than) from the calculated wheel gauge-to-track gauge differences of 10 and 3.5 millimeters (0.4 and 0.1 inches) for AAR and transit conditions, respectively.

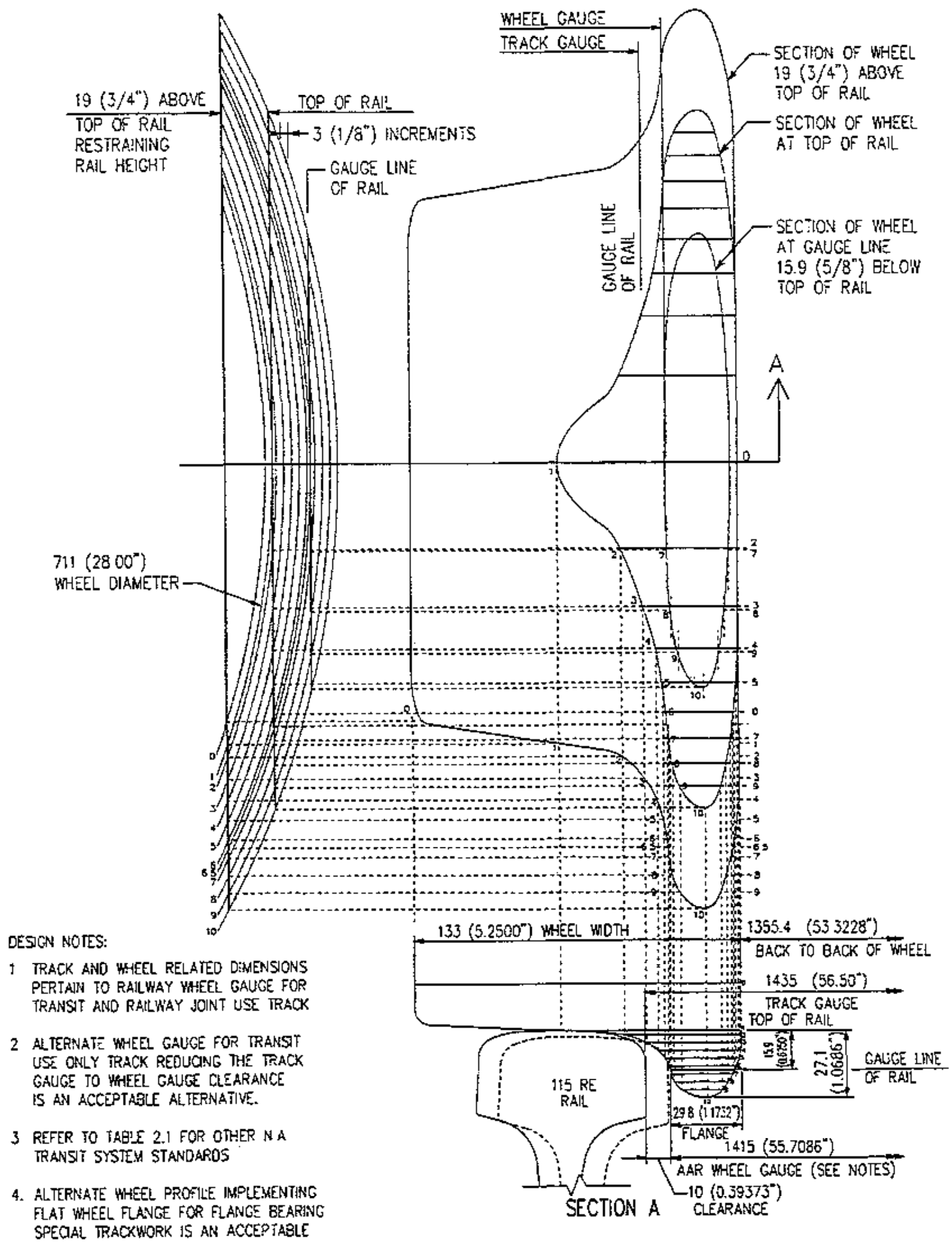


Figure 4.2.5 Nytram Plot—Modified AAR-1B Transit Wheel

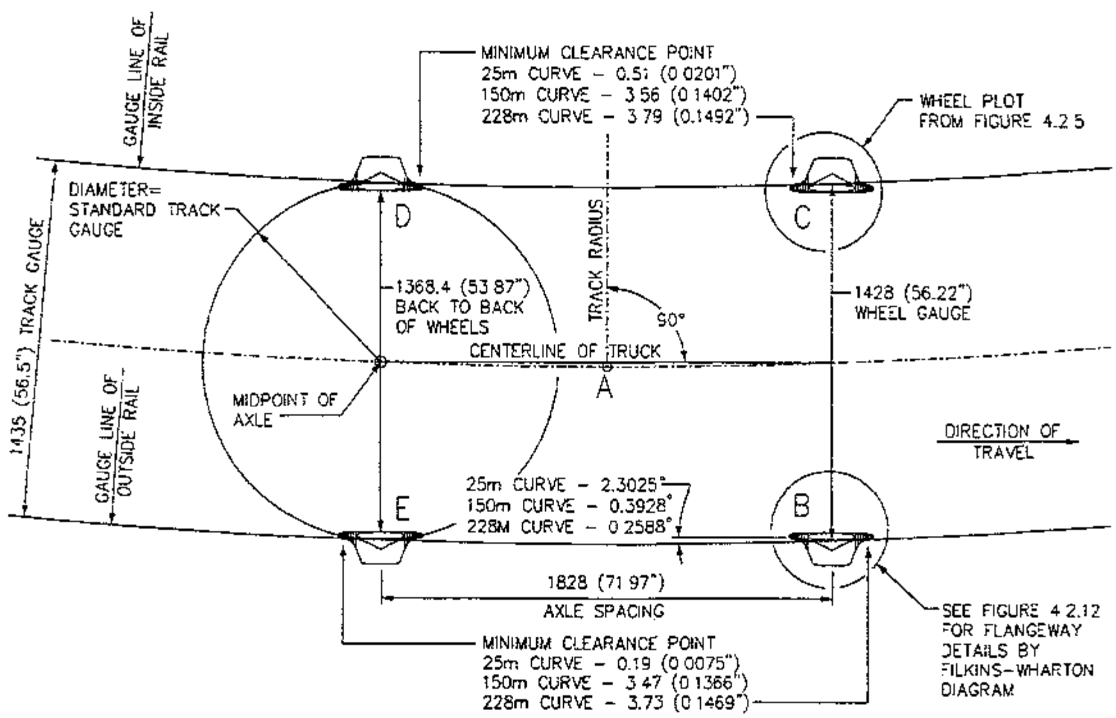


Figure 4.2.6 Nytram Plot—1428 Transit Wheel Gauge, 1828 Axle Spacing, 25-Meter Curve

Similar plots were undertaken with the same truck parameters for track curves with 150- and 228-meter (492- and 748-foot) radii. The clearance results have been entered on this figure The intersection angles between the perpendicular truck and the tangent point to the track arc have been calculated and are shown for the three curve radii for comparison. To determine flangeway widths and wheel attack angle, truck skewing must be considered as described later in this section.

Figure 4.2.7 illustrates a vehicle truck with transit wheel gauge, 2300-millimeter (90.55-inch) axle spacing on a 25-meter (82-foot) radius track curve positioned on the center of track perpendicular to the radius line. A similar scenario to the above illustration was undertaken to establish the clearance distances for the three specific track curve radii.

Figure 4.2.8 illustrates a vehicle truck with AAR wheel gauge, 1828 millimeter (72-inch) axle spacing on a 25-meter (82-foot) radius track curve positioned on the centerline of track perpendicular to the radius line. The vehicle wheel plots are taken from Figure 4.2.5. A similar scenario to that in Figure 4.2.6 was undertaken to establish the clearance distances at the wheels and the intersection angle of the truck wheel to the track arc for the three specific track curve radii.

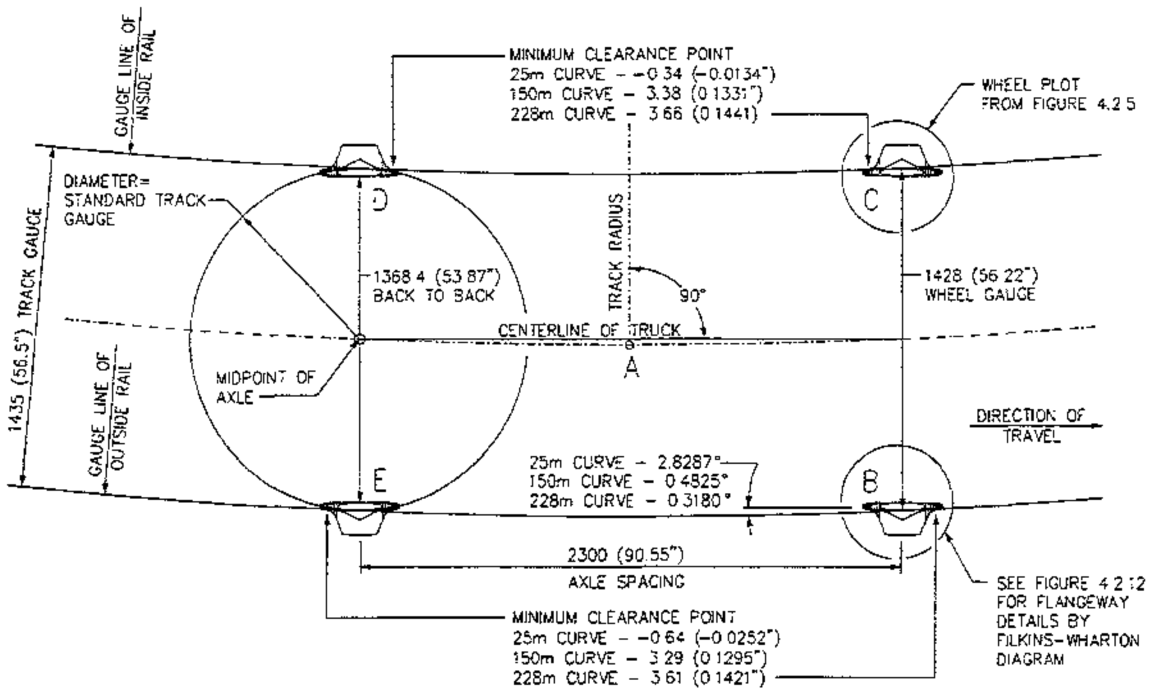


Figure 4.2.7 Nytram Plot—1428 Transit Wheel Gauge, 2300 Axle Spacing, 25-Meter Curve

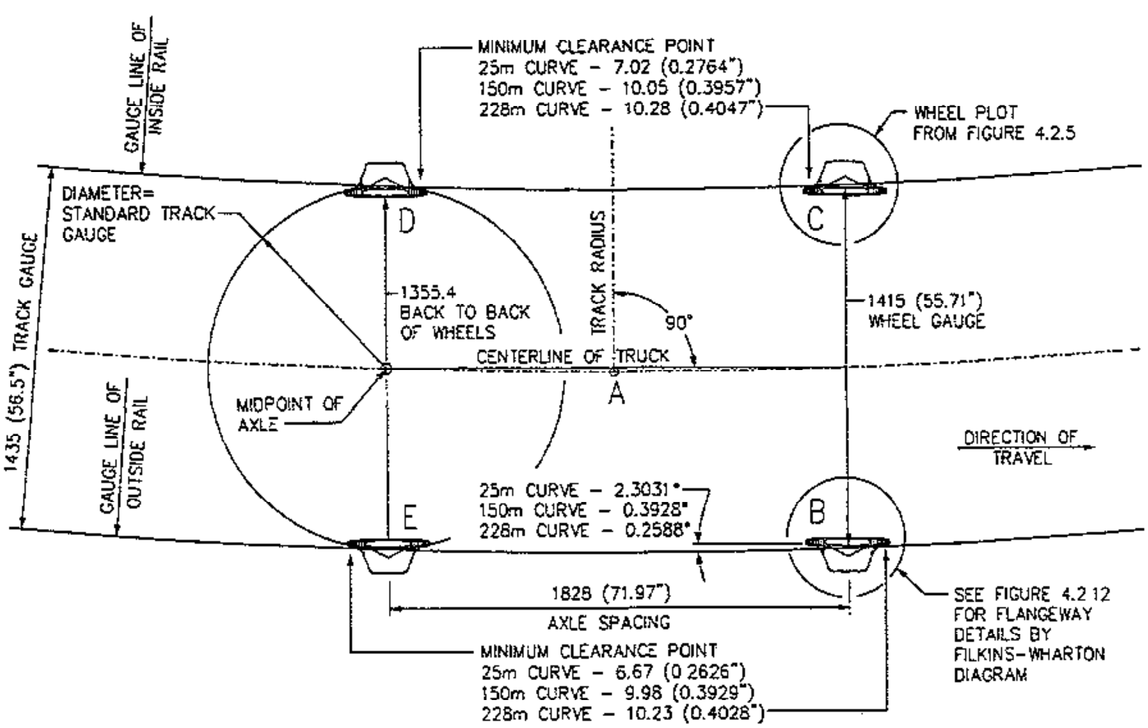


Figure 4.2.8 Nytram Plot—1415 AAR Wheel Gauge, 1828 Axle Spacing, 25-Meter Curve

Figure 4.2.9 illustrates a vehicle truck with AAR wheel gauge, 2300-millimeter (90.55-inch) axle spacing on a 25-meter (82-foot) radius track curve positioned on the center of track perpendicular to the radius line. A similar scenario to that in Figure 4.2.6 was undertaken to establish the clearance distances at the wheels and the intersection angle of the truck wheel to the track arc for the three specific track curve radii.

The above illustrations show the relationships between the various wheel gauges, axles centers, curve radii and the standard track gauge. Had the wheel to rail clearances indicated binding or potential binding as in Figure 4.2.7, the track gauge would have to be widened.

The above illustrations depict a truck superimposed on a track curve perpendicular to the radius line. To simulate the steering action of the vehicle truck traversing through the various track curves, a set of drawings with the same truck parameters as above has been developed.

The simulation represents the steering action of the truck wherein the lead outside wheel on the truck encounters the curved outside rail resulting in steering or deflecting of the lead axle and the truck. Once the outside wheel initially contacts the rail, the wheel action causes the lead axle and the truck to rotate about the contact point seeking a second wheel flange to rail contact point if the curve radius is short and/or the primary suspension of the truck is relatively stiff. Trucks with moderate self-steering capability may not encounter the second contact point.

Figure 4.2.10 illustrates two vehicle trucks with transit wheel gauge, 1828-millimeter (72-inch) and 2300-millimeter (90.55-inch) axle spacings on a 25-meter (82-foot) radius track curve. The track gauge is both standard and wide gauge at 1435 millimeters (56.5 inches) and 1438 millimeters (56.625 inches), respectively. Track gauge was widened based on potential wheel binding with 2300-millimeter (90.55-inch) axle spacing. The drawing indicates:

- The sequence of maneuvers required to position the traversing truck in the curving position.
- The angle of attack of the lead wheel to the outside running rail.
- The measured inside flangeway width to allow outside wheels to touch or barely touch the outside running rail if a restraining rail is considered.
- The wheel positions once the truck has completed the skew and second wheel contact is made.

For comparison, **Figure 4.2.11** has been developed using AAR wheel gauge with 1828- and 2300-millimeter (72- and 90.55-inch) axle spacings.

The drawings do not account for either potential axle swivel that might be permitted by a flexible primary suspension system at the journal box or any possible twisting or racking of the vehicle truck into a parallelogram configuration. These are conditions that may be inherent in each agency's vehicle.

This type of interface study should be undertaken with the joint involvement of the project's vehicle and track designers. The drawings do not consider restraining rail; however, a measured inside rail flangeway width has been stated on the drawings as a reference. If restraining rail is required on a system due to restricted sharp radius track curves, then a similar scenario should be undertaken using the parameters of the vehicle truck and track system to establish the

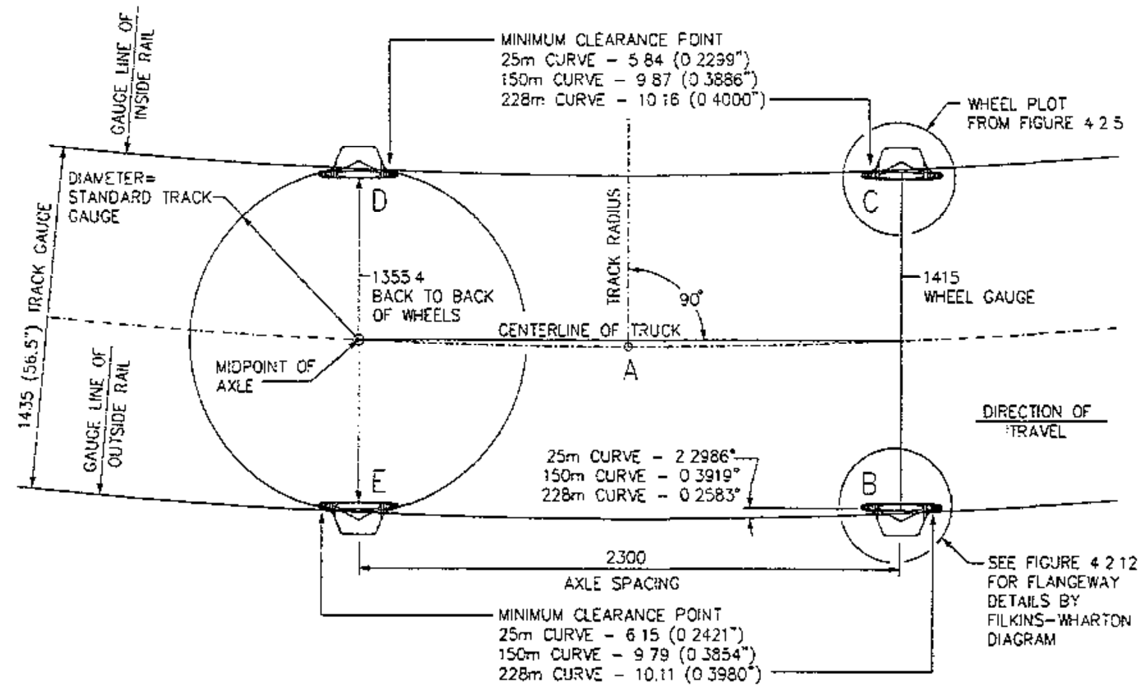


Figure 4.2.9 Nytram Plot—1415 AAR Wheel Gauge, 2300 Axle Spacing, 25-Meter Curve

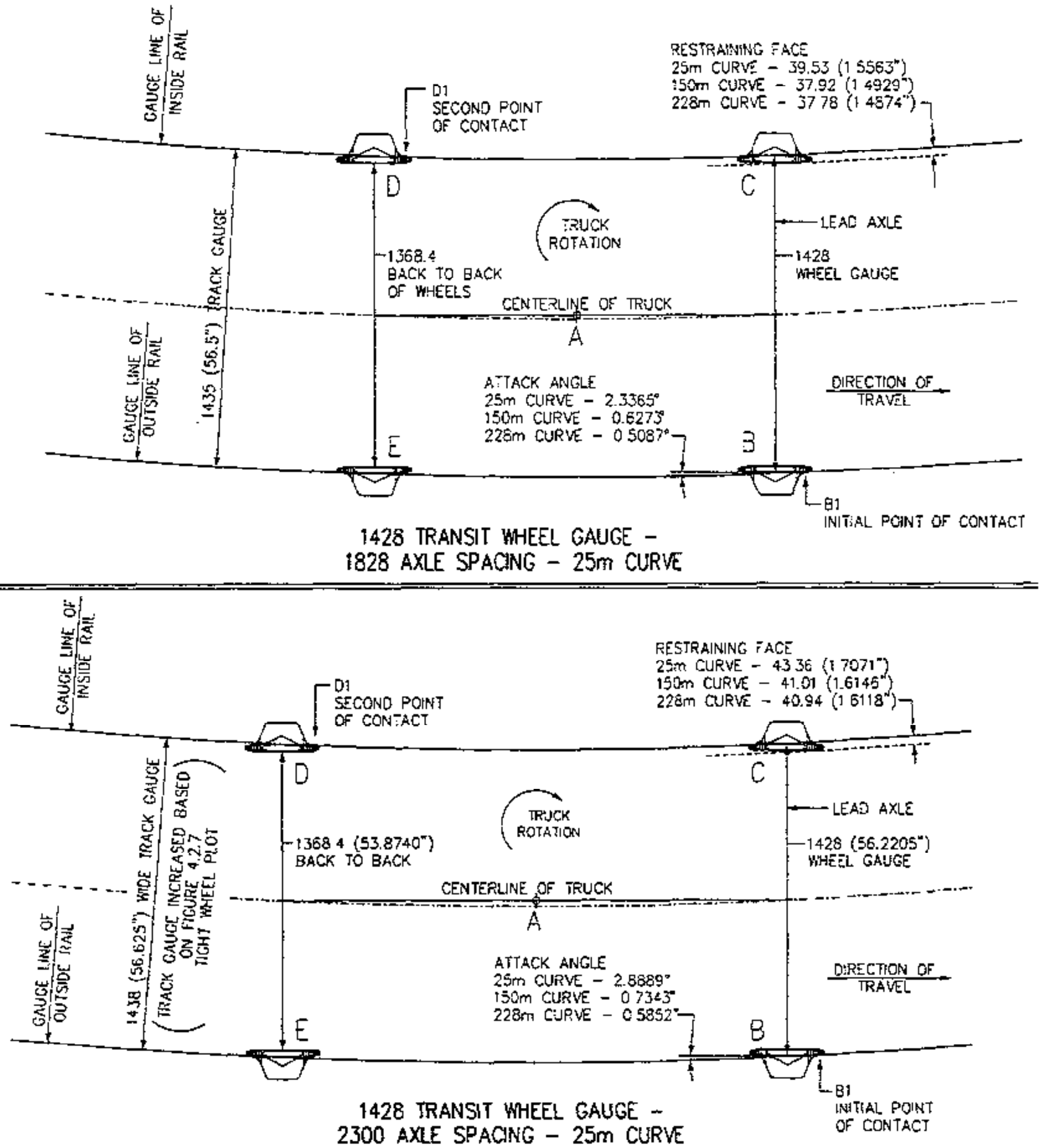
flangeway. For extremely sharp radius curves requiring double restraining rails, the same procedures are required to establish both flangeway widths. Truck rotation about an initial contact of the inside lead axle wheel on the restraining rail face is possible if the designer elects to provide clearance at the outside lead axle wheel. From the illustrations it is apparent that the AAR wheel gauge requires a wider flangeway than the transit wheel gauge due to basic clearances between the wheel and the rail. Under these same conditions, it may be necessary to increase track gauge so as to provide either wheel contact on both the restraining rail and the outside running rail or to provide clearance between the outside wheel and its running rail.

As a guideline, it is recommended that the inside restraining rail flangeway width be set to provide dual wheel contact so that the inside back face of wheel makes contact with the restraining rail face while the outside wheel is simultaneously contacting the gauge corner of the outside rail. This will divide the lateral steering force between both wheels and rails. In practice, this condition may not be immediately obtained, however, rail wear at either the outside running rail or inside restraining rail will eventually balance the curving action.

4.2.9.2 Filkins-Wharton Flangeway Analysis

Flangeway widths are a primary concern when girder rail is to be used in the track system.

Victor Angerer, in a paper before the Keystone Railway Club (1913), said that *"...theoretically for track laid to true ga[u]ge every combination of radius of curve and wheel base of truck, with a given wheel flange, calls for a specific width of groove to make the inside of the flange of the inside wheel bear against the guard and keep the flange of the outside wheel from grinding*



TRUCK ROTATION SCENARIO

A. LEAD AXLE ROTATED ABOUT CENTER OF TRUCK (POINT "A") TO DETERMINE WHEEL CONTACT WITH RUNNING RAIL (INITIAL CONTACT POINT B1).

B. HOLDING OUTSIDE WHEEL POSITION (POINT B1) ENTIRE TRUCK ROTATED ABOUT LEAD AXLE OUTSIDE WHEEL UNTIL CONTACT WAS MADE AT A SECOND WHEEL LOCATION.

C. SECOND CONTACT POINT WAS ESTABLISHED ON INSIDE REAR AXLE WHEEL (POINT D1 AGAINST INSIDE RUNNING RAIL.)

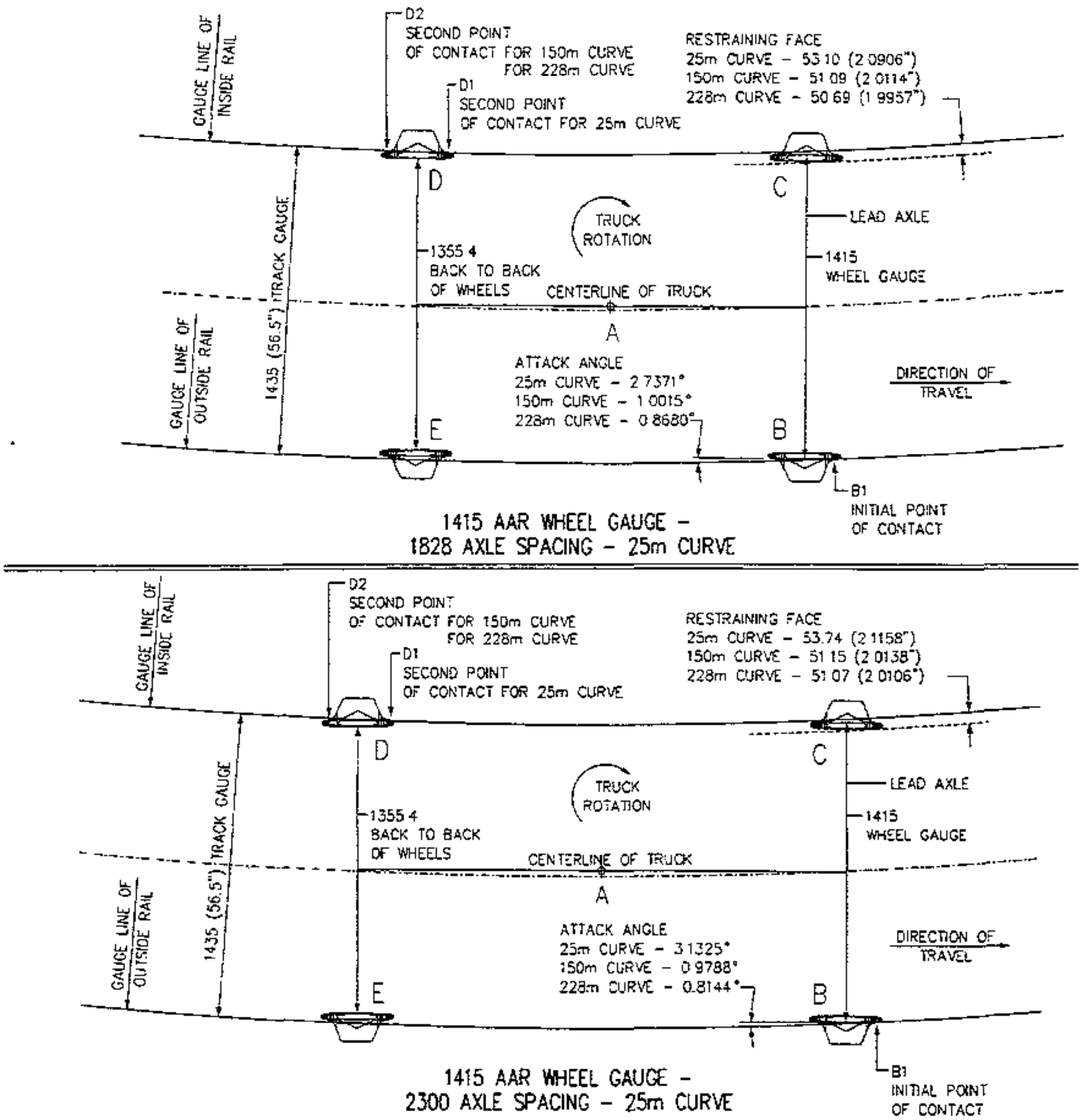
D. CLEARANCES EXISTED BETWEEN ALL OTHER WHEELS AND RAIL HEADS.

E. USING THIS ROTATED TRUCK POSITION AND WHEEL NYTRAM PLOT, THE ATTACK ANGLE & RESTRAINING RAIL CLEARANCES AS NOTED WERE DETERMINED.

F. OTHER WHEEL CLEARANCES MAY BE DETERMINED BY A SIMILAR METHOD.

G. TOLERANCES HAVE NOT BEEN INCORPORATED.

Figure 4.2.10 Nytram Plot—Rotated Truck Position on Track, Transit Wheel Gauge



TRUCK ROTATION SCENARIO

A. LEAD AXLE ROTATED ABOUT CENTER OF TRUCK (POINT "A") TO DETERMINE WHEEL CONTACT WITH RUNNING RAIL (INITIAL CONTACT POINT B1)

B. HOLDING OUTSIDE WHEEL POSITION (POINT B1) ENTIRE TRUCK ROTATED ABOUT LEAD AXLE OUTSIDE WHEEL UNTIL CONTACT WAS MADE AT A SECOND WHEEL LOCATION

C. SECOND CONTACT POINT WAS ESTABLISHED ON INSIDE REAR AXLE WHEEL (POINT D1 & D2 AGAINST INSIDE RUNNING RAIL)

D. CLEARANCES EXISTED BETWEEN ALL OTHER WHEELS AND RAIL HEADS

E. USING THIS ROTATED TRUCK POSITION AND WHEEL NYTRAM PLOT, THE ATTACK ANGLE & RESTRAINING RAIL CLEARANCES AS NOTED WERE DETERMINED

F. OTHER WHEEL CLEARANCES MAY BE DETERMINED BY A SIMILAR METHOD

G. TOLERANCES HAVE NOT BEEN INCORPORATED

Figure 4.2.11 Nytram Plots—Rotated Truck Position on Track, AAR Wheel Gauge

against the ga[u]ge-line and possibly mounting it. It is manifestly impracticable to provide guard rails with such a variety of grooves or to change the grooves of the rolled rail. The usual minimum of 1-9/16 inch is wide enough to pass the AREA standard flanges on a 6-foot wheel base down to about a 45-foot radius, and the maximum width of 1-11/16 inches down to about a 35-foot radius. On curves of larger radius the excess width should be compensated for by a corresponding widening of the ga[u]ge. If the groove in the rolled rail is too narrow for given conditions, it must be widened by planing on the head side of the inside rail, to preserve the full thickness of the guard, and on the guard side of the outside rail to preserve the full head. Unusual wheel bases such as 8 feet or 9 feet may require widening of the gage on some curves. This widening of gage is necessary only to bring the guard into play when the groove is too wide for some one combination of wheel and flange. In T-rail curves the guard is formed of a rolled shaped guard, or a flat steel bar, bolted to the rail. In special work and curves in high T-rail track a girder guardrail is often used. This is desirable, as it gives the solid guard in one piece with the running rail. The idea that a separate guard can be renewed when it is worn out does not work out in practice, as it is usually the case that when the guard is worn the running rail is also worn to such an extent that it will soon have to come out also."[1]

This excerpt provides still timely guidance in determining flangeway requirements, particularly for design of restraining rail systems and evaluating the possible use of presently available girder rails.

The tight wheel-to-track gauge freeplay and small wheel flange profiles that were common on traditional street railways required smaller flangeways than those needed for railroad service. Hence girder rails that were rolled for streetcar systems had much smaller flangeways than those for steam railroads running on paved track in warehouse and wharf districts. These smaller flangeways are more conducive in areas with pedestrian traffic although it should be noted that AREMA standards for flangeways through grade crossings comply with American with Disabilities Act (ADA) requirements.

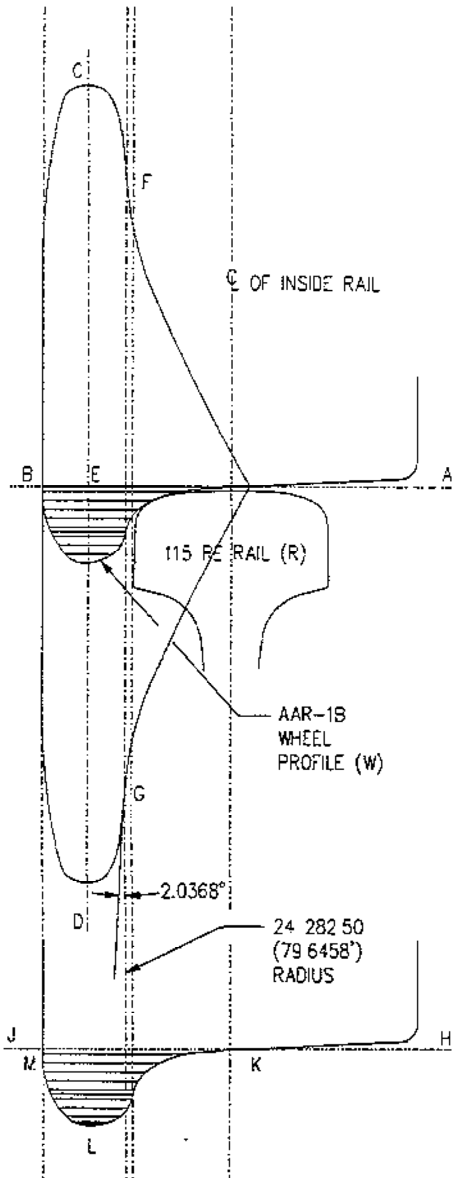
The Filkins-Wharton diagram analysis was a simple and effective technique to establish the flangeway openings required to suit wheel flange profiles, track curve radii and axle spacings. The following describes the Filkins-Wharton diagram procedures.[1]

Figure **4.2.12** represents an AAR-1B wheel placed on 115 RE rail on a 25-meter (82-foot) radius curve. In the illustration, the wheel is adjacent to the rail gauge line. The wheelbase or distance between axles is 1828 millimeters (72 inches). In the illustration, A-B is the horizontal cut plane passing through the AAR-1B wheel profile (W) resting on the 115 RE rail head (R).

C-D-E represents the plan view of the section produced by plane A-B similar to the Nytram plot at top of rail. The line C-D-E is perpendicular to the axle.

The length of rail head with a 25-meter (82-foot) centerline radius adjacent to section C-D-E is short enough to be considered a straight line.

The line F-G represents a perpendicular line to the radius line and forms an intersecting angle of 2.0368° to the wheel axis C-D-E. All four wheels will approximately produce a similar angle for line F-G using the combination of curve radius and wheelbase.



PARAMETERS:

- AAR-1B MODIFIED NARROW FLANGE WHEEL
- 25 METER TRACK CURVE
- 1828 (72") WHEEL BASE
- 711 (28") WHEEL DIAMETER
- 1415 (55 7087) WHEEL GAUGE

Figure 4.2.12 Filkins-Wharton Diagram for Determining Flangeway Widths

Geometric construction is applied to project the resulting flange profile on the plane H-J. Plane H-J is perpendicular to the rail head and radial to the track curve. Projecting the points of the wheel in plan along the track arc to line H-J produces the outline K-L-M.

Outline K-L-M represents the absolute minimum groove section required to permit the vehicle truck AAR-1B wheel profile and stated wheelbase to negotiate through the stated track curvature.

Additional flangeway clearances will be required to allow relatively free movement and to compensate for tolerances in the wheel mountings, wheel profiles and track gauge tolerances, which results in a wider flangeway width. Flangeway depth must consider wheel tread wear and special trackwork design features as flange bearing flangeways.

Figure 4.2.13 illustrates the flangeway requirements using outline K-L-M considering both flangeways using Ri 59N rail and standard track gauge and AAR wheel gauge.

Comparing these results with the Nytram plots and CADD system, similar flangeway requirements are established. The Nytram plot CADD method appears to be a more comprehensive method of establishing flangeway widths and also provides the angle of attack and potential clearances.

The above interface issues are basic in establishing clearances. Research in wheel rail interface has introduced sophisticated rail head grinding procedures to improve the tracking patterns of wheels as discussed in Section 5.2 of this Handbook.

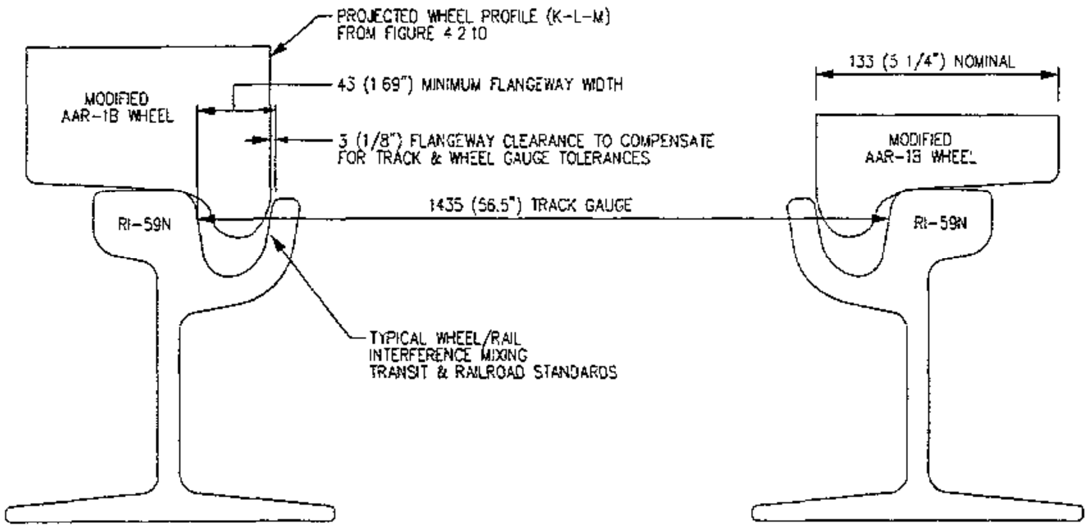


Figure 4.2.13 Filkins-Wharton Plot to Establish Flangeways

4.2.10 Gauge Implications of Track Construction and Maintenance Tolerances

The most precisely calculated standards for track gauge and flangeways will be of no value if the track is not constructed and maintained in a manner that ensures that the design intent is achieved in practice. Obviously, perfectly constructed and maintained tracks are not possible, and the cost of achieving such would probably exceed the value of benefits that would ensue. Accordingly, tolerances must be specified that both protect the design objective as closely as possible and are practical and achievable with the materials and equipment available.

Tolerances fall into three categories:

- Construction Tolerances: These will be the strictest. Track construction tolerances are most often specified with the use of new materials in mind. If used materials, such as relay grade rail, are employed, then construction tolerances may have to be less restrictive.
- Maintenance Tolerances: These represent the acceptable limits of wear for track systems components. After components are worn to this level, performance is considered to be sufficiently degraded such that wear is likely to occur at an accelerated rate. At that time, maintenance should be performed to restore the system to a condition as close as possible to its new, as-constructed state.
- Safety Tolerances: These represent the levels beyond which the system is unsafe for operation at a given speed. The FRA Track Safety Standards are a well-known example. If track systems are permitted to degrade to an unsafe condition, performance will be unsatisfactory, wear will be excessive, and the cost of restoration to a satisfactory state will be high.

The reduced differential distance between track gauge and wheel gauge in transit systems governs the gauge tolerances for both. The practice is to have a plus tolerance for track gauge and a minus tolerance for wheel gauge.

Transit track construction tolerances are more restrictive than conventional railroad standards The tolerances apply to the following track standards—track gauge, guard rail gauge, cross level and superelevation, vertical track alignment and horizontal track alignment. The rate of change within the tolerance limits is important in both the longitudinal track surface (vertical) and alignment (horizontal) planes.

Table 4.2.1 lists recommended track construction tolerances for the three general types of track construction. Track maintenance limits that define allowable wear and surface conditions are not included, as they should be developed with the needs of a particular transit operating agency in mind. Future updates of this Handbook should include guidance on the development of maintenance tolerances.

Table 4.2.1 Track Construction Tolerances

Type of Track	Track and Guard Rail Gauge[5]	Cross Level [5]	Construction Tolerances		Location Tolerances	
			Horizontal Alignment Deviation[1][5]	Vertical Alignment Deviation[1][5]	Horizontal Alignment Variable[6]	Vertical Alignment Variable[6]
Ballast (Main Line)	+3 +(0.1250") -0 -(0.0000")	3 (0.1250")	6[2] (0.25"[2])	6[2] (0.25"[2])	15 (0.3937")	15 (0.3937")
Direct Fixation	+3 (+0.1250") -1 (-0.0625")	3 (0.1250")	6[2] (0.25"[2])	6[2] (0.25"[2])	10 (0.3937")	10 (0.3937")
Embedded	+3 (+0.1250") -1 (-0.0625")	3 (0.1250")	6[2] (0.25"[2])	3[3][4] (0.1250"[3][4])	6 (0.2500")	6 (0.2500")
Ballast (Yard)	+4 (+0.3125") -1 (-0.0625")	4 (0.3125")	9 (0.3750")	9 (0.3750")	15 (0.5906")	15 (0.5906")

NOTES:

(1) Deviation is the allowable construction discrepancy between the standard theoretical designed track and the actual constructed track.

(2) Deviation (horizontal) in station platform areas shall be: 0 millimeters (inches) toward platform, 3 millimeters (0.125 inches) away from platform. Refer to Figure 2.8.1.

(3) Deviation (vertical) in station platform areas shall be: plus 0, minus 6 millimeters (0.2500 inches), or in conformity with latest American with Disabilities Act requirements. Refer to Figure 2.8.1.

(4) Deviation at top of rail to adjacent embedment surface shall be plus 6 millimeters (0.2500 inches) minus 0.

(5) Rate of change variations in gauge, horizontal alignment, vertical alignment, cross level and track surface shall be limited to 3 millimeters per 5 meters (0.1250 inches per 16 feet) of track.

(6) Variable is the allowable construction discrepancy between the overall location of track and the actual final location of the constructed track. (not to be confused with tolerances pertaining to track standards). Tracks adjacent to fixed structures shall resort to deviation limits.

4.3 TRACK SUPPORT MODULUS

Railway track acts as a structural element that undergoes stress and strain as a vehicle passes over the track. The rail, fastener, tie, ballast, subballast, and subgrade are each a component of the track structure. Each undergoes some deflection as the wheel passes. The analysis of how the track structure reacts to wheel loads has been studied analytically since Professor Talbot and his committee wrote the first definitive work on this subject in 1918 for AREMA. This Handbook provides sufficient information to design track; for additional reference, the designer is advised to study either the Talbot Reports of 1920 or Dr. Hay's Railroad Engineering, which both provide a more detailed explanation. [2,5]

Track modulus is an important subject, with complex mathematical calculations, to allow for track analysis as a structure to determine appropriate rail weights, tie size and spacing, ballast depth, the need for subballast, and the need for special subgrade preparation for ballasted track. Similar mathematical calculations are undertaken for direct fixation track.

The track modulus factor value (μ) established in this section is a requirement of track design and one of the variables used in the calculations for ballasted track structural design (Section 4.4.3) and direct fixation track structure design (Section 4.5.3). In addition, the track modulus is a parameter found in many of the calculations used by noise and vibration engineers when considering wheel impacts, contact separation and velocities.

4.3.1 Modulus of Elasticity[2]

Ballasted track is often characterized as a beam supported on a continuous series of springs. Track modulus can be defined simply as the amount of deflection in these springs from a given wheel load. The greater the deflection, the lower the modulus. Conversely, a track with little deflection has a high modulus, which is generally considered important for ride quality and good serviceability. Most of the deflection of the track structure occurs in the ballast and subgrade, with only small deflections at the rail and tie. In order to minimize deflections, the track designer must focus on a thick section of well-compacted ballast and subballast with a sound dry compacted subgrade. This is crucial if total deflections for ballasted track are to be kept under the 6-millimeter (0.2-inch) limit suggested by AREMA.

In direct fixation track, the track modulus is much higher because the rail fasteners are made of neoprene and/or rubber which have a controlled restricted deflection.

When rails are embedded directly into concrete pavement, the modulus becomes very high since there is almost no deflection by rigid pavements.

The following explanation deals with ballasted track modulus, which can be determined using the following equation:[1]

$$p = -uy \quad (1)$$

where: p is the upward pressure per unit on the ballast or sub-ballast

u is a factor determining the track stiffness or "modulus of track"

y is the vertical deflection measured at the base of rail

The modulus of track is defined as the vehicle load per unit length of rail required to deflect the rail one unit. An example follows.

Assume a wheel load of 9,090 kilograms (20,000 pounds), converted to an 88,960-N force, results in a track vertical deflection of 10 millimeters (0.394 inches) The force required to deflect the track 25.4 millimeters (1 inch) is:

$$\frac{P}{88{,}960} = \frac{25.4}{10} \qquad \left[\frac{P}{20{,}000} = \frac{1}{0.394}\right]$$

$$P = 225{,}960 \text{ N} \qquad \left[P = 50{,}761 \text{ lbs.}\right]$$

Expressed (in metric) for a deflection of 1 millimeter, force per unit deflection is thus:

$$Pu = \frac{P}{25.4} = \frac{225{,}960}{25.4} = 8{,}896 \text{N/mm}$$

$$\left[P = \frac{50{,}761}{1 \text{ in}} = 50{,}761 \text{ lb./in}\right]$$

The force required to deflect the track per unit; i.e., 1 millimeter (1 inch), with track tie spacing at 760 millimeters (30 inches) is:

$$\frac{Pu}{\text{Tie Spacing}} \text{ or } \frac{8{,}896}{760} = 11.7 \text{ N/mm/mm or N/mm}^2$$

$$\left[\frac{50{,}761}{30} = 1{,}692 \text{ lbs./in./in. or psi}\right]$$

The above calculated force required to deflect one rail on one tie 1 millimeter with a tie spacing of 760 millimeters is known as the modulus of track elasticity.

The above analysis assumes that the rail deflection is either known, or that maximum rail deflection is the primary criteria for the track design. Developing a high track modulus without increasing the weight of rail will dramatically reduce the bending moments in the rail.

4.3.2 Track Modulus of Various Track Types

The stiffness of rail, fastenings and supporting structure determines the stiffness of track. The types of track encountered on an LRT system—ballasted, direct fixation and embedded—have a wide range of stiffness because the components of each track substructure are dramatically different. Ballast provides the most flexible track structure support, while embedded track is usually the stiffest.

4.3.2.1 Ballasted Track

Determination of track modulus for ballasted track can be made by strictly following the Talbot formula shown in Section 4.3.1

In many cases for ballasted track, the maximum rail deflection is not known, or the maximum rail deflection is to be estimated from a given track structure. The latter condition is frequently encountered in ballasted trackwork design.

The track modulus can be estimated considering the crosstie size, structure depth of subballast and ballast, type of ballast rock or stone, and the crosstie spacing. As a guideline, track modulus using 115 RE rail section can be expected to be in the following ranges:

- 8–17 N/mm^2 (1500 – 2500 psi): 450 millimeters (17.7 inches) depth of sub-ballast and limestone ballast, timber ties spaced at 550 millimeters (22 inches)
- 17–24 N/mm^2 (2500 – 3500 psi): 550 millimeters (21.7 inches) depth of well-compacted subballast and heavy stone ballast, timber ties spaced at 550 millimeters (22 inches)
- 24–34 N/mm^2 (3500 – 5000 psi): 600 millimeters (23.6 inches) depth of well-

compacted subballast and heavy granite ballast, timber ties spaced at 520 millimeters (20.5 inches)

Track modulus has been known to vary and lose stiffness with a change in applied load; that is, modulus under a 63,500-kilogram (70-ton) car may have a lesser value when measured under a 90,700-kilogram (100-ton) car: A modulus of 13.8 to 17.3 N/mm^2 (2000–2500 psi) represents good timber tie ballasted track. The value can, and most likely will, rise to 34.6 to 55.3 N/mm^2 (5000–8000 psi) for track with concrete cross ties spaced at 610 millimeters (24 inches).

4.3.2.2 Direct Fixation Track

As stated above, the track stiffness or the amount of vertical deflection of the track structure under vehicle load is the basis for determining the track support modulus. Unlike ballasted track, however, the track component deflections and elastic properties of direct fixation track are generally known. In direct fixation track, the vertical deflection occurs in the:

- Bending of the rail
- Elastomer portion of the direct fixation fastener
- Intermittent seating of the direct fixation fastener to the concrete or at the layers of vertical shims below the fastener
- Intermittent seating of the rail at the rail seat
- Flexure of the direct fixation slab at the supporting subbase materials for at-grade installations.

The track modulus of direct fixation track is determined by establishing the nominal spring rate of the elastomer component of the direct fixation fastener. Elastomer vertical static spring rates vary widely. Two popular spring rate ranges are:

15,780 to 24,540 N/mm (90,000 to 140,000 lb./in)

and

42,060 to 56,080 N/mm (240,000 to 320,000 lb./in)

Fastener spacing, like the spacing of ties in ballasted track, is a factor in the stiffness of direct fixation track; a common spacing for fasteners is 760 millimeters (30 inches). The spring rate in direct fixation fasteners is often adjusted to mitigate ground borne vibrations. This adjustment then affects the track modulus.

The following is an example on establishing the modulus of track elasticity for direct fixation track:

$$\frac{P}{s} = \mu$$

where

p is the upward pressure per unit length on the fastener

s is the fastener spacing

μ is a factor determining the track stiffness also known as the "modulus of track"

p is a pre-determined value based on the spring rate of the direct fixation fastener elastomer as stated above

s is a set value based on the desired direct fixation fastener spacings - 760 millimeter (30 inch) spacing

$$\frac{P}{s} = \frac{17{,}530}{760} = 23.1\text{N/mm/mm}$$

$$\left[\frac{100{,}000}{30} = 3{,}333\text{ lbs/in./in.}\right]$$

$$\frac{P}{s} = \frac{52.{,}580}{760} = 69.2\text{N/mm/mm}$$

$$\left[\frac{300{,}000}{30} = 10{,}000\text{ lbs/in/in}\right]$$

The above calculated force required to deflect one rail on one fastener 1 millimeter with a fastener spacing of 760 millimeters is known as the modulus of track elasticity.

The track moduli calculated above are somewhat understated. The dynamic spring rate of most elastomeric direct fixation rail fasteners are 10 to 50% higher than the static spring rate. Dynamic spring rate can be most easily visualized by considering that the elastomer has not fully recovered, or is in various stages of resonance, when the next wheel load is applied.

The net effect of the dynamic spring rate is to increase the effective spring rate and thus the track modulus. Most direct fixation rail fasteners show an increase of 30% in spring rate during dynamic qualification testing. The static track moduli calculated above should be multiplied by 1.30, unless rail fastener test results indicate that another value is more appropriate.

4.3.2.3 Embedded Track

The track modulus for embedded track is very dependent upon the design of the rail support and underlying base slab.

For embedded ballasted tie track with pavement overlay, the track modulus is in the range of ballasted track, 10.4 to 31.1 N/mm^2 (1,500 to 4,500 psi). See Section 4.3.2 1 for ballasted track modulus values. If the pavement extends down into the ties, and especially if the pavement is constructed underneath the ties, the track structure behaves more like a slab. Ballasted track equations are not valid for the latter case.

Some recent embedded track designs are essentially direct fixation trackwork installed in troughs formed in an underlying concrete slab. Where the infill material provides little or no structural support, or where only elastomeric side pieces are used, the track modulus is identical to the direct fixation track analysis indicated in Section 4.3.2.2.

It is more difficult to determine the track modulus for most embedded trackwork designs for the following reasons:

- The rail is continuously supported. The Talbot premise of beam supports on an elastic foundation does not apply
- Rail deflections can be extremely small.
- The spring rate for the rail support material is not known or easily determined.

Track modulus values have very little meaning for designs where the rail is completely encased in concrete. Rail deflections, if any, are in the range of 0.025 millimeters (0.001 inches). The corresponding track modulus is extremely large, and may even be dependent on the deflection of the underlying track slab. The slab deflection is also a minor value.

An embedded track design with limited resiliency, such as the rail trough liner design used in Baltimore and Seattle, is known from field measurements. In Baltimore, the embedded rail trough features a 2.3-millimeter (90-mil) thick polyethylene lining at its perimeter for stray current mitigation and limited resiliency. Track measurements taken under a 53.375-N (12,000-pound) wheel load indicated that the rail deflected from 0.050 to 0.25 millimeters (0.002 in to 0.010 inches). This corresponds to an average force per unit deflection of approximately 356,000 N/mm (2,000,000 lb./in). As the force per unit deflection and track modulus are identical for continuously supported track, the track modulus is thus seen to be 356,000 N/mm^2 (2,000,000 psi). Similar track moduli would be expected from a fully encased high grade polyurethane fill.

A more complex evaluation would be needed for a design that uses rigid fastener plate supports. For concrete infill, the track modulus would be extremely large. For an elastomeric or asphalt infill, the track modulus would be calculated from the rail deflection between rigid supports using conventional structural continuous beam formulas.

Finally, a rail boot or similar continuous elastomeric pad under the rail may be incorporated in the embedded trackwork design.

Representative track moduli may be estimated from values for data from one manufacturer It uses a 50 Durometer elastomer with an 8-millimeter (0.3-inch) thickness at the rail base. The elastomer is ridged for additional resiliency. The track modulus from this design is approximately 1037 N/mm^2 (150,000 psi). An additional elastomer layer is optional with this design, increasing pad thickness to 19 millimeters (0.75 inches). The track modulus is decreased to 207 N/mm^2 (30,000 psi).[3] Note that the track modulus change is not a linear function of elastomer thickness in this case, but varies in accordance with elastomer pad shape.

Where the assumption of a linear elastomeric pad deflection is reasonable, a rough estimate of track modulus can be obtained by using a rail deflection of 15% of the elastomer pad thickness.[4]

4.3.3 Transition Zone Modulus

4.3.3.1 Interface Between Track Types

The interface points between embedded and ballasted track segments and between direct fixation and ballasted track are typically locations of sudden changes in track modulus. If special design consideration is not given to such areas, particularly in line segments where the transit vehicles operate at speeds greater than typical yard operation, the ballasted track will invariably settle and the stiffer track will incur structural damage. The passengers will experience an abrupt transition in the form of vertical acceleration, similar to hitting a bump in the road with a car.

Track modulus can vary dramatically among various track types. Well-maintained ballasted track, where timber or concrete crossties are supported by a stipulated depth of ballast and sub-ballast, can have a track modulus as low as 17.2 N/mm^2 (2,500 psi) or as high as 48.3 N/mm^2 (7,000 psi). Concrete crosstie and timber crosstie track with elastic rail fastenings tend toward the higher end of the scale. Embedded or direct fixation track, where a concrete base slab supports the rail, typically have a higher modulus value and greater stability as do non-ballasted "open" deck bridge structures where the rail is supported on rigid structural abutments and spans.

Locations where the track modulus changes abruptly are prone to vertical alignment problems, particularly when the predominant traffic moves from the stiffer to the more flexible track. A typical example is the interface between an open deck bridge and adjoining ballasted track. Railroads have long been aware of track alignment problems in these areas and have attempted to compensate by installing transition or approach ties similar to those shown on AREMA Plan No. 913-52. Various arrangements of long-tie installations are used on different railroads, sometimes with an incremental decrease in the crosstie spacing. The objective of these designs is to gradually stiffen the ballasted track structure over an extended distance, thereby reducing the abrupt change in track stiffness at the bridge abutment. Transition tie arrangements have also been placed at the ends of concrete tie installations where the track modulus differential between the concrete and timber crossties often results in additional surface maintenance requirements. Similar conditions repeatedly occur on transit track installations between ballasted track and both embedded and direct fixation track. Special transition track design must be considered to maintain an acceptable ride quality at these locations without incurring excessive maintenance costs.

4.3.3.2 Transition Zone Design Details

In North America, the current standard to compensate for the track modulus differential is to use a reinforced concrete transition slab (also called an approach slab) to support the ballasted track. These transition slabs (**Figure 4.3.1**) extend from the end of the abutment or the embedded track slab, a minimum of approximately 6 meters (20 feet) into the ballasted section. The top of the slab typically is located 300 millimeters (12 inches) below the bottom of the ties immediately adjacent to the stiffer track, gradually increasing to 350 millimeters (14 inches) at the far end of the slab. This design replaces compressible subballast materials with a stiffer base, while also gradually decreasing the thickness and compressibility of the ballast layer. Center-to-center distances between track crossties are generally reduced in the transition slab section to provide additional stability and increase the track modulus. However, even a well-designed transition zone will experience some track surface degradation during operation, requiring periodic inspection and resurfacing to avoid pumping track conditions.

4.3.3.3 Transition Zone Improvements

The action of the rail at a transition zone represents a sine curve produced by the wheel load leaving the stiffer track section. The rail shows a downward deflection approximately 1 meter (3 feet) from the transition point or end of direct fixation or embedded concrete slab, with a resulting upward force approximately 1 meter (3 feet) into the direct fixation or embedded track portion. The rail sine wave disturbs the ballasted track and attacks the direct fixation or embedment track installations, leading to deterioration of components and track conditions.

4.3.3.3.1 Transition from Direct Fixation Track to Ballasted Track

The ballasted track side of the transition zone, even with a transition slab, cannot consistently produce a uniformly varying track modulus due to the tendency of ballast to compact, pulverize, and become fouled. Such deterioration leads to settlement voids, hard spots, and pumping track. Regular maintenance of the ballast is needed to protect the rails and maintain ride quality.

Fortunately, direct fixation fastener design continues to evolve and a greater range of fastener spring rates is now available. A direct fixation track modulus of 23.1 MPa (3,333 lb/in per inch of rail), which compares favorably with standard concrete crosstie installation, is now possible. Softer direct fixation fasteners in the zone immediately adjacent to the ballasted track transition zone can alleviate some of the transition problems that are not addressed by conventional transition slabs.

4.3.3.3.2 Transition from Embedded Track to Ballasted Track

Embedded track design continues to evolve and improve; however, the rail deflections that would be required to match typical ballasted track modulus values are difficult to achieve in embedded track. The track sine wave

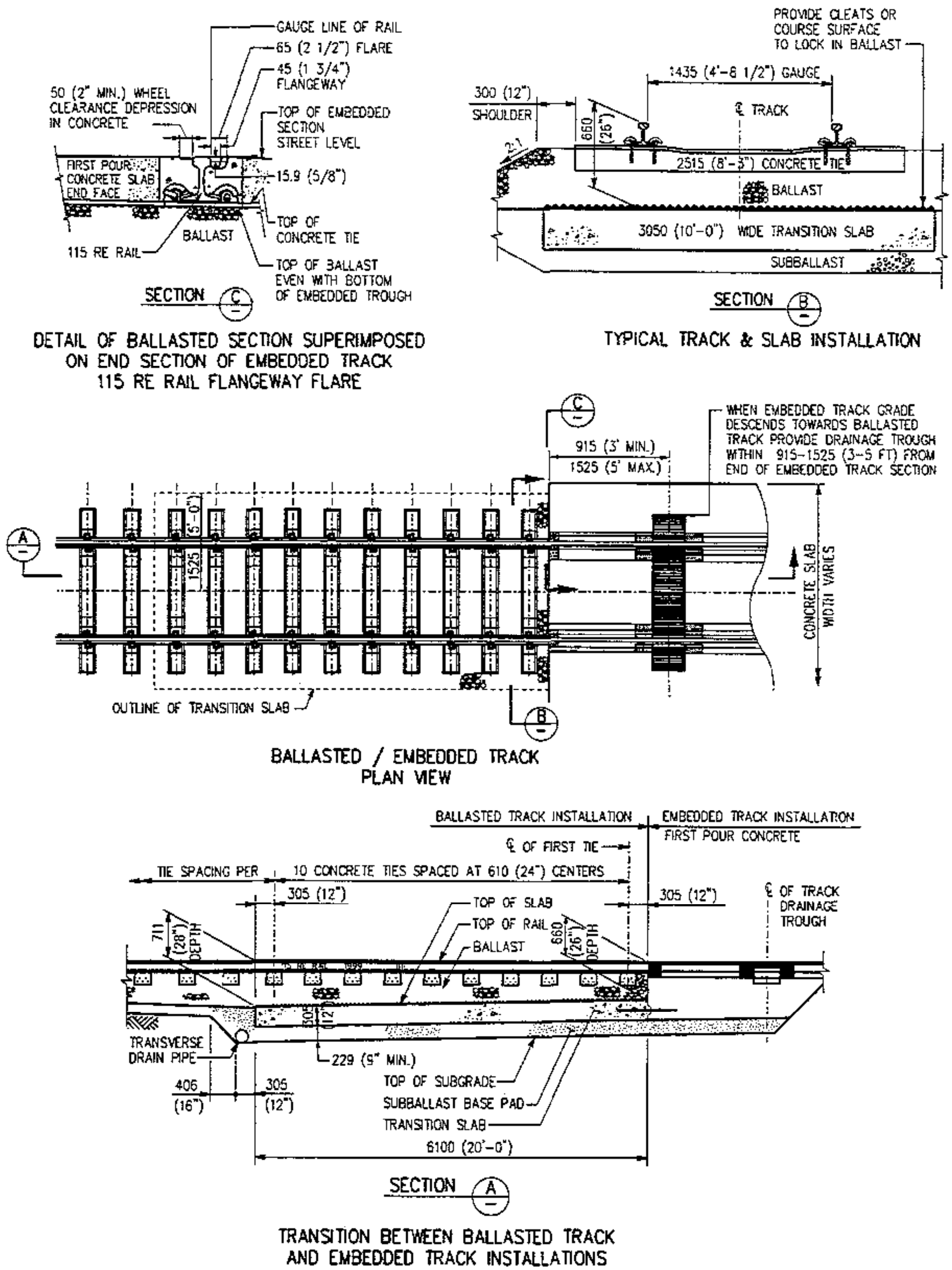


Figure 4.3.1 Track Transition Slab

phenomenon in the rail places extremely high bending forces in the contained rail within the embedded track immediately adjacent to the ballasted-to-embedded track transition point. The differential in track modulus between embedded and ballasted track may be too large to overcome by introducing a flexible rail support in the area adjacent to the interface.

4.3.3.3.3 Design Recommendation

The track designer must eliminate the pronounced sine curve action in the rail at the transition zone. Eliminating or reducing the sine curve is more achievable in direct fixation track than in embedded track using conventional track components. The following recommendation applies to both types of track transition interfaces.

The sine curve may be reduced to a functional level by stiffening the rail in the vertical axis. A stiffer rail will act as a beam to bridge the crucial transition point. The beam or stiffer rail section should project a minimum of 5 meters (16.4 feet) in each direction from the transition interface point. Rail stiffening can be achieved by several means; the following are suggested procedures:

- Attachment of a standard joint bar section to the rail with standard track bolts, spring washers and heavy duty nuts. The standard joint bar section would straddle the interface point.
- The use of an inherently stiffer rail section across the interface. If the standard running rail section is 115 RE, the use of thick-web 115 TW, could provide the required bridging effect. A special transition rail section could also be machined from the European heavy blank rail section 180/105. The ends of the transition rail section could be machined to provide a pressure weld connection to the adjacent running rail. The cross section of the transition rail could also be continuously varied to provide a stiffness gradient suitable for the purpose. The transition rail of sufficient length (10 meters (32 feet)) would straddle the interface point.

Whatever design is developed, it should be compatible with conventional concrete or timber crosstie fastenings, direct fixation fasteners, and installation within the selected embedded track design.

4.4 BALLASTED TRACK

Ballasted track is the most prevalent track type used in light rail transit. While ballasted track for light rail transit resembles conventional railroad track in appearance, its design may have to contend with issues such as electrical isolation and acoustic attenuation. In addition, it may be required to accommodate continuous welded rail on an alignment that includes curves far sharper and grades far steeper than would ever be encountered on a freight railroad or even a "heavy rail" transit route.

Proper design of the roadbed and ballast elements of the track structure is a key issue. It is essential in providing an adequate foundation for the track so as to minimize future maintenance requirements. Roadbed and ballast sections should be designed to minimize the overall right-of-way width, while providing a uniform, well-drained foundation for the track structure.

4.4.1 Ballasted Track Defined

Ballasted track can be described as a track structure consisting of rail, tie plates or fastenings, crossties and the ballast/subballast bed supported on a prepared subgrade. The subgrade may be a compacted embankment, an excavation or cut section, or a bridge structure. Ballasted track is generally the standard for light rail transit routes that are constructed on an exclusive right-of-way outside of a central business district.

Ballasted track can be constructed to various designs, depending on the specific requirements of the transit system. Depending on the portion of the system under design, a satisfactory ballasted track design could be anything from timber crossties with conventional tie plates, cut spikes, and rail anchors, to concrete crossties with elastic rail fastenings that incorporate insulating components. While the loadings typically are limited to those of the light rail vehicles only, heavier loading standards may be required. Ballasted track may need to accommodate freight railroad loadings where the track is to be shared with a commercial railroad. Light rail structural loading is one-quarter to one-third of that imposed on freight railroad tracks.

Prior to developing a ballasted track design, several vehicle/track related issues must be resolved, including: vehicle wheel gauge, wheel profile, and truck design; the track gauge and rail section; and the ability of the vehicle to negotiate the track in a satisfactory operational manner. These are addressed in other chapters of this Handbook. If the track is to be located in an acoustically sensitive area, the designer should also consider noise and vibration mitigation measures as discussed in Section 4.4.10.

4.4.2 Ballasted Track Criteria

To develop ballasted track design, the following track components and standards must be specified:

- Rail section
- Track gauge
- Guarding of curved track and restraining rail features
- Rail fastenings and tie plates
- Type of track tie and corresponding track structure to suit operations

4.4.2.1 Ballasted Track Rail Section and Track Gauge

Refer to Section 4.2 and Chapter 5 of this Handbook for guidance on determining rail section, track gauge, and flangeway requirements.

4.4.2.2 Ballasted Track with Restraining Rail

Refer to Section 4.2.8 herein for determining requirements, locations and limits for guarding track with restraining rail. Specific details for various types of restraining rail designs are included in Chapter 5.

4.4.2.3 Ballasted Track Fastening

Refer to Section 5.4 for requirements concerning crosstie rail fastenings.

4.4.3 Ballasted Track Structure Types

There are generally two standard designs for track structures on ballasted track·

- Timber crosstie track
- Concrete crosstie track

Ballasted track design can result in a suitable track structure using either timber or concrete crossties. The differential track support or track modulus dictates the quality of the track, the ride and future maintenance requirements. Concrete crosstie ballasted track provides a more reliable track gauge system and tighter gauge construction tolerances. This results in a smoother ride with less differential track settlement.

Chapter 2 documents the types and magnitudes of loads transferred from the vehicle wheel to the rail. The rail must support the vehicle and the resulting loads by absorbing some of the impact and shock and transferring some forces back into the vehicle via the wheels. The initial impact absorber on the vehicle is the elastomer in the resilient wheels (if used) followed by the primary suspension springs and then the secondary suspension system. The initial impact absorber on the track is the rail, specifically the rail head, followed by the fastening or supporting system at the rail base and then the remaining track structure. A resilient rail seat pad is used to absorb some of the force on concrete crossties On timber crossties the resiliency in the wood itself acts as the absorber. All components absorb and distribute a portion of the load.

Many transit systems have used both timber and concrete crossties. In some instances, the main line track on new installations was constructed using concrete crossties with standard rail insulation. Regardless of the type of main line crossties, yard maintenance facility tracks are generally built with timber crossties either with or without insulated fasteners. The track structure's design (degree of resiliency) dictates the amount of load distributed to the rail and track structure and the magnitude of force returned to the wheels and vehicle.

4.4.3.1 Ballasted Track Resilience

Ballasted track design allows partially controlled rail deflection in both the vertical and horizontal directions. This phenomenon of rail action contributes to successful track operation by distributing the load to the surrounding track components and structure.

Specific track design decisions must be made regarding the type of track structure (timber crosstie/concrete crosstie) and corresponding track structure resiliency or track support stiffness.

Rail supported on timber crossties and a moderate ballast/subballast section, results in a track modulus range of 14 to 17 N/mm^2 (2,000 to 2,500 lb /inch per inch of rail).

Resilient rail base pads are placed on concrete crossties, both to protect the concrete tie seat and to impede the impact and vibration associated with wheel passage from migrating from the rail to the crosstie. They are a determining parameter of track modulus. A reduced pad height (6 millimeters or 0.2 inches) and a very stiff elastomer or polyethylene pad produce a stiff track support resulting in an increased rail support modulus.

Rail supported on concrete crossties and an ample ballast/subballast section results in a track modulus range of 31 to 45 N/mm^2 (4,500 to 6,500 lb/inch per inch of rail).

4.4.3.2 Timber Crosstie Ballasted Track

On many light rail transit systems constructed in the early 1980s, timber crossties were considered to provide sufficient electrical isolation. Some projects, including those that reconstructed existing trolley systems, did not take extraordinary measures to insulate the track because other measures were either taken or in-place to control traction power stray current. Contemporary designs typically incorporate insulation systems within the crosstie rail fastening to control stray currents close to their source. Typically, non-insulated rail fastenings are employed only in yard tracks, where the yard has its own traction power substation and stray currents are unlikely to leave the site. Non-insulated, ballasted track may also be used in rights-of-way where there are no parallel utilities.

Timber crosstie ballasted track consists of the rail placed on a tie plate or rail fastening system positioned on the crosstie which is supported by a ballast and subballast trackbed as shown in **Figures 4.4.1** and **4.4.2** for single- and double-track, respectively.

4.4.3.2.1 Timber Crosstie Fastening

Conventional tie plates, cut spikes and rail anchors were sufficient to establish a ballasted track installation using timber crossties for railroad and earlier contemporary transit track. However, current track design generally includes protection of the negative return rail from stray electrical currents.

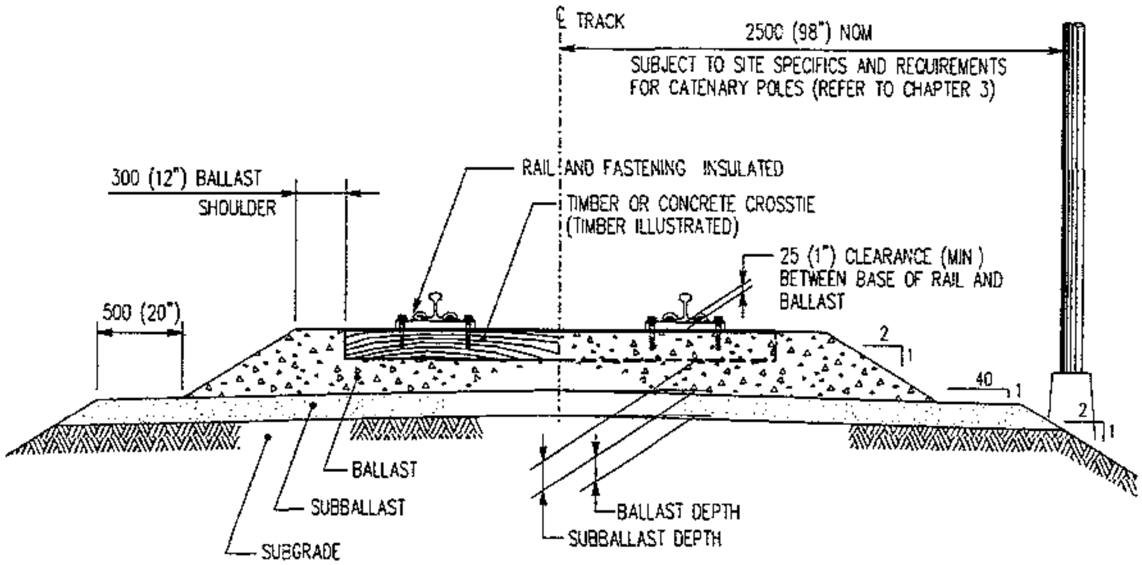


Figure 4.4.1 Ballasted Single Track, Tangent Track (Timber Crosstie)

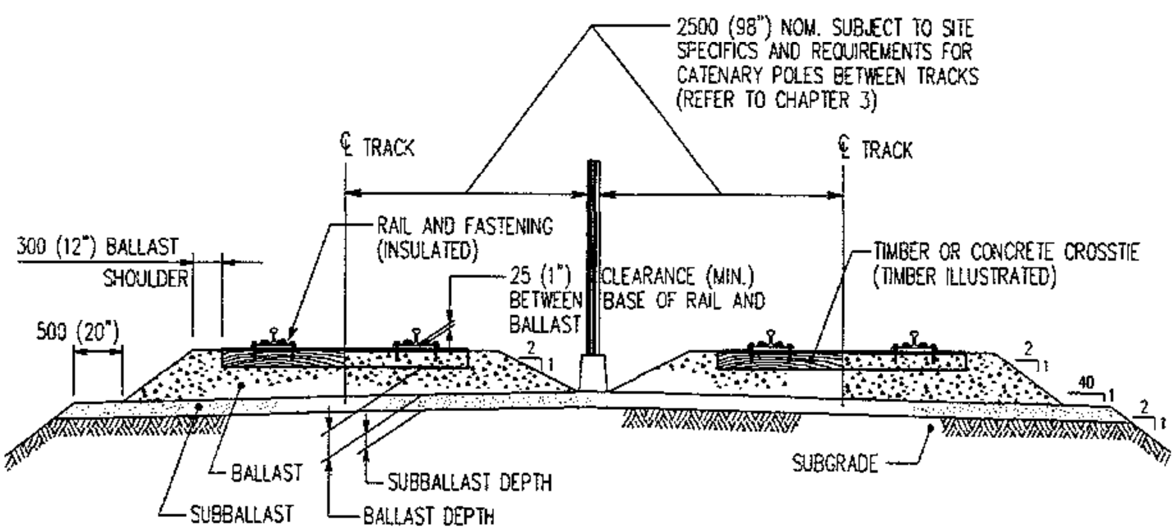


Figure 4.4.2 Ballasted Double Track, Tangent Track (Timber Crosstie)

Although wood is an insulating material, the use of the timber crosstie to protect against stray current has proven insufficient over time. Isolating the rail from the surrounding track structure is an important design element that must be quantified to determine the extent of insulation.

Timber crossties are generally insulated at the base of the tie plate or fastening plate. To insulate the fastening plate, a high-density polyethylene (HDP) pad (a minimum of 12 millimeters (0.5 inches) projecting on all sides of the plate) is placed between the bottom of the fastening plate and the top of the tie. To protect the screw spike holding the fastening plate to the tie, a special insulating collar/thimble is positioned in the anchor screw spike hole to isolate the screw spike from the fastening plate. For additional design information on timber crosstie fastenings, refer to Chapter 5.

4.4.3.2.2 Timber Crossties

Timber crossties have been standard for light rail transit installations for years and continue to be the standard for older established transit agencies. Life-cycle cost comparison of timber ties and concrete ties must be performed using a uniform baseline, including all fastenings and hardware needed for each type of tie. The tie spacing for timber ties is generally shorter than for concrete ties, which contributes to this comparison. Conventional rail anchors projecting into the ballast section will create a stray current leakage path, another issue to be considered in the analysis. Also, the material cost for timber crossties can vary widely over a short period of time. That said, many transit agencies continue to use timber ties with satisfactory results.

Timber crossties for a transit system should be hardwood (oak, maple, birch), with a cross section of 175 x 230 millimeters (generally 7x9 inches) for mounting an insulated fastening system.

For additional information on timber crossties refer to Chapter 5. Determining timber crosstie spacing for transit track is discussed in Section 4.4.4.

4.4.3.3 Concrete Crosstie Ballasted Track

Concrete crossties are gaining popularity in light rail transit installations. They have been shown to have lower life-cycle costs, provide better ride quality, and incur lower track surfacing maintenance costs.

The concrete crosstie is typically insulated at the base of the running rail to protect the negative return running rail from potential stray currents. Concrete crosstie ballasted track consists of the rail placed in the rail seat area and the tie supported by a ballast and subballast trackbed as shown in **Figures 4.4.3** and **4.4.4** for single- and double-track, respectively.

4.4.3.3.1 Concrete Crosstie Fastening

The success of the concrete crosstie is partly due to the introduction of elastic (spring clip) fastenings at the rail hold down location. Fastening designs have evolved to meet new requirements for electrical isolation and to incorporate an elastic fastening to replace the spike, bolt and rail anchor.

The insulating barrier must be at the base of the rail or mounting surface to provide electrical isolation of the rail from the surrounding track components. The insulating barrier consists of a base rail pad and insulators for the edges of the rail base. As shown in Figure 5.4.1 of this handbook, the rail is fully insulated from the mounting surface.

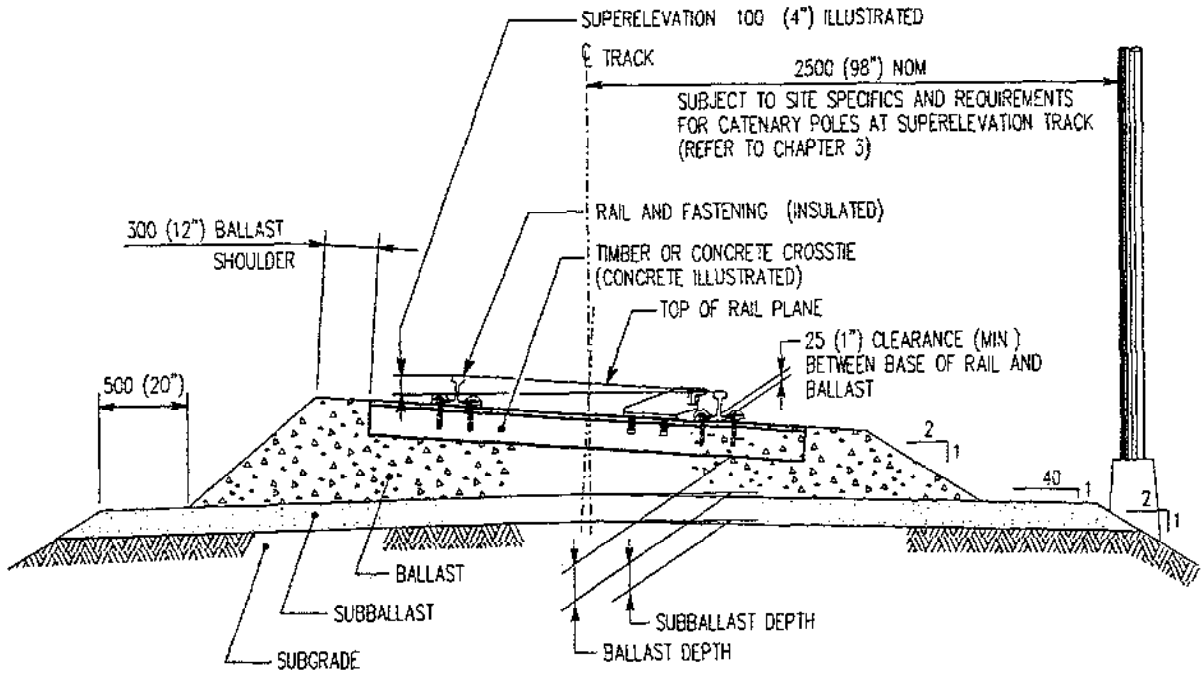


Figure 4.4.3 Ballasted Single Track, Curved track (Timber Crosstie)

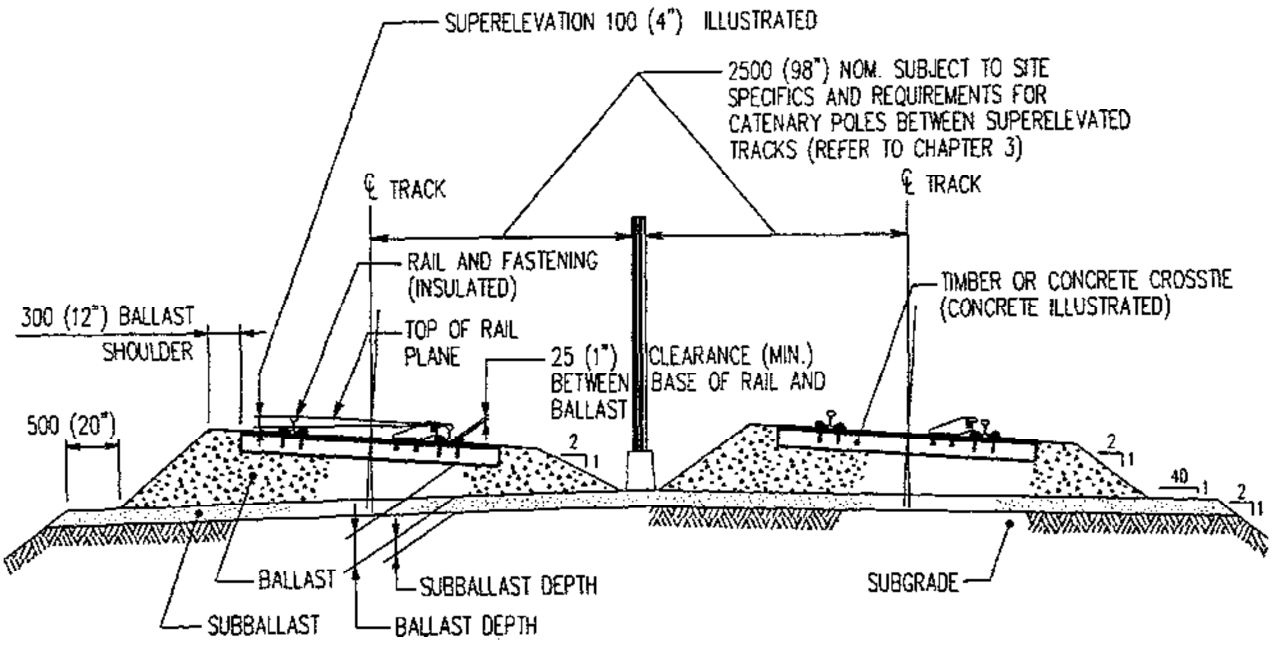


Figure 4.4.4 Ballasted Double Track, Curved Track (Timber Crosstie)

The concrete crosstie design includes the specific type of elastic fastening system (spring clip) with insulating rail seat pad and rail base insulators. The elastic clip provides sufficient toe load to the rail base to act as the longitudinal rail anchor, eliminating the conventional rail anchors used with timber crossties.

4.4.3.3.2 Concrete Crossties

The standard transit concrete crosstie is generally 255 millimeters (10 inches) wide and 2515 millimeters (99 inches) long at the base of tie. The tie is tapered, with a 190-millimeter (7.5-inch) height at the rail seat and a 165-millimeter (6.5-inch) height at the center of the tie. The ties are prestressed, precast concrete produced in a factory with climate controls for the curing process. For additional information on concrete crossties refer to Chapter 5.

4.4.4 Crosstie Spacing

Ballasted track structure design is dependent on the vehicle wheel load, a predetermined track modulus target or standard, the selected rail section, the type and size of tie, and the depths of ballast and subballast. These are combined to meet the criteria established by AREMA for both ballast pressure and subgrade pressure.

Ballasted track designs can meet or exceed the AREMA pressure requirements by altering the variable parameters (track modulus, tie spacing and ballast depth) as needed. As a guideline the following sample calculations are provided for design of ballasted track with timber or concrete crossties.

Design computations based on Talbot, Timoshenko, Hay formulas and other guidelines assume the following typical light rail transit installation data:

Rail Section	115 RE
Vehicle Load per Wheel	5,400 kilograms (12,000 pounds)
Track Modulus	
- Timber Tie	17.2 N/mm^2 (2,500 lbs/inch per inch of rail)
- Concrete Tie	34.5 N/mm^2 (5,000 lbs/inch per inch of rail)
Desired Load Transfer to	
- Ballast	<0.45 MPa (65 psi)
- Sub Grade	<0.14 MPa (20 psi)
Ballast Depth	255 millimeters (10 inches)
Subballast Depth	200 millimeters (8 inches)
Tie Sizes	
- Timber	180 x 230 x 2590 millimeters (7 x 9 x 102 inches)
- Concrete	190 x 250 x 2515 (7.5 x 10 x 99 inches)

Design Calculations:

Tie Seat Load = $\beta \cdot a \cdot P$ [Timoshenk o 1929]

where :

a = tie spacing (variable)

P = axle load = 107 kN (24 kips) - twice the wheel load

$$\beta = \left(\frac{u}{4EI}\right)^{1/4}$$

Timber Tie: u = track modulus

= 17.2 N/mm^2 (2500 lb/inch per inch of rail)

Concrete Tie: u = track modulus
= 34.5 N/mm^2 (5000 lb/ inch per inch of rail)

E = modulus of steel = 206,800 N/mm^2 (30 x 10^6 psi)

I = modulus of inertia
= 27.4×10^6 mm^4 (65.9 in^4)

Tie Bearing Area = tie width x tie length

$$\text{Timber} = 230 \times 2590 (9'' \times 102'')$$
$$= 595\,700 \text{ square mm } (918 \text{ sq. in.})$$
$$\text{Concrete} = 250 \times 2515 \,(10'' \times 99'')$$
$$= 628750 \text{ square mm } (990 \text{ sq.in})$$

$$\text{Ballast Load} = \frac{\text{Tie Seat Load}}{2/3 \text{Tie Bearing Area}} \text{ [Hay 1982]}$$

Subballast Load at Tie Centerline =

$$1.23 \frac{\left(\frac{\text{Seat Load}}{\text{Tie Bearing Area}}\right) \times \text{Tie Width}}{\text{Ballast Depth}} \text{ [Talbot 1919]}$$

Subgrade Load at the Tie Centerline is similar to subballast load calculation except depth includes ballast and subballast heights.

Using the above formulas, **Table 4.4.1** presents the values according to the parameters.

Tie spacing can be determined from this table. Neither the AREMA recommended maximum ballast pressure 0.45 MPa (65 psi) nor the maximum subgrade pressure 0.14 MPa (20 psi) should be exceeded.

The preceding computations are representative of the calculations needed to design the ballasted track structure. The parameters that alter the actual design are predetermined track modulus; type of tie (timber or concrete); depth of ballast and subballast; and tie spacing. The challenge for the engineer is to combine these parameters to achieve the best life-cycle costs and lowest maintenance costs.

4.4.4.1 Crosstie Spacing—Tangent/ Curved Track

The above calculations determine the crosstie spacing and affect the track modulus or the vertical track stiffness. Lateral track stability can also affect crosstie spacing.

The horizontal track alignment for a light rail transit system can be far more severe than for other railway systems, such as rapid transit, commuter rail, or freight railroads. Ballasted track is far more difficult to construct and maintain in reduced tight radius curves. Special consideration should be given to increasing lateral track stability by reducing the crosstie spacing.

Lateral track stability is provided by ballast friction contact along the sides and bottom of the tie and by the end area of tie. The end area of the tie provides a calculated degree of lateral stability. Increasing the ballast shoulder width beyond a 450-millimeter (18-inch) limit provides no increase in stability. Reducing crosstie spacing, thereby increasing the number of ties, can increase lateral track stability. Timber crossties have proven to provide greater lateral stability than concrete ties based on the theory that the ballast's sharp edges penetrate the tie surfaces increasing the friction and locking the tie in position. On the other hand, the concrete tie's increased weight also provides increased lateral stability.

To improve the lateral stability of concrete crossties, some tie manufacturers have developed a serrated or "scalloped" side tie surface increasing the ballast's locking capabilities.

Based on the above calculations, the track designer should consider reducing the conventional crosstie spacing by 75

Table 4.4.1 Ballasted Track Design Parameters

			Tie-Ballast Load				Subballast Load		Subgrade Load Ballast + Subballast	
	Tie	Tie Seat Load	230 (9") Tie		250 (10") Tie		255 (10") Ballast		455 (18")	
Track Modulus	Spacing (mm)	kN (kips)	MPa	(psi)	MPa	(psi)	MPa	(psi)	MPa	(psi)
17.2 N/mm2 (2500 lb./in/in)	510 (20")	50.7 (11 4)	0.127	18 5	n.a.	n a.	0 094	13.7	0 096	7 6
β=0 00093/mm (0 0237 /in)	610 (24")	60.7 (13.6)	0 152	22 1	n.a.	n a.	0 113	16 4	0.115	9 1
	685 (27")	68.2 (15.3)	0.171	24 9	n.a.	n a	0 127	18.5	0.130	10.3
	760 (30")	75.6 (17 0)	0.189	27 6	n.a.	n a.	0.141	20.5	0.144	11.4
	810 (32")	80.6 (18.1)	0.202	29.4	n.a.	n.a.	0.150	21.8	0.153	12.1
34.5 N/mm^2 (5000 lb /in/in)	510 (20")	60.0 (13.5)	n.a	n.a.	0 142	20 4	0.115	16.8	0.115	9 3
β=0.0011 /mm (0.0282 /in)	610 (24")	71 8 (16 1)	n.a	n.a	0.170	24 3	0.138	20 0	0 138	11.1
	685 (27")	80.6 (18 1)	n a.	n a	0.191	27.3	0 155	22.5	0 155	12.5
	760 (30")	89 5 (20 1)	n a	n.a	0 212	30.3	0 172	25 0	0 172	13.9
	810 (32")	95.3 (21.4)	n.a.	n.a.	0.226	32.3	0.183	26.6	0.183	14.8

Note: MPa = N/mm^2

millimeters (3 inches) for track curves with radii less than 300 meters (1000 feet).

To improve lateral stability, especially with conventional smooth concrete ties, a tie anchor can be bolted to the tie. The tie anchor is a blade penetrating below the tie into the ballast bed providing additional lateral stability. Tie anchors can be attached to alternate ties in the track curve.

4.4.5 Special Trackwork Switch Ties

The current tendency of transit agencies is to use standard timber hardwood ties for special trackwork turnout, crossover and double crossover arrangements for both main line and maintenance facility and storage yard installations. Transit agencies using concrete crossties on main line and yard installations also use timber special trackwork ties in both locations.

Concrete switch ties have been developed by the railroad industry to reduce maintenance on heavy haul freight lines. Concrete switch ties are expensive to design, fabricate and install. They have not proven to be cost-effective in light rail applications.

Turnout standards vary among transit agencies. Therefore various concrete tie geometric layouts and designs would be required to meet the requirements of each agency. Standardization and simplicity in tie design is required to allow the transit industry to develop a uniform economical standard concrete switch tie set for various turnout sizes.

4.4.5.1 Timber Switch Ties

The present standard for timber switch ties is hardwood, predominantly oak. Tropical hardwood ties such as Bonzai, lecki and Azobe have been introduced to the North American railway industry with mixed success.

The reader is cautioned about using tropical woods. Thorough research on the specific wood selected, and the origin of the wood, is recommended before a procurement is undertaken.

The standard timber switch tie is generally a 180- x 230-millimeter (7- x 9-inch) section with various lengths from 2,750 to 4,880 millimeters (9 to 16 feet).

Extra long timber switch ties, up to 6,710 millimeters (22 feet) and longer may be required to accommodate special trackwork locations, such as crossovers and double crossovers where the track centers remain at the standard width of 3,810 to 4,420 millimeters (12.5 to 14.5 feet).

Similar to a main line timber crosstie installation, an insulated switch plate design may be required to protect against stray current leakage. Insulated switch and frog plates are similar in design to main line timber crossties. The concern for stray current control has occasionally resulted in the installation of special trackwork direct fixation fasteners on timber switch ties. However, this application is a relatively new design concept for transit agencies and is proving to be extremely expensive.

4.4.5.2 Concrete Switch Ties

Concrete switch tie standard designs for special trackwork installations are evolving. The railroad industry and transit, commuter and heavy metro rail systems have been experimenting and standardizing concrete switch ties for special trackwork. The special trackwork concrete ties used to date include the larger size turnouts, No. 15 and 20, and high-speed turnouts. Light rail transit systems generally restrict turnout size to No. 8 or 10; therefore a minimum of design layout has occurred to accommodate these sizes.

Standard concrete switch tie designs and layouts will be different from the timber switch tie arrangement. Tie spacings are increased to allow for a wider than conventional tie crib opening using a special trackwork concrete tie approximately 250 millimeters (10 inches) wide.

The lengths of the concrete switch ties will conform to the special trackwork layout, with a possible specific length for each tie location in lieu of groups of specific tie lengths. The design will include the requirements for mounting special trackwork fastenings in switches, frogs and guard rails. The designer and/or tie manufacturer will choose between embedded shoulders or single rail fasteners through the remaining portions of the special trackwork layout.

Similar to timber switch tie installations, an insulated special trackwork fastening may be required to control stray current on concrete switch ties. Insulated switch, frog and guard rail fastening plates may be similar to conventional timber crosstie installations. Standard concrete tie insulated rail fastenings are acceptable where individual rails are installed on the switch timber.

For more information on special trackwork timber and concrete switch ties refer to Chapter 5 of this handbook.

4.4.6 Ballast and Subballast

Ballast is an integral material in the support of the track structure. The quality of the ballast material has a direct relationship to the overall performance of the track structures.

The quality, size and type of ballast material used can improve the performance of the track substructure by providing an increased strength to the track system.

Concrete crosstie installations normally require a higher quality ballast, a larger gradation of ballast, and a more restrictive selection of rock aggregate. For additional information on ballast material refer to Chapter 5.

4.4.6.1 Ballast Depth

The variables to be considered in establishing the track structure section are discussed above and listed in Table 4.4.1. Additional variables include the track gauge, depth of tie, and superelevation of track curves. Figures 4.4.1 and 4 4.2 illustrate and quantify the general desired design section for ballasted track.

The depth of ballast from the bottom of the tie to the top of the subballast can be determined by undertaking the aforementioned calculations. The depth of subballast below the ballast to the top of the subgrade can be determined from these calculations.

For tangent track, the minimum depth of ballast is generally measured from the underside of the tie to the top of subballast at the centerline of each rail. For curved superelevated track, the depth of ballast is measured below the low rail with respect for the top of subballast at the centerline of track as shown in Figure 4.4.2.

On tangent multiple track installations, the minimum ballast depth is measured under the rail nearest to the crown of the subballast section as shown in Figure 4.4.3. On curved multiple track installations it is measured on each track under the inside rail closest to radius point as shown in Figure 4.4.4.

4.4.6.2 Ballast Width

The width of ballast section is determined by the rail installation and tie length. The ballast shoulder resists lateral track movement and keeps the track from buckling when the rail is in compression. Continuous welded rail requires a 300-millimeter (12-inch) ballast shoulder measured from the end of the tie to the top of ballast shoulder slope. The top slope of the ballast shoulder should be parallel to the top of the tie. The side slope of the ballast shoulder should have a maximum slope of 1:2. As mentioned in Section 4.4.4.1, the ballast shoulder may be increased in sharp radius curved track to provide additional lateral stability. The subballast and subgrade sections must be increased to provide sufficient support width if the ballast shoulders are increased.

4.4.6.3 Subballast Depth and Width

Subballast is the lower or base portion of the ballast bed located between the base of the ballast section and the top of the road bed subgrade. Subballast is generally a pit run material with smaller, well-graded crushed stone. The subballast acts as a barrier filter separating the ballast section from the embankment road bed materials. It provides both separation and support for the ballast.

The depth of the subballast below the ballast can be determined using the preceding calculations. The ballast and subballast are integral parts of the track structure. Track design considers the thickness of both in the calculations to meet AREMA recommendations of 0.14 MPa (20 psi) uniform pressure transmitted to the subgrade.

The width of the subballast section is determined by the width of the road bed embankment subgrade. The subballast should extend the full width of the embankment capping the top surface.

The subballast layer acts as a drainage layer for the subgrade surface allowing water to flow to the embankment shoulders.

The end slope of the subballast generally conforms to the slope of the embankment.

To allow for an eventual ballast slope slough and provide walking or flat area for track maintenance, the subballast width should project beyond the toe of the ballast slope a minimum of 600 millimeters (24 inches).

To support embankment materials under special trackwork installations and at-grade road crossings, a geotextile (filter fabric) may be used at selected locations. The track designer should review supplier information on geotextiles and consider the application of 0.54 kilogram/m^2 (16 ounce/yd^2) geotextiles and double layers under special trackwork locations. Geogrid and geoweb material may be used to stabilize and strengthen the subgrade materials below turnouts and at grade crossings. These materials augment the function of subballast.

4.4.6.4 Subgrade

The subgrade is the finished embankment surface of the roadbed below the sub-ballast, which supports the loads transmitted through the rails, ties, and ballast. The designer should analyze the subgrade to determine whether it has both uniform stability and the strength to carry the expected track loadings. AREMA recommends that, for most soils, pressure on subgrade be lower than 0.14 MPa (20 psi) to maintain subgrade integrity. Uniformity is important because differential settlement, rather than total settlement, leads to unsatisfactory track alignment. The use of geotextiles or geogrids between the subgrade and subballast can be advantageous under some conditions.

4.4.7 Ballasted Track Drainage

The success of any ballasted track design depends directly on the efficiency of the ballasted track to drain well and proper maintenance of the drainage system This includes the exposed ballast and subballast bed that cast off surface runoff and the designed parallel drainage system, ditch and culvert piping that carry the runoff.

Drainage of the embankment or excavated sections is of utmost importance. Ballasted track, by the nature of its design, is susceptible to contamination from both track traffic and the surrounding environment. Dirt, debris and fines are either dropped or blown onto the trackway, contaminating the ballast section. This contamination creates a non-porous or slow draining ballast bed, which can lead to eventual deterioration and breakdown of the track structure.

Many conventional methods are practiced to maintain ballasted track structure. These include ballast shoulder cleaning and complete track undercutting to keep the ballast bed clean to ensure it drains well.

4.4.8 Stray Current Protection Requirements

Stray current corrosion protection is a subject described more fully in Chapter 8 of this handbook. The track structure design requires an electrical barrier to insulate the rail. Ballasted track generally provides this electrical barrier at the rail fastenings. An insulating resilient material with a specified bulk resistivity provides the barrier at the base of fastening plate on timber ties and at the rail base on concrete ties.

For more information on electrical barriers at fastenings refer to Chapter 5.

4.4.9 Ballasted Special Trackwork

The ballasted special trackwork portion of any transit system will require specific designs to match the size of the components.

Ballasted special trackwork in contemporary light rail transit systems generally consists of turnouts paired to act as single crossovers for alternate main line track operations. Operating requirements and alignment restrictions may dictate the installation of a double crossover consisting of four turnouts and a crossing (diamond). Turnouts are used at the ends of transitions from double track to single track installations as well as at junction points to alternate transit routes and accesses to sidings

Turnouts in the maintenance facility and storage yard areas are generally positioned to develop a "ladder track" arrangement that provides access to a group of parallel tracks with specific track centers For additional information on ballasted special trackwork design, refer to Chapter 6.

4.4.10 Noise and Vibration

The vehicle traveling over the track produces noise and vibration. The impact of this noise and vibration may become significant for alignments through otherwise quiet neighborhoods. Track design has a significant effect on both noise and wheel squeal, however, to be effective, the control system must consider the wheel and the track as a unit. Chapter 9 provides guidelines with respect to trackwork design for low noise and vibration and introduces various concepts in noise and vibration control.

Trackwork design can have a substantial effect upon wayside noise and vibration and should be considered early in the design of facilities to provide for special treatments Cost-effective designs consider the type of vehicle involved, the soft primary suspensions that produce ideal levels of ground vibration above 30 Hz, or the stiff primary suspensions that produce levels that peak at 22 Hz. Noise and vibration control is a system problem that involves the track and the vehicle wheels and trucks Familiarization with the contents of Chapter 9 herein, along with American Public Transit Association (APTA) and/or Federal Transit Administration (FTA) requirements for wayside and groundborne noise limits, is essential to sound designs that limit noise and vibration.

4.4.11 Transit Signal Work

Although the design of the signal control system will not greatly impact ballasted track design, it can affect specific parts of the design. The prime example of this interrelationship is the need for the insulated joints in the running rails to accommodate train control requirements. Such joints are normally required at the extremities of interlockings, each end of station platforms, grade crossings, within individual turnouts and crossovers, and at other locations to be determined by the train control requirements.

The light rail transit signaling system may include track circuit signal systems within ballasted track zones. Impedance bond installation requirements must be coordinated within the track structure design. Insulated joints at limits of track circuits are to be opposite and within 1.2 meters (4 feet) of each other to facilitate underground ducting and traction crossbonding.

For additional information on transit signal work, refer to Chapter 10

4.4.12 Traction Power

Traction power requirements impact the track design at two specific locations: the catenary pole locations in relation to centerline of track and the running rail, which is used as the negative return for the traction power system. The catenary poles impact the track centerline distance when they are located between the tracks. Clearance distances pertinent to the transit vehicle as well as any other potential users of the track (i e., freight or track maintenance vehicles) must be considered by the track and catenary designers. Isolation of the running rail used as the negative return conduit is essential for both timber and concrete crosstie ballasted track.

For additional information on traction power refer to Chapter 11.

4.4.13 Grade Crossings

Track designers must develop an acceptable interface wherever streets cross the light rail tracks at grade. Grade crossings are manufactured as prefabricated units of rubber, concrete, or wood. These prefabricated units are designed to resist leakage of DC current, as well as signal current. They are designed to be easily installed and replaced during maintenance of the track. All grade crossings must create a flangeway between the street paving and the rail.

Some grade crossings are created by using flangeway timbers along the rails to form the flangeway and paving the remainder of the area with asphalt. Although this style is not as durable as the prefabricated units, it may be quite adequate in storage and maintenance facilities.

The most critical design element of all grade crossings is adequate drainage for the track. Runoff from the street must be directed away from the track, and the track must be designed with perforated pipe drains to keep the trackbed dry. Additional stabilization of the subgrade with geo-synthetic materials may be very cost-effective in reducing track surfacing costs Failure to provide good drainage will result in pumping track and broken pavements.

The use of embedded track at grade crossings is proving to be a very reliable crossing design. Embedded track provides a virtually maintenance-free installation with proper insulating properties for the rail and a relatively smooth road crossing surface for automobiles.

Coordination with the street design is also necessary to match the normally crowned street cross section with the level grade crossing.

4.5 DIRECT FIXATION TRACK (BALLASTLESS OPEN TRACK)

4.5.1 Direct Fixation Track Defined

Direct fixation track is a "ballastless" track structure in which the rail is mounted on direct fixation fasteners that are attached to a concrete deck, slab, or invert. Direct fixation track is the standard method of construction for tracks on aerial structures and in tunnels. It is also used for construction of at-grade track under unusual circumstances, such as when there is a short segment of at-grade track between two direct fixation bridge decks.

Prior to designing direct fixation track, several vehicle/track related issues must be resolved. These issues relate to the vehicle's wheel gauge, wheel profile, and truck design; the track gauge and rail section; and the compatibility of the vehicle with the guideway geometry. Acoustic concerns are also very important.

4.5.2 Direct Fixation Track Criteria

To develop direct fixation track design, the following track components and standards must be specified:

- Rail Section
- Track Gauge
- Guarding of curved track and restraining rail
- The type of direct fixation track structure to be used (booted tie or a direct fixation rail fastener type)
- If direct fixation rail fastener construction is selected, the type of fastener and supporting structure to be employed—cementitious grout pad or concrete reinforced plinth.

4.5.2.1 Direct Fixation Track Rail Section and Track Gauge

Refer to Section 4.2 and Chapter 5 of this Handbook for determination of rail section, track gauge and flangeway requirements.

4.5.2.2 Direct Fixation Track with Restraining Rail

Refer to Section 4.2.8 to determine the requirements, locations, and limits for guarding track with restraining rail.

4.5.2.3 Direct Fixation Track Fastener

Refer to Chapter 5, Section 5 4 to determine the requirements for specifying direct fixation fasteners.

4.5.2.4 Track Modulus

Direct fixation track is typically much stiffer vertically than ballasted track. This rigidity must be attenuated if transmission of noise and vibration is to be avoided. Careful selection of an appropriate track modulus and specification of direct fixation rail fasteners with an appropriate spring rate must be made in accordance with Section 4.3 and Chapter 9 of this handbook.

4.5.3 Direct Fixation Track Structure Types

Direct fixation track construction includes the following designs

- Encased Ties This is the original form for direct fixation track, dating to the late 19th century. Timber crosstie track was constructed in skeleton form and then the bottoms of the crossties were encased in concrete. Because the concrete held the track rigidly to gauge, typically only every fourth or fifth tie would be a full-length crosstie. Intermediate ties would be short tie blocks that support only a single rail. Such designs incorporated no specific measures to control stray traction power currents or groundborne vibrations. Except in very limited circumstances for maintenance of existing systems, encased timber tie track is no longer constructed.
- Cemetitious Grout Pads: This form of direct fixation track mounts each individual rail fastener on an individual grout pad, thereby guaranteeing the construction tolerances in the final elevation of the concrete trackbed. The fasteners are held in place by anchor bolts that are cored into the concrete base.

- Concrete Plinths: This form of direct fixation track forms rectilinear concrete blocks or plinths that support several direct fixation fasteners under a single rail. The plinths can vary in length and typically support between three and six fasteners, although longer plinths support up to twelve fasteners. Periodic interruptions of the plinths allow cross track drainage into a trough that is typically located along the track centerline.
- Ballastless Booted Tie Blocks: This form of direct fixation track is an updated version of the encased tie design. It typically incorporates two block concrete crossties that have an elastomeric "boot" on the bottom of each tie that provides electrical and acoustic isolation between the ties and the encasing concrete. As with the earlier design, most ties would be single blocks with no crosstie member between the rails.

Variations of the above designs can be found, such as direct fixation rail fasteners bolted directly to structural steel bridge members. Such arrangements are generally in response to a site-specific design issue and will not be addressed in this handbook.

4.5.3.1 Cementitious Grout Pads

Cementitious grout pad track designs include:

- Short cementitious grout pads of sufficient width to allow for installation of the direct fixation fastener that is formed and poured directly to the concrete deck or invert. A typical configuration is as shown at the left rail in **Figure 4.5.1**.
- Short cementitious grout pads mounted within a recessed opening in the concrete deck or invert, as shown at the right rail in Figure 4.5.1.

Grout pads typically support only a single fastener, although current practice is to build longer pads to support at least four fasteners. The longer design provides improved integrity of the pads and ease of maintenance if a fastener is replaced or repositioned.

4.5.3.1.1 Cementitious Grout Pad on Concrete Surface

The short cementitious grout pad design acts as a leveling course between the underside of the direct fixation fastener and the concrete deck or invert surface. The anchor bolt inserts are set in the deck slab to provide the structural integrity of the fasteners.

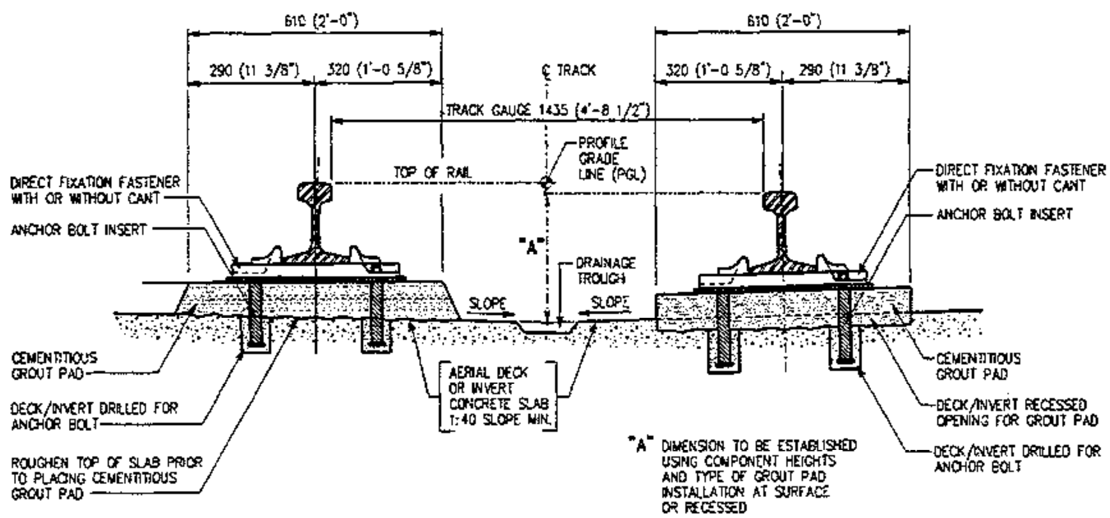


Figure 4.5.1 Cementitious Grout Pad Design—Direct Fixation Track

This design requires core drilling of the concrete invert to grout the anchor bolt in place The drilling can be undertaken either prior to or after grout pad installation. The bolt assemblies are permanently anchored with an epoxy grout material.

The cementitious grout pad can be formed and poured before the rail fastener is placed; however it may be difficult to achieve an absolutely level and true top surface for the rail fastener. If the grout pad is slightly too high, grinding may be required. If it is too low, it may be necessary to place metallic or elastomeric shims beneath the rail fasteners.

Alternatively the assembled rail and rail fasteners can be suspended at proper grade and alignment above the concrete invert and the grout either pumped or "dry packed" under the rail fastener. If this approach, known as "top down" installation, is taken, it is essential to ensure that the grout does not enter the recesses on the bottom surface of the direct fixation rail fastener which could compromise the rail fastener spring rate. This can be avoided by placing a minimum of one shim beneath the direct fixation rail fastener before grout placement. It is also necessary to lift the rail and fasteners after the grout has cured to locate and fill in any voids or "honeycomb" in the top surface of the grout pad that are caused by trapped air or improper grout placement.

Grout pads typically depend on the strength of the bond between the concrete invert and the grout for their stability. Reinforcing steel typically cannot be used because the pad is so thin. The concrete invert is typically roughened before grout placement and epoxy bonding agents can be used to enhance the bond between the grout and the concrete.

4.5.3.1.2 Cementitious Grout Pad in Concrete Recess

Some transit systems have experienced grout pad delamination, because cementitious grout pads have a tendency to curl or pull away from the parent concrete deck or invert during curing and aging. It is possible to achieve better bonding with less likelihood of such failures by forming the grout pad within recesses in the concrete invert. The recessed design provides additional deck or invert bonding by locking the four sides of the pad.

The anchor bolt assembly drilling can be undertaken either prior to or after grout pad installation. Prior drilling is recommended as it results in less disturbance to the bond of the cast-in-place grout pad.

4.5.3.1.3 Cementitious Grout Material

The selection of a cementitious grout material must be undertaken carefully. The use of incompatible special epoxy grouts, bonding agents and additives can result in pad delamination and cracking. The material should be compatible with the deck or invert concrete and have similar thermal expansion characteristics. It must also be compatible with the service environment of the trackway.

Large inaccuracies in the elevation of the concrete invert and track superelevation can result in both very thin and very thick grout pads. Both can be troublesome but thin pads are particularly prone to early failure. Cementitious grout pads that are less than 38 millimeters (1.5 inches) thick are generally more susceptible to fracture.

As a guideline, although the cementitious grout pad design has and is currently used on some transit systems, it is not recommended due to the design's history of pad failure. Cementitious grout pads tend to delaminate and break down, requiring high maintenance, particularly in colder climates subjected to freeze-thaw cycles. Locations with minimal clearance requiring a low-profile direct fixation track structure may be the best application of the cementitious grout pad system.

4.5.3.2 Reinforced Concrete Plinth

The recommended direct fixation track design is the raised reinforced concrete plinth system. The reinforced concrete plinths used for direct fixation track include various designs to suit tangent track, curved track, superelevated track, and guarded track with restraining rail. The designs affect the lengths and shapes of the plinths and the reinforcing bar configurations as follows.

4.5.3.2.1 Concrete Plinth in Tangent Track

Concrete plinth in tangent track generally consists of two designs:

- Concrete plinths of sufficient width and height for mounting of the direct fixation fastener directly to the concrete deck or invert, as shown at the left rail in **Figure 4.5.2**.
- Concrete plinths of sufficient width and height for installation of a direct fixation fastener within a recessed opening in the concrete deck or invert, as shown at the right rail in Figure 4.5.2.

4.5.3.2.1.1 Concrete Plinth on Concrete Surface. The concrete plinth width and height must be sufficient to accept the full length of the fastener and anchor bolt assembly. It must also accommodate the reinforcing steel that is required to confine the concrete mass that supports the direct fixation rail fastener and anchor bolt insert.

The concrete plinth is connected to the deck or invert concrete surface with a series of stirrups or dowels protruding from the deck or invert. Additional plinth reinforcing steel is connected to and supported by these stirrups or dowels.

The anchor bolt inserts may be installed by the cast-in-place method or drilled and epoxy grouted in place. Cast-in-place installation is recommended as it results in less disturbance to the plinth and eliminates any possible

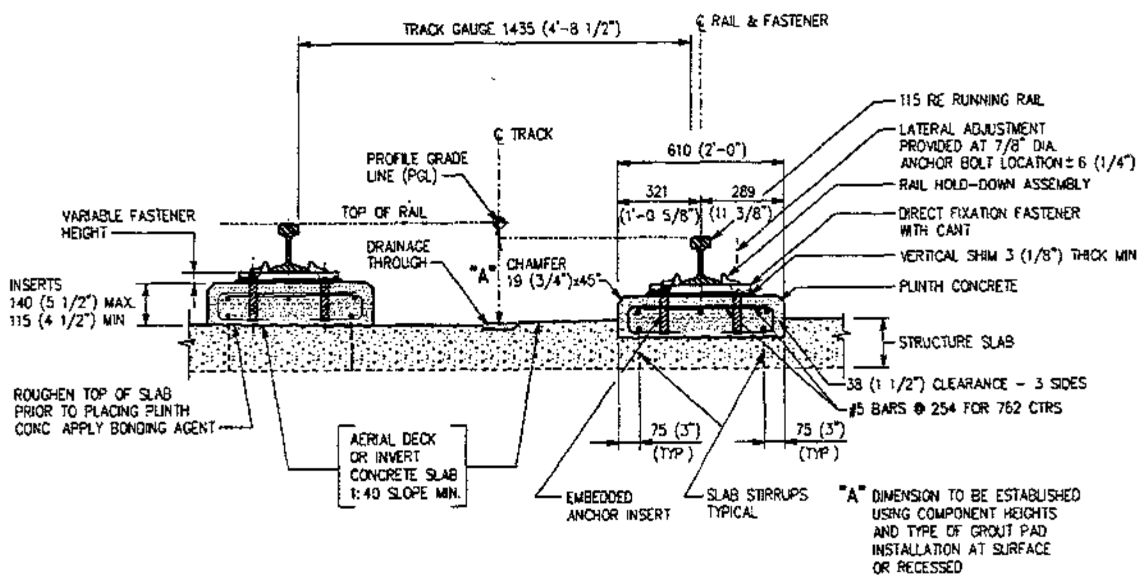


Figure 4.5.2 Concrete Plinth Design—Tangent Direct Fixation Track

problems with drilling through reinforcing steel. It also eliminates the extra work and potential problems of dealing with the epoxy grout materials used in the core drilling method.

4.5.3.2.1.2 Concrete Plinth in Concrete Recess. Similar to the grout pad method, the concrete plinth design has a variant wherein the second pour concrete can be recessed into a trough in the base concrete slab. The recessed design allows a reduced plinth height above the deck or inverts and provides additional deck or invert bonding by locking in the four sides of the plinth.

The recessed design obviously requires that a trough be formed in the trackway invert, an additional work activity and hence expense to the contractor building the trackway. The extra cost associated with forming the trough is not insignificant and designers should carefully weigh the costs and benefits of the recessed design before deciding on a preferred method. The trough may also compromise the structural integrity of the base slab, particularly on aerial structures, so the design must be coordinated with the structural design team.

Some designers object to the placement of the plinths directly on the concrete base because it places the top of rail elevation about 360 millimeters (14 inches) above the invert. In the event of a derailment, where the wheels do not end up on top of the plinths, substantial damage to the underside of the rail vehicle could result. The placement of the plinths in a recess minimizes this concern.

4.5.3.2.2 Concrete Plinth on Curved Track

Concrete plinth design for curved track must consider track superelevation. The track designer must provide guidance to the construction contractor for setting the height of the plinth formwork so that the required superelevation is achieved. In addition, care must be taken to ensure that the rotation of the concrete plinth at the low rail leaves sufficient room for the anchor insert assembly

The plinth height is established by the elevation of the low inside rail of the curved track as shown in **Figure 4.5.3**. Applying the profile grade elevation at the low rail of the curve, the superelevation is established by rotating the top of rail plane about the gauge corner of the low rail. The addition of superelevation alters the cross slope and thickness of the concrete plinths so that the typical section is no longer symmetrical.

The embedment of the field side anchor bolt insert of the low rail fastener establishes the height of the plinths. The reinforcing bar requirements and configurations depend on the plinth heights.

Plinth or second-pour concrete direct fixation track can be mounted either directly to the surface or the recessed opening in the concrete deck or invert. The latter arrangement can be particularly advantageous in superelevated curved track since it can substantially reduce the plinth height at the high rail.

4.5.3.2.3 Concrete Plinth in Guarded Track with Restraining Rail or Safety Guard Rail

The use of either a restraining rail or a safety guard rail in direct fixation track will require that the concrete plinths be wider than normal. **Figure 4.5.4** illustrates a typical plinth for use with restraining rail. A similar arrangement is required for a safety guard rail system. This concrete plinth arrangement can be either mounted directly to the surface or the recessed opening in the concrete deck or invert.

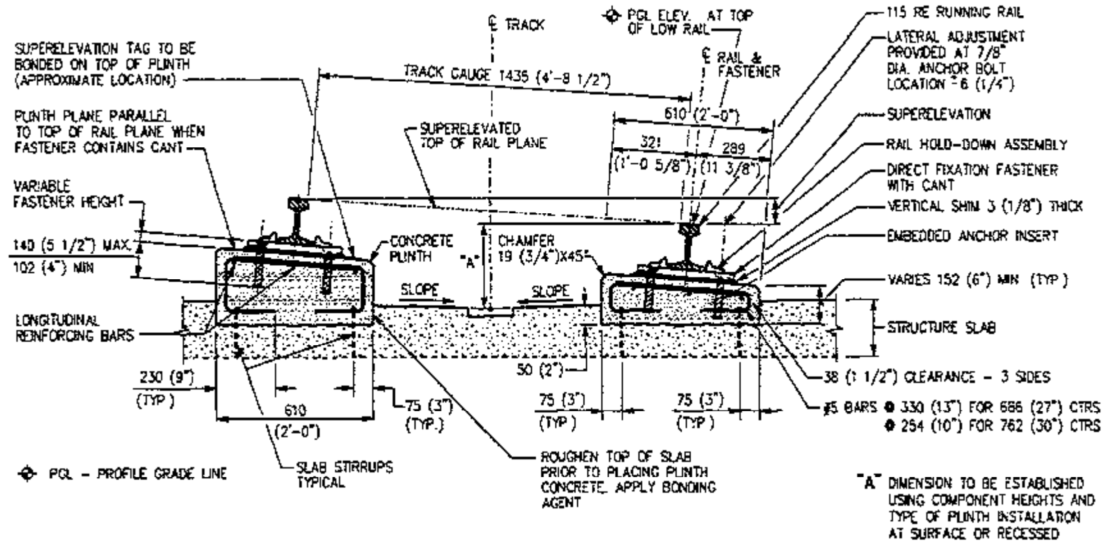


Figure 4.5.3 Concrete Plinth Design—Curved Superelevated Direct Fixation Track

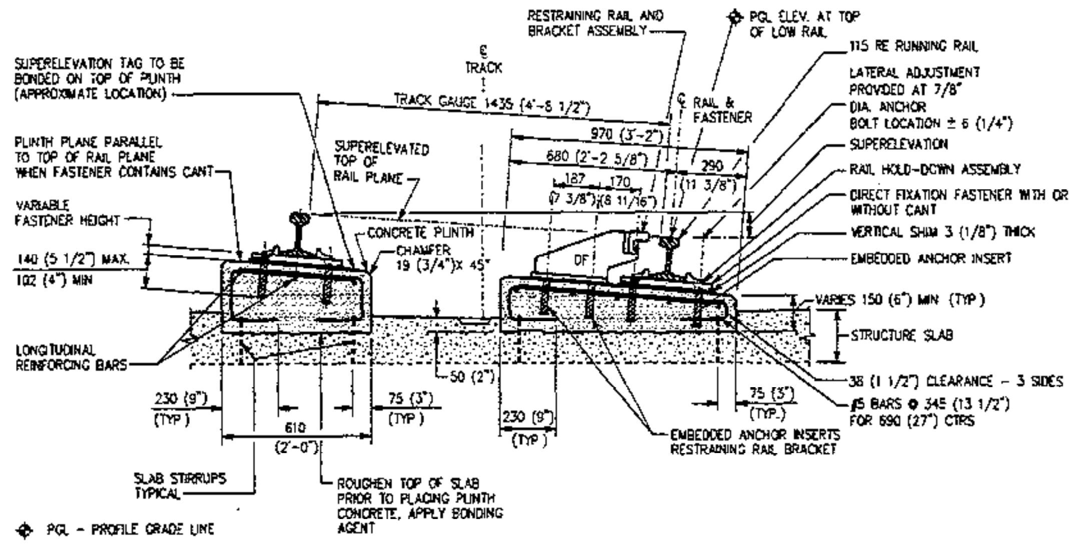


Figure 4.5.4 Concrete Plinth Design—Curved Superelevated Guarded Direct Fixation Track with Restraining Rail

4.5.3.2.4 Concrete Plinth Lengths

Concrete plinths can be formed in various lengths. Typical plinths of intermediate lengths will accommodate three to six direct fixation fasteners between drainage chases as shown in **Figure 4.5.5**.

Concrete plinth lengths are dependent on several track design factors: whether the track is tangent or curved, whether formwork in curved track is curved or chorded, and the locations of construction joints and expansion joints in the invert. Concrete plinths in curved track are generally constructed in short tangent segments for ease of formwork. Concrete plinth lengths are affected by differential shrinkage of structure and plinth, local climate conditions and temperature ranges.

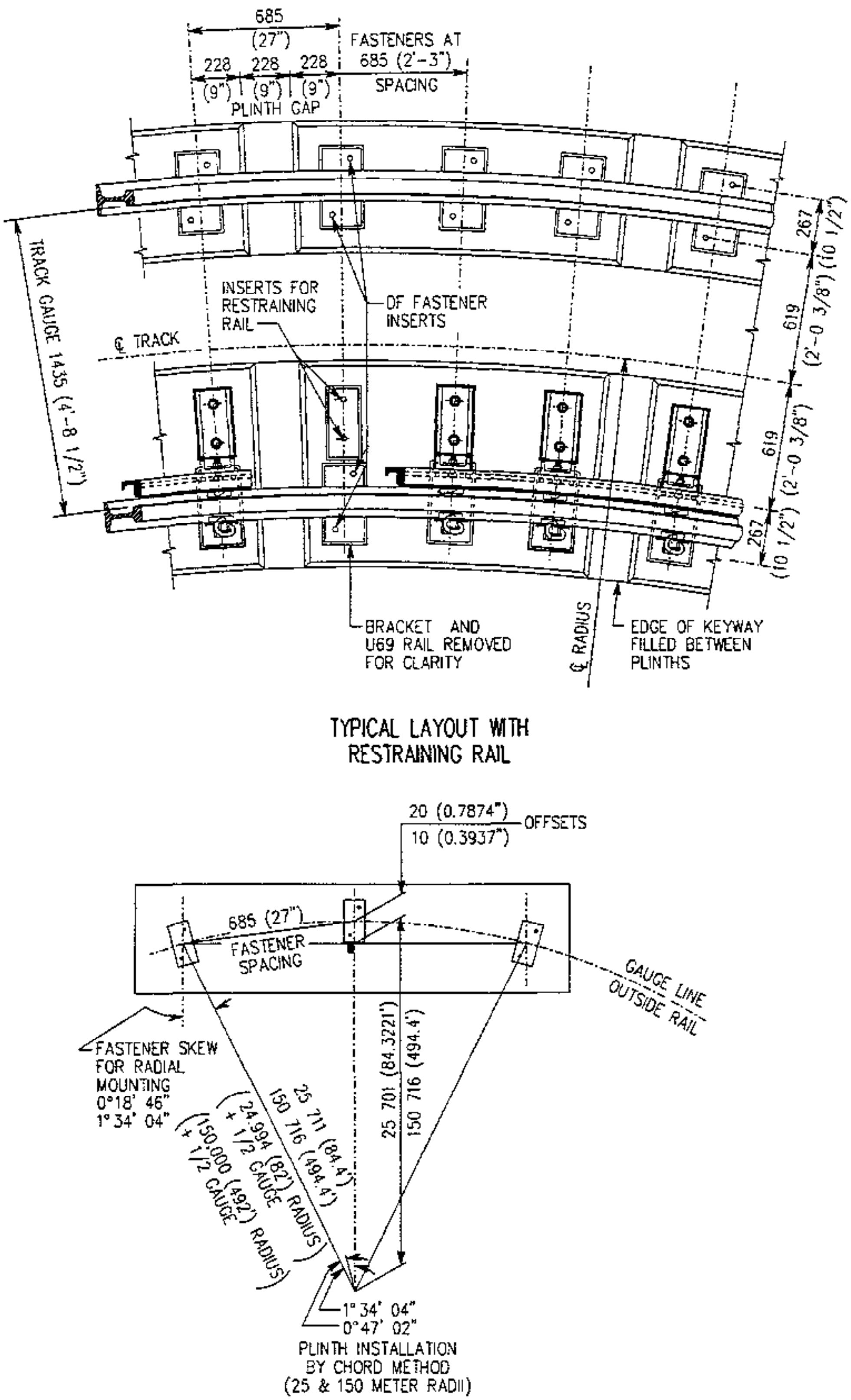


Figure 4.5.5 Concrete Plinth Lengths

4.5.3.2.5 Concrete Plinth Height

The heights of the rail section and the direct fixation fastener and the length of the anchor bolt insert must be determined to establish the height of the concrete plinth.The track structure deck slab or invert slope should generally slope at 1:40 towards the centerline of track. On curved track, the structure itself may be superelevated and parallel to the eventual top of rail plane. In addition, the longitudinal surface drainage gradient is critical to provide adequate drainage of the trackbed.

The key dimension to establishing the plinth height is dimension "A" shown in Figure 4.5.3 from the top of rail plane to the intersection of the deck or invert slopes at the track centerline.

The plinth heights should be kept to a minimum to enhance structural stability, especially if the deck or invert is relatively level and the track alignment requires 100 to 150 millimeters (4 to 6 inches) of superelevation at the outside rail.

4.5.3.2.6 Direct Fixation Vertical Tolerances

The height of the direct fixation fastener is critical to vehicle ride quality and interaction between rail and track structure. To achieve a near-perfect track surface longitudinally, the use of shims between the top of plinth and the base of direct fixation fastener is often implemented. The maximum difference in elevation between adjacent fasteners should be less then 1-1/2 millimeters (1/16 inch), the thinnest shim thickness. Shims generally range in thickness to 12 millimeters (1/2 inch) to compensate for either inferior construction or eventual structure settlement. Fastener shim thicknesses above the 12-millimeter range exist and special anchor bolt lengths are then required. Fasteners installed out of longitudinal surface by more than 1-1/2 millimeters have been known to hinder longitudinal structure slippage, where zero toe load is the fastener design and the rail and structure are thermally independent.

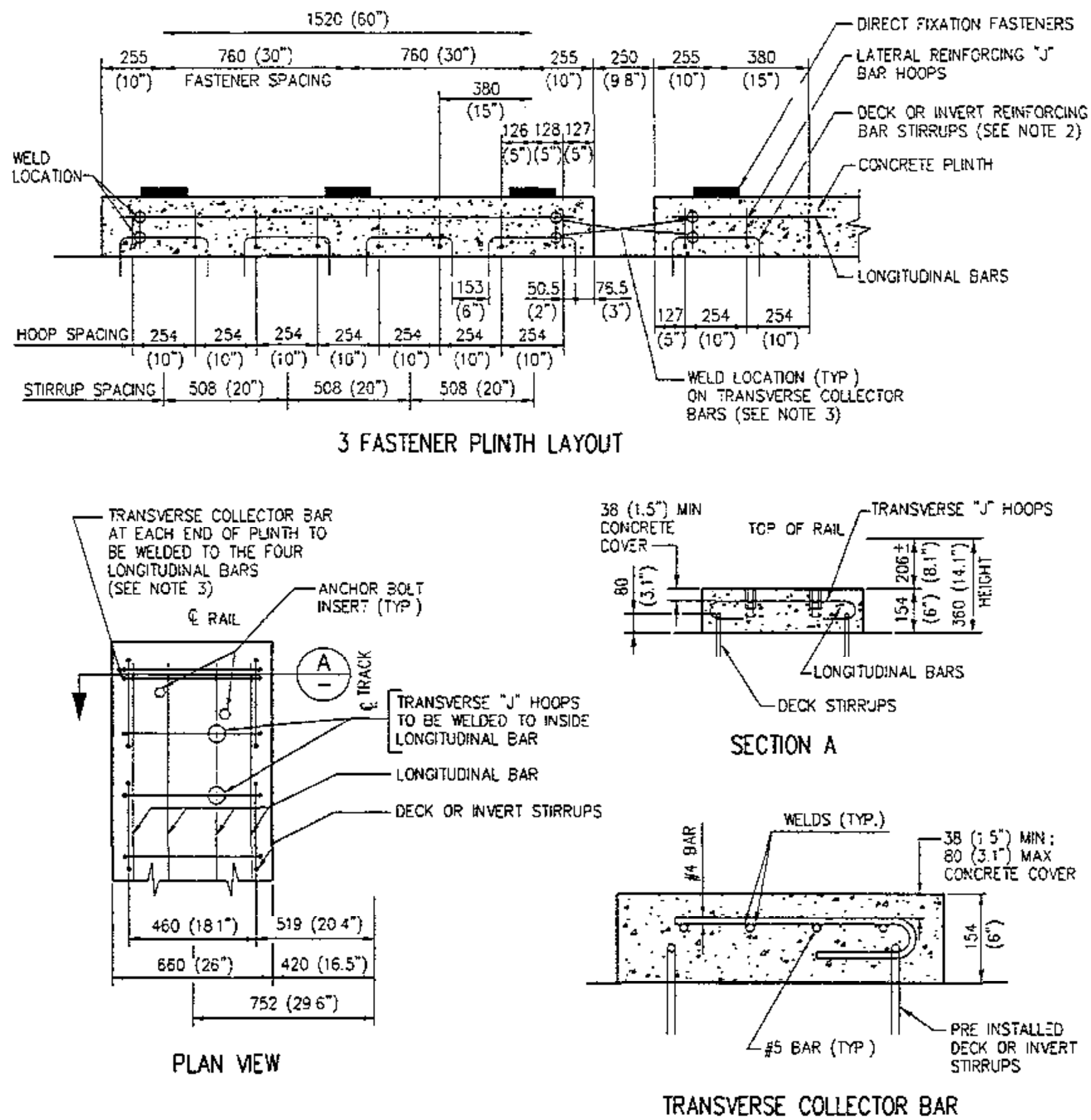
4.5.3.2.7 Concrete Plinth Reinforcing Bar Design

The plinth reinforcement begins with the construction of the trackway invert. A series of stirrups or dowels is placed longitudinally in the concrete plinth, positioned to clear the embedded anchor bolt inserts and the ends of plinth openings or gaps. The stirrups should protrude a minimum distance of 75 millimeters (3 inches) from the deck or invert to allow both the transverse reinforcing steel and the plinth concrete to lock under the stirrups. The stirrup height must be designed to suit the eventual concrete plinth height and reinforcement design.

Different contractors often construct the bridge deck or trackway invert and the track. The invert contractor is normally responsible for the proper placement of the stirrup reinforcing steel that projects from the base concrete. This reinforcing steel must be properly installed and protected from damage after installation. The wheels of construction equipment often damage stirrups. The use of the recessed plinths may help mitigate this problem.

The plinth reinforcement that is installed by the trackwork constructor consists of a series of "J" hook bars and longitudinal bars. A transverse collector bar is sometimes placed at the ends of each concrete plinth for stray current control as shown in **Figure 4.5.6**.

The design size of the concrete plinth determines the size and outline of the "J" hooks and the length of the longitudinal bars. Tangent track will require a constant height to conform to the general height of the concrete plinth Curved track alignments with superelevation will require various sizes and



NOTES:

1. ON CURVES OF LESS THAN 240m RADIUS, MAXIMUM PLINTH LENGTH IS FOUR FASTENERS
2. DECK OR INVERT REINFORCING BAR STIRRUPS PRE-INSTALLED
3. ELIMINATE WELDS AND TRANSVERSE COLLECTOR BARS IF EPOXY-COATED REINFORCING BARS ARE USED

Figure 4.5.6 Concrete Plinth Reinforcing Bar Design

shapes of reinforcing bar "J" hooks as shown in Figure 4.5.6. Design size of reinforcing bars and stirrup locations must include the requirements of providing 38 millimeters (1.5 inches) minimum of concrete cover from the edge of bar to the face of the concrete and a 20-millimeter (0.75-inch) clearance at the fastener anchor bolt inserts.

The reinforcing bar network must be continuous to control stray current corrosion within the direct fixation track system. The aerial deck, at-grade slab, or tunnel invert reinforcing bar system must be continuous and connected to a negative ground system. A similar continuous network must be established and connected to a negative ground system through the deck or slab reinforcing system to provide similar protection to the second pour concrete plinth reinforcing bar system.

The concrete plinth reinforcing bar system can be made electrically continuous by the following methods:

- The deck or invert stirrups installed during the initial construction must be connected (welded) to the deck or invert reinforcing bar network.
- The concrete plinth reinforcing bar system must be completely connected (welded) to the protruding deck or invert stirrups.
- When the stirrups or dowels are not connected (welded) to the deck or invert reinforcing bar system, then the concrete plinth reinforcing bar network must be completely connected (welded) and connected to a negative ground system. This requires connections between each plinth at the concrete plinth openings or gaps.
- The use of epoxy-coated reinforcing bars in the stirrups and the concrete plinth reinforcing bar network provide the required stray current corrosion protection. Care must be exercised during construction to retain complete protective epoxy coating coverage on the stirrups and concrete plinth reinforcing bar network. Chipped or damaged epoxy coating must be covered in an acceptable protective paint compatible with the initial epoxy coating material recommended by the epoxy coating manufacturer.

In some cases, surface water can penetrate the joint between the plinth concrete and the base concrete causing corrosion of the stirrups. In tunnels that do not have adequate means of leak control, the potential of surface water penetrating the separation point may be unavoidable, leading to reinforcing bar rusting and corrosion. Various sealants, such as epoxies, have been used to attempt to seal this joint but virtually every product available will eventually dry out, harden and peel away. The use of a sealant can actually exacerbate a seepage condition by trapping water beneath the plinth concrete. As a guideline, sealants are discouraged and the use of epoxy-coated reinforcing steel for stirrups is recommended.

4.5.3.3 Direct Fixation Fastener Details at the Rail

Typically, the track system will have the rail positioned with a cant of 1:40 toward the track centerline. Rail cant in direct fixation track may be achieved by several methods:

- The top surface of the concrete plinth or grout pad can be sloped to match the required cant. In such cases, the direct fixation fail fastener itself would be flat, with no built-in cant.
- The plinth concrete or grout pad can be poured level (or parallel with the top of rails in superelevated track) and the rail fasteners can be manufactured with the desired cant built into the rail seat of the fastener.

Both methods can produce acceptable results. Placing the cant in the rail seat of the fastener simplifies the construction of plinth formwork and better ensures that the desired cant will actually be achieved, particularly when bottom-up construction is anticipated. If top-down construction is used, rail cant can be reliably achieved in the concrete if the jigs used to support the assembled rails and rail fasteners incorporate cant adjustment capability. If canted fasteners are used, it may still be necessary to procure flat fasteners for use in special trackwork areas.

Lateral adjustment capability and fastener anchor bolt locations are important elements in the design and configuration of direct fixation rail fasteners. The rail cant location must be considered when positioning embedded anchors. Rail cant at the base of rail or at the top of the concrete alters the anchor positions (refer to **Figure 4.5.7**). Excessive shimming on a canted concrete surface may tilt the rail head closer to the center of track, which impacts track gauge. For additional information on direct fixation fasteners, see Chapter 5.

4.5.3.4 Direct Fixation "Ballastless" Concrete Tie Block Track [3]

Conventional construction for direct fixation track includes the installation of either cementitious grout and concrete plinths with elastomeric rail fasteners or encased monoblock ties in a concrete embedment as shown in **Figure 4.5.8**. One alternative to the fastener-on-plinth system to provide a "softer" track is the Low Vibration Track (LVT) shown on **Figure 4.5.9**. Versions of this type of installation and its predecessors date back to the mid-1960s. It is marketed as a direct equivalent to the elastomeric rail fastener.

Although not new technology, the LVT is relatively new to the transit industry. Earlier versions of this type of dual-block concrete tie trackwork incorporated a steel angle gauge bar between the concrete blocks. The LVT design does not incorporate the gauge bars, since the concrete encasement holds gauge.

The individual tie blocks support the rail. Microcellular elastomeric pads support the blocks. The pads and tie blocks are enclosed in a rubber boot before installation.

The microcellular pad provides most of the track's elasticity. A rail pad also provides some cushioning of impact loads, although it was found that improper rail pad design could act in resonance with the underlying microcellular pad to create excessive rail corrugation.

When properly designed, LVT can be engineered to provide whatever track modulus or spring rate is required by changing the composition or thickness of the microcellular pad. The most common application has a spring rate in the range of 15,760 to 24,500 N/mm (90,000 to 140,000 lb/in) to provide maximum environmental benefits.

LVT, and most encased tie systems, reduce the need for reinforcing steel. LVT does not require a reinforced invert, which often makes this system more competitive with a plinth type of installation.

The installation of LVT—and almost all encased tie systems—requires "top-down" construction, where the rail is suspended from temporary supports, with ties and rail fasteners attached, at the final profile elevation. The encasement concrete is then poured into the tunnel invert around the track. When the concrete is cured, the supports are removed. An undesirable feature of LVT track design is the rail's lack of lateral adjustment capability once the track is in place.

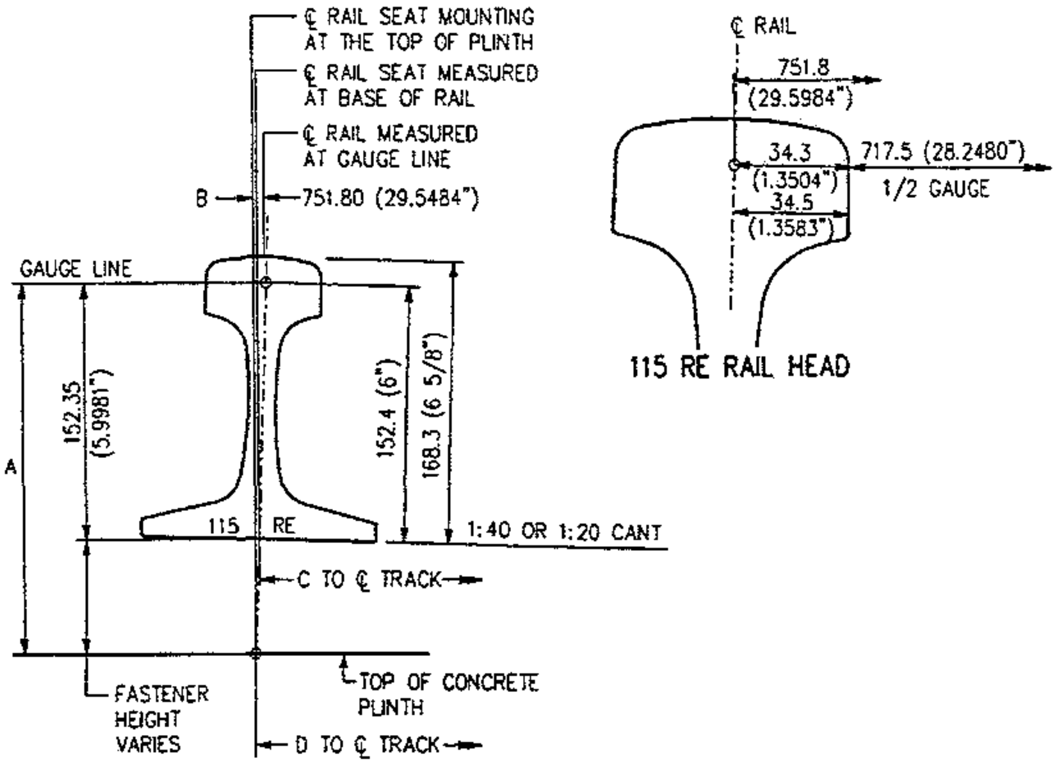


CHART FOR CANT 1:40

FASTENER HEIGHT	A RAIL + FASTENER HEIGHT	B OFFSET ℄ HEAD – ℄ MOUNTING	C CANT ESTABLISHED AT RAIL BASE	D CANT ESTABLISHED AT TOP OF CONCRETE
0	152.35	3.81 (0.1500")	755.61 (29.7484")	755.61 (29.7484")
19.05 (3/4")	171.40	4.29 (0.1689")	755.61 (29.7484")	756.09 (29.7673")
25.40 (1")	177.75	4.44 (0.1748")	755.61 (29.7484")	756.24 (29.7732")
31.75 (1 1/4")	184.10	4.60 (0.1811")	755.61 (29.7484")	756.40 (29.7795")
38.10 (1 1/2")	190.45	4.76 (0.1874")	755.61 (29.7484")	756.56 (29.7858")
44.45 (1 3/4")	196.80	4.92 (0.1937")	755.61 (29.7484")	756.72 (29.7921")
50.80 (2")	203.15	5.09 (0.2004")	755.61 (29.7484")	765.89 (29.7988")
57.15 (2 1/4")	209.50	5.24 (0.2063")	755.61 (29.7484")	757.04 (29.8047")
63.50 (2 1/2")	215.85	5.40 (0.2126")	755.61 (29.7484")	757.20 (29.8110")

CHART FOR CANT 1:20

FASTENER HEIGHT	A RAIL + FASTENER HEIGHT	B OFFSET ℄ HEAD – ℄ MOUNTING	C CANT ESTABLISHED AT RAIL BASE	D CANT ESTABLISHED AT TOP OF CONCRETE
0	152.35	7.62 (0.2999")	759.42 (29.8984")	759.42 (29.8984")
19.05 (3/4")	171.40	8.57 (0.3374")	759.42 (29.8984")	760.37 (29.9358")
25.40 (1")	177.75	8.89 (0.3499")	759.42 (29.8984")	760.69 (29.9484")
31.75 (1 1/4")	184.10	9.20 (0.3624")	759.42 (29.8984")	761.00 (29.9606")
38.10 (1 1/2")	190.45	9.52 (0.3749")	759.42 (29.8984")	761.32 (29.9732")
44.45 (1 3/4")	196.80	9.84 (0.3874")	759.42 (29.8984")	761.64 (29.9858")
50.80 (2")	203.15	10.16 (0.3999")	759.42 (29.8984")	761.96 (29.9984")
57.15 (2 1/4")	209.50	10.48 (0.4124")	759.42 (29.8984")	762.28 (30.0110")
63.50 (2 1/2")	215.85	10.79 (0.4249")	759.42 (29.8984")	762.59 (30.0232")

Figure 4.5.7 Rail Cant and Base of Rail Positioning

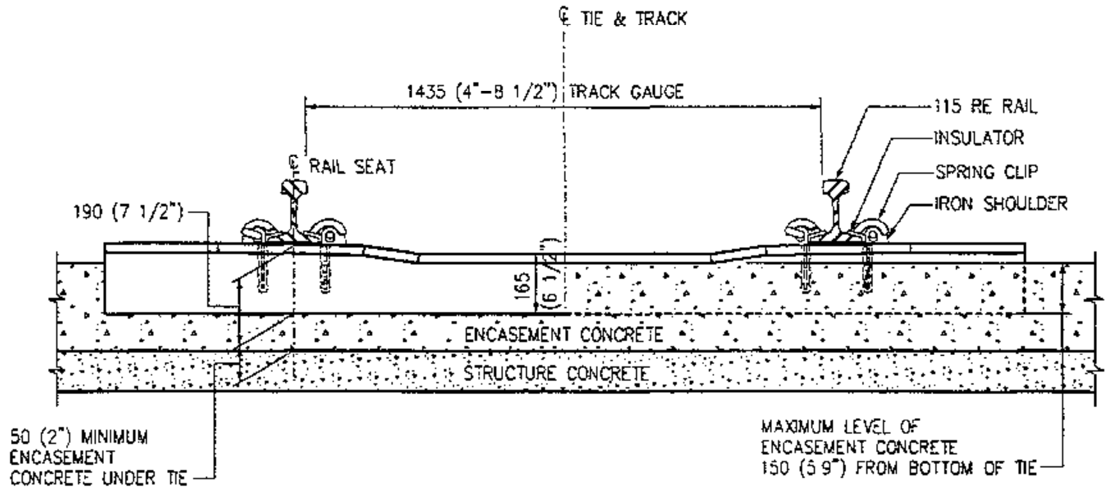


Figure 4.5.8 Encased Concrete Crosstie

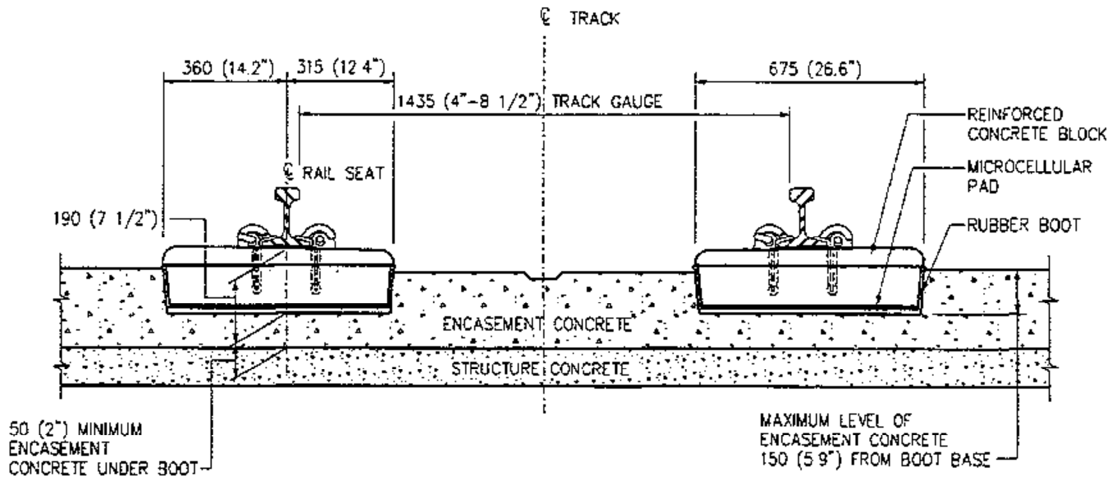


Figure 4.5.9 Standard LVT System

Encased tie systems vary widely in cost, but can usually be installed quite rapidly, compared to plinth type systems. LVT block replacements are feasible on a small scale, consisting of a slightly smaller block grouted in the cavity of a removed tie block.

4.5.4 Direct Fixation Track Drainage

Drainage is as important to the success of a direct fixation track installation as it is to any other type of track structure. This includes both drainage of water from the top surface of the track and the subsurface support system.

Direct fixation track built on a bridge structure will obviously not have to directly contend with any subsurface drainage issues. Direct fixation track constructed at-grade or in a tunnel, on the other hand, must be properly drained beneath the track slab. Standard underdrain details, similar to those used in highway design, must be provided to keep groundwater out of the under-track area. The successful direct fixation track will include an efficient surface drainage system. Experience has shown that foresight in the design of surface drainage for the direct fixation track structure is required to avoid accumulation of standing water or trapped water pockets.

At the interface of ballasted track to direct fixation track, the direct fixation track system should include.

- Protection for adjacent ballasted track segments; the direct fixation track surface runoff should be directed away from the ballasted track.
- A transverse drainage chase or diverting wall directing surface runoff to the drainage system in lieu of runoff into the ballasted track area.
- Concrete plinths that do not butt up to the ballast wall retainer or drainage diverting wall Lateral drainage chases between the last plinth face and the ballast wall retainer are essential.

The design positioning of deck surface drainage scuppers must consider the rotation of the deck or invert due to superelevation.

4.5.5 Stray Current Protection Requirements

The track structure design requires an electrical barrier at the rail. Direct fixation track generally provides this electrical barrier within the direct fixation fastener body. An insulating resilient material with a specified bulk resistivity forms the elastomeric and insulating portion of the fastener. The coating of the rail with an epoxy insulating material should be considered in areas of extensive tunnel seepage or perpetual dampness .

The electrical barrier for the low vibration encased tie direct fixation track system is provided at the rail base. Similar to concrete tie fastenings, the electrical barrier is established by an insulated resilient rail seat pad and spring clip insulators.

For more information on electrical barriers on direct fixation fasteners, see Chapter 5.

4.5.6 Direct Fixation Special Trackwork

The direct fixation special trackwork portion of any transit system will require special treatment and a different concrete plinth design than main line direct fixation track. The supporting plinths or track slabs require detailed layout, as well as coordination with the signal and electric traction design of the fasteners, switch rods, and gauge plates.

Direct fixation special trackwork in contemporary light rail transit systems generally consists of turnouts grouped to act as single crossovers for alternate track operations. Operating requirements may dictate the installation of a double crossover with four turnouts and a crossing (diamond). Using double crossovers in tunnels and on bridges may incur higher track costs, but may be very economical in providing structural cost savings.

4.5.7 Noise and Vibration

The vehicle traveling over the direct fixation track produces noise and vibration. The impact of this noise and vibration generally becomes significant on alignments through sensitive areas, such as near hospitals. Track design has a significant effect on both noise and wheel squeal, and the designer must consider the wheels, trucks, and the track as one integrated system. Chapter 9 provides guidelines with respect to trackwork design for low noise and vibration and introduces various concepts in noise and vibration control.

Trackwork design can have a substantial effect upon wayside noise and vibration. Noise and vibration should be considered early in facilities design to provide for special treatments. Cost-effective designs consider the type of vehicle involved, the soft primary suspensions that produce ideal levels of ground vibration above 30 Hz, or the stiff primary suspensions that produce levels that peak at 22 Hz. See Chapter 9 of this handbook.

4.5.8 Transit Signal Work

Although design of the signal control system will not greatly impact direct fixation track design, it can affect specific parts of the design. The prime example of this interrelationship is the need for insulated joints in the running rails to accommodate train control requirements. Such joints are normally required at the extremities of interlockings, each end of station platforms, within individual turnouts and crossovers, and at other locations to be determined by the train control design.

The light rail transit signaling system may include track circuit signal systems within the direct fixation track zones. Impedance bond installation requirements must be coordinated with concrete plinth track structure design. Insulated joints at the limits of the track circuits must be opposite and within 1.2 meters (4 feet) of each other to facilitate underground ducting and traction crossbonding. Reinforcing bars in the concrete may prevent track circuits from operating reliably.

For additional information on transit signal work, refer to Chapter 10.

4.5.9 Traction Power

Traction power requirements impact the track design at two specific locations: the catenary pole locations in relation to the track centerline and the running rail, which is used as the negative return for the traction power system. The catenary poles impact the direct fixation track centerline distance and aerial structure width when they are located between the tracks. Clearance distances pertinent to the transit vehicle and any other potential users (i.e., track maintenance vehicles) are a design issue that must be considered by the track and catenary designers together. Isolation of the running rail, when used as a negative return conduit, is essential and a specific resistivity in the elastomer is a key design issue.

For additional information on traction power refer to Chapter 11.

4.6 EMBEDDED TRACK DESIGN

Embedded track is perhaps the single most distinguishing characteristic—the signature track—of a light rail transit system in a central business district. Deceptively simple in appearance, it is arguably the most difficult and expensive type of transit track to successfully design and construct. In addition to typical structural design issues that affect any track, embedded track design must also address difficult questions with respect to electrical isolation, acoustic attenuation, and urban design, all in an environment that does not facilitate easy maintenance. The "correct design" may be different for just about every transit system. Even within a particular system, it may be prudent to implement two or more embedded track designs tailored to site-specific circumstances.

4.6.1 Embedded Track Defined

Embedded track can be described as a track structure that is completely covered—except for the top of the rails—within pavement. Flangeways can be provided either by using grooved head girder rail or by forming a flangeway in the embedment material.

Embedded track is generally the standard for light rail transit routes constructed within public streets, pedestrian/transit malls, or any area where rubber-tired traffic must operate. On several transit systems, both highway grade crossings and tracks constructed in highway medians have used embedded track.

Embedded track can be constructed to various designs, depending on the requirements of the system. Some embedded track designs are very rigid while others are quite resilient.

Prior to developing an embedded track design, several vehicle/track related issues must be resolved, including vehicle wheel gauge, wheel profile, and truck design; the track gauge and rail section; and ability of the vehicle to negotiate the track in a satisfactory manner.

4.6.2 Embedded Rail and Flangeway Standards

To develop embedded track designs, the following track components and standards must be specified:

- Rail section to be used: girder groove (guard) rail or tee rail
- Track gauge in the embedded section
- Flangeway width provided in girder rail or formed section
- Guarding of flangeways in curved track and restraining rail

Refer to Section 4.2 and Chapter 5 to determine rail section, track gauge and flangeway requirements.

4.6.2.1 Embedded Details at the Rail Head

The rail section and wheel profile used on a transit system must be compatible. Further, the rail installation method must be carefully detailed if the track system is to be functional and have minimal long-term maintenance requirements.

Traditional street railway/tramway systems used wheels with relatively narrow tread surfaces and narrow wheel flanges. The chief reason for this was to ensure minimal projection of the wheel tread beyond the rail head where it could contact the adjoining pavement, damaging both the wheel and the pavement. Such wheels had tread widths as narrow as 50 millimeters (2 inches) and overall wheel widths of only 75 millimeters (3 inches) Problems with these wheels, particularly in the vicinity of special trackwork, resulted in most systems adopting wheels with much wider treads.

Wheels with an overall width of 133 millimeters (5.25 inches) are common on new start systems. Increasing the wheel tread width beyond the rail head introduces an overhang with potential for interference between the outer edge of the wheel and the embedment materials. To avoid wheel or pavement damage, either the rail head must be raised above the surrounding embedment material or the pavement immediately adjacent to the rail must be depressed as shown in **Figure 4.6.1**.

Other factors must be considered when positioning the rail head with respect to the pavement surface. In resilient embedded track design, a rail head vertical deflection ranging from 1.5 to 4 millimeters (0.060 to 0.160 inches) must be considered. In embedded track, eventual vertical rail head wear of 10 millimeters (0.39 inches) or more must be accommodated. In addition, the wheel tread surface will wear and can result in a 3-millimeter (0.12-inch) or greater false flange height. Over the life of the installation, the total required vertical displacement

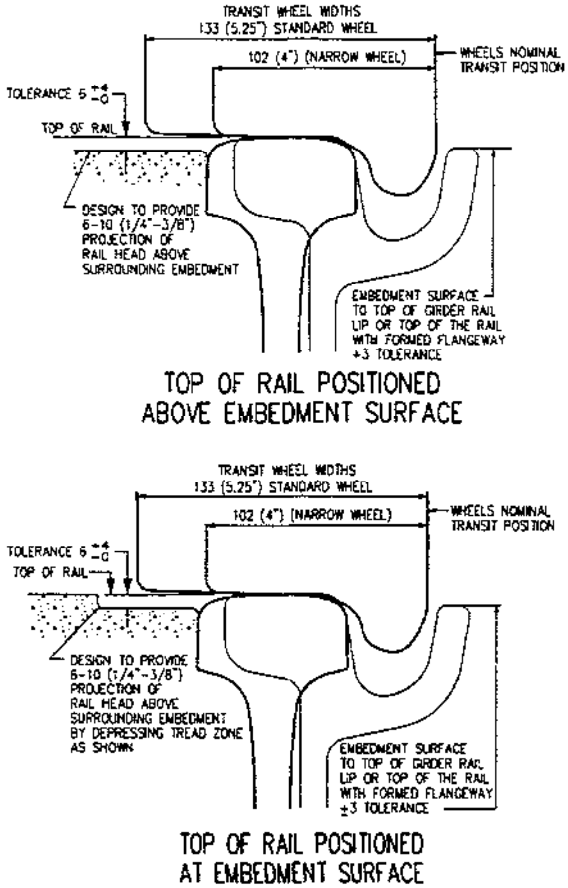


Figure 4.6.1 Embedded Rail Head Details

between the rail head and the pavement surface immediately adjacent to the rails could exceed 15 millimeters (0.59 inches).

A 15-millimeter (0.59-inch) projection of the rail above the pavement would be excessive for an initial installation. Such a rail projection could hinder snow plowing operations at grade crossings and could be hazardous in vehicle and pedestrian areas. A 6-millimeter (0.24-inch) protrusion is recommended for initial installation, which should accommodate resilient vertical deflection, some initial vertical rail head wear, and a moderate amount of false flange wheel wear.

False flanges should not be allowed to progress, especially to the 3-millimeter (0.12 inch) height, and the track designer should stress that the vehicle system maintenance policies must include a regular wheel truing program.

When rail head wear has eliminated approximately half of the projecting 6 millimeter (0.12-inch) vertical head clearance, the original projecting dimension can be restored by production grinding of the embedment material.

4.6.2.2 Wheel/Rail Embedment Interference

The width of a light rail vehicle wheel is a major design issue. Each design option has certain drawbacks such as:

- Wide wheels increase the weight (mass) on the unsprung portion of the truck and project beyond the field side of the head of most rail designs. Wide wheels are therefore susceptible to developing hollow treads and false flanges and could require more frequent wheel truing to maintain acceptable tracking through special trackwork.

- Narrow wheels result in limited tread support at open flangeways and increase the possibility of wide gauge derailments. This typically forces the adoption of either flange-bearing special trackwork or the use of movable point frogs.

- Medium wheels partially reconcile the problems noted above, but introduce the possibility of undesirable wheel tread protrusion beyond the field side of narrow rail head designs. They also provide limited tread support in special trackwork and may require flange-bearing special trackwork or movable point frogs.

As stated in Section 4.6.2.1, embedded track design must consider the surrounding embedment material's exposure to the overhanging or protruding wheel treads.

The following table summarizes head widths of typical girder rail and tee rail sections. These rail sections are illustrated in Figures 5.2.1, 5.2 2, and 5.2.3 of this handbook.

Rail Section	Head Width
NP4a	56 mm (2.205 in)
Ri 52N	56 mm (2.205 in)
Ri 53N	56 mm (2.205 in)
Ri 59N Girder	56 mm (2.205 in)
Ri 60N Girder	56 mm (2.205 in)
GGR-118 Girder *	56 mm (2.205 in)
128RE-7A Girder *	76.2 mm (3 in)
149RE-7A Girder *	76.2 mm (3 in)
115 RE Tee Rail	69.1 mm (2.720 in)

* Rail sections that are not currently rolled.

If wheel tread width exceeds rail head width on the selected embedded rail, interference between the outer edge of the wheel and the embedding pavement is inevitable as the rail wears vertically. As a rule, wheel widths from 127 to 133 millimeters (5 to 5.25 inches) will overhang the rail head. The ATEA sought to avoid such problems by having no standard wheel tread more than 75 millimeters (3 inches) wide and no standard plain girder rail section head less than 63 millimeters (2.5 inches) wide.

A railway wheel or transit wheel that overhangs the rail head must be clear of the surrounding embedment material as shown in Figure 4.6.1. Raising the rail head will facilitate future rail grinding and delay the need for undercutting or grinding the surrounding embedment material to provide clearance for the wheel tread. Embedded track top of rail tolerances must be realistic when considering concrete slab placement during track construction. A projection 6 to 10 millimeters (0.25 to 0.375 inches) above the surrounding surface is realistic. Rail positioned below 6 millimeters (0.25 inches) is not recommended.

Trackside appliances such as electrical connection boxes, clean out drainage boxes, drainage grates and special trackwork housings must be depressed or recessed in the vicinity of the rail head to provide for various wheel tread rail wear and rail grinding conditions. As a guideline, depressed notch designs in the covers, sides and mounting bolts of the track enclosures adjacent to the rail head are recommended. A depth of 15 millimeters (0.6 inches) provides adequate clearance throughout the life of the rail installation.

4.6.3 Embedded Track Types

Chapter 2 documents the types and magnitudes of loads transferred from the vehicle wheel to the rail. The rail must support the vehicle and the resulting loads by absorbing some of the impact and shock and transferring some of the force back into the vehicle via the wheels. The initial impact absorber on the vehicle is the elastomer in the resilient wheel, followed by the primary suspension chevron springs, then the secondary suspension system air bags. The initial impact absorber on the track is the rail, specifically the rail head, followed by the fastening or supporting system at the rail base and then the remaining track structure. The track structure's degree of resiliency dictates the amount of load distributed to the rail and track structure and the magnitude of force returned to the wheels and vehicle.

4.6.3.1 Non-Resilient Embedded Track

Rail supported on a hard base slab, embedded in a solid material such as concrete with no surrounding elastomeric materials, has a high modulus of elasticity and will support the weight of the vehicle and absorb a moderate amount of the wheel impact and shock. A majority of the impact loads will be transferred back into the vehicle via the wheels. Non-resilient rail can be considered as continuously supported beam with a minor amount of rail base surface transfer.

Non-resilient track has had mixed success. Eventual spalling of the surrounding embedment and surface failure are common problems. This is especially evident in severe climates where freeze/thaw cycles contribute to track material deterioration. Concrete embedment alone does not provide rail resiliency. It creates a rigid track structure that produces excessive unit stresses below the rail, causing potential concrete deterioration. Such designs are highly dependent on the competency of the concrete immediately adjacent to the rails. Field quality control during concrete placement and vibration are very important. Rigid track was usually successful under relatively lightweight trams and streetcars, but has often failed prematurely under the higher wheel loadings of the current generation of light rail transit vehicles.

The size and mass of the base slab, typically a concrete slab 400 to 600 millimeters (16 to 24 inches) thick, tends to dampen some impacts generated by passing vehicles. This results in reduced and usually minor transfers of vibration to surrounding structures.

Several transit systems feature embedded rail suspended in resilient polyurethane materials. This rather simple form of embedment completely encapsulates the rail, holding it resiliently in position to provide electrical isolation and full bonding of the rail and trough to preclude water intrusion. These installations have been successful with no visible defects. Experience has shown that polyurethane has a tendency to harden and lose some of its resiliency after roughly 5 years. This hardening results in surface deterioration from wheel contact, but does not progress to the point where it is detrimental to surrounding structures or otherwise considered faulty by the general public. Like all engineered structures, these installations age and slowly deteriorate to the point where replacement is required.

Bituminous asphaltic embedment materials provide a minor degree of resiliency, but tend to shrink and harden with age, leading to excessive interface gaps between the rail and asphalt or roadway concrete. When bituminous asphalt hardens, it tends to fracture and break down. The resulting water intrusion will accelerate deterioration of the entire track structure.

As a guideline, although concrete embedment and bituminous asphalt materials have been used in track paving embedment, they are not recommended. An elastomeric rail boot or other elastomeric components are available to provide resiliency at the rail surface and potential rail deflection both vertically and horizontally.

4.6.3.2 Resilient Embedded Track

Direct fixation transit track and conventional ballasted track are both resilient designs with a proven record of success. This success is due, in no small measure, to their ability to deflect under load, with those deflections being within acceptable operating limits for track gauge and surface. These rail designs are able to distribute loads over a broad area, thereby avoiding—except for the rail-wheel contact—point loading of the track structure which could cause track failure. Resilient track has been successful in ballasted track and direct fixation track installations and has had improved results in embedded track installations Non-resilient embedded track designs typically fail in excessive loading situations, such as a very sharp curve, where the rigid nature of the embedment materials prevents the rail from distributing loads over a broad enough area thereby overstressing portions of the structure. A key goal in embedded track design is to duplicate the rail deflections and resiliency inherent in ballasted and direct fixation track systems to provide an economical long-term track structure.

Rail supported on a resilient base, with a moderate modulus of elasticity, embedded on a solid track slab will support the weight of the vehicle and absorb and distribute a greater amount of the wheel impact and shock. Some of the impact load will be transferred back into the vehicle via the wheels. Resilient rail evenly distributes vehicle loads along the rail to the surrounding track structure. The frequency ranges developed by each light rail vehicle will determine the parameters of the resilient track structure design and its components.

The guidance of a noise and vibration expert is recommended to coordinate the design of the resilient track structure with light rail vehicles equipped with resilient wheels. Such wheels attenuate vibration caused by wheel-rail contact, reducing the vibrations entering the carbody and affecting the ride quality. They do not provide significant attenuation of groundborne acoustic effects.

4.6.3.3 Super Resilient Embedded Track (Floating Slab)

Groundborne noise and vibration are a concern for embedded track sections adjacent to or near noise and vibration sensitive facilities, such as hospitals, auditoriums, recording studios, and symphony halls. Numerous methods for controlling groundborne noise and vibration exist, including floating slabs, ballast mats, rockwool batts, and resilient fasteners. The decision to use floating slab design is based on site-specific critical requirements and is often the preferred method to dampen and control the transfer of low frequency groundborne noise and vibration in the embedded track.

Floating slab design consists of two concrete slabs, with the initial base slab constructed on the subgrade and a second slab that includes the track structure, with resilient isolators positioned between the two slabs. The base slab is usually U-shaped, making the entire structure somewhat similar to the "bathtub" concept.

The resilient isolators between the base slab and the track slab can take several forms. Most common, particularly in older installations, are large diameter elastomer "hockey pucks" or "donuts" that are sized, spaced, and formed to provide the desired spring rate and acoustic attenuation. Some newer installations have substituted ballast mat sheets and rockwool batts for the donuts. In all cases, the secondary isolators must be placed between the sides of the track slab and the vertical walls of the base slab to limit lateral track movement and to provide acoustic isolation. Those isolators can either be individual elastomer blocks, continuous elastomer sheeting, or ballast mats extending up the base slab wall. As with any bathtub design, the exposed joint between the track slab and the base slab must be well-sealed to limit water intrusion and accumulation of surface contaminants in the voids around the base isolators, which will degrade the system's performance. Drainage of the void area beneath the base slab is critical. The design should provide for periodic inspection and flushing out of the void area

Based on site-specific rail features, vibration radiation, and the distance to surrounding structures, the floating slab, ballast mat or rockwool batt design is best undertaken by a noise and vibration expert experienced in dampening and isolation. For additional information on noise and vibration, refer to Section 4 6.6 and Chapter 9.

4.6.3.4 A Special Resilient Rail Installation for Vibration Sensitive Zones

A relatively new track design concept to dampen vibrations is emerging in Germany. The continuous elastic embedded rail system as shown in **Figure 4.6.2** consists of prefabricated sections of rail, rubber and steel forms, preassembled for track installation. The assembled rail is supported under the head with no rail base contact, providing increased vertical deflection with controlled lateral deflection based on the elastomer tapered configuration. The bolt tension and compression of the rubber control total deflection. The entire assembly is mounted on a concrete base slab with an intermediate grout material at the base of the assembly and then embedded.

The reduction in vibration emissions in the critical low-frequency range makes the continuous elastic rail system a viable alternative to floating slab designs in environmentally sensitive track zones.

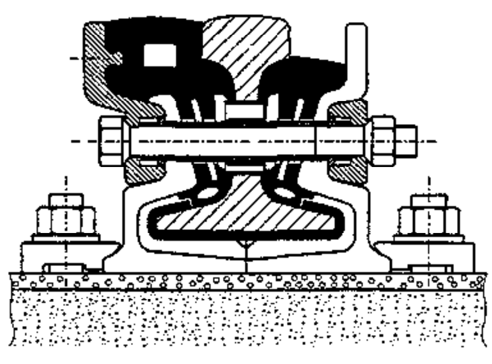


Figure 4.6.2 Special Resilient Rail Installation for Vibration Sensitive Zones

Other German companies in the elastomer component and product line have similarly been experimenting with encased rail designs.

4.6.4 Embedded Track Structure Types

There are generally two types of track structures in embedded track design:

- Concrete slab track structure
- Conventional ballasted track with embedment

4.6.4.1 Concrete Slab Track Structure

Concrete slab embedded track designs consist of various styles that include:

- Continuous single-pour concrete slab with two rail pockets or troughs for the installation of the rails (**Figure 4.6.3**). Stray current protection is provided at the rail or within the trough area.
- Two-pour concrete slab with cold joint between the two pours located at the base of rail (**Figure 4.6.4**). Stray current protection is provided at the rail or within the trough area.
- Three-pour concrete slab with a bathtub design providing stray current protection below and beside the concrete track slab (**Figure 4.6.5**).

The initial concrete slab width can be designed to accommodate both single-track and double-track installations. As a guideline, the preferred design for ease of installation is two single-track concrete slab pours with an expansion or construction joint at the centerline of both tracks. The required accuracy of the track alignment and the finished top of rail concrete surface should

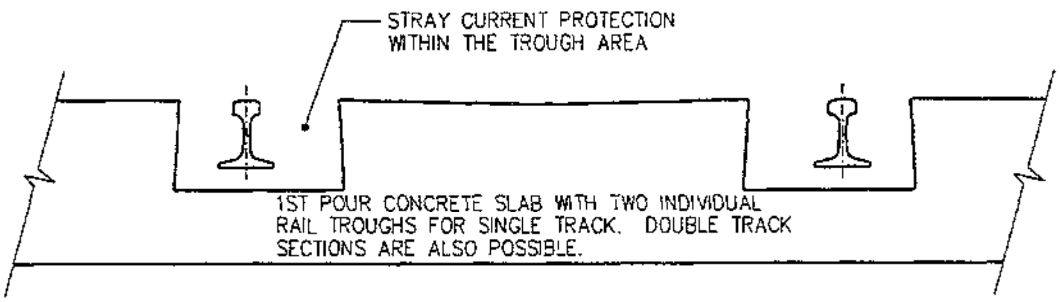


Figure 4.6.3 Concrete Slab with Two Individual Rail Troughs

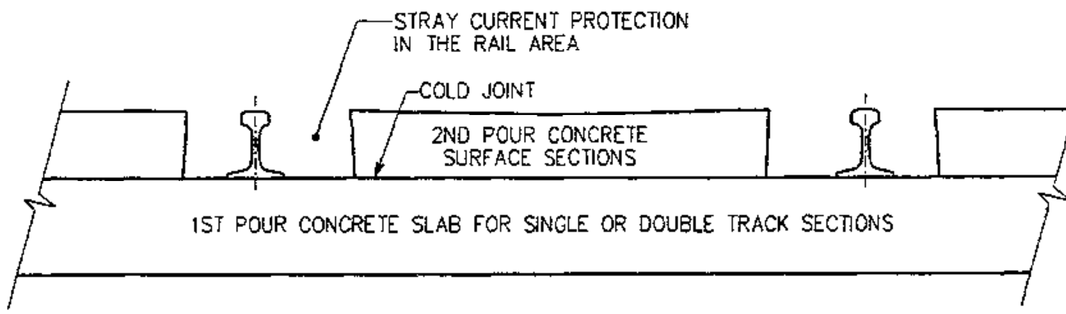


Figure 4.6.4 Two-Pour Concrete Slab with Two Individual Rail Troughs

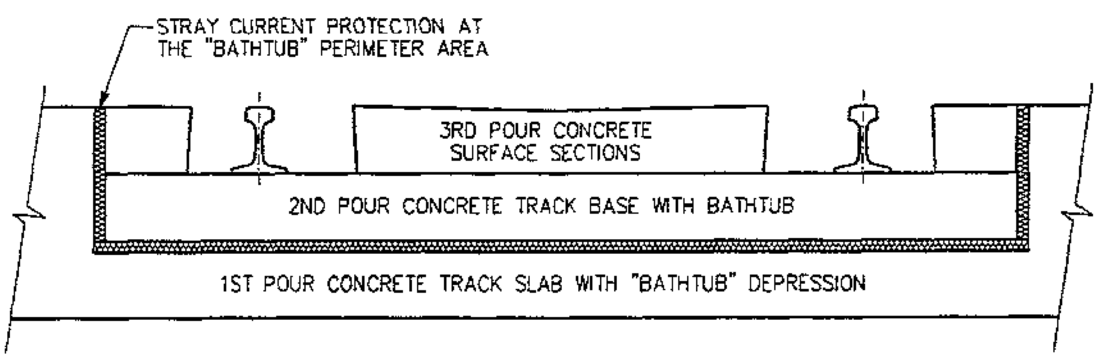


Figure 4.6.5 Three-Pour Concrete "Bathtub" Installation

control the staging and methods of embedded track construction.

4.6.4.1.1 Rail Installation

The methods of installation, positioning and retention of the rail depends on the specific design criteria selected.

Floating rail installation relies on the embedment materials to secure and retain the rail in position without any mechanical connections between the rail and the track slab. The installation design is a two-step process. First, the rail is either positioned within the trough (**Figure 4.6.6A**) or on the initial concrete base slab (**Figure 4.6.6B**) using temporary jigs. Next sufficient trough or base embedment material (concrete or polyurethane) is placed to completely encapsulate the base of rail, thereby locking the rail in its final position. The temporary jigs are then removed and a second application of trough fill material generally encapsulates the remaining rail to top of rail.

If girder rail is used, no special surface finishing is required. If tee rail is employed, either a flangeway can be formed on the gauge side of the rail or the embedment material can be deliberately left low. Regardless of rail section, the surface of the embedment material must be left low on the field side of the rail to provide for false flange relief and future rail wear.

Meeting construction tolerances for floating rail installations depends on the contractor's ability to rigidly hold the rails in proper alignment during the initial embedment material pour. Once set, the rail position cannot be adjusted to meet construction tolerances or future maintenance needs. Irregularities in the rail alignment due to either rail manufacturing tolerances or thermal effects during construction can cause misalignments that can only be fixed by removal and replacement. Maintaining the alignment during the embedment pours can be especially difficult in curved track. The contract specifications should require the contractor to submit a detailed quality control plan for meeting the tolerances.

Rail fastening installations use mechanical rail base connections to secure the rail in position. The installation may consist of the following methods:

- Core drilling and epoxy grouting the fastening anchor inserts or bolts to the initial concrete slab as shown in Figure **4.6.7A**.
- Cast-in-place fastening anchor inserts into the initial concrete slab as shown in **Figure 4.6.7B**.

Such designs require limited horizontal and vertical alignment adjustment prior to embedment. This is provided by the leveling nuts and slotted holes in the rail base plate as shown in Figure 4.6.7A . Slotted plate holes may provide for horizontal adjustment and additional shims for vertical adjustment as shown in Figure 4.6.7B.

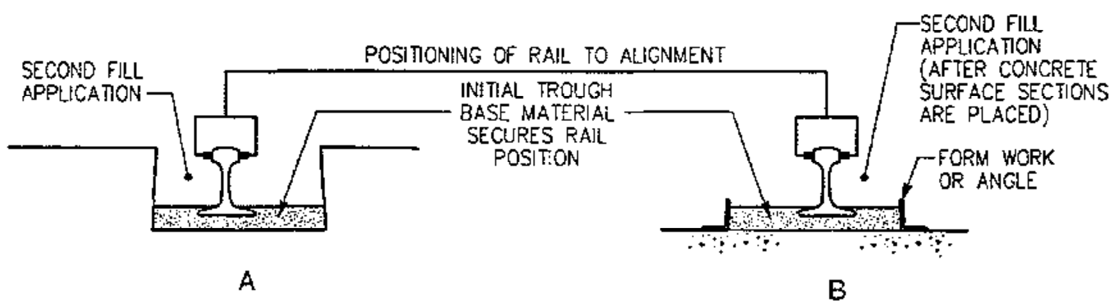


Figure 4.6.6 Initial Rail Installations—Base Material

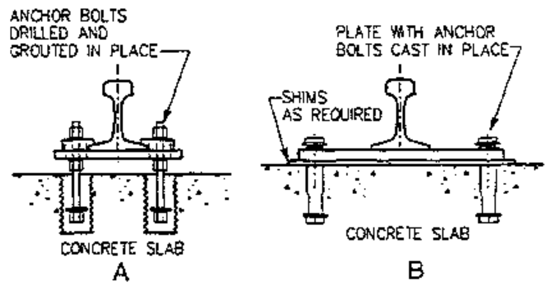


Figure 4.6.7 Rail Fastening Installations

Rail fastening embedded track designs must consider the ability of the rail to distribute lateral loads to the rail fasteners. If the rails are rigidly secured at centers of 900 to 1000 millimeters (approximately 35 to 40 inches), and the surrounding embedment materials are more flexible, the track will have hard spots that will cause the rail to wear abnormally. Elastomer pads should be considered to dampen the hard spots. Direct fixation rail fasteners may be used to secure the rail to the base slab. The fasteners provide resiliency in all directions as well as electrical isolation.

Anchor plates may also be used. The benefits of using anchor plates in embedded track are:

- Rigid control of rail position during two-pour initial installations
- Anchor plates can be reused during future rail changeout to control rail position
- Track can be used in partially completed installations to either confirm track installation or maintain revenue service

Steel ties or gauge rods can be intermixed with anchor plates in embedded track to assist in controlling the rail and establishing the track gauge. Gauge bars spaced at 1,500 millimeters (5 feet) on curves and 3,000 millimeters (10 feet) on tangents are common. Steel ties in every fourth fastening position may also be considered.

The use of steel ties or gauge rods is a factor in stray current control design. Individual trough isolation is impossible due to the steel tie or rod extending beyond the trough or rail area. Gauge rods can usually be insulated within individual cross troughs; however the installation is cumbersome and quality control is difficult. Steel ties are even more difficult due to their irregular cross section.

The use of steel ties and gauge bars in embedded track sections tends to produce a surface crack in rigid pavements directly above or near the embedded tie or bar. To control surface deterioration, a scored crack control slot or indentation is recommended. This may not be specifically necessary in installations where the pavement surface consists of brick or other individual pavers.

4.6.4.1.2 Stray Current Protection Requirements

An effective mitigation barrier against stray current corrosion is to protect both the rails and nearby metallic structures from electrolytic corrosion. The track structure requires an electrical barrier be provided at the rail location as shown in **Figure 4.6.8,** unless the bathtub design (Figure 4.6.5) can confine currents within the overall track structure. Refer to Chapter 8 for additional details on the theories of stray current.

Principal measures to minimize traction current leakage are:

- The use of continuous welded rail providing superior traction power return over conventional electrically bonded jointed track.
- Insulating either individual rails or the entire track structure from the earth.

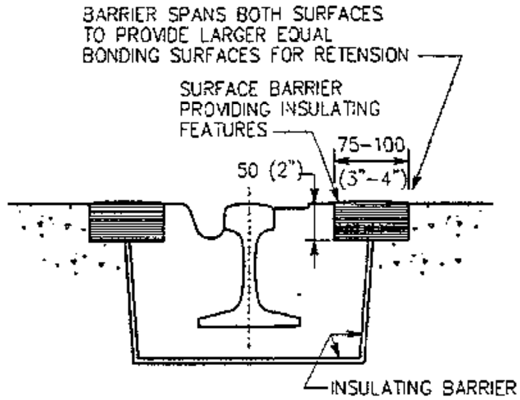


Figure 4.6.8 Insulating Surface Barrier at Trough Edges

- Insulating embedded switch machines and any other track system appliances from the earth.
- Continuous welding of the steel reinforcement in the supporting base slab to act as a stray current collector and electrical drains to carry intercepted current back to the traction power substation.
- Cross bonding of rails with cables installed between the rails to maintain equal potentials for all embedded rails.
- Rail bond jumpers at mechanical rail connections, especially within the special trackwork installations.

Key details concerning the above measures that affect the track structure design are:

- Type of insulation to be installed, whether it is located at the rail face, along trough edges, or around the entire periphery of the track structure as in the bathtub concept.
- Type of insulation to be installed at switch mechanisms or track mechanisms
- Provisions for cross bond cables between rails on each track and occasionally between rails on different tracks.
- Ductwork that must be provided in the embedment materials.
- Provision for rail bond jumpers exothermically welded to the rail on either side of a bolted joint or completely around special trackwork components prior to embedding the track.

Prior to installation of the embedded track structure, a corrosion survey should be undertaken to establish the existing baseline stray current levels. Periodic monitoring should be performed after installation of embedded track to detect current leakage and to control or improve insulation performance.

Stray current protection design can include one or more of the following concepts:

- Coating of the rail surface (except the head and gauge face) with an insulating dielectric epoxy such as coal tar.
- Embedding the rail and filling the entire trough with an insulating dielectric polyurethane or other suitable insulating material.
- Lining the rail trough with an insulating dielectric material, which provides a barrier between the potentially conductive trough fill material and the concrete track slab.
- Lining the rail in an elastomeric boot, thereby totally encapsulating the surface except for head and gauge face.
- Insulating the anchor bolts or anchor inserts that require insulation due to penetration beyond the insulated rail trough zone into the base concrete track slab. This insulating design can be accomplished by either coating the penetrating stud or anchor insert to provide a continuous seal at the base of the concrete trough or insulating liner location.

- Insulation at the trough edge containing the rail is critical in stray current corrosion control, including the interface at the top of embedment. A wide band or insulating barrier is required to retard surface current leakage through water, dirt and debris that may accumulate on the surface as shown in Figure 4 6.8.

Additional information on corrosion control is included in Chapter 8 of this handbook.

4.6.4.1.3 Rail Embedment Materials

Rail embedment or trough fill materials range from very elaborate and expensive to simple and moderately priced, including elaborate extruded elastomer sections, cast-in-place resilient polyurethane components, concrete fills of various compositions, and an asphaltic bituminous mortar

Embedment designs for resilient track that utilize the general track structure, as described above, have incorporated the following materials to retain and allow for designated rail deflections with varying success.

4.6.4.1.3.1 Extruded Elastomeric Trough Components. Extruded elastomeric sections or components are designed to fit the rail contour. Generally these materials are only placed above the base of rail and other measures must be taken to prevent stray current migration from the rail base. Using extruded insulation requires the two-pour method for base slab installation, including installation of the rail prior to placing the surrounding extruded component sections. Finally the top pavement is then placed on the gauge and field sides of the extrusion. Stray current corrosion protection may be provided by the material used to fabricate the extruded sections. Providing insulating protection to the total rail surface, including any portion of the rail base not in contact with extruded sections, is an important requirement. Extruded sections are available in separate parts that encase the entire rail as shown in **Figure 4.6.9** These designs require a specific concrete base installation sequence to provide complete support under the base of rail. As an insulating material, extruded elastomer has proven to meet the required bulk resistivity of 10^{12} ohm-cm that is needed to be effective.

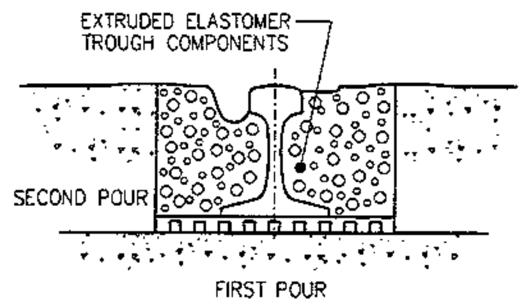


Figure 4.6.9 Extruded Elastomer Trough Components

4.6.4.1.3.2 Resilient Polyurethane. Polyurethane components can be used as trough fillers. Resilient polyurethane has proven to be an ideal rail base support material that provides a minimum of rail deflection. Altering the urethane compound to adjust its durometer hardness can control the actual amount of deflection.

Elastomeric polyurethane is an effective stray current protection barrier that binds well to both cleaned rail surfaces and concrete trough surfaces. It is, however, expensive, both for material procurement and the labor associated with mixing and installation. To reduce the volume of polyurethane required, premolded rail filler blocks shaped to fit the web of the rails can be used as shown in **Figure 4.6.10**. The embedment design must consider rail base deflections. Embedment materials for the rail head and web areas

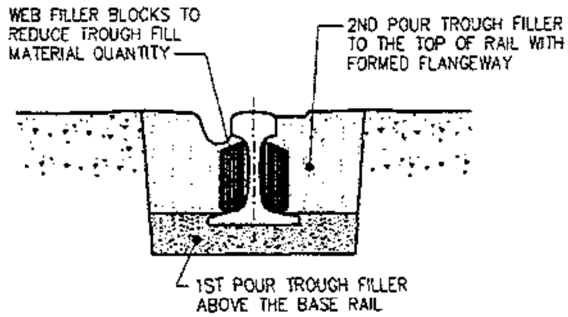


Figure 4.6.10 Polyurethane Trough Filler with Web Blocks

should both be resilient in nature to allow for the rail movement. Solid or non-resilient encasement materials surrounding the rail will negate the resilient characteristics of the polyurethane and lead to premature failure of the non-resilient materials.

Polyurethanes are a difficult and expensive material for in-track construction. Urethanes are highly susceptible to chemical reaction with moisture in the air, the fine sand additive for bulk, and surface dampness during application. Their chemical characteristics make it essential that mixing, handling and application be undertaken carefully by qualified contractors. Polyurethanes in the liquid form seek a level surface, adding to the difficulty of installation in embedded tracks with an inclined profile grade line.

As an insulating material, polyurethane has proven to meet the required bulk resistivity of 10^{12} ohm-cm.

4.6.4.1.3.3 Elastomer Pads for Rail Base. Elastomer pads are a satisfactory rail base support material that provide a minimum amount of rail deflection depending on the spring rate of the elastomer and its specific durometer hardness. Natural rubber elastomer pads mixed with proper quantities of carbon black and wax have exhibited satisfactory performance and long life. Although water seepage typically will not damage the elastomer pads, proper drainage of the rail trough should improve performance, provide assurance that the expected life cycle will be realized, and increase the effectiveness of the pads as a stray current deterrent The embedded track design must consider rail base deflections with matching resilient rail web and head embedment materials to allow for rail movement. Solid or non-resilient embedment materials surrounding the rail will defeat the elastomer pad's resiliency and lead to premature failure of the non-resilient materials.

As an insulating agent, either synthetic elastomer compounds or natural rubber have met required bulk resistivity of 10^{12} ohm-cm.

4.6.4.1.3.4 Elastomeric Fastenings (Direct Fixation Fasteners). To duplicate successful open direct fixation track design with acceptable rail deflections, embedded track designs have incorporated direct fixation concepts. Bonded direct fixation fasteners and component plate and elastomer pad fastenings may be considered

Successful direct fixation fasteners or fastening designs are essential to embedded track design. Direct fixation fastener design features are discussed in Chapter 5 of this Handbook.

The embedment design must consider rail deflection at the fastener. The surrounding embedment materials must be resilient, with extruded prefabricated sections that conform to the rail fishing zone with clearance apertures for the fastener and clip assembly as shown in **Figure 4.6.11**. Solid or non-resilient embedment materials surrounding the rail will defeat the direct fixation fastener's resiliency and potentially lead to premature failure of the non-resilient materials.

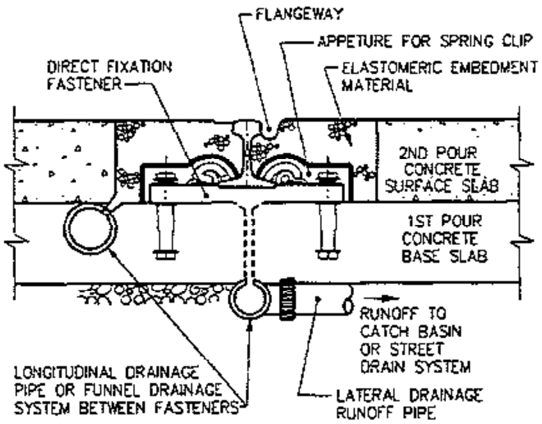


Figure 4.6.11 Direct Fixation Fastener with Internal Drain System

Direct fixation fasteners with surrounding flexible elastomers are subject to infiltration seepage into the rail seat cavity. Although water seepage may not seriously damage the elastomer components, proper drainage should improve performance and provide electrical insulation at the direct fixation fastener for stray current control.

As an insulating agent, direct fixation fasteners meet the required bulk resistivity of 10^{12} ohm-cm.

4.6.4.1.3.5 Rail Boot for Embedded Track. Rail boot designs have proven to be a satisfactory rail base support material that provides minimal rail deflection depending on the design. Natural rubber elastomers mixed with proper quantities of carbon black and wax exhibit satisfactory performance. Configuration of the elastomeric rail boot with voids and the elastomer spring rate allow for a specific magnitude of rail deflection both vertically and horizontally.

The rail boot installation design is subjected to water seepage entering both inside and outside the boot area. To improve performance, proper drainage of both areas of the rail installation should be provided. Rail boot designs are currently available for both tee rail sections and popular girder groove and guard rail sections. Boots are also available for dual tee rail and bolted restraining rail assemblies.

As an insulating material, the rail boots have met the required bulk resistivity of 10^{12} ohm-cm.

4.6.4.1.3.6 Concrete and Bituminous Asphalt Trough Fillers. Concrete, cementitious grout components are available to use as trough fillers. The first-pour trough filler encapsulating the rail base and providing continuous support below the rail can be a non-shrink cementitious grout. The cementitious grout with a reduced aggregate size, less than 12 millimeters (0.5 inches) to ensure the rail base cavity is entirely filled, should be placed from one side of the rail to be certain no voids are formed in the base cementitious pour.

The second-pour trough filler, which completes the cavity fill, can be a concrete mix with a 20-millimeter (0.75-inch) aggregate size. Application of silicate fume ash to the concrete mix has proven beneficial in controlling stray currents. To control eventual concrete shrinkage cracks, polyethylene fibers 50 to 65 millimeters (2 to 2.5 inches) long can be included in the second-pour surface trough filler.

Both filler materials should have a minimum concrete strength of 27.6 MPa (4,000 psi) at 28 days.

Bituminous asphaltic components have been used as a trough filler material. Similar care must be taken during placement to be certain that voids are not generated at the rail support. Bituminous asphalt materials with resistivity characteristics can be used as an insulating barrier.

4.6.4.1.4 Embedded Track Drainage

In all but the driest climates, the success of any embedded track design will depend directly on the efficiency of the embedded track's drainage systems. This includes not only systems for intercepting surface runoff, but also methods for draining water that seeps into the rail cavity zone. Experience has shown that surface water will seep and accumulate in the rail area, particularly around the rail base and web. This moisture can cause rail corrosion and deterioration of the surrounding embedment material, eventually leading to failure of the pavement and the rail fastening system.

Drainage of the rail embedment trough or cavity is of the utmost importance. Sealing the interface between the rail and the adjoining embedment material is virtually impossible. Similarly, construction joints between the rail trough and slab concrete or surface sealants are susceptible to potential water seepage. Regardless of how well the surface sealants are designed and installed, seepage will eventually occur and possibly lead to deterioration or disintegration of the fill components, particularly in climates susceptible to freeze/thaw cycles. To prevent this, the embedment trough or rail cavity zone must be designed with a reliable permanent drainage system as shown in Figure 4.6.11.

Another penalty of poor drainage or no drainage is that trapped or standing water can result in unacceptable levels of stray current leakage, particularly in areas where streets are salted.

4.6.4.1.4.1 Surface Drainage. Embedded track installations complicate pavement surface drainage because the exposed rail head and flangeways intercept and redirect stormwater runoff. The road profile and cross slopes direct the runoff toward the rail and flangeways. In addition, if the roadway pavement is crowned in the conventional manner, the pavement cross slope results in the track being out of cross level in tangents and perhaps even negatively superelevated curves For additional information on surfacing and cross level refer to Chapter 3.

Whenever possible, the profile and cross section of the road should be modified to conform to the optimum track profile and cross section. This often requires that the roadway geometry be compromised to accommodate rail elevations, curb and gutter elevations, and sidewalk grades.

The surface runoff entering the flangeways should be minimized and trackway road surfaces should slope away from the rail locations. Some transit system designs have sloped the road surface within the track gauge area toward the track centerline and the "dummy gauge" zone to a line of drains midway between the tracks. The road surfaces on the field side of the rails should slope toward the curb line or the surrounding roadway surfaces.

Inevitably, some runoff will get into the flangeways. This water must be drained away. Transverse lateral drainage chases should always be provided at low points on vertical curves, immediately up-grade at embedded special trackwork and at transitions between embedded track and any open track design. Additional drainage chases should be provided periodically along straight track grade sections so that runoff, debris, sand, or other material can be carried away and the flangeway kept relatively clear.

Drains in embedded track areas are typically transverse drains or drainage chases perpendicular to the rails. They consist of a grate-covered chamber that is connected to the adjacent storm sewer system. The design of the rail through the drainage chase opening should consist of the exposed bare rail supported on each side of the chase, wherein the rail acts as a suspended beam. The bottom of the track flangeway must have an opening wide enough to ensure that it will not become clogged with leaves or other debris. This is easily undertaken with tee rail construction. If girder rail is employed, it is common to machine a slot in the bottom of the flangeway. Such slots typically cannot be much more than 25 to 30 millimeters (1 to 1.125 inches) wide. They also frequently get clogged. Where clogging is likely, an improved design might be to cut away the girder rail lip in the drainage chase area.

When the embedded track design includes individual longitudinal troughs in the concrete for each rail, the transverse track drainage chases can also drain seepage from the inner rail trough or rail cavity. The design exposes the end faces of the concrete rail troughs on each side of the drainage chase as shown in **Figure 4.6.12**. The exposed faces can be utilized as rail trough or rail cavity drainage systems. Frequent drainage chases, spaced less than 150 meters (500 feet) apart, should be considered and connected to the internal longitudinal drainage pipe system to provide adequate drainage and allow periodic maintenance flushing of the system.

The transverse trough drains should act as lateral drainage collectors for the embedded longitudinal drain pipes. The longitudinal drain pipes, opened at the trough drains, can also be used for periodic flushing of the embedded pipes. This provides a continuous and maintainable drainage system. Transverse trough drains should be placed immediately in front of switchpoint components to protect embedded special trackwork installations. Transverse drains in these locations collect water that drains toward the special trackwork In addition, the transverse drain can act as a dividing point between the different designs used in embedded main line track and special trackwork.

4.6.4.1.4.2 Internal Drainage. Embedded track systems require internal drainage of the rail cavity zone when loose extruded components or non-adhering trough fill materials are selected Polyurethane fill material totally encapsulating the rail and bonded to the trough walls does not appear to require internal drainage. Drainage slots perpendicular to the rail base should be provided for adequate drainage at the base of the rail or the bottom of the rail trough zone. Longitudinal drain pipes outside of the rail trough and fastening system should be provided to collect and carry accumulated water away from the rail cavity zone as shown in Figure 4.6.12.

4.6.4.2 Ballasted Track Structure With Embedment

Early 20th century embedded track designs for urban trams included ballasted track with timber crossties constructed to railway standards and subsequently embedded to the top of rail. These standards still exist today and are perpetuated by the original transit agencies, although contemporary embedded track designs are being contemplated.

Embedded track design using standard ballasted track design requires use of a fill material to the top of rail as shown in **Figure 4.6.13**. In contemporary track design, the negative return running rail must be insulated to control or confine stray current leakage.

Typical ballasted track elements used in embedded track design include an insulating barrier at the rail, tie plate and fastening to isolate the rail from the timber or concrete

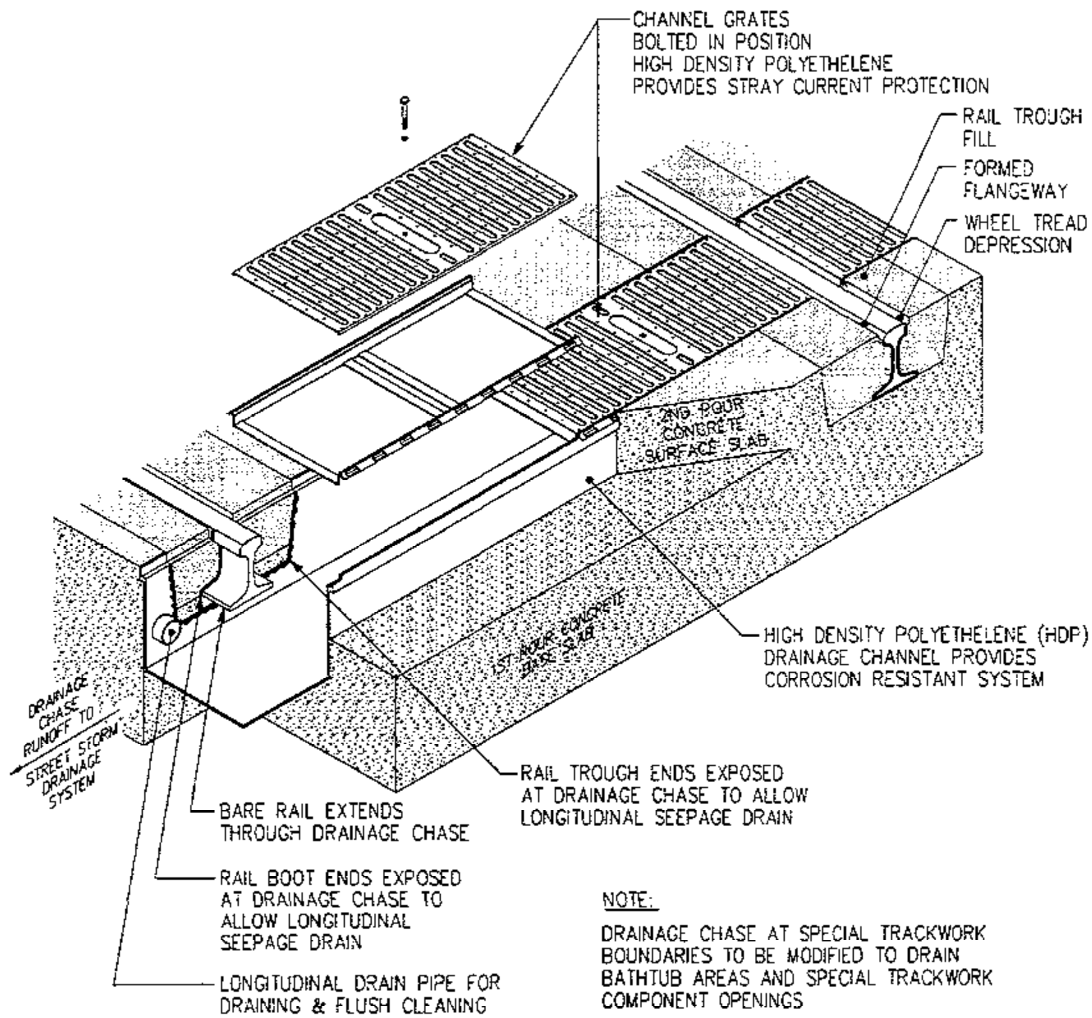


Figure 4.6.12 Cut Away Section Embedded Track Drainage Chase

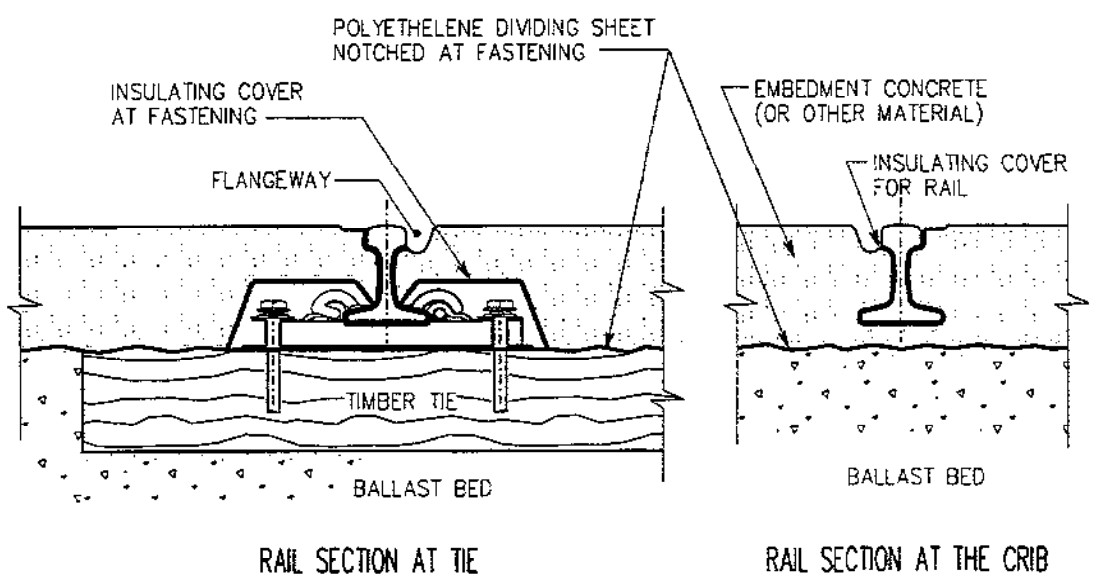


Figure 4.6.13 Ballasted Track Structure with Embedment

crosstie and the surrounding embedment concrete or other fill material.

The embedded ballasted track structure is a proven standard that provides a long, durable track life with minimal maintenance, other than rail grinding and occasional road surface repair for more serious deterioration. This longevity can be attributed to the built-in drainage system provided by the ballast and sub-ballast trackbeds. However, this drainage system also experiences ballast abrasion and settlement that degrades track performance. Embedded ballasted tie track has a history of inferior rail and road surface alignment. This includes rails sinking below the top of the embedment or road surface, fracturing of the embedment surface especially at the designated crosstie spacings, concrete surface fractures, and bituminous concrete surface cracks and sagging between crossties.

Embedded ballasted tie track installed with an independent roadway surface such as brick, pavers or Belgian Block with a sand mortar were relatively successful. The success of the old systems, it is believed, was due entirely to the flexibility of the brick and blockstone pavements and their resultant ability to adjust to vehicle loads and thermally induced movements. The key to this was the use of hot tar to seal the joints between the pavers, thereby excluding most moisture. The down side was extensive electrolytic corrosion due to the base of rail being in contact with ballast and the sand bedding of the pavers. Their performance in this regard might be improved by an insulated bathtub design.

4.6.5 Embedded Special Trackwork

The embedded special trackwork portion of any transit system will require special treatment and quite possibly a different design concept from the main line embedded track design.

In contemporary light rail transit systems, embedded special trackwork generally consists of turnouts grouped to act as single crossovers for alternate track operations. Operating requirements may dictate the installation of a double crossover with four turnouts and a crossing (diamond). An extensive embedded track transit system could utilize complex embedded special trackwork arrangements beyond simple single and double crossovers. For additional information on embedded special trackwork design, refer to Chapter 6.

The magnitude of the components, the requirements for stray current protection, and the need to secure the components dictate special trackwork embedment design. Stray current protection at the rail face, as well as component surfaces with irregular configurations, potential gauge bars and gauge plates, may be difficult. To simplify the installation, the bathtub design concept is recommended for embedded special trackwork.

The bathtub design allows for stray current protection to be clear of the special trackwork switches, frogs and crossing (diamond) components. This simplifies trackwork installation and improves stray current protection as shown in **Figure 4.6.14**.

Embedded special trackwork will also require the use of special plates to support the various track elements. These must be designed to develop uniform deflections.

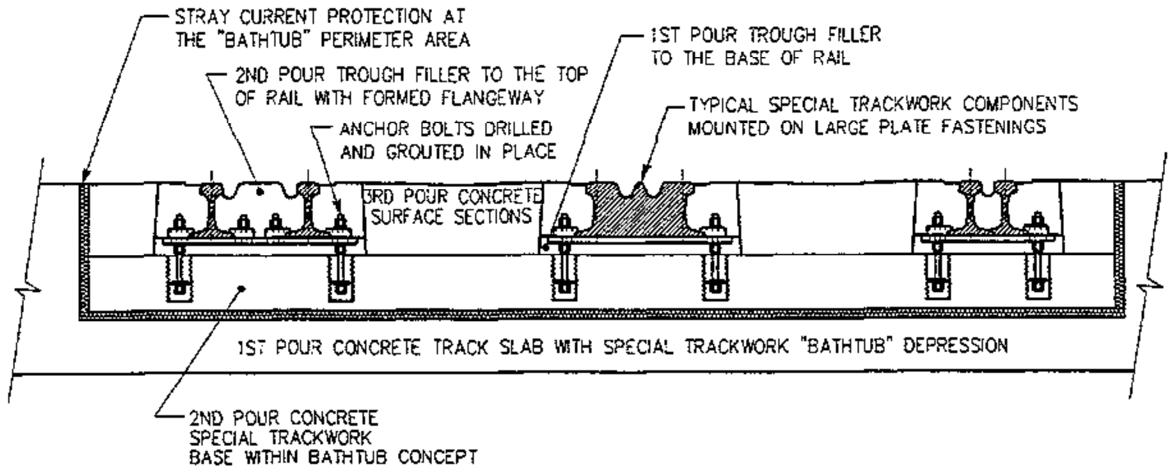


Figure 4.6.14 Special Trackwork—Embedded "Bathtub" Design

4.6.6 Noise and Vibration

Vehicle wheel loads are transmitted from the wheel/rail interface to the track structure. Unlike ballasted or direct fixation track with load distribution to the ties or fasteners, embedded track uses a concrete slab and continuous elastomeric system to distribute the load throughout the surface of the rail base. This design concept spreads the load more evenly along the resilient rail installation. Embedded track with a fully supported rail base provides an improved track structure.

Resilient elastomers dampen the rail, reducing rail vibration and rail-radiated noise. The resilient elastomer controls the degree of vibration and deflection. A softer elastomer provides a lower spring rate in the elastomer material, leading to reduced vibration in the rail .

The spring rate is used in determining the track modulus or track stiffness and the amount of vertical deflection in the rail. The elastomer, in conjunction with the vehicle suspension system, affects the vehicle/rail interface – specifically, track performance, noise, and vibration in the immediate rail area.

Noise and vibration control should be considered in the vehicle truck design, particularly with respect to the use of resilient wheels and the details of the primary suspension system. The primary suspension is located between the journal and the truck frame. The primary suspension characteristics are dependent on the spring elements, number of layers or total deflection, and their angular formation. The elastomeric spring of the suspension reduces noise by acting as a vibration isolator. It also acts as a barrier to the transmission of structure borne noise.

In selecting the suspension characteristics of the extruded elastomer, elastomeric base pad, or the rail boot elastomer used to support the rail, vehicle parameters such as normal weight and crush loads must be considered. Each light rail vehicle, with different truck suspensions, wheel bases and weights, may require a different track dynamic suspension system. The advice of a noise and vibration expert in this endeavor is recommended as stated in Chapter 9 of this Handbook.

4.6.7 Transit Signal Work

Transit signal requirements in embedded track sections differ from the general design standards for ballasted and direct fixation track. Embedded track within city streets or transit malls may be exposed to mixed traffic conditions and may share the right-of-way with automobiles, trucks and buses. Signal equipment, such as switch machines or loops for train-to-wayside signals, may need to be installed in this area. Space must be provided to mount these devices as well as drainage pipes and conduits for cables to control these devices. Conduits for power and track circuits may be needed. Reinforcing bars in the concrete may impact the reliable operations of track circuits.

4.6.8 Traction Power

Traction power requirements in embedded track sections differ from the standards for ballasted or direct fixation track. The immediate traction power impacts of catenary pole location and isolation of the negative return rail play a major part in embedded track design. Embedded track areas in downtown business sections, on city streets and in transit malls generally avoid positioning catenary poles between the tracks. The issue of catenary poles within central business districts is so controversial that, in many designs, the contact wire and catenary system was suspended from the sides of existing buildings or on poles in sidewalk areas. The total system and track design must consider catenary pole locations that blend into the existing environment without severely impacting the current roadways, sidewalks and general public's perception of an area. The tight track curvature within central business districts also impacts the design and installation of the catenary system, because many more poles are needed to ensure that the contact wire remains near the track centerline.

The traction power return system definitely impacts the design of the rail installation in embedded track. Unlike ballasted and direct fixation track standards, where the rail is actually insulated from the ground at the base of rail or within the fastening system, the entire rail surface except top of rail and gauge face must be insulated in embedded track designs This requirement contributes to the challenge of designing embedded rails that provide an insulated, resilient and durable track system using off-the-shelf materials.

Embedded ductwork within the track structure provides access for power cables and cross bonds to achieve equalization in the rails.

For additional information on stray current control and traction power, refer to Chapters 8 and 11, respectively.

4.6.9 Typical Embedded Concrete Slab Track Design Guideline

The previous sections describe the various embedded track concepts, designs, and materials available to the track designer. The track designer must develop a set of installation drawings and corresponding specifications to allow for construction of the embedded track segments of the transit system. These must reflect an understanding of the various track and vehicle parameters.

A typical embedded track design guideline follows. The design described herein is arbitrary; actual track design should be developed by the track designer based on site-specific requirements, economics, and aesthetics to match the environment. The goals of embedded track design are to produce a track system that provides long-term performance, with a minimum of interference to the neighboring structures, and is relatively easy to maintain or replace.

The embedded track design guideline is illustrated in **Figure 4.6.15**. The author, as a track designer, selected this embedment arrangement for the following reasons.

- This embedded track design allows for shared street operation with other vehicles or may be used in a pedestrian mall.
- The vertical and horizontal position of concrete base slab is established by survey, using the constructed skeleton track method.
- The concrete base slab first pour encases the steel ties or leveling beams and individual tie plates, as well as anchor bolts. This creates a cold joint at the base of rail.
- After the base slab is poured and cured, the track is available for vehicle testing and operation
- The forming of two rail troughs provides a joint that facilitates concrete removal for replacement of worn rail.
- The use of a rail boot or other insulating elastomeric system is needed to isolate the rail The rail boot is shown, but any of these systems may be equally effective.
- The elastic spring clip arrangement simplifies the rail hold down and provides a degree of rail base flexure

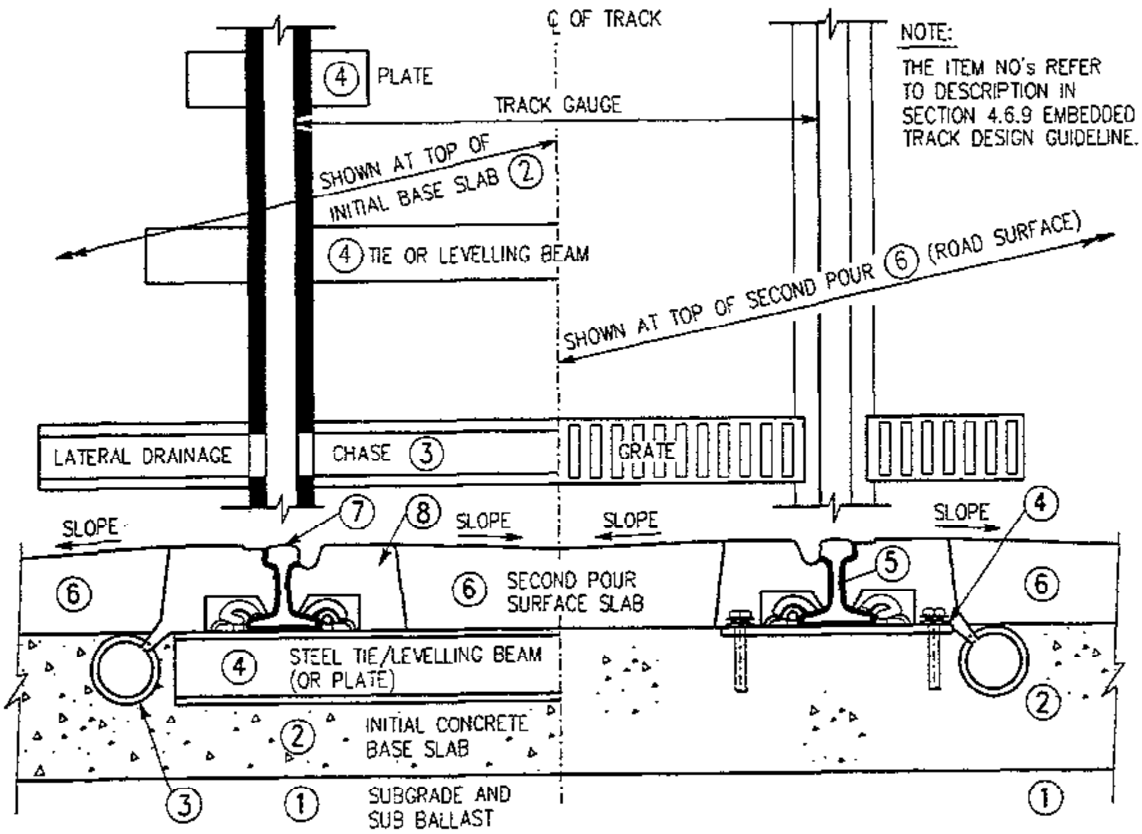


Figure 4.6.15 Typical Embedded Track Design

- The protective covers over the rail fastening components allow for their reuse at the time of rail replacement. The intent is to retain the steel ties and individual plates in the base slab pour, allowing for similar rail section positioning and rapid replacement. This facilitates a quick return to revenue service operations.

The following notes are meant to augment the detailed embedded track design shown in Figure 4.6.15. The item numbers refer to the component number in the figure.

Item 1 This includes the well-compacted subgrade and sub-ballast system with an adequate storm drainage system connected to existing or new street storm drains. A protective barrier sheeting, styrofoam barrier, or rockwool batts at the top of sub-ballast system may be considered for vibration and noise attenuation.

Item 2 a The reinforced concrete base slab (first pour) should have a minimum thickness of 300 to 350 millimeters (12 to 14 inches), to act as a vibration absorption barrier and provide support to the track structure.

b The base slab may be a single- or double-track configuration as needed for specific street configurations. Concrete pours may be single or double track, depending on track centers.

c The concrete base slab contains an internal longitudinal track drainage runoff system with provisions for deeper transverse track drainage chases.

d The concrete base slab encases and secures the embedded track rail fastening system.

e The base slab has concrete placed up to the base of rail or resilient boot. This provides a construction cold joint between the first and second concrete pours, just below the trough fill material embedding the rail. The finished base slope in the trough zone should be sloped toward formed drainage slots.

Item 3 a. The embedded track drainage system built within the concrete base slab consists of transverse track drainage chases and a longitudinal drainage system at the rail cavity zone.

b. The transverse track drainage chases are placed at 150- to 200-meter (500- to 650-foot) intervals and strategically positioned at vertical curve sags, special trackwork approaches, and the ends of embedded track locations. These control surface runoff and internal rail cavity drainage.

c. The transverse track drainage chases act as lateral runoffs for the embedded longitudinal rail cavity drain pipe system.

d. The concrete base slab contains a longitudinal drain pipe and periodic drain slots parallel and adjacent to the rail to drain the rail zone.

e The longitudinal drain pipe should be positioned clear of the rail fastening system.

f. Drainage systems that are invisible once the construction is completed will almost never receive the maintenance attention required The ease of maintenance is critical to a successful system.

Item 4 a. The rail fastening system consists of steel ties and individual steel plates with appropriate spring clips, welded shoulders, protective insulators for rubber boot, and a protective housing for the spring clip area.

b. The steel tie is embedded in the initial concrete base slab with the top of tie level with the top of concrete pour. The steel plates should similarly be embedded to the top of concrete. The steel plates are secured to the initial concrete base slab by anchor bolts or studs.

c. The concrete finish in the rail base area between the steel tie and plates is trowelled smooth.

Item 5 a. The rail is encased in a resilient elastomer boot or liner, positioned on the steel tie rail seat area and the individual mounting plates. The rubber booted rail is fastened to the ties and plates by spring clips. The clips have rubber protective rail base insulators at each shoulder.

b. Rail deflection is provided through the resilient rubber boot liner and minor deflections of the spring clips.

c To allow for rail deflection and movement at the spring clips, a special protective cover is installed providing a void in the trough embedment material.

d The insulating rubber boot must be a continuously bonded system, utilizing connector splices overlapping the boot configuration. To promote internal boot drainage of the zone between the rubber boot and rail surface, special drain hoses are incorporated. The drain hoses are positioned in the existing drain slots adjacent to the rail trough. They project into the center of the PVC longitudinal drain pipe, to provide the required stray current protection.

e. The resilient elastomer rail boot must be continuous, providing a void or holiday free insulation system to retard stray electrical current leakage.

Item 6 a The surface slab (second pour) is approximately 180 millimeters (7 inches) high and is placed to the top of rail Block outs for rail troughs are formed. The surface finish is determined by specific transit requirements, architectural treatment and the type of roadway traffic or pedestrian mall.

b. The top surface is finished with slopes away from the rail cavity toward the centerline of track and the field side of rail. These sloped portions within the track gauge drain longitudinally along the track to the transverse drainage chases.

c. The placement of the surface slab completes the longitudinal drainage slots from the rail cavity to the longitudinal drain pipe.

d. The top concrete surface slab requires embedded PVC casings for traction power or signal connections between the rails or tracks. Provision should be made for rail connection boxes, drainage boxes and periodic transverse drainage chases.

Item 7 a. The running rail is insulated for stray current control utilizing the rail boot concept The running rails can be either tee rail or girder groove rail.

b. The running rail is continuously welded rail (thermite welded or flash butt) wherever practical. Precurving of the rail may be required to facilitate restricted street alignments that result in sharp track curvature. The weld finish is flush with the parent rail steel surface to allow for proper boot fit.

c. Various trackwork accessories adjacent to the rail must be individually designed to suit the rail boot insulation in order to minimize electrical stray current.

d. The booted rail is checked for insulation, clip application, and the track position is confirmed prior to application of the protective housing and the installation of trough fill.

Item 8 a. The rail trough embedment concrete fill (third pour) is placed only after confirmation that rail installation is correct. The embedment encapsulates the rail and fastenings completing the surface roadway.

b. The surface finish includes a gauge side flangeway for tee rail or entire capsulation to the top of the girder rail lip. The field side has a depression of 6-millimeter depression (0.2- inch) throughout, with special depressions in the fixed adjacent trackwork accessories. This allows for rail grinding.

c. The surface slopes beyond the flangeway and wheel tread depressions slope away from the rail head. Track gauge pavement slopes intersect at the center of track. Field side pavement slopes away from the rail area towards the curb lines.

These design concepts are representative of the type of considerations required to design embedded track. An alternate set of parameters will require a similar design process to coordinate and interface the various disciplines involved. The key design features of any track installation include adequate drainage, corrosion control, insulating protection, noise and vibration abatement measures, and accommodation for signal and traction power components. Understandably, the track design and vehicle design must be compatible for the development of a successful transit system.

4.6.10 Turf Track: Another Type of Embedded Track

Over the years, European light rail transit systems have found a need to blend the transit track and system into the landscape. To fulfill this requirement, a specific track design similar to embedded track or partially embedded track has evolved, recognized as "turf track." The turf track standard consists of concrete plinths or beams running parallel under the rail to support the track. The rail is installed on elastomer base pads. The rails are connected to retain gauge with conventional gauge rod bolted to the web of the rail. The base of rail is not connected to the concrete plinth. The rail web area is filled with a prefabricated filler block that adheres to the rail. The top of the rail and the filler block is sealed with a bituminous sealant. The vegetation is a special blend of plants expected to retain a stunted growth and require minimal cutting. The filler blocks and the bituminous sealant provide the stray current protection. **Figure 4.6.16** shows a typical turf track installation.

Many European cities appear to be adopting turf track or track landscaping as one of their main standards. Landscape embedded track was developed for selected purposes:

- Reduce the visual effect of ballasted track
- Reduce the noise from trams to the utmost extent
- Provide year-round greenery in the vicinity of the track

A select turf is required to grow to a maximum height of 30 to 40 millimeters (1.2 to 1.6 inches) requiring minimal watering and maintenance. Landscape track has proven to reduce noise by 6 to 8 dBA. Other types of landscape track structure can be designed to suit the needs of specific locations. To ease the concerns of communities and residents along certain sections of the light rail system about transit-related impacts, turf track or some specific track design may prove to be very beneficial.

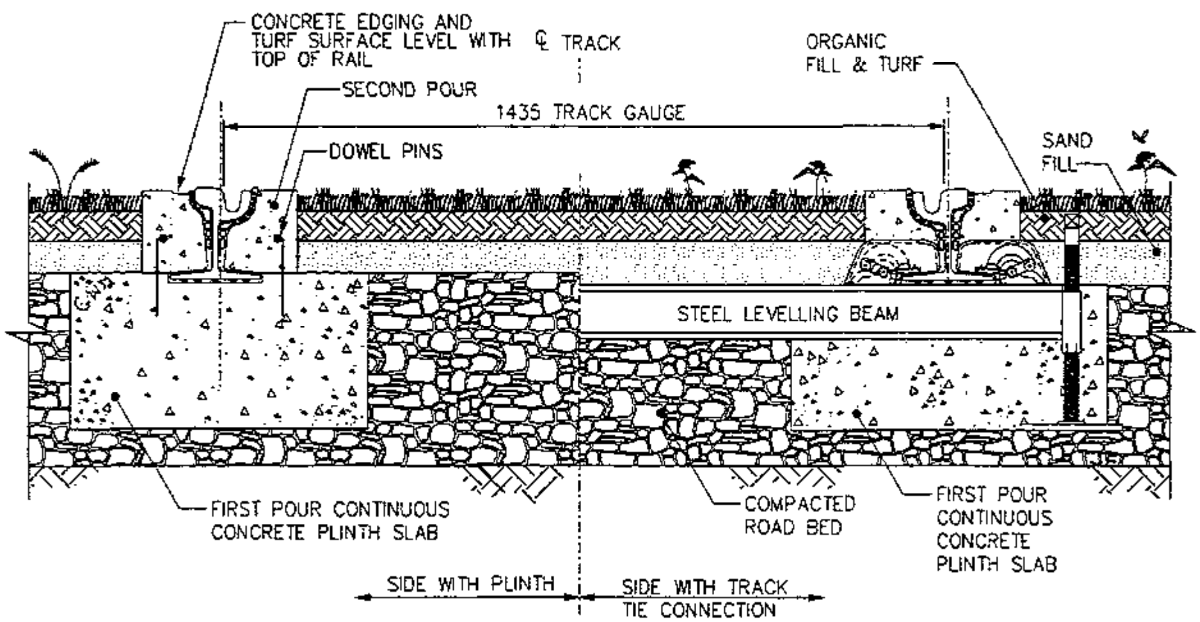


Figure 4.6.16 Turf Track—Another Type of Embedded Track

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