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DESIGN OF TRACK TRANSITIONS

This digest summarizes the results of TCRP Project D-7/Task 15. The digest was prepared by the Transportation Technology Center, Inc. (TTCI) in Pueblo, Colorado. David Read and Dingqing Li served as principal authors.

CONTENTS

INTRODUCTION

This digest reviews and analyzes various track transition designs among ballasted and nonballasted track forms and structures and offers guidance to improve track and operating performance. The research is based on similar work conducted for freight railroads, modified, as necessary, for the transit operating environment. The results should be of interest to engineers involved in the design, construction, maintenance, and operation of rail transit systems.

SUMMARY

In rail transit systems, at-grade ballasted track frequently changes to a nonballasted track configuration or to ballasted track on a structure. The abrupt change in track support that can occur at these locations is often associated with accelerated rates of track geometry and component degradation, high maintenance demand, and poor ride quality. Accordingly, a number of techniques have been proposed to improve track performance by providing a transition to smooth the stiffness interface between the dissimilar track types. A review of typical transition designs, as found in the existing literature, and analyses of representative designs are the subjects of this digest.

A review of published material dealing with track transition problems and solutions was undertaken as the initial phase of the study. The literature indicated that transitions were designed to (1) equalize the stiffness and rail deflection of the ballasted and nonballasted tracks, usually by controlling the resilience of the rail on the nonballasted track, or (2) provide a gradual increase in the stiffness of the ballasted track to match that of the nonballasted track.

Several designs seek to increase the stiffness of the ballasted track by placing a structural element, such as concrete slabs or an asphalt pavement layer, between the track granular layer (ballast/subballast layers) and the subgrade. These structural layers are generally tapered or stepped to allow a gradual increase, or ramping up, of the stiffness within about 20 ft of the nonballasted track interface.

Other designs seek to match the stiffness/deflection characteristics of the nonballasted track to the ballasted approach track using elastomeric pads at the rail seat or beneath the tie plates. This technique requires measurement of the ballasted approach track to determine its nominal stiffness and track modulus values and testing of the rail/tie pad stiffness characteristics to ensure that the pad stiffness matches the approach track modulus at the

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appropriate wheel loading. Elastomeric materials have also been placed on the bottoms of ties installed on ballast deck bridges to equalize the stiffness/deflection of the bridge and approach tracks.

The following performance improvements were noted in case studies from the literature review:

- Use of longer ties and a concrete approach slab by the Metropolitan Atlanta Rapid Transit Authority (MARTA) to transition from ballasted at-grade track to direct-fixation structures.
- Transition from at-grade ballasted track to a direct-fixation structure on a commuter/intercity passenger service railway in the United Kingdom using an approach slab along with vertically adjustable direct-fixation fasteners to allow design tamping of the ballasted approach track.
- Installation of stone columns to strengthen and improve the drainage of a weak bridge approach subgrade on a Union Pacific main line.
- Use of a transition grade crossing system designed to smooth the track modulus across the approach to a highway crossing and reduce impact rail loads at the crossing on New Jersey Transit's Atlantic City line.
- Installation of tie pads on open wood-tie bridge decks having stiffness/resiliency characteristics designed to match the track modulus of the approach track on Amtrak's northeast corridor (NEC) and on a Norfolk Southern mainline with freight/intercity passenger service.
- Reducing the track modulus on a Union Pacific ballast deck bridge by replacing the existing concrete deck ties with composite (plastic) ties or with concrete ties with a rubber pad cast into the tie bottom.

The importance of following geotechnical best practices regarding soil selection, compaction, and drainage of the approach subgrade was also discussed in a number of papers, especially highway research papers. A properly designed and constructed subgrade will have a nominal stiffness adequate for the applied load environment, will tend to perform consistently through wet and dry cycles, and will not be prone to differential settlement. These attributes make it easier to match the vertical response of the at-grade track and the track on a structure.

It should be made clear that much of the literature reviewed was based on research performed on freight and intercity passenger tracks. There was not much literature generated from transit research. Although the higher wheel loads and speeds of freight/intercity rail traffic create more intense track transition problems than rail transit, the basic track performance issues are similar. Therefore, the experiences and results of research projects involving freight and intercity passenger tracks are considered applicable to the transit environment.

Following the literature review, a number of representative track transition designs were analyzed using the GEOTRACK computer model. GEOTRACK is a well-established and validated model that predicts a quasi-static response of the track to an applied vertical wheel load.

The analysis produced track modulus and vertical rail deflection values for a variety of track configurations: wood and concrete ties on low-, average-, and high-stiffness subgrades; at-grade track with concrete approach slabs and hot mix asphalt (HMA) underlayment; direct-fixation track with typical fastener pad vertical stiffness values; open deck bridges with wood ties; and ballast deck bridges with concrete ties.

Three wheel loads considered to be representative of the rail transit environment were analyzed: 12,000, 15,000, and 22,500 lb. The 12,000-lb load was intended to represent light rail operations, the 15,000-lb load is the static weight of a Metro North cab car with full seated passenger load (Kentner et al. 1994, p. 270), and the 22,500-lb wheel load represents the Metro North static wheel load plus a 50% dynamic factor.

Results of the GEOTRACK analysis were as follows:

- Matching the rail deflection on direct-fixation track to the deflection of the at-grade ballasted track, through careful design and specification of the direct-fixation fastener vertical stiffness, provides the best possibility for an effective and seamless transition between the two track configurations. However, ballasted track on low-stiffness subgrades also requires strengthening with either a concrete approach slab or HMA underlayment to match the direct-fixation track. Otherwise, the pad stiffness of the direct-fixation track would need to be unreasonably low.
- A concrete approach slab placed between the ballast and subballast layers was the most ef-

fective technique for increasing ballasted track stiffness. HMA underlayment installed between the ballast and subgrade also produced benefits to low-strength track, but it was not as effective as concrete in increasing the stiffness of track on very low-stiffness subgrades.
- Increasing the subgrade stiffness reduced the differences between concrete slab and HMA layer thicknesses.
- Placing additional rails on the ties of the ballasted track to increase the stiffness of the track panel had modest benefits for low-stiffness subgrades. This condition often exists when bridge guard rails extend past the abutment onto the approach track.
- Other changes to the track superstructure, such as reduced tie spacing, installation of longer ties, or installation of ties with larger cross sections had an insignificant effect on track modulus or rail deflections and, therefore, would not be especially effective transition designs.

BACKGROUND

The metropolitan environments in which rail transit systems operate require the placement track not only in at-grade ballasted configurations, but also on bridges and elevated structures and in tunnels and street pavements. Locations where the at-grade ballasted track changes to a structure are often associated with accelerated rates of geometry and component degradation, high maintenance demand, and poor ride quality. In addition to deterioration of the track surface, alignment, and cross level, component problems can include exposed tie ends and reduced crib ballast from ballast migration, tie skewing and bunching, cracked concrete ties, accelerated plate cutting of wood ties, gage widening and loss of rail cant, deterioration of ballast from pumping and frequent tamping, and accelerated rail surface fatigue.

The track interface at bridge abutments, grade crossings, slab/embedded track, and turnouts/rail crossings are potential problem areas, and it is generally recognized that effective transition designs may be required to optimize track performance at these locations.

This digest presents the results and conclusions of an investigation into track transition designs. The investigation included a review of available literature from the railway industry and an analysis of designs thought to be representative of, and applicable to, the rail transit environment.

DEFINITIONS

Definitions for terms used throughout this digest are listed below.

Approach Slab—A reinforced concrete slab installed as a structural element in the track substructure to increase the stiffness/modulus of the track. Most slabs are reinforced concrete and are designed either with a taper to gradually increase the stiffness over an approach distance of about 20 ft, or are uniform in thickness but placed at an angle with tapering of the ballast depth to achieve the same ramping effect.

At Grade—Track that is constructed on a prepared soil subgrade foundation.

Ballasted/Nonballasted Track—Ballasted track has a layer of aggregate between the ties and the subgrade to distribute the applied wheel loads to the underlying layers; provide vertical, lateral, and longitudinal resistance to track panel movement; to drain moisture away from the ties; and to facilitate surfacing and lining of the track. Ballasted track is usually at grade, but it may be located on a structure (as in the case of ballast deck bridges). Nonballasted track designs vary, but, in the context of this digest, nonballasted track will be considered to be a direct-fixation track form.

Damping—The capacity to attenuate, diminish, and/or control oscillations or deflections of an element of a system expressed as a unit of force that is dissipated per unit of distance and unit of time (lb/in./sec). Track damping is provided primarily by the resilience of rail seat and tie pads, by the resilience of the ballast layer, and by the friction between ties and ballast. Track that is highly resilient has more damping than track that is less resilient.

Deep Pile Foundation—Foundations of aerial structure that are driven to bedrock.

Design Tamping—A track surfacing technique developed in the United Kingdom in which the track is over-lifted to compensate for the rapid rate of initial settlement.

Direct-Fixation Track—Nonballasted track in which the rail is mounted directly to a concrete base—such as the deck of an aerial structure, a tunnel invert, or an at-grade slab—with a direct-fixation fastening system.

Elastomer—Polymer materials having the elastic properties of natural rubber.

Fastener Stiffness—The combined stiffness, expressed as the unit of applied force per unit of deflection (lb/in.), of the fastening system and the tie at a specific applied load. For wood-tie track with steel-tie plates and no tie pads, the fastener stiffness is basically the compressibility of the wood. Fastener stiffness of concrete-tie track is primarily the stiffness of the rail seat pad and pads on the tie bottom, if used. The stiffness of concrete-tie pads can vary between 300 and 2,000 kip/in. Fastener stiffness on direct-fixation track consists of the resilience of the elastomeric elements of the fastening system. Typical direct-fixation track fastener stiffness values are between 100 and 300 kip/in.

GEOTRACK Model—A computer model that represents the track as a multilayered elastic structure and predicts the quasi-static response of the track to an applied wheel load. Input parameters include rail, tie, and substructure layer definitions as well as wheel load. Output parameters include rail deflections, track modulus, tie/ballast/subgrade pressures, and tie bending moments. Reference is made to GEOTRACK several times in this digest's literature review (see "Track Transition Literature Review") and is the basis of the analysis described in the section titled "Analysis of Representative Track Transition Designs." A more detailed description of GEOTRACK is also included in this section.

Hot Mix Asphalt (HMA) Underlayment—A layer of asphalt pavement that is installed in ballasted track as a structural element in the substructure to increase the bearing capacity of the subgrade. Typical HMA layer thickness varies between 8 and 12 in. and can be installed between the ballast and subballast layers or directly on the subgrade in lieu of a granular subballast layer. HMA is a mixture of aggregate and bitumen, and its stiffness properties can be designed by varying the ratio of the constituents and the aggregate particle size distribution. Recommended use of HMA in the rail transit environment is available online from the Asphalt Institute.

Resilient Modulus (E_r)—A geotechnical parameter that is expressed as a unit of force per unit of area (ksi) and is used to define the elastic response of a soil to load. In the context of this digest, E_r can be thought of as being equivalent to the modulus of elasticity. Typical values range from 2 ksi for a low-strength soil, such as a high-plasticity clay, to 20 ksi for granular soil that has been placed at optimum density. E_r is also used to describe the resilient behavior of aggregate materials such as ballast and pavements.

Track Stiffness/Track Modulus—Track stiffness is the ratio of an applied vertical force to the vertical deflection of the rail and is expressed as a unit of force per unit of deflection (lb/in.). Track modulus is the supporting unit of force per unit length of rail per unit rail deflection (lb/in./in.). Track stiffness includes the bending stiffness of the rail, whereas track modulus is concerned only with the support condition below the rail. A further discussion of these parameters is included in the section titled "Track Stiffness and Modulus."

TRACK TRANSITION LITERATURE REVIEW

Track transition issues affect all types of rail operation, and a number of papers have been written defining the causes and/or proposing solutions. The results of a limited number of case studies have also been documented. The purpose of this section is to summarize the existing literature in terms of problem definitions, case studies, and recommended designs and proposed mitigation techniques. Please note that although a few papers are specific to rail transit, much of the existing literature is related to the freight and intercity passenger rail environments.

Problem Definition

According to Li and Davis (2005) and Li et al. (2003), track transition problems, specifically problems at bridge approaches, can be attributed to the following factors:

- An abrupt change in the vertical stiffness of the track causes the wheel to experience an equally abrupt change in elevation because of the uneven track deflection. The change in elevation causes vertical acceleration of the vehicle mass that generates an increase in the applied loading. This mechanism can be self-perpetuating as the dynamic loads increase the differential deflections and settlement leading to even higher forces (Kerr and Moroney 1993; Frohling et al. 1995; Hunt and Winkler 1997). The effect of the load increase depends on the direction of the train. When the train is moving from a higher to a lower stiffness condition—such as exiting a bridge deck, grade crossing, or tunnel invert—the dynamic load is applied to the lower-stiffness track, increasing the rate of settlement. This condition is characterized by deterioration of the track geometry, ballast migration, and tie movement on the lower-stiffness track, as shown in Figure 1. When the train is moving from a lower- to higher-stiffness track, the load increase occurs on the high-stiffness side of the transition over a short distance and is more of an impact loading. In this situation, typical problems are rail surface fatigue, tie deterioration, and rail seat pad deterioration as Figure 2 shows. In addition to the track stiffness change, the damage potential at track transitions is related to vehicle axle loads, speeds, and suspension characteristics.

- Even if the dynamic effects are minimal, at-grade ballasted track may inherently settle more than ballasted track on a structure or direct-fixation track, creating a dip in the surface at the transition. This is especially true when the structure abutment is built on a deep pile foundation where settlement is negligible.
- Settlement of at-grade track can be highly variable because of geotechnical issues affecting the subgrade performance such as low-strength soils, deficient soil placement and compaction, poor drainage, and erosion (Briaud et al. 1997; Smekal 1997; Hoppe 2001). Environmental factors such as wet/dry and freeze/thaw cycles also affect subgrade settlement behavior.

Sasaoka and Davis (2005) categorize track transition problems and solution approaches in terms of differential settlement, track stiffness, and damping changes that are intrinsic to the different structures.

Figure 1 Typical differential settlement of a freight railroad ballasted track bridge approach.

Figure 2 Cracked concrete ties at the abutment of a freight railroad ballast deck bridge caused by impact loads.

Using analytical techniques, an optimum damping value of 300 lb/in./sec/tie/rail was suggested for railway track that is adequately resilient and capable of efficiently distributing dynamic loads, particularly the higher-frequency impact loads. Field tests, however, showed a value of 50 lb/in./sec/tie/rail to be typical of stiff structures such as ballast and open deck bridges. Increased track damping on these structures will attenuate the dynamic loading at transitions.

It is clear that the above issues are related and whether considered from the viewpoint of uneven track stiffness and deflections or differential settlement driven primarily by geotechnical conditions, the goal of any technique intended to improve the performance of transition track is to minimize dynamic loads by equalizing or smoothing the vertical support condition and the dissipation of dynamic energy across the transition.

Track Stiffness and Modulus

This section briefly discusses the terms "track stiffness" and "track modulus." Track stiffness (k) is the ratio of the applied wheel load (P) to rail deflection (y):

$$k = P/y$$

Hay (1982) and others define track modulus as the supporting force per unit length of rail per unit deflection. The relationship between track stiffness and track modulus is defined with continuous beam on elastic foundation analysis as

$$u = (k)^{4/3} / (64EI)^{1/3}$$

where

u = the track modulus (lb/in./in.),
E = the rail modulus of elasticity, and
I = the rail moment of inertia.

It is important to note the fundamental difference between track stiffness and track modulus: track stiffness includes all track components, including the rail, whereas the track modulus calculation excludes the flexural stiffness of the rail and only represents the rail support condition. Track modulus is considered to be an important indicator of track quality and strength and is a required term in many track design calculations.

Although ballasted track modulus is not often measured directly, as is the case with track geometry, measured track modulus values that have been published for specific track configurations in the freight operating environment (Kerr and Moroney 1993; Hay 1982; Read et al. 1994) indicate that moduli of 2,500 lb/in./in. or higher are typical of stable track structures, and values less than 1,500 lb/in./in. would be indicative of track prone to significant rail deflection and rapid track geometry degradation. To equate these numbers to rail transit, reference is made to Chapter 4 of *TCRP Report 57: Track Design Handbook for Light Rail Transit,* in which similar values are listed (Parsons Brinckerhoff Quade & Douglas, Inc. 2000). *TCRP Report 57* gives typical modulus values for good-quality, timber-tie ballasted track as 2,000 to 2,500 lb/in./in. and 5,000 to 8,000 lb/in./in. for concrete-tie track.

Extremely high track modulus can also adversely affect track performance. According to Redden et al. (2002), track modulus values higher than 10,000 lb/in./in. are undesirable because of the propensity for increased dynamic loads. Because the track is a resilient load distribution system, a decrease in resilience caused by a stiff support condition also decreases the transfer of wheel loads to adjacent ties, thereby increasing rail seat forces and ballast pressures. Lack of resilience also tends to amplify impact rail forces that are generated by wheel and rail surface anomalies and the high-frequency rail vibrations associated with them. These high-frequency vibrations are often associated with corrugation development (Ahlbeck 1990; Hay 1982) and can generate undesirable noise and vibration conditions.

As stated, track modulus represents the overall stiffness of the rail support system including rail fasteners and pads, ties, ballast, and subgrade. A parametric study performed by Selig and Li (1994), using the GEOTRACK model, indicated that stiffness of the subgrade was the most influential parameter of ballasted track modulus. Secondary influence parameters included the granular layer (ballast and subballast) thickness, rail fastener pad stiffness, and tie type (wood or concrete). Tie spacing and tie dimensions had minimal influence on the modulus. These findings implied that (1) maintenance activities not directly related to improvement of the subgrade, such as surfacing and tie renewals, will not significantly affect the track modulus and (2) environmental conditions that may affect subgrade properties and strength, such as wet/dry and freeze/thaw cycles, can substantially change track modulus on a seasonal basis.

The modulus of direct-fixation track is almost entirely a function of the stiffness and resilience of the elastomeric elements in the rail fastening system. The modulus of direct-fixation track is, therefore, much more consistent and easier to estimate than that of at-grade ballasted track.

Transition Problems Test Results

The following section presents the results of tests sponsored by the Association of American Railroads and the Federal Railroad Administration on freight railroad transition problems.

Track Geometry Degradation (Differential Settlement)

Figure 3 shows a comparison of the results of tests on average track settlement on four ballast deck railroad bridges and their approaches (Li and Davis 2005). As illustrated, the approaches experienced more track geometry degradation than the tracks on the bridges and the open tracks. The settlement of the track on the bridges was approximately one-third of the settlement from the bridge approaches. Figure 4 further illustrates the differential nature of track settlement in the approach

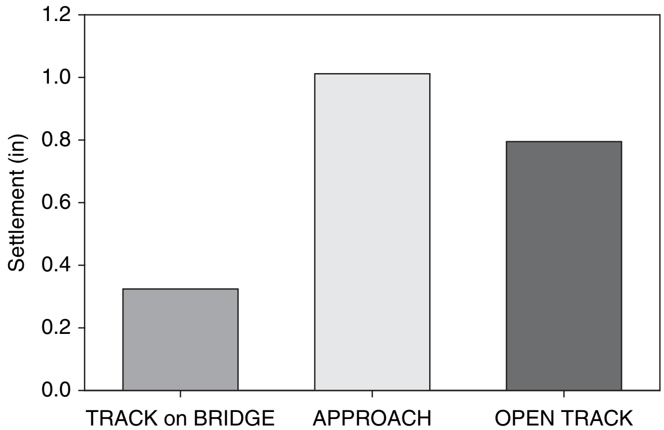


Figure 3 Comparison of track settlement accumulated over a maintenance interval (elevation change of unloaded rails).

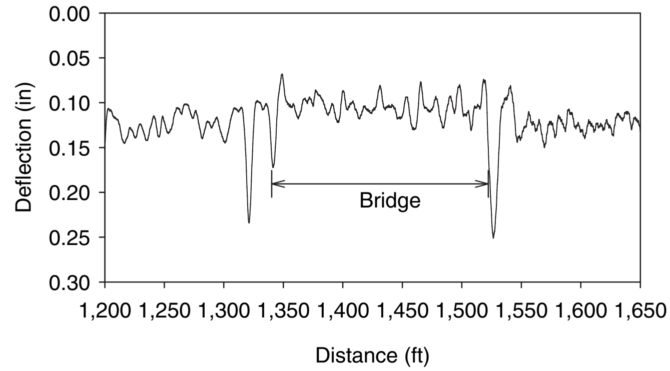


Figure 5 Loaded track deflection profile.

areas (settlement results versus distance from the bridge abutment).

Figures 3 and 4 show accumulated track geometry degradation (differential track settlement). These results were measured from the unloaded rail surfaces using survey equipment. Figure 5 shows the deflection profile results obtained under the TLV (Track Loading Vehicle) moving test load (40-kip wheel load) for one of the four sites tested. The results were obtained after a surfacing maintenance operation, when the unloaded track profiles were "smooth." Nevertheless, as illustrated in Figure 5, the approaches still showed large and variable track deflections under load, indicating an apparent factor contributing to poor vehicle/track interactions. Note that deflection results shown in Figure 5 included not only the contribution from the ballast, subballast, and subgrade layers, but also the contribution of possible gaps and slacks between ties and ballast, which would close under the loaded condition.

Track Modulus

Figures 6 and 7 show track modulus test results obtained for two railroad ballast deck concrete bridges (with concrete ties) and their approaches (Li and Davis 2005). As shown, the track structure on concrete bridges had high stiffness characteristics. On average, the measured track modulus on these bridges was approximately 10,000 lbs/in./in., which, as mentioned previously, is too high to accommodate desirable vehicle/track dynamic interaction. In addition, the change of track stiffness between bridge and approach was also too high (by a factor of 2, on average).

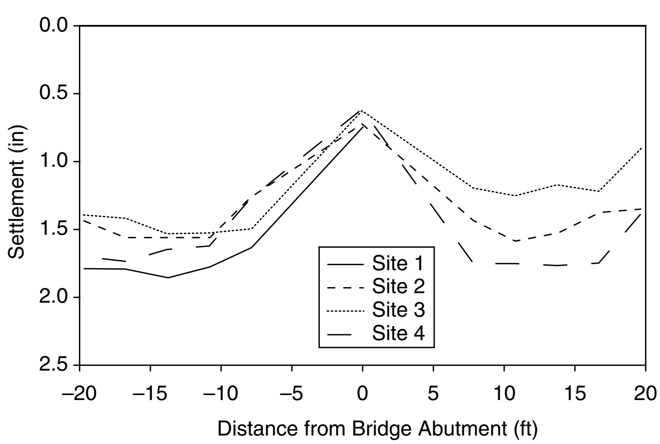


Figure 4 Settlement in approach areas (track settlement on bridges not shown, negative and positive distance indicate two approaches for each bridge).

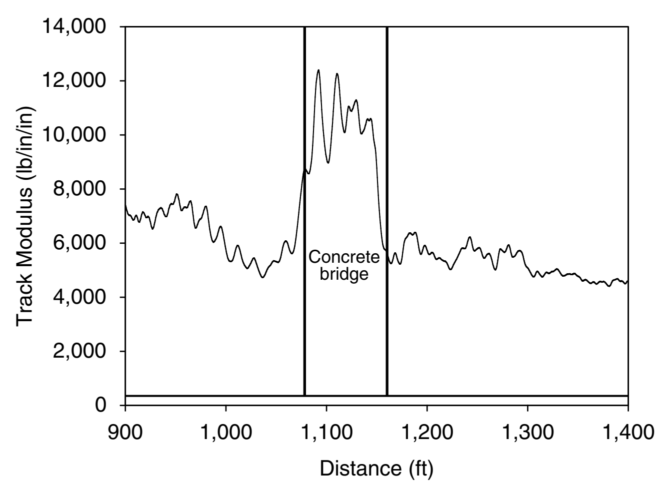


Figure 6 Track modulus test results (Site 1).

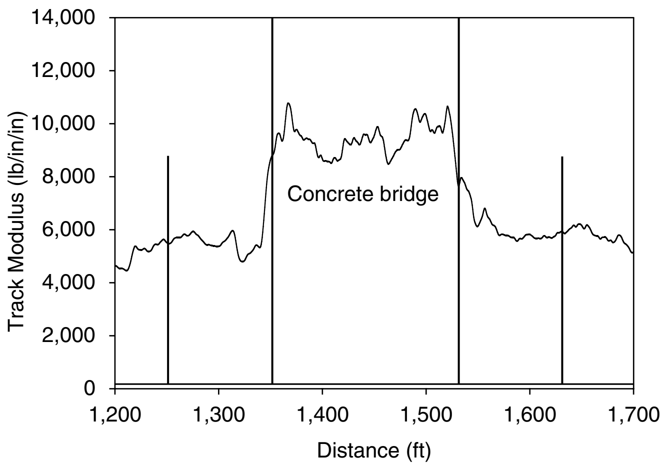


Figure 7 Track modulus test results (Site 3).

Discussion of Transition Remedies

In the literature, a number of remedies have been proposed or used to provide gradual stiffness transition. The following is a summary and discussion of those remedies.

Kerr and Moroney (1993) Transition Categories

Kerr and Moroney (1993) propose the following three categories of track transition remedies:

- Smoothing the stiffness/modulus step change at the interface by gradually increasing stiffness on the lower-stiffness side of the transition, as shown in Figure 8.
- Increasing the bending of the rail-tie structure (track panel) on the low-stiffness side of the transition.
- Lowering the stiffness on the high side of the transition.

Increasing Track Stiffness with Long Ties

One of the oldest, simplest, and most widely used transition designs is installation of a series of increasingly longer ties on the ballasted track side of the transition. A typical layout is found in Plan No. 913-52 of the American Railway Engineering and Maintenance of Way Association (AREMA) Portfolio of Trackwork Plans (AREMA 2005a) and is shown in Figure 9.

This method assumes the track stiffness is increased by the larger bearing area of the ties. However, as Kerr and Moroney (1993) point out, its effectiveness depends on uniform density of the ballast beneath the tie from the gage-side rail seat to the end of the tie (i.e., uniform tamping in this area). Longer ties may also exceed the embankment width on narrow bridge approaches, allowing ballast to migrate from the tie ends.

Using GEOTRACK analysis, Sussman and Selig (1998) indicate that although a longer tie may engage a larger ballast bearing area, it does little to increase the track stiffness. To increase stiffness, they recommend longer ties at reduced spacing and/or increasing the tie cross section, which in effect creates a stiffer track panel.

MARTA Variable Length Timber-Tie Transition

A case study was published by Patel and Jordan (1996), involving the Metropolitan Atlanta Rapid Transit Authority (MARTA), in which four 10-ft timber ties followed by four 11-ft and four 12-ft tim-

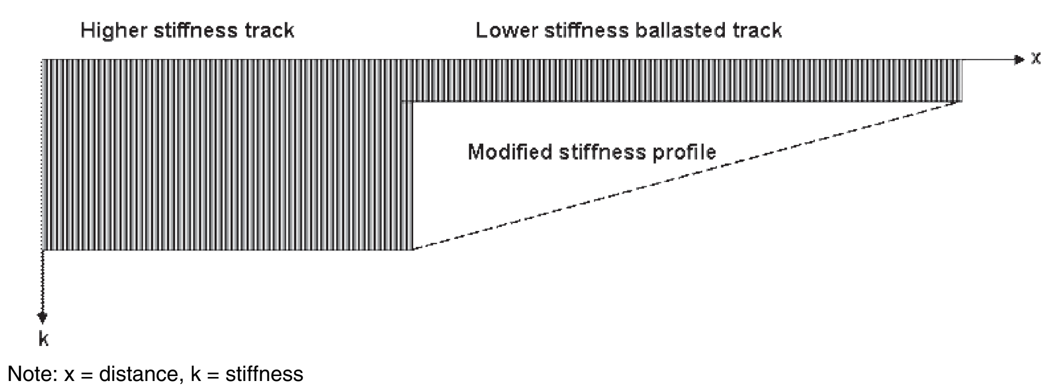
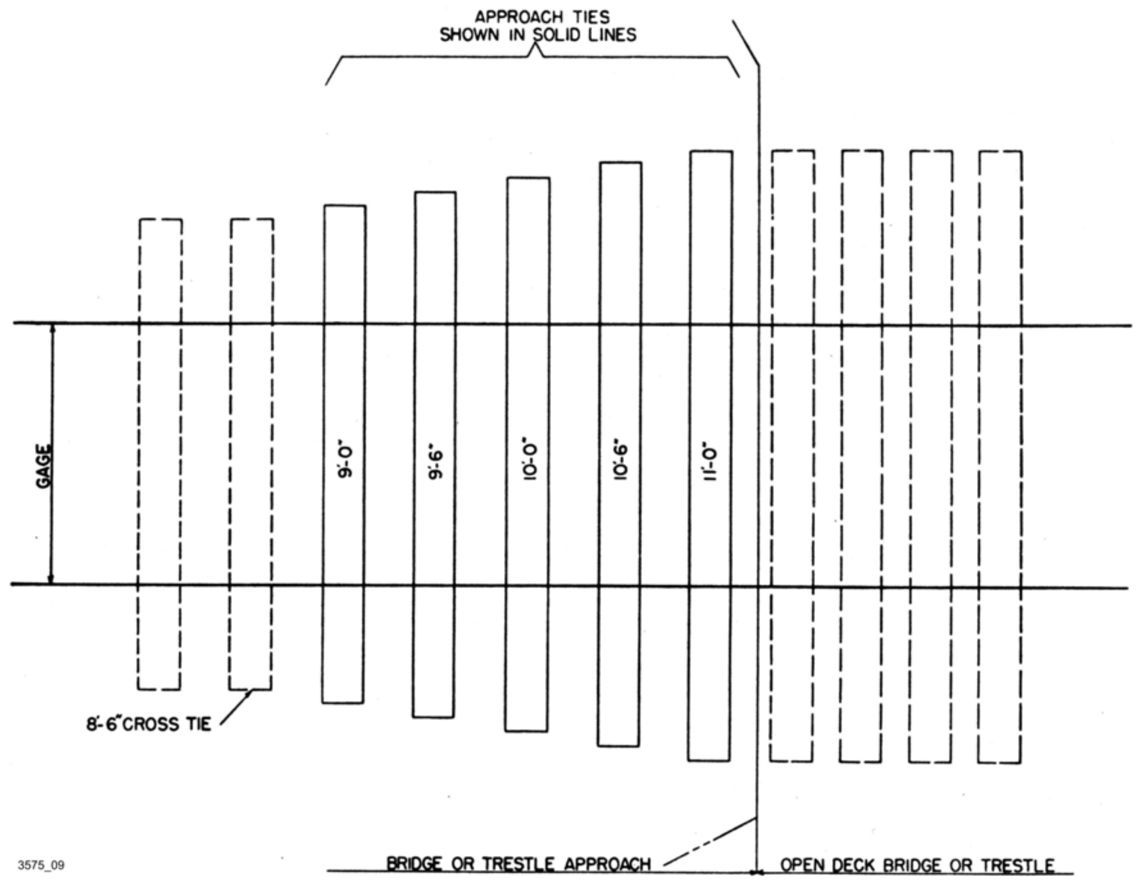


Figure 8 Transition remedy in which the stiffness step change is modified with a gradual increase in stiffness.



Source: AREMA 2005a.

Figure 9 AREMA Plan No. 913-52 approach ties for open deck bridges and trestles.

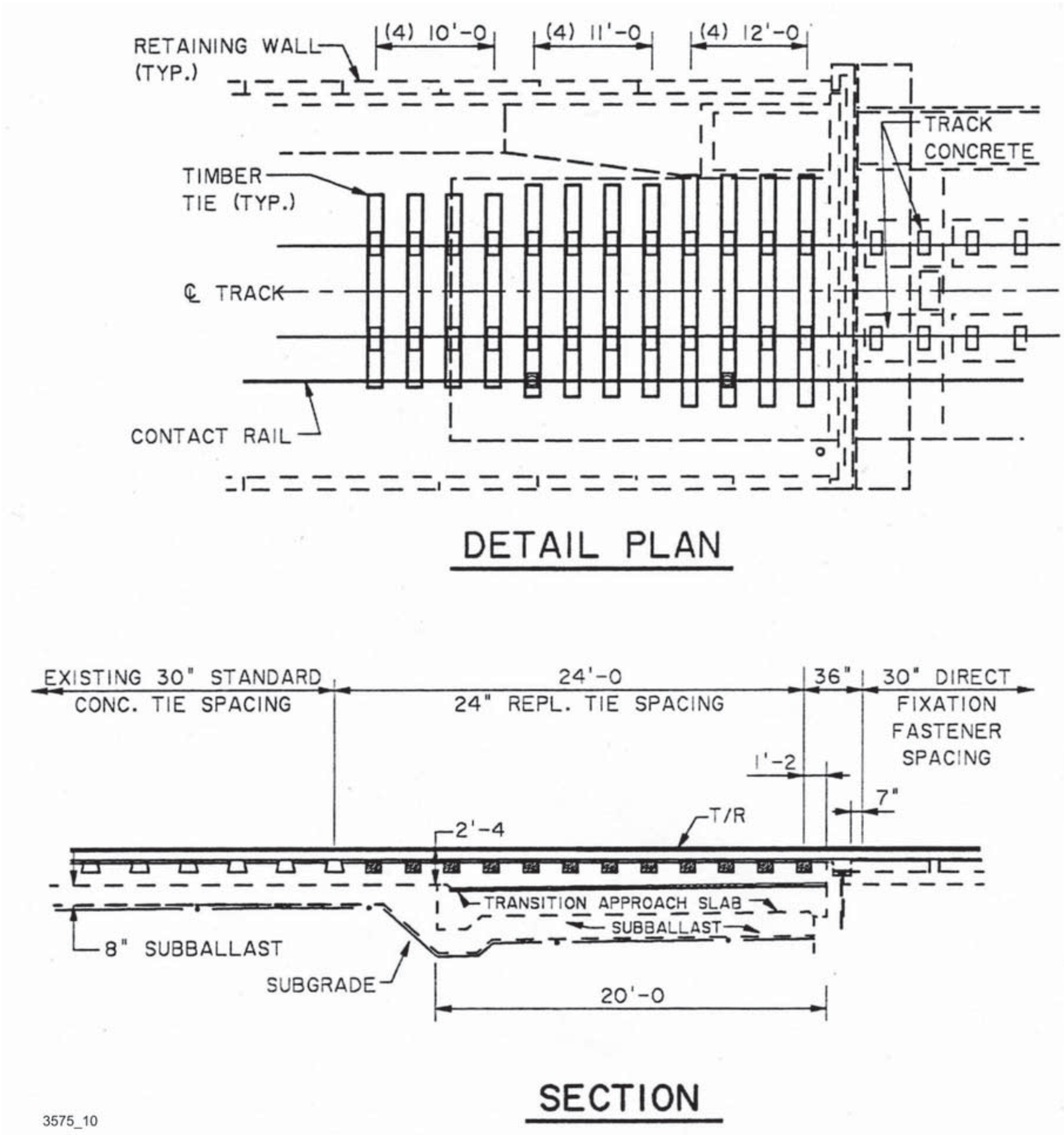
ber ties were installed at 24-in. centers as a transition between ballasted at-grade, concrete-tie track and direct-fixation structures. The transition also included a 20-ft-long concrete transitional slab on the ballasted track approach.

After modeling a number of options with GEOTRACK, the design shown in Figure 10 was chosen for the test. Patel and Jordan (1996) indicate that the variable length design reduced maintenance costs by a factor of 3 when compared to designs that included the approach slab but not long ties. The variable length design has been adopted for future new construction.

HMA Underlayment

The positive performance of an HMA pavement layer placed between the subgrade and ballast to reinforce weak subgrades is well documented in Rose 1998, Rose et al. 2002, and Li et al. 2001. These studies indicate that when properly designed and installed an HMA layer will reduce subgrade stresses and differential settlement and extend track maintenance cycles.

Because it is a structural layer, HMA can reduce subgrade stresses to levels that will not exceed the compressive strength of low-strength soils. However, in tests on the Union Pacific Railroad, Li and Davis (2005) found that HMA, placed on the approach to a ballast deck concrete bridge with a well-compacted subgrade, did not reduce the geometry deterioration of the approach compared with a similar approach without HMA. In the Li and Davis 2005 study, the track modulus of the approach with HMA was about 6,000 lb/in./in., which was very similar to the modulus of the non-HMA approach. The modulus on the ballast deck bridge in both cases was between 9,000 and 12,000 lb/in./in. The test data indicated that the HMA layer provided little improvement to a subgrade



Source: Parsons Brinckerhoff Quade & Douglas, Inc. 2000.

Figure 10 MARTA variable length timber-tie transition design.

with high load-bearing capacity, and the differential settlement seen on the approaches was caused primarily by settlement in the ballast layer rather than the subgrade.

These results suggest that HMA and other methods used to improve performance of weak subgrades, such as geocell and soil cement, will not improve ballast performance on stiff subgrades. For cases in which the approach track stiffness is already high, it would appear that trying to further increase the approach stiffness is not as effective as reducing the stiffness of the bridge track.

Increasing Approach Stiffness at Grade Crossing

A transition to improve ride quality and maintenance demand at the approach to a grade crossing is described by Zarembski and Palese (2003). In this case, a transition grade crossing design was developed, installed, and tested on New Jersey Transit's

Atlantic City line. The design was developed with the aid of an analytical model and provides a transition from low-modulus "parent" track to a high-modulus, concrete-panel grade crossing in the following steps:

1. Standard track with spikes and wood ties,
2. Wood ties with Pandrol clips,
3. 10-ft ties with Pandrol clips and single 8-ft field-side crossing panel installed between the rails,
4. 10-ft ties with Pandrol clips and 8-ft gage-side crossing panel installed between the rails, and
5. Full 24-ft crossing.

Measurements of track modulus and vehicle acceleration taken before and after installation of the transition grade crossing indicated that the transition was effective at smoothing the track stiffness difference and that a 77% reduction in the dynamic overloading in the crossing had been achieved.

Additional Rails

The German Federal Railways have developed a design for the InterCity Express (ICE) high-speed lines on which lengths of rails are installed between the running rails and on the field side of the running rails to stiffen the ballasted track panel (Kerr and Moroney 1993). This condition often exists by default, when guard rails installed on open deck bridges extend beyond the abutment to the ballasted track.

Concrete Bridge Approach Slabs

A reinforced concrete slab that rests on the abutment or slab structure and is tapered toward the at-grade end is often used at transitions to direct-fixation aerial structures and tunnel/subway inverts. AREMA recommends using a slab that is a minimum of 20 ft long and that is tapered from 18 in. at the structure end to 12 in. at the at-grade end. *TCRP Report 57* (Parsons Brinckerhoff Quade & Douglas 2000) shows a slab that is 12 in. thick and 20 ft long over which the ballast depth tapers from 12 in. at the structure end to 14 in. at the at-grade end (see Figure 11).

General specifications for an approach slab design, based on a successful trial in the United Kingdom, are provided by Sharpe et al. (2002). In addition to the slab, this design calls for vertical adjustment of the rail on the direct-fixation bridge deck. The adjustable fasteners permit the rail on the ballasted side to be raised higher than the desired final elevation and to settle to the desired final elevation (design tamping). The paper indicates that incorporating the design-tamping capability has improved the transition performance over that of an approach slab by itself.

The use of approach slabs is also a common highway transition practice (Briaud et. al. 1997). The most successful highway slabs have slope changes of 1/200 or less, which is more gradual than railway designs, which are typically 2-in. changes over 20 ft or 1/120.

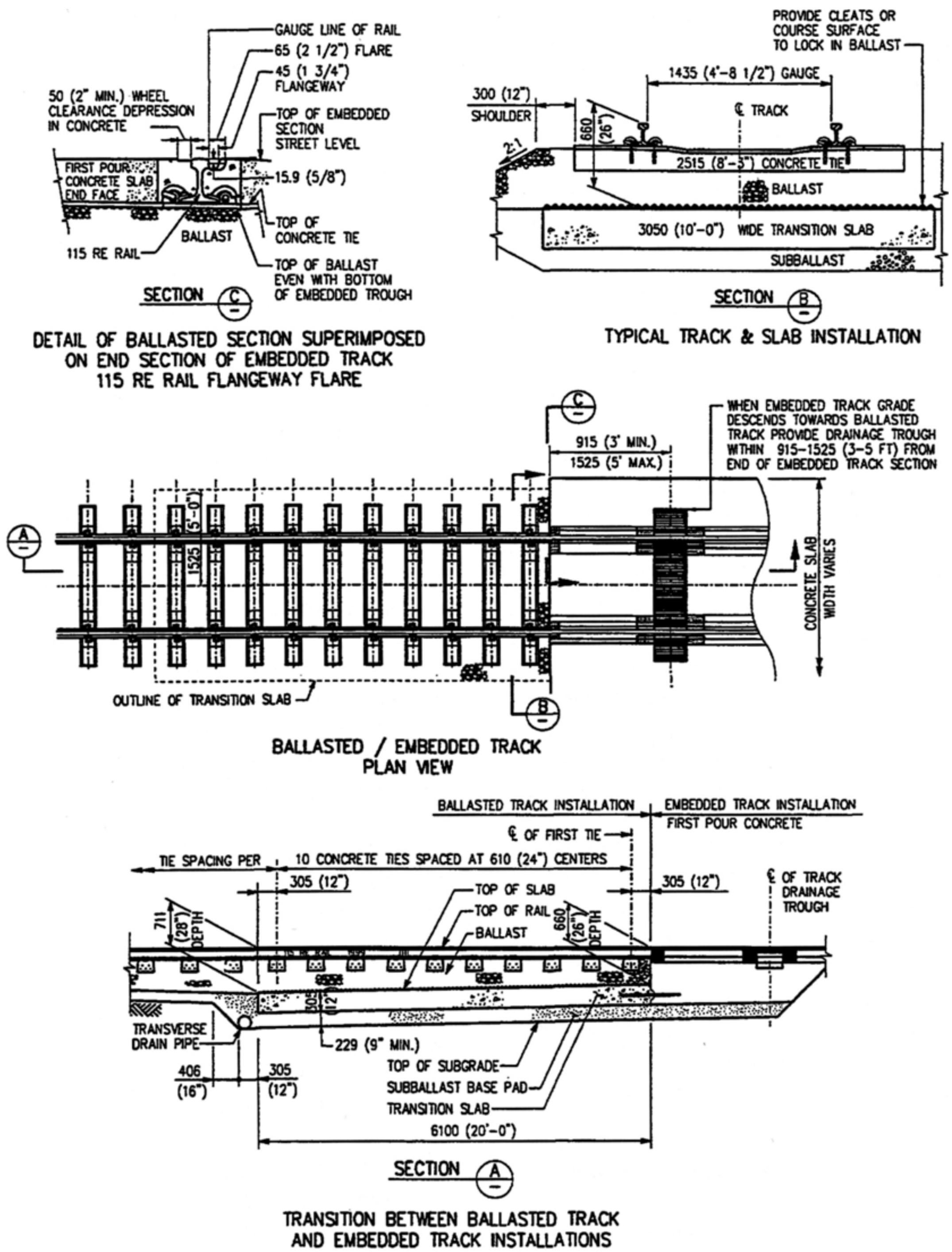
Slab Track Approach

Concrete approach slabs 25 ft in length were installed at the Transportation Technology Center (TTC) in Pueblo, Colorado, to provide the transition from at-grade, concrete-tie track to a 500-ft-long concrete slab track test section (Bilow and Li 2005). The cast-in-place, 12-in.-thick reinforced concrete approach slab, prior to construction of the slab track, is shown in Figure 12. This transition design uses concrete ties with about 16 in. of ballast between the ties and the approach slab. The slab also has vertical walls to confine the ballast shoulder below the subgrade level.

Track modulus data taken on the completed track (see Figure 13) showed the modulus at the approach slabs to be more than two times the modulus of the slab itself. In this case, the stiffness of the slab track direct fastening system had been successfully designed to approximate the nominal modulus of the surrounding wood-tie track (approximately 2,500 lb/in./in.). But the approach slab transition was over designed, creating an unnecessarily high (6,000 to 7,000 lb/in./in.) track modulus at the interface.

Stone Columns

Stone columns (geo-piers) were installed at the Union Pacific Cedar River bridge approach for long-term performance monitoring (Davis et al. 2003). A stone column is simply a hole, 30 in. in diameter and 7 ft deep, that is bored into the subgrade beneath the rail seat and backfilled with aggregate material that is compacted in 6-in. layers. In this case, 10 pairs of columns spaced longitudinally at 5-ft centers were installed (see Figures 14 and 15). Stone columns are designed to strengthen and enhance drainage of weak subgrades. The test results have been positive,



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Source: Parsons Brinckerhoff Quade & Douglas 2000.

Figure 11 Transition design from *TCRP Report 57: Track Design Handbook for Light Rail Transit.*

Figure 12 Slab track transition at TTC.

Figure 14 Hole boring in approach subgrade for stone column.

with no record of maintenance at the site during the first year of service.

Piles

In addition to stone columns, Li et al. (2003) indicate that other types of piles, including concrete, timber, and sand columns are accepted methods of stabilizing weak subgrades. Unless the end of the pile is on a firm foundation, skin friction provides most of the load transfer capacity. Therefore, the pile's effectiveness will depend on its length, and different lengths can be used to smooth the stiffness of the approach.

Other Geotechnical Considerations

The use of stone columns, HMA, soil cement, geosynthetic materials, and piles are all techniques that can be used to reduce differential settlement of an approach track by reinforcing or stabilizing a weak subgrade. However, consideration should also be given to maximizing the subgrade performance, especially during construction, with established geotechnical best practices such as the following:

- Determining the soil characteristics prior to construction by performing in situ testing.
- Using select noncohesive soils or applying admixtures to existing soils if needed to improve subgrade strength.
- Maintaining optimum moisture content and using correct compaction techniques for the soil type being placed, as well as ensuring adequate compaction when placing soil next to structures such as abutment backwalls.

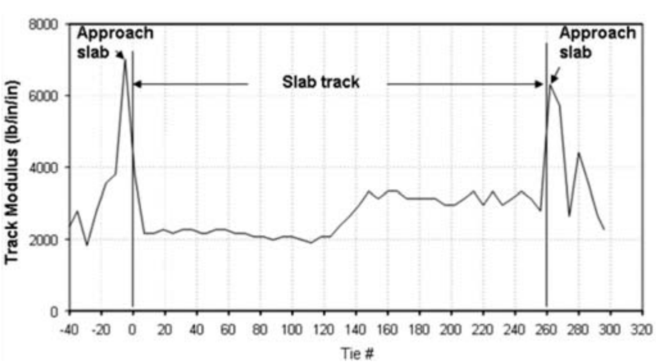

Figure 13 TTC slab track modulus data showing increase in modulus of the approach slabs.

Figure 15 Stone columns installed in approach subgrade.

- Ensuring maximum and uniform soil density by performing adequate soil density testing during construction.
- Removing ruts, crowning or sloping the subgrade surface, and/or using edge drains at the toe of the ballast section to prevent pocketing of free water in the track granular layer.
- Lowering ground water levels or installing cutoff layers if needed to prevent capillary movement of ground water upward into cohesive soil embankments.
- Allowing for adequate embankment width to accommodate the ballast/subballast depth.
- Allowing for adequate embankment slope angles or the use of benches, retaining walls, or sheet piles for slope stability and control of erosion.

A case where minimal maintenance has been performed on the approaches to an open deck steel bridge subjected to 40-ton axle load traffic is referenced by Joy et al. (2001). The approach embankments were constructed with a silty-sand material that was well compacted, and the paper stated that the performance of the approach was relatively good because of the embankment strength, width, and drainage.

The track granular layer should also be adequate in terms of ballast and subballast material quality, layer depth, and cross section (Li et al. 2003). Granular layer recommendations include the following:

- 12-in. ballast layer depth,
- Well-compacted subballast layer conforming to AREMA specifications in Chapter 1, Section 2.11, of the *AREMA Manual for Railway Engineering* (AREMA 2005b).
- Total granular layer depth (ballast plus subballast) using the formula in Chapter 1, Section 2.11.2.3, of the *AREMA Manual for Railway Engineering* (AREMA 2005b), and
- The use of wing walls attached to the back wall of the abutment or other methods to contain the ballast and prevent migration.

Rail Seat Pads on Open Deck Bridges and Direct-Fixation Structures

One category of track transition remedies involves reduction of the track stiffness on the stiff or structure side of the transition. This can be accomplished with elastomeric pads placed between the rail and rail seat. To be effective, the stiffness of the pads should match the track modulus of the at-grade approach using a methodology described by Kerr and Bathurst (2000), or the stiffness of the pads should meet damping requirements that attenuate high-frequency impact loads (Sasaoka and Davis 2005).

The target vertical pad stiffness in Kerr and Bathurst 2000 is equal to the fastener spacing multiplied by the desired track modulus. For example, the pad stiffness for a direct-fixation structure with fasteners at 30-in. centers needed to match a modulus of 3,000 lb/in./in. on the approach track would be 90,000 lb/in. The pad stiffness for the same approach modulus to an open deck bridge with ties at 16-in. centers would be 48,000 lb/in. *TCRP Report 57* (Parsons Brinckerhoff Quade & Douglas 2000) gives typical rail vertical stiffness values for direct-fixation track as 75,000 to 150,000 lb/in. *CRP-CD-3: Performance of Direct-Fixation Track Software: Design Guidelines and Software* (Battelle 1999) indicates that pad spring rates below 100,000 lb/in. ease the transition to ballasted track.

It should be kept in mind that these vertical stiffness values are based on deflection of the rail at maximum wheel load and include deflection of the tie and structure in addition to the pad. In the case of direct-fixation concrete structures, deflection of the concrete is negligible; however, in the case of wood or composite tie decks, compression of the tie material may represent a substantial part of the total rail deflection.

Reducing Track Stiffness on Ballast Deck Bridges

Several test sites were established on a high-density freight route to determine the effectiveness of various tie materials at reducing the track stiffness on ballast deck bridges (Sasaoka et al. 2005). In all cases, concrete ties were installed on the approach and on the ballast decks. Track measurements showed that modulus values on the bridges exceeded 8,000 lb/in./in. and were 2,000 to 3,500 lb/in./in. higher than modulus values on the approaches. Two methods were tested to reduce the bridge track modulus: (1) replacing concrete ties with composite (plastic) ties on the bridge deck and (2) installing concrete ties on the bridge deck with 1-in.-thick rubber pads cast into the bottom of the ties.

Figure 16 shows track modulus measured on the approaches and decks of bridges with three different tie types (concrete, composite, and concrete with rub-

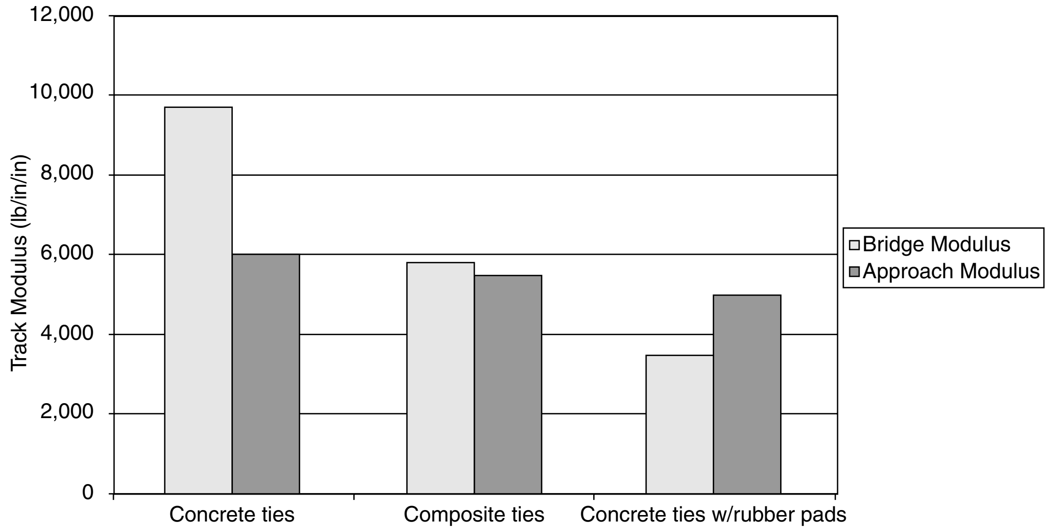

Figure 16 Comparison of track modulus values for different ballast deck bridge tie types.

ber ties). As can be seen in Figure 16, both composite ties and concrete ties with rubber pads were successful at reducing the modulus on the bridge. The composite ties equalized the modulus of the bridge and the modulus of the approach, and the rubber pads reduced the modulus of the bridge by a factor of 2.8.

Rubber Tie Mats

Another technique to reduce the stiffness on a ballast bridge deck was developed in Japan in the 1970s for the Shinkansen high-speed network. According to Li et al. (2003), rubber mats were placed between the ties and ballast to reduce dynamic loads and ballast deterioration. The shape of the mats was designed to achieve a specific spring rate, and results of extensive testing indicated that the mats were effective in reducing ballast wear. There was no mention, however, of how well the mats attenuated the dynamic loads or the quality of their long-term performance.

Summary of Findings

Descriptions of a variety of track transition designs and remedies were found in the literature reviewed. In most cases, the techniques were aimed at either increasing the stiffness of the approach track or decreasing the stiffness and adding damping to the stiff track. Case studies in which at least initial performance improvements were noted included the following:

- Use of longer ties and a concrete approach slab by MARTA to transition from ballasted at-grade track to direct-fixation structures.
- Transition from at-grade ballasted track to a direct-fixation structure on a commuter/intercity passenger service railway in the United Kingdom using an approach slab along with vertically adjustable direct-fixation fasteners to allow design tamping of the ballasted approach track.
- Installation of stone columns to strengthen and improve the drainage of a weak bridge approach subgrade on a Union Pacific main line.
- Design of a transition grade crossing system to smooth the track modulus across the approach to a highway crossing and reduce impact rail loads at the crossing on the New Jersey Transit Atlantic City line.
- Installation of tie pads on open wood-tie bridge decks having stiffness/resilience characteristics designed to match the track modulus of the approach track on Amtrak's northeast corridor and on a Norfolk Southern main line with freight/intercity passenger service.
- Reduction of the track modulus on a Union Pacific ballast deck bridge by replacing the existing concrete deck ties with composite (plastic) ties or with concrete ties with a rubber pad cast into the tie bottom.

The importance of following geotechnical best practices regarding soil selection, compaction, and drainage were also discussed in a number of studies. Properly designed and constructed subgrades can greatly minimize track transition problems.

ANALYSIS OF REPRESENTATIVE TRACK TRANSITION DESIGNS

Introduction

In this section of the report, typical transition methods and conditions are analyzed using the GEOTRACK model. The model predicts a number of track response parameters, including vertical rail deflections (y), track modulus (u), and ballast and subgrade pressures for various track configurations, component properties, and wheel loads.

The objective of the analysis is to determine the response of specific transition designs, based on the following track input variables, to representative rail transit wheel loadings.

Representative transition configurations are the following:

- At-grade ballasted track to direct-fixation aerial structure,
- At-grade ballasted track to open deck bridge,
- At-grade ballasted track to ballast deck bridge,
- At-grade ballasted track with concrete approach slab to direct-fixation aerial structure,
- At-grade ballasted track with HMA layer to direct-fixation aerial structure,
- At-grade ballasted track with additional rails to direct-fixation aerial structure, and
- At-grade ballasted track with AREMA long-tie approach to direct-fixation aerial structure.

Track input variables are the following:

- At-grade ballasted track:
  - 7-in. × 9-in. × 8.5-ft wood ties at 20-in. spacing,
  - 7.5-in. × 10-in. × 8.25-ft concrete ties at 28-in. spacing,
  - 12-in. ballast layer,
  - 8-in. subballast layer, and
  - Low, average, and high subgrade stiffness values (resilient modulus values of 2, 10, and 20 ksi, respectively).
- Direct-fixation track:
  - Fasteners at 30-in. spacing and
  - Fastener stiffness values of 100, 150, 200, and 300 kip/in.
- Open deck bridge:
  - Wood ties at 16-in. spacing.
- Ballast deck bridge:
  - Concrete ties with 10-mm resilient tie pad at 28-in. spacing,
  - Concrete ties with 1-in.-thick resilient tie bottom pads at 28-in. spacing, and
  - 8- and 12-in. ballast layer.
- HMA underlayment:
  - 8- and 12-in. layer.

GEOTRACK Description (Selig and Waters 1994)

The GEOTRACK computer model predicts the quasi-static response of the track to applied wheel loads. GEOTRACK represents the rail and ties as linear elastic beams that are connected with linear springs. The ties are supported on a multi-layer elastic system that represents various elements of the track substructure. The rail can span up to 17 ties, and up to 4 wheel loads can be applied on the rail.

The rail is defined by weight (lb/yd), cross area (A), modulus of elasticity (E), and moment of inertia (I). The fastener stiffness is defined as the vertical spring rate of the rail seat pad and, in the case of wood ties, includes compression of the wood. Ties are defined by length, cross section, weight, spacing, moment of inertia, and modulus of elasticity.

The substructure is represented by as many as five elastic layers of defined depth with the depth of the bottom layer always being infinite. In addition to depth, each layer is defined by its resilient modulus (E_r), which can be thought of as the soil's modulus of elasticity, Poisson's ratio (v), and material density.

The GEOTRACK model treats the applied wheel loads as a vertical component only. Although GEOTRACK allows multiple wheel loads, only single wheel loads were used in this analysis.

Three wheel loads were analyzed: 12,000, 15,000, and 22,500 lb. The 12,000-lb load was intended to represent light rail operations, the 15,000-lb load was based on the static weight of a Metro North cab car with full seated passenger load (Kentner et al. 1997, p. 270), and the 22,500-lb wheel load represents the Metro North static wheel load plus a 50% dynamic factor.

The component property values used in the analysis are listed in Table 1.

Table 1 Basic GEOTRACK input properties used in the analysis

Single Wheel Load (kips)	Light rail	Commuter car with full load	Commuter car with 50% dynamic factor
	12	15	22.5

Rail	Modulus of elasticity (E) (ksi)	Moment of inertia (I) (in4)	Cross-sectional area (A) (in2)	Gage rail center-to-center (in)	Weight (lb/yd)
	30,00	65.9	11.25	59.25	115

Ties and Fasteners		Cross section (in x in)	Length (in)	Weight (lb)	Spacing (in)	E (ksi)	I (in4)	Fastener stiffness (kip/in)
	Wood	7 x 9	102	220	20	1,500	257	400
	Concrete	7.5 x 10	99	600	28	4,500	469	1,000; 300
	Direct-Fixation*	7.5 x 10	99	600	30	4,500	469	100; 150; 200; 300

Granular Layers		Density (lb/cubic ft)	Poissons ratio	Resilient mod ulus (E_r) (ksi)	Depth (in)
	Ballast	110	0.3	40	12
	Subballast	120	0.35	25	8

Subgrade Layers		Density (lb/cubic ft)	Poisson's ratio	E_r (ksi)	Depth (in)
	Low Stiffness	90	0.35	2	infinite
	Average Stiffness	110	0.35	10	infinite
	High Stiffness	120	0.35	20	infinite

Bedrock Layer	Density (pcf)	Poisson's ratio	E_r (ksi)	Depth (in)
	150	0.35	100	infinite

HMA Layer	Density (lb/cubic ft)	Poisson's ratio	E_r (ksi)	Depth (in)
	145	0.3	800	8; 12

Concrete Slab	Density (lb/cubic ft)	Poisson's ratio	E (ksi)	Depth (in)
	150	0.4	4,500	8; 12; 18

* Direct-fixation parameters represent the plinth.

Analysis of Representative Track Configurations

In this section, GEOTRACK model outputs of the vertical rail deflection, track modulus, and ballast and subgrade pressures calculated for the representative track configurations are presented. In each case, the track configuration is described, and the rail deflections and modulus values from the 15,000-lb load along with the significant component properties are shown graphically. All the output values are listed in a table format.

At-Grade Ballasted Track

Conventional ballasted track on a subgrade foundation was modeled for three different subgrade conditions: (1) low-stiffness subgrade ($E_r = 2$ ksi), (2) average-stiffness subgrade ($E_r = 10$ ksi), and (3) high-stiffness subgrade ($E_r = 20$ ksi). The subgrade E_r values were based on test data from TTC in Pueblo, Colorado, and other sources (Read et al. 1994).

Table 2 lists the rail deflections, track modulus values, ballast pressures at the top of the ballast layer, and subgrade pressures at the top of the subgrade layer for wheel loads of 12, 15, and 22.5 kips. The layer properties, rail deflection, and track modulus values are shown for wood and concrete ties in Figures 17 and 18, respectively.

Direct-Fixation Track Analysis

Direct-fixation track on an aerial structure was modeled with fasteners spaced at 30-in. centers. The plinths were represented as the ties, the concrete deck slab and girders were represented as a 72-in. concrete layer, and the foundation was represented as a bedrock subgrade. Fastener stiffness values of 100, 150, 200, and 300 kip/in. were included in the analysis.

Table 3 lists the deflection and track modulus values for wheel loads of 12, 15, and 22.5 kips. The layer properties, rail deflection, and track modulus values for each fastener stiffness are shown in Figure 19.

Open and Ballasted Deck Bridge Analysis

Open deck bridges with wood ties attached to a steel superstructure and ballast deck bridges with wood and concrete ties were modeled similarly to the direct-fixation structure with the bridge superstructure sitting on a deep foundation at bedrock. The open deck bridge was modeled with wood ties at 16-in. centers and with and without a tie pad of 100 kip/in. stiffness. The ballast deck bridge was modeled with concrete ties at ballast depths of 12 and 8 in. and wood ties at ballast depth of 12 in. The concrete ties were equipped with a 10-mm studded rubber tie pad with stiffness of 300 kip/in. Concrete

Table 2 At-grade ballasted track rail deflection, track modulus, ballast stress, and subgrade stress data

		Concrete Ties			Wood Ties		
		12 kips	**15 kips**	**22.5 kips**	**12 kips**	**15 kips**	**22.5 kips**
High-Stiffness Subgrade E_r = 20 ksi	Rail Deflection (in)	0.021	0.027	0.040	0.026	0.032	0.048
	Modulus (lb/in/in)	9,236	9,236	9,236	7,269	7,269	7,269
	Ballast Stress (psi)	16.9	21.1	31.6	14.4	18.0	26.9
	Subgrade Stress (psi)	3.7	4.6	7.0	3.6	4.5	6.8
Average-Stiffness Subgrade E_r = 10 ksi	Rail Deflection (in)	0.030	0.038	0.057	0.033	0.042	0.063
	Modulus (lb/in/in)	5,757	5,757	5,757	5,100	5,100	5,100
	Ballast Stress (psi)	15.8	19.8	29.6	13.9	17.4	26.1
	Subgrade Stress (psi)	3.3	4.2	6.2	3.4	4.2	6.3
Low-Stiffness Subgrade E_r = 2 ksi	Rail Deflection (in)	0.091	0.114	0.170	0.096	0.120	0.180
	Modulus (lb/in/in)	1,336	1,336	1,336	1,249	1,249	1,249
	Ballast Stress (psi)	20.0	25.0	37.6	11.4	14.3	21.4
	Subgrade Stress (psi)	1.9	2.4	3.6	2.0	2.5	3.8

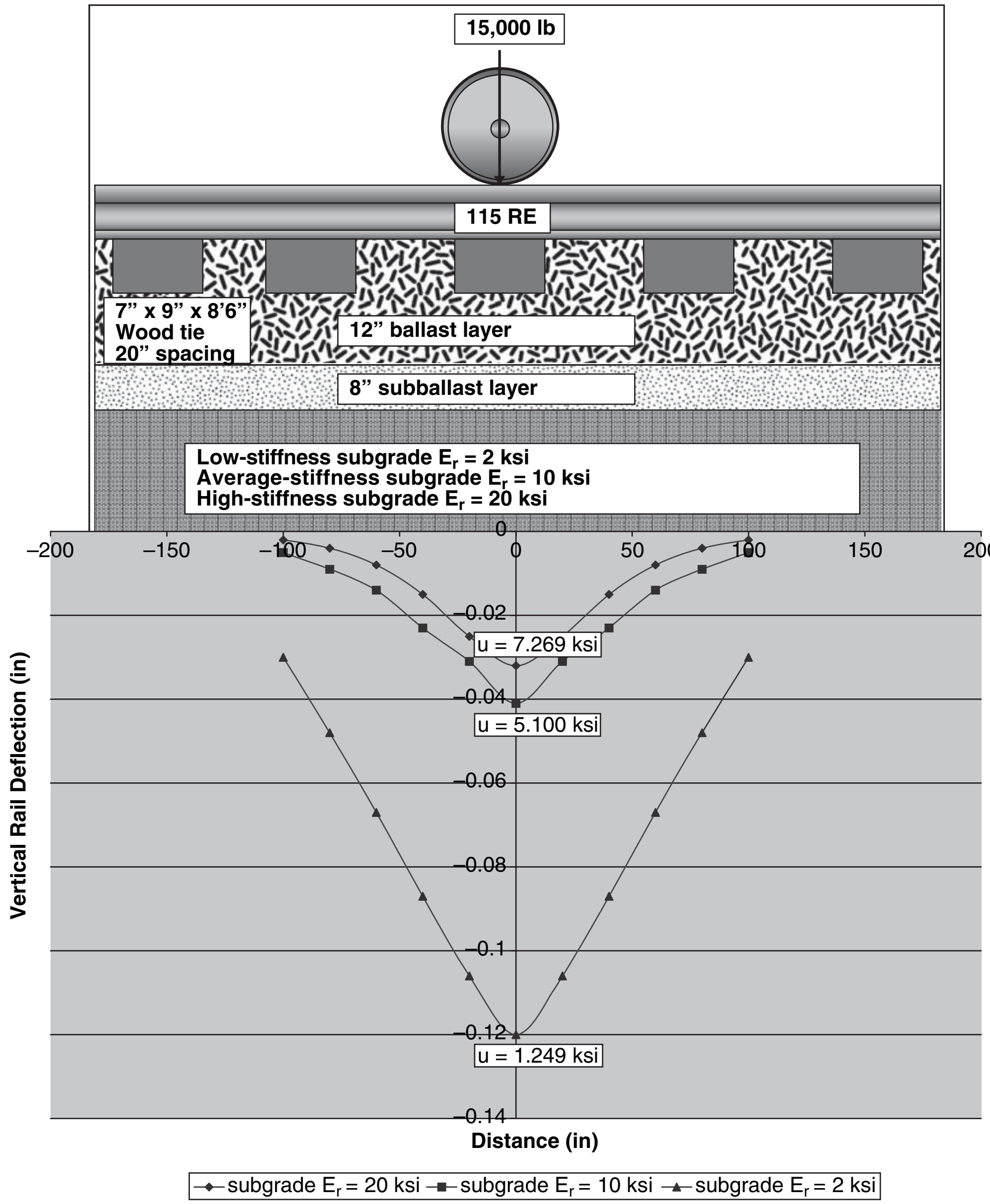

Figure 17 Rail deflection and track modulus values for at-grade wood-tie ballasted track under 15-kip wheel loading and low-, average-, and high-stiffness subgrades.

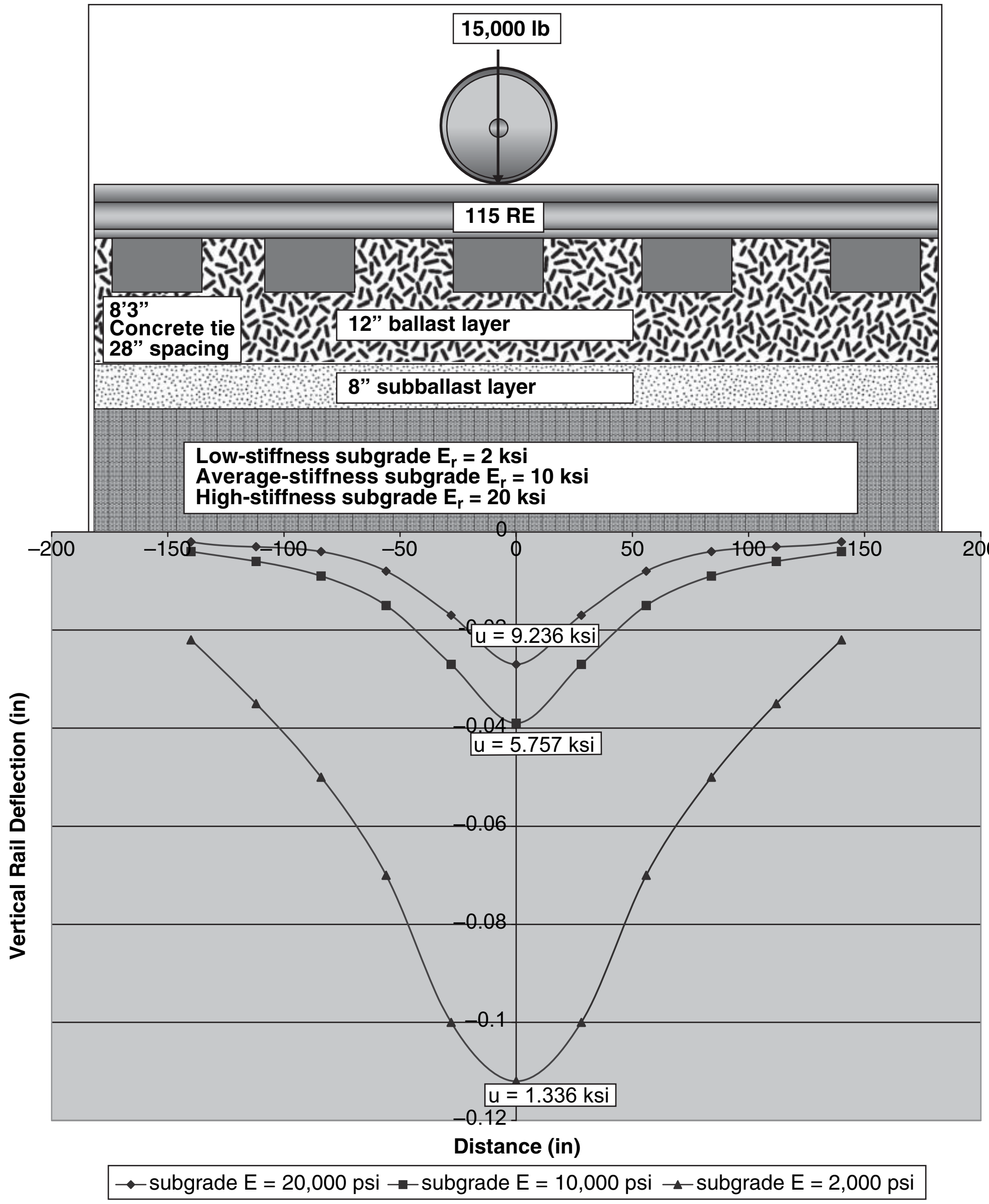

Figure 18 Rail deflection and track modulus values for at-grade concrete-tie ballasted track under 15-kip wheel loading and low-, average-, and high-stiffness subgrades.

Table 3 Direct-fixation aerial structure rail deflection and track modulus data

		12 kips	15 kips	22.5 kips
100 kip/in Fastener Stiffness	Rail Deflection (in)	0.046	0.057	0.086
	Modulus (lb/in/in)	3,330	3,330	3,330
150 kip/in Fastener Stiffness	Rail Deflection (in)	0.034	0.042	0.063
	Modulus (lb/in/in)	4,997	4,997	4,997
200 kip/in Fastener Stiffness	Rail Deflection (in)	0.027	0.034	0.051
	Modulus (lb/in/in)	6,668	6,668	6,668
300 kip/in Fastener Stiffness	Rail Deflection (in)	0.020	0.025	0.038
	Modulus (lb/in/in)	10,018	10,018	10,018

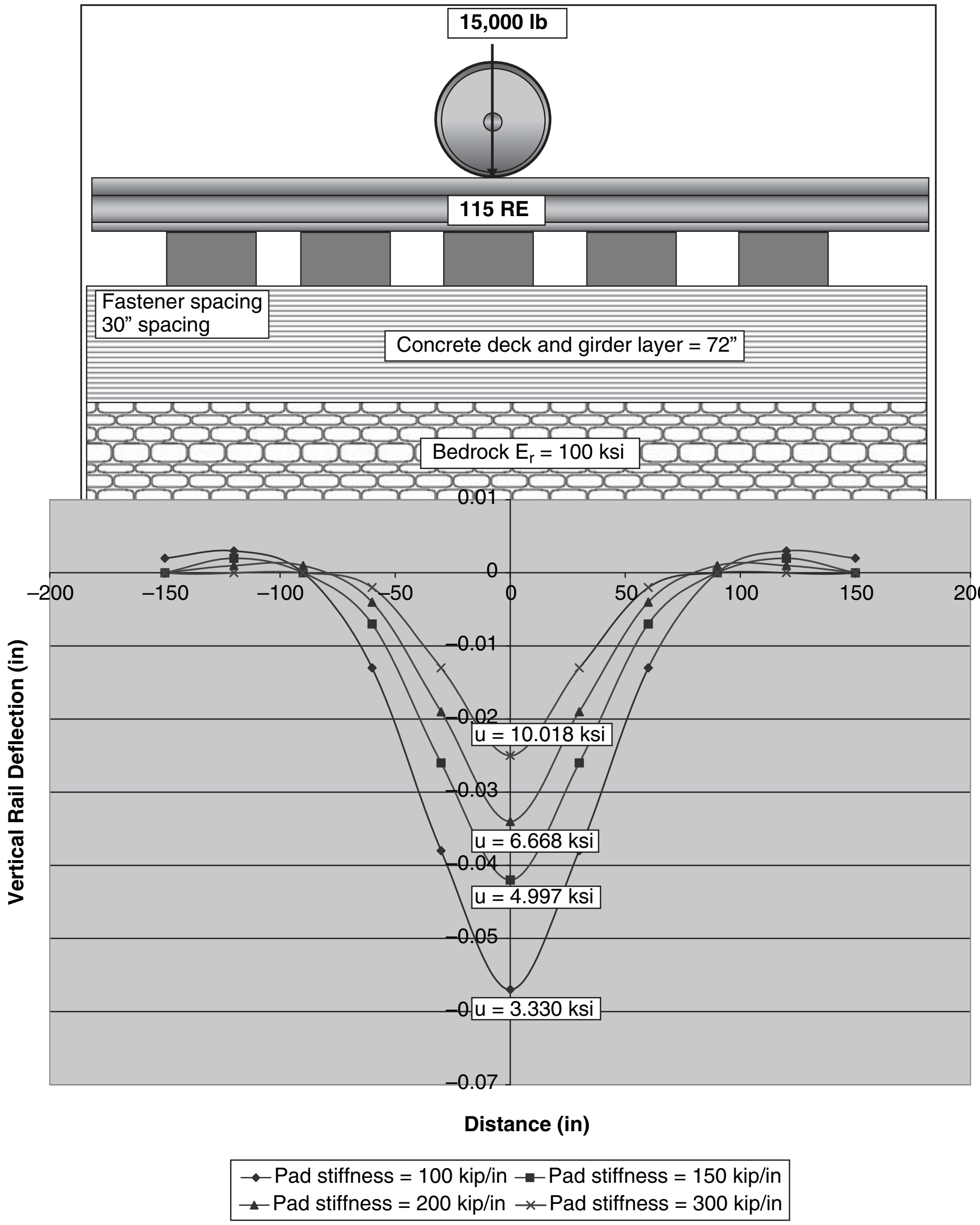

Figure 19 Rail deflection and track modulus values for direct-fixation track and various pad stiffnesses on an aerial structure under 15-kip wheel loading.

ties were also modeled with a rubber pad of 100 kip/in. stiffness bonded to the tie bottom.

Table 4 lists the deflection and track modulus values for wheel loads of 12, 15, and 22.5 kips. The layer properties, rail deflection basin, and track modulus values for each fastener stiffness are shown for the ballast deck bridge in Figure 20.

Concrete Approach Slab

A 20-ft-long reinforced concrete approach slab placed between the ballast and subballast layers was modeled for wood- and concrete-tie track. Variables in the analysis included average and low-stiffness subgrade (E_r = 10 and 2 ksi), tie type, and slab thickness. An approach slab on a high-stiffness subgrade was not analyzed as the track modulus values would greatly exceed 10,000 lb/in./in., which is considered to be excessive.

Tables 5 and 6 list the rail deflections, track modulus values, ballast pressures at the top of the ballast layer, and subgrade pressures at the top of the subgrade layer for wheel loads of 12, 15, and 22.5 kips. The layer properties, rail deflection basin, and track modulus values are shown in Figures 21 and 22.

HMA Underlayment

An HMA layer placed between the ballast and subballast layers as an approach transition was modeled for wood- and concrete-tie track. Variables in the analysis included low-, average-, and high-stiffness subgrade and tie type. Substructure layers included 12-in. ballast and 8-in. subballast.

Tables 7 and 8 list the rail deflection, track modulus, ballast pressure at the top of the ballast layer and subgrade pressure at the top of the subgrade layer for wheel loads of 12, 15, and 22.5 kips. The layer properties, rail deflection basin, and track modulus values are shown in Figures 23 and 24.

Additional Rails

The transition design in which two additional rails are added to the track panel to increase the stiffness of the panel and reduce rail deflection was analyzed. In this case, the rail was doubled in weight, area, and moment of inertia to simulate the additional rail. Variables in the analysis included subgrade stiffness (low, average, and high as before) and HMA layer depth.

Table 9 lists the rail deflection, track modulus, ballast pressure at the top of the ballast layer, and

Table 4 Open and ballast deck bridge rail deflection and track modulus data

		12 kips	15 kips	22.5 kips
Ballast Deck Bridge with 8-in Ballast Depth and Concrete Ties	Rail Deflection (in)	0.021	0.026	0.039
	Modulus (lb/in/in)	9,595	9,595	9,595
Ballast Deck Bridge with 8-in Ballast Depth and Rubber Pad on Bottom of Concrete Ties	Rail Deflection (in)	0.045	0.056	0.084
	Modulus (lb/in/in)	3,432	3,432	3,432
Ballast Deck Bridge with 12-in Ballast Depth and Concrete Ties	Rail Deflection (in)	0.021	0.026	0.040
	Modulus (lb/in/in)	9,336	9,336	9,336
Ballast Deck Bridge with 12-in Ballast Depth and Rubber Pad on Bottom of Concrete Ties	Rail Deflection (in)	0.045	0.057	0.085
	Modulus (lb/in/in)	3,398	3,398	3,398
Ballast Deck Bridge with 12-in Ballast Depth and Wood Ties	Rail Deflection (in)	0.020	0.025	0.037
	Modulus (lb/in/in)	10,315	10,315	10,315
Open Deck Bridge with Wood Ties	Rail Deflection (in)	0.013	0.016	0.025
	Modulus (lb/in/in)	17,287	17,287	17,287
Open Deck Bridge with Wood Ties and 100-kip/in Stiffness Tie Pad	Rail Deflection (in)	0.030	0.037	0.056
	Modulus (lb/in/in)	5,903	5,903	5,903

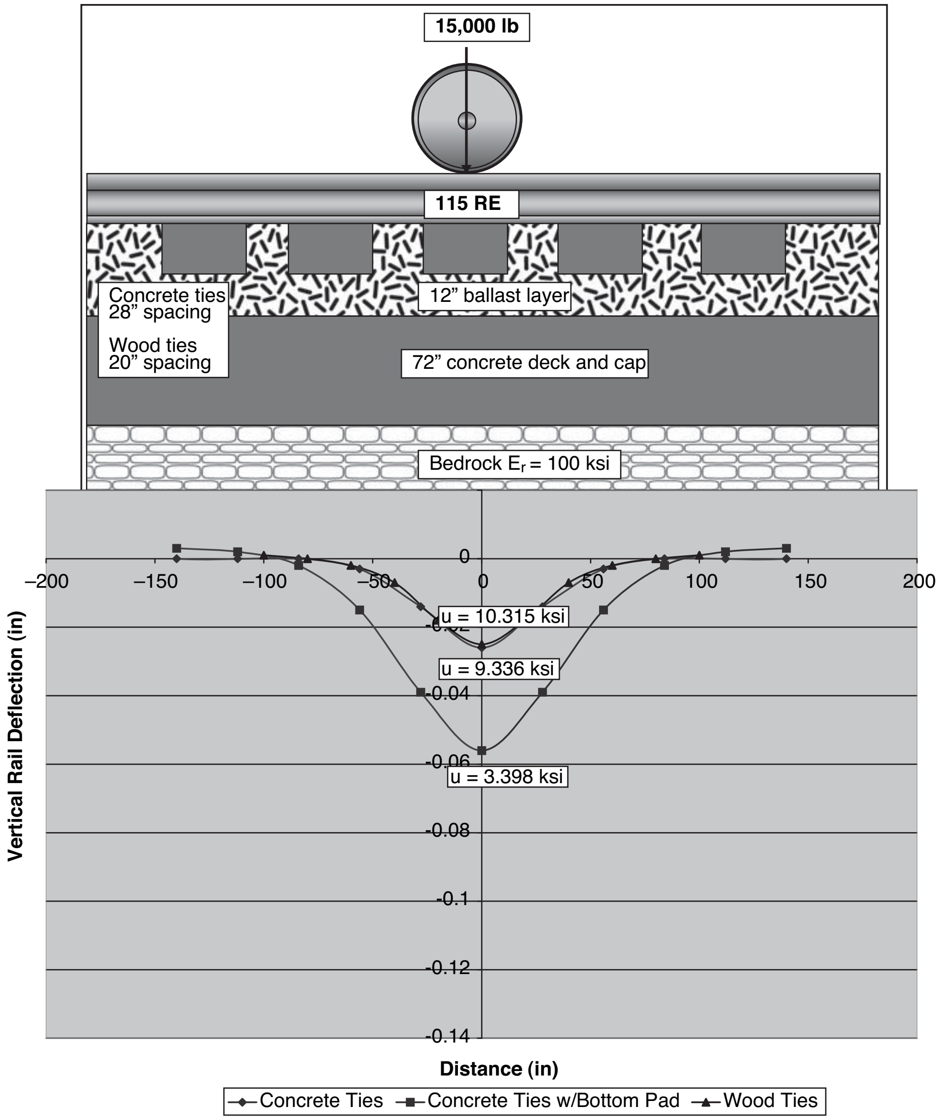

Figure 20 Rail deflection and track modulus values for wood and concrete ties on ballast deck bridge under 15-kip wheel load.

subgrade pressure at the top of the subgrade layer for wheel loads of 12, 15, and 22.5 kips.

Transition Analysis

A number of graphs are presented in this section to compare the track modulus and rail deflection values for the various modeled track configurations. In each case, the at-grade ballasted track is shown on the left of the graph, the direct-fixation or bridge structure is shown on the right side of the graph, and the transition designs are shown between the two.

Track Modulus Transition

In Figure 25, the track modulus of concrete-tie track is compared to the modulus of a direct-fixation structure and ballast deck bridge with concrete ties. The at-grade ballasted track data shows the track modulus range for subgrade resilient moduli of 2, 10, and 20 ksi. Concrete approach slabs of 8-, 12-, and 18-in. thicknesses and HMA layers of 8- and 12-in. thicknesses are also included in Figure 25 to show their effectiveness at increasing the track modulus of low-stiffness and average subgrades. Figure 26 shows a similar graph for wood-tie track.

Table 5 Rail deflection, modulus, ballast stress, and subgrade stress data for a concrete approach slab with concrete ties

		8-in Slab			12-in Slab			18-in Slab		
		12 kips	15 kips	22.5 kips	12 kips	15 kips	22.5 kips	12 kips	15 kips	22.5 kips
Average-Stiffness Subgrade	Rail Deflection (in)	0.025	0.031	0.046	0.022	0.027	0.041	0.019	0.024	0.036
	Modulus (lb/in/in)	7,622	7,622	7,622	8,896	8,896	8,896	10,759	10,759	10,759
	Ballast Stress (psi)	17.3	21.7	32.5	18.4	23.0	34.6	14.0	17.5	26.3
	Subgrade Stress (psi)	1.3	1.6	2.7	0.9	1.1	1.6	0.6	0.7	1.0
Low-Stiffness Subgrade	Rail Deflection (in)	0.061	0.076	0.114	0.049	0.061	0.091	0.037	0.047	0.070
	Modulus (lb/in/in)	2,288	2,288	2,288	3,085	3,085	3,085	4,404	4,404	4,404
	Ballast Stress (psi)	16.8	2.1	27.4	18.6	23.2	34.8	13.8	17.3	24.9
	Subgrade Stress (psi)	0.7	0.8	1.3	0.4	0.5	0.8	0.2	0.3	0.5

Rail Deflection Transition

In addition to track modulus, it is useful to compare the rail deflections of the various track configurations. Because track modulus is a power function of the rail deflection, as shown in Figure 27, small amplitude deflections tend to correspond to increasingly higher modulus values. Considering track modulus alone may, therefore, exaggerate the transition requirements as compared with the rail deflection.

In Figures 28 through 30, rail deflections for the various track transitions that were calculated for concrete track under wheel loads of 12, 15, and 22.5 kips are shown. The layouts of the various transition configurations are similar to the track modulus graphs, with the at-grade track on the left, the structures on the right, and the transition designs in the middle. The wood-tie data are shown in Figures 31 through 33.

Analysis of Tie Length, Tie Cross Section, and Tie Spacing

Increased tie length and cross section and decreased tie spacing are often considered to be effective track transition configurations. GEOTRACK modeling, however, indicated that these transition methods had little, if any, benefit in terms of reduced rail deflection or increased track modulus. However, there may be benefits in terms of other performance criteria not discussed in this digest.

Table 6 Rail deflection, modulus, ballast stress, and subgrade stress data for a concrete approach slab with wood ties

		8-in Slab			12-in Slab			18-in slab		
		12 kips	15 kips	22.5 kips	12 kips	15 kips	22.5 kips	12 kips	15 kips	22.5 kips
Average-Stiffness Subgrade	Rail Deflection (in)	0.029	0.036	0.054	0.026	0.033	0.049	0.023	0.029	0.044
	Modulus (lb/in/in)	6,129	6,129	6,129	6,967	6,967	6,967	8,138	8,138	8,138
	Ballast Stress (psi)	16.5	19.1	31.0	18.8	23.5	35.3	15.1	18.9	28.3
	Subgrade Stress (psi)	1.3	1.6	2.4	0.9	1.1	1.6	0.5	0.7	1.0
Low-Stiffness Subgrade	Rail Deflection (in)	0.065	0.082	0.122	0.053	0.066	0.100	0.042	0.053	0.079
	Modulus (lb/in/in)	2,080	2,080	2,080	2,730	2,730	2,730	3,718	3,718	3,718
	Ballast Stress (psi)	14.9	18.6	27.9	18.6	23.3	35.0	16.3	20.4	30.6
	Subgrade Stress (psi)	0.7	0.8	1.3	0.4	0.5	0.8	0.2	0.3	0.4

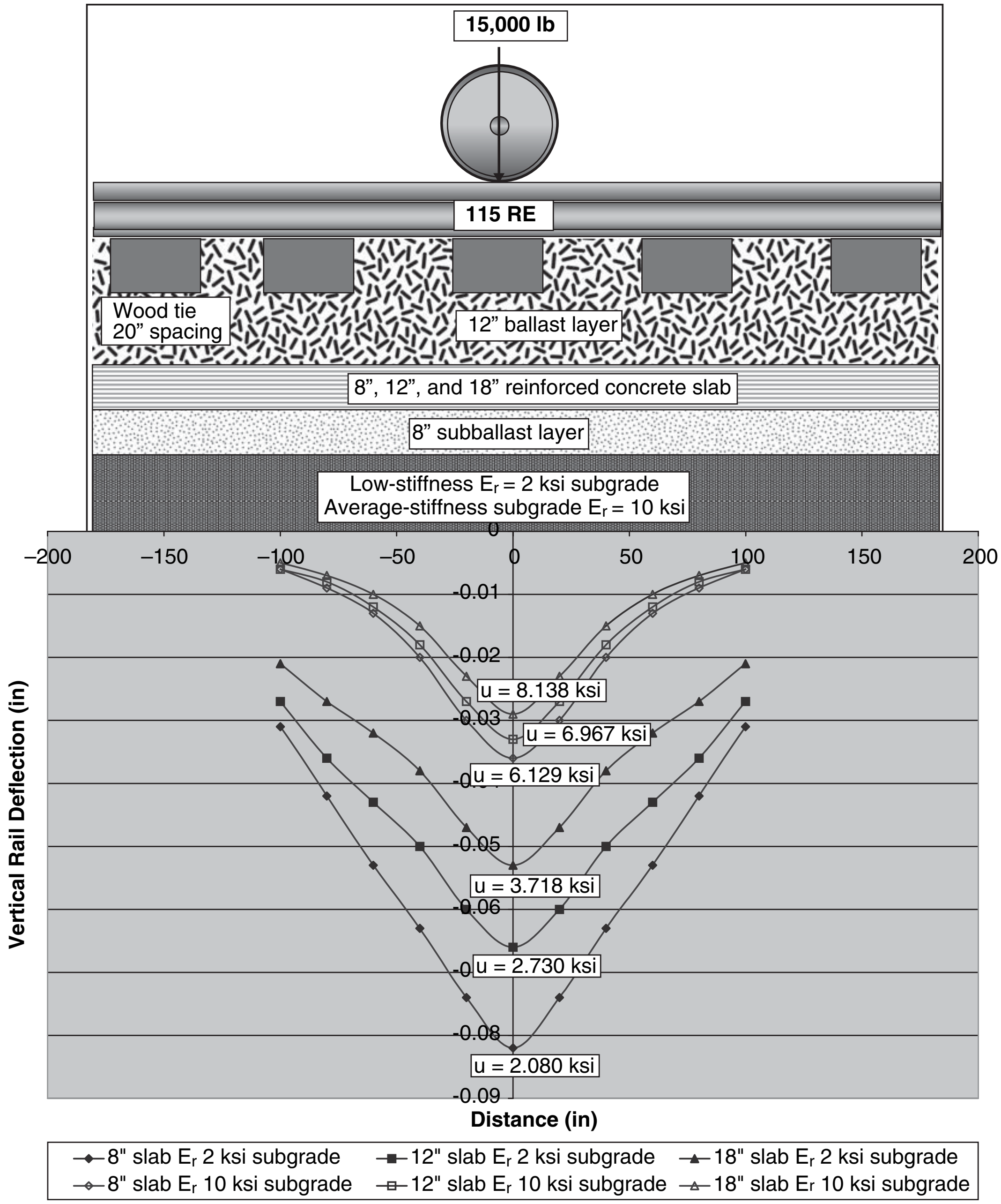

Figure 21 Rail deflection and track modulus values for 8-, 12-, and 18-in. depth concrete approach slab transitions with wood ties on low- and average-stiffness subgrades under 15-kip wheel load.

Matching Fastener Stiffness with Subgrade Resilient Modulus

Subgrade E_r values that are compatible with fastener stiffness values in terms of track modulus and rail deflection are shown in Table 10. The compatibility criterion used in Table 10 was ±0.01 in. for rail deflection. This analysis shows the subgrade conditions with wood or concrete ties that most closely match the resilience of the rail on a structure at typical fastener stiffnesses and that, therefore, would minimize the need for an additional transition design.

Matching Slab and HMA Transition Designs to Fastener Stiffness

In Table 11, the track modulus and rail deflections of the concrete approach slab or HMA underlayment transition designs are matched to the fastener stiffness values on the structure using the same compatibility

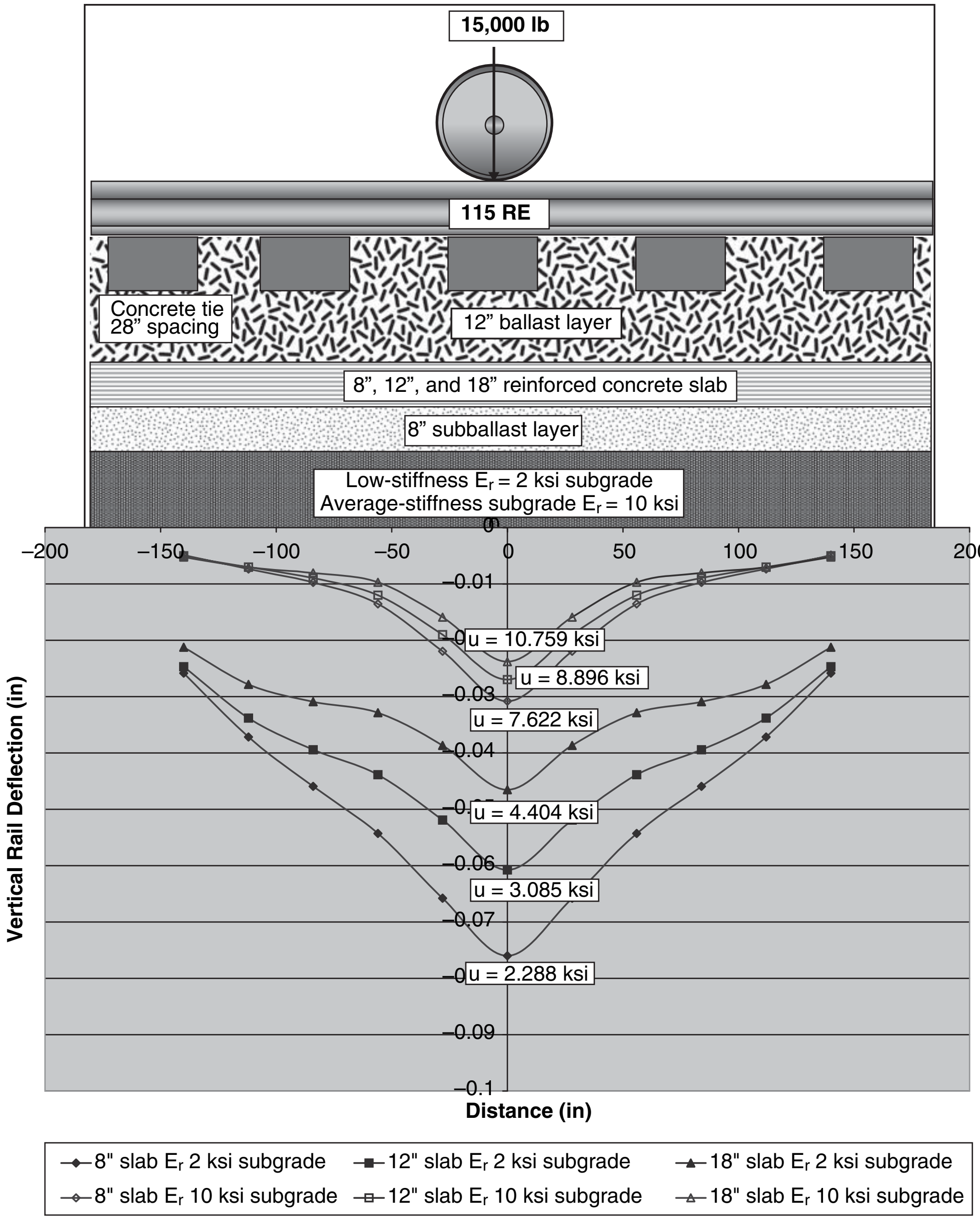

Figure 22 Rail deflection and track modulus values for 8-, 12-, and 18-in. depth concrete approach slab transitions with concrete ties on low- and average-stiffness subgrades under 15-kip wheel load.

criterion (± 0.01 in. for rail deflection) that was used in Table 10. This analysis shows the transition designs that most closely match the resilience of the rail on a structure at typical fastener stiffnesses for given subgrade E_r and tie types.

Analysis Conclusions

The following conclusions were drawn from the GEOTRACK analysis of representative track transition designs:

- The track modulus and rail deflection of at-grade ballasted track were dominated by the subgrade stiffness. Therefore, to significantly increase the stiffness of at-grade ballasted track, modification or reinforcement of the subgrade is required.
- The track modulus and rail deflection of direct-fixation track and track on ballast deck/open deck bridges are dominated by the vertical fastener stiffness as provided by elastomeric elements at the rail seat or tie bottom. Direct-

Table 7 Rail deflection, modulus, ballast stress, and subgrade stress data for HMA underlayment with concrete-tie track

		8-in Layer			12-in Layer		
Concrete Ties		**12 kips**	**15 kips**	**22.5 kips**	**12 kips**	**15 kips**	**22.5 kips**
High-Stiffness Subgrade	Rail Deflection (in)	0.020	0.024	0.037	0.019	0.023	0.035
	Modulus (lb/in/in)	10,368	10,368	10,368	11,059	11,059	11,059
	Ballast Stress (psi)	17.2	21.5	32.2	16.2	20.3	30.4
	Subgrade Stress (psi)	2.4	3.0	4.5	2.1	2.6	3.8
Average-Stiffness Subgrade	Rail Deflection (in)	0.026	0.034	0.050	0.024	0.031	0.047
	Modulus (lb/in/in)	6,819	6,819	6,819	7,492	7,492	7,492
	Ballast Stress (psi)	16.2	22.2	33.3	15.6	21.6	32.5
	Subgrade Stress (psi)	2.0	2.5	3.8	1.7	2.1	3.2
Low-Stiffness Subgrade	Rail Deflection (in)	0.071	0.090	0.135	0.062	0.079	0.118
	Modulus (lb/in/in)	1,834	1,834	1,834	2,190	2,190	2,190
	Ballast Stress (psi)	17.1	23.5	35.2	17.1	24.0	35.9
	Subgrade Stress (psi)	1.1	1.4	2.0	0.9	1.0	1.7

Table 8 Rail deflection, modulus, ballast stress, and subgrade stress data for HMA underlayment with wood-tie track

		8-in Layer			12-in Layer		
Wood Ties		**12 kips**	**15 kips**	**22.5 kips**	**12 kips**	**15 kips**	**22.5 kips**
High-Stiffness Subgrade	Rail Deflection (in)	0.024	0.030	0.045	0.023	0.029	0.043
	Modulus (lb/in/in)	7,960	7,960	7,960	8,311	8,311	8,311
	Ballast Stress (psi)	17.2	21.5	32.3	17.1	21.3	32.0
	Subgrade Stress (psi)	2.4	2.9	4.4	2.0	2.5	3.8
Average-Stiffness Subgrade	Rail Deflection (in)	0.031	0.039	0.058	0.029	0.037	0.055
	Modulus (lb/in/in)	5,580	5,580	5,580	6,038	6,038	6,038
	Ballast Stress (psi)	16.5	20.7	31.0	17.8	22.2	33.3
	Subgrade Stress (psi)	2.0	2.5	3.7	1.6	2.1	3.1
Low-Stiffness Subgrade	Rail Deflection (in)	0.077	0.096	0.144	0.067	0.084	0.126
	Modulus (lb/in/in)	1,682	1,682	1,682	1,994	1,994	1,994
	Ballast Stress (psi)	14.6	27.3	18.2	17.2	21.5	32.2
	Subgrade Stress (psi)	1.1	2.1	1.4	0.9	1.1	1.7

fixation fastener stiffness between 100 and 200 kip/in. matches the rail deflections of track on subgrades with resilient moduli between 5 and 15 ksi.

- Concrete approach slabs placed between the ballast and subballast layers produced the most substantial track modulus/rail deflection benefits. HMA underlayment also provided benefits, but was not as effective as concrete in terms of layer thickness. For example, a 12-in.-thick HMA layer produced about the same decrease in rail deflections as an 8-in. concrete slab on subgrades with resilient modulus less than 5 ksi.
- Increasing subgrade resilient modulus reduced the potential benefit from increasing the thickness of concrete slabs or HMA layers. For example, rail deflections were reduced 0.06 in. by an 8-in. concrete slab on a 2-ksi resilient modulus and reduced 0.10 in. by an 18-in. slab on the same subgrade, giving a difference of 0.04 in. between the two thicknesses. The dif-

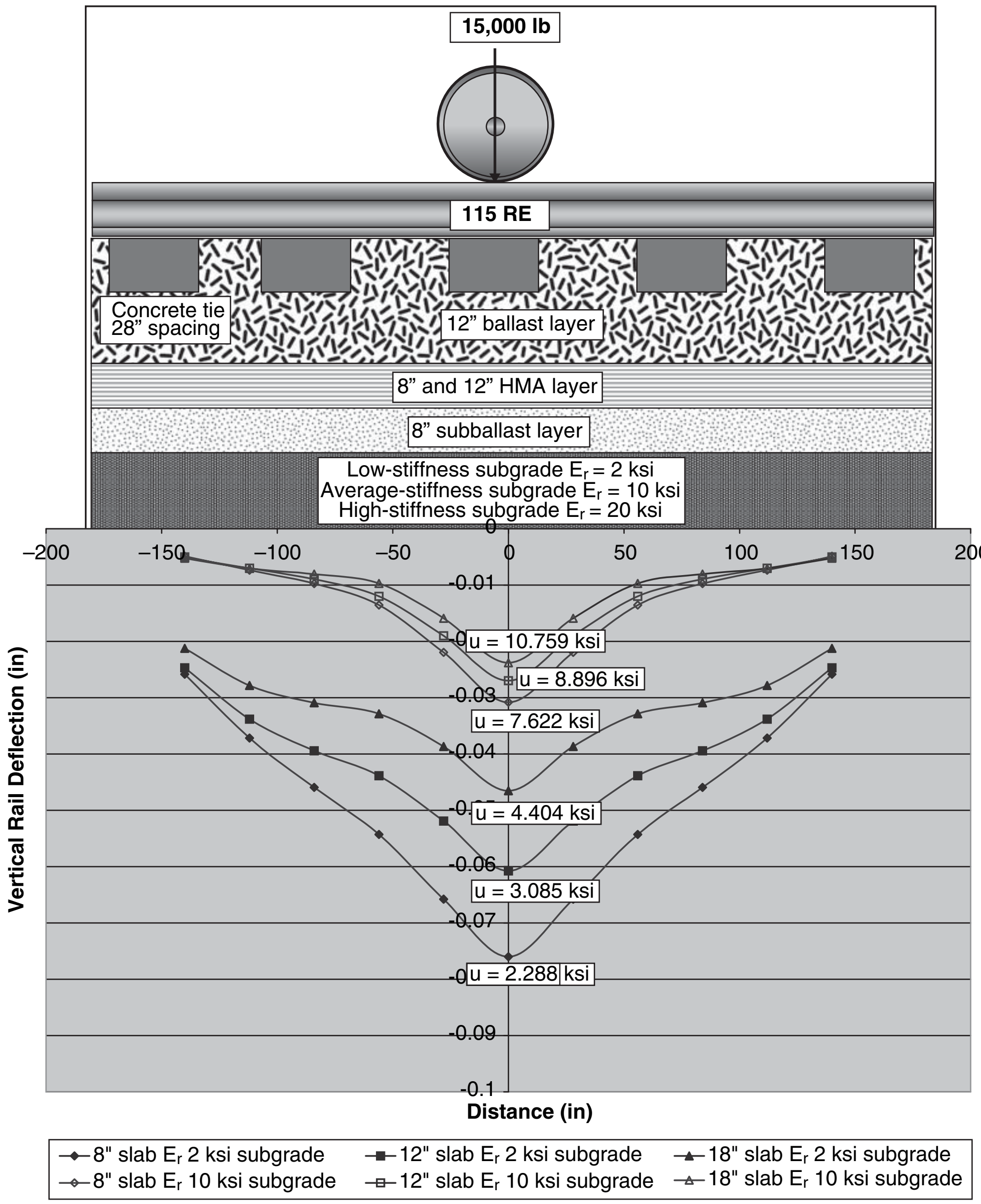

Figure 23 Rail deflection and track modulus values for 8-, 12-, and 18-in. depth HMA underlayment transitions on low-, average-, and high-stiffness subgrades with concrete ties under 15-kip wheel load.

ference between the deflections on a 10-ksi subgrade, however, was 0.01 in., or about one-fourth that of the 2-ksi subgrade. There was almost no deflection difference between the 8- and 12-in. HMA layers on a 10-ksi subgrade.

- Placing two additional rails on the ties to increase the stiffness of the track panel produced modest benefits with subgrades having resilient modulus less than 5 ksi.
- Other changes to the track superstructure, such as reduced tie spacing, installation of longer ties, or using ties with larger cross sections, had an insignificant effect on the modulus or rail deflections.
- The analyzed transit wheel loads generated differentials in the rail deflection amplitudes at the transition interface that were less than 0.1 in. for almost all the transition conditions analyzed. The largest rail deflection differential (0.15 in.) was seen at the transition between a ballasted track with very weak subgrade and an open deck bridge with a commuter car dynamic

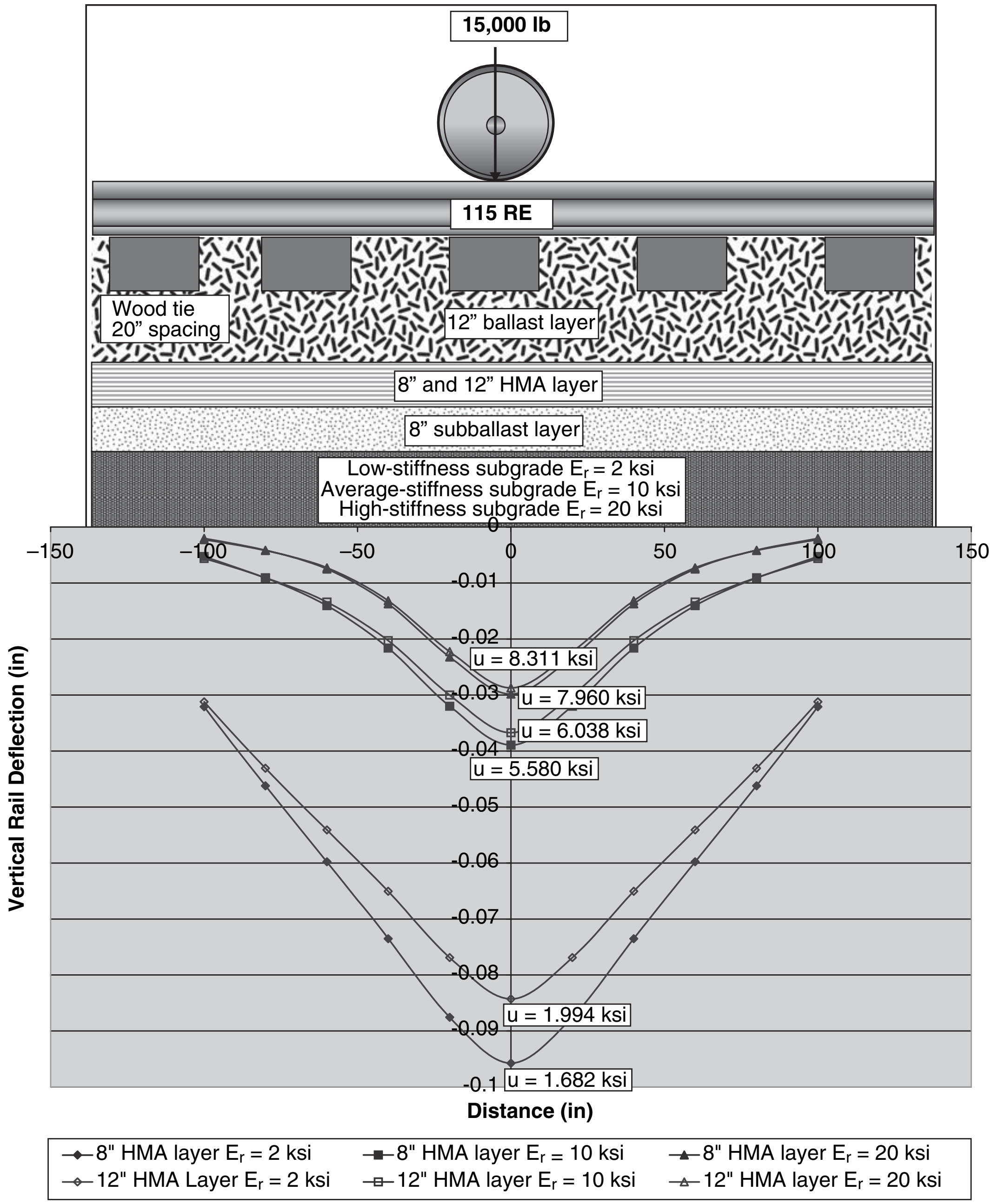

Figure 24 Rail deflection and track modulus values for 8-, 12-, and 18-in. depth HMA underlayment transitions on low-, average-, and high-stiffness subgrades with wood ties under 15-kip wheel load.

load of 22.5 kips. This same transition under the light rail 12-kip wheel load produced a deflection differential of about 0.09 in. Typical deflection differentials between ballasted track on average-stiffness subgrades and direct-fixation structures were less than 0.04 in.

- Embedded track configurations were not analyzed. As currently structured, GEOTRACK is incapable of modeling a rail with continuous support, as is the case with embedded track.

DISCUSSION OF TRANSITION DESIGNS

The following transition designs are considered to be the most efficient for rail transit applications based on the preceding literature review and GEOTRACK analysis:

- Matching the vertical fastener stiffness of direct-fixation track, ballast deck, or open deck bridges to the track modulus and rail deflection behavior of the at-grade ballasted track,

Table 9 Rail deflection, modulus, ballast stress, and subgrade stress data for additional rail design

		Concrete Ties			Wood Ties		
Concrete Ties		**12 kips**	**15 kips**	**22.5 kips**	**12 kips**	**15 kips**	**22.5 kips**
High-Stiffness Subgrade	Rail Deflection (in)	0.019	0.024	0.036	0.023	0.028	0.043
	Modulus (lb/in/in)	8,538	8,538	8,538	6,770	6,770	6,770
	Ballast Stress (psi)	14.5	17.8	26.7	12.0	15.0	22.5
	Subgrade Stress (psi)	3.0	4.0	6.0	3.2	4.0	5.9
Average-Stiffness Subgrade	Rail Deflection (in)	0.027	0.034	0.052	0.031	0.039	0.059
	Modulus (lb/in/in)	5,234	5,234	5,234	4,420	4,420	4,420
	Ballast Stress (psi)	14.9	18.7	28.0	11.2	14.0	21.1
	Subgrade Stress (psi)	2.7	3.4	5.1	2.7	3.4	5.1
Low-Stiffness Subgrade	Rail Deflection (in)	0.083	0.104	0.156	0.088	0.109	0.164
	Modulus (lb/in/in)	1,195	1,195	1,195	1,118	1,118	1,118
	Ballast Stress (psi)	18.1	22.7	34.0	9.1	11.4	17.1
	Subgrade Stress (psi)	1.6	2.0	3.0	1.6	2.1	3.1

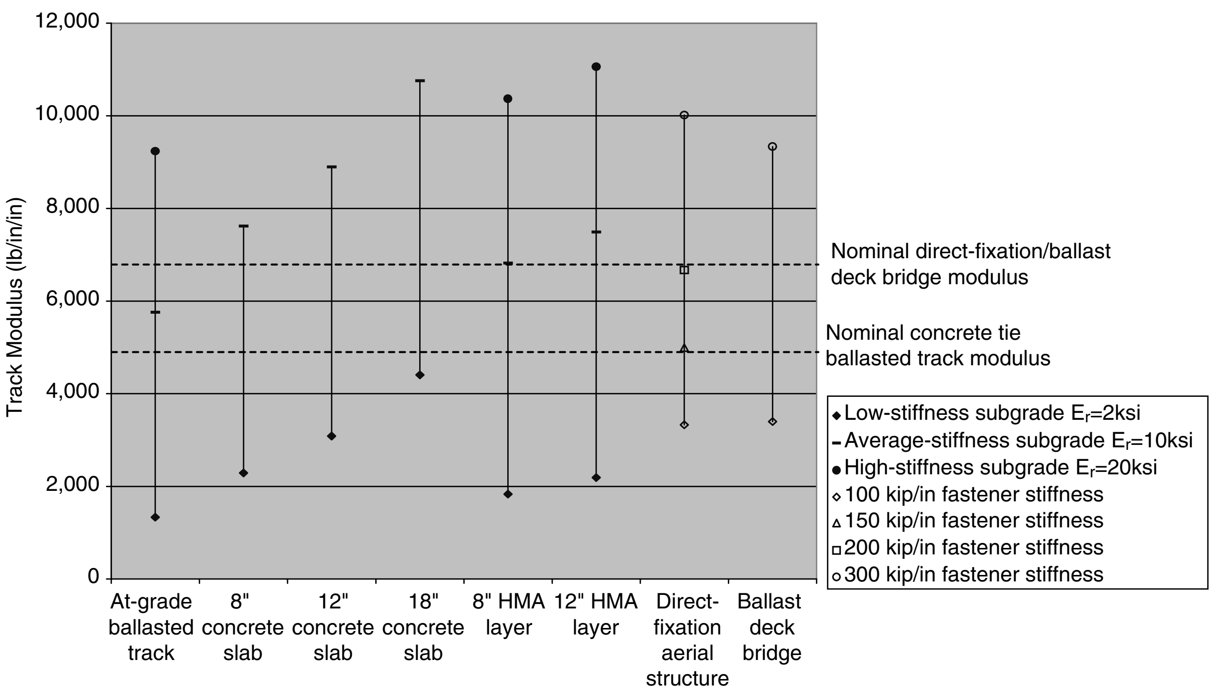

Figure 25 Comparison of track modulus values for concrete-tie track transition configurations.

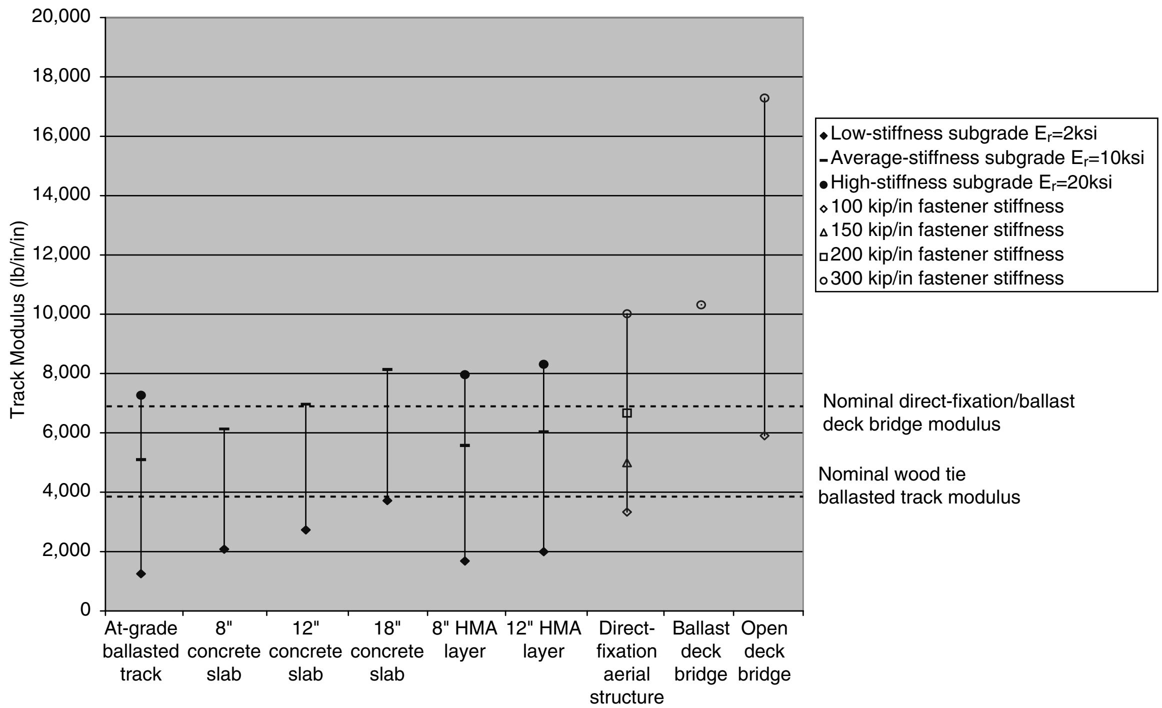

Figure 26 Comparison of track modulus values for wood-tie track transition configurations.

without modification of the at-grade track, provides the most efficient and cost-effective design. Direct-fixation fasteners with stiffness values between 100 and 200 kip/in. are compatible with ballasted tracks with average-stiffness subgrades (E_r values between 5 and 15 ksi). The analysis showed the rail deflection differentials for these designs to be less than 0.04 in. for all three wheel loads.

- The use of 10-mm concrete-tie pads with a nominal stiffness of 200 to 300 kip/in. on ballast deck bridge concrete ties provides adequate resilience to transition to ballasted track on an average-stiffness subgrade.
- The use of resilient tie pads with a nominal stiffness of 100 kip/in. on open deck timber bridges provides adequate resilience to transition to ballasted track on an average subgrade.
- Low-stiffness subgrades with E_r values less than 5 ksi require some modification in addition to the controlled resilience of the structure track. These subgrades are typically made up of cohesive soils (clays and silts) with moisture contents higher than optimum. Increasing the modulus of track on a low-stiffness subgrade requires modification of the physical state of the soil and/or installation of a structural reinforcing layer between the ballast and subgrade such as HMA underlayment or a concrete approach slab. The introduction of a structural layer, however, creates an additional interface point at the end of the slab/layer that is away from the structure, and this interface may require a second transition design in the form of increased ballast depth or stepping the layer thickness to be implemented.
- Avoiding the creation of weak subgrade conditions during new construction by careful soil selection and the application of geotechnical best practices is recommended.

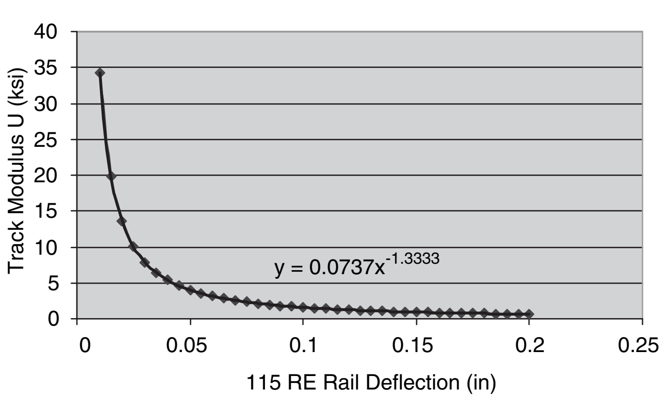

Figure 27 Track modulus as a function of rail deflection under 15-kip load.

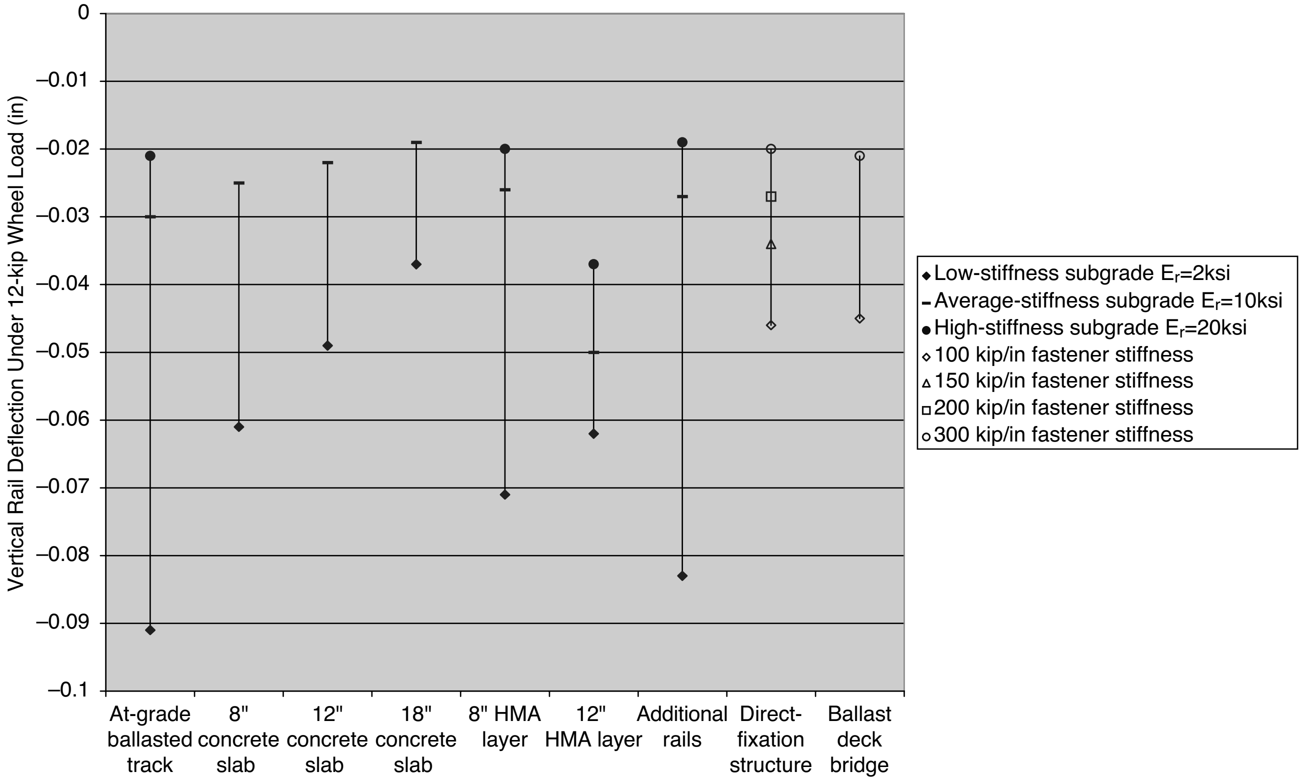

Figure 28 Comparison of rail deflection data for concrete-tie track transition configurations under 12-kip wheel loading.

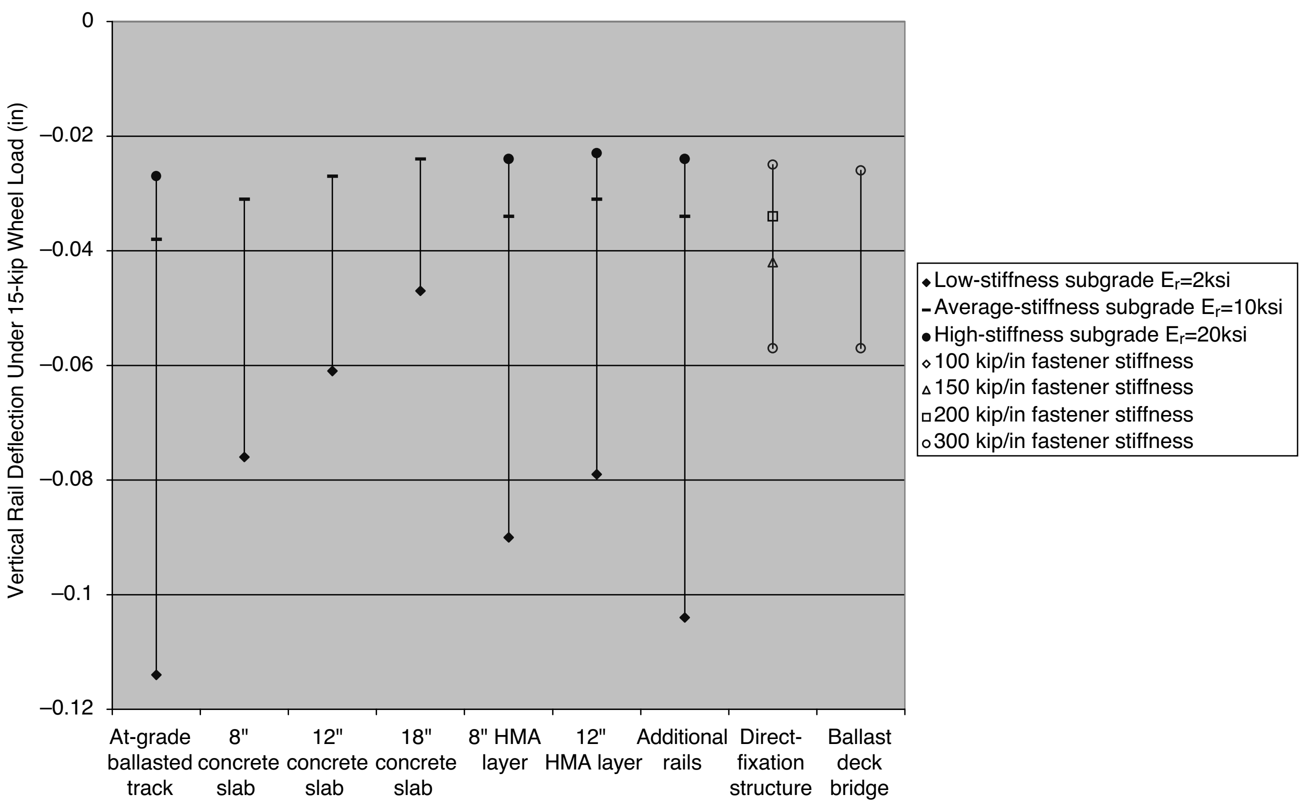

Figure 29 Comparison of rail deflection data for concrete-tie track transition configurations under 15-kip wheel loading.

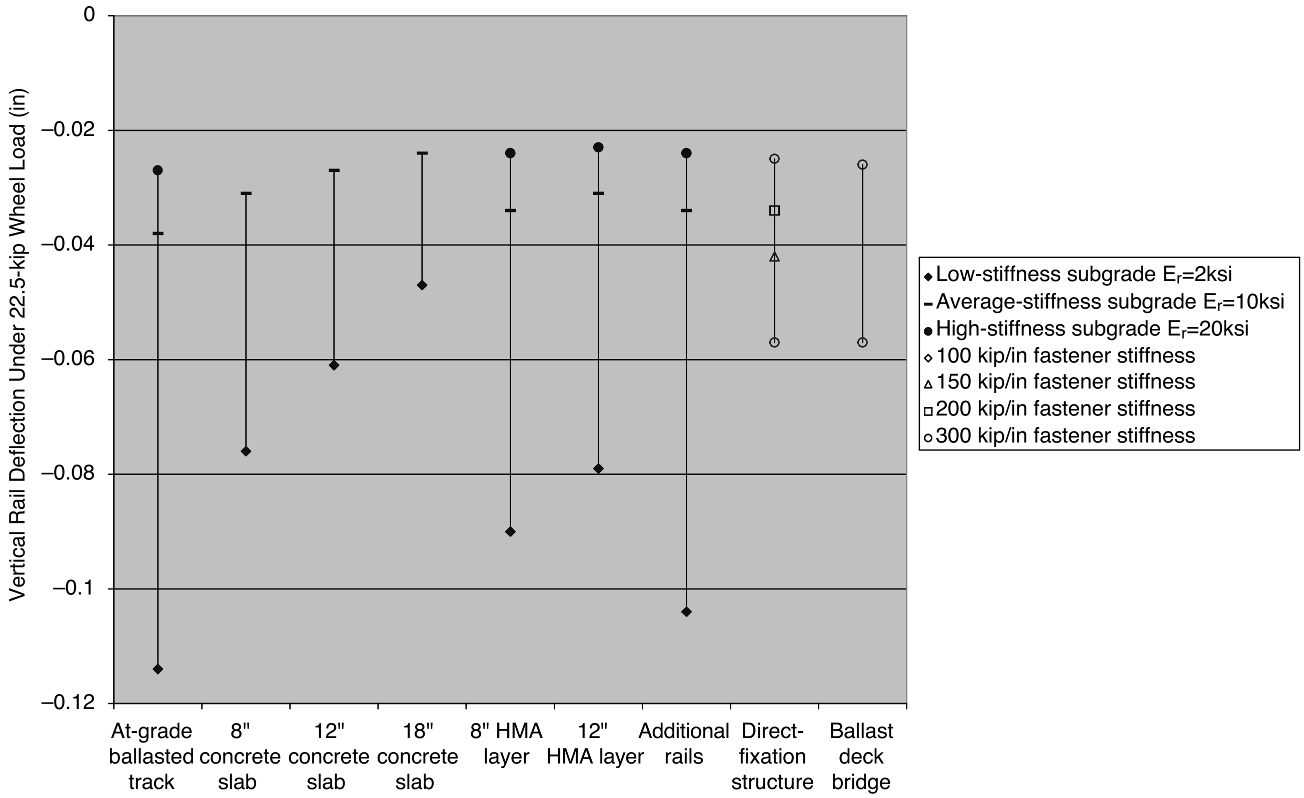

Figure 30 Comparison of rail deflection data for concrete-tie track transition configurations under 22.5-kip wheel loading.

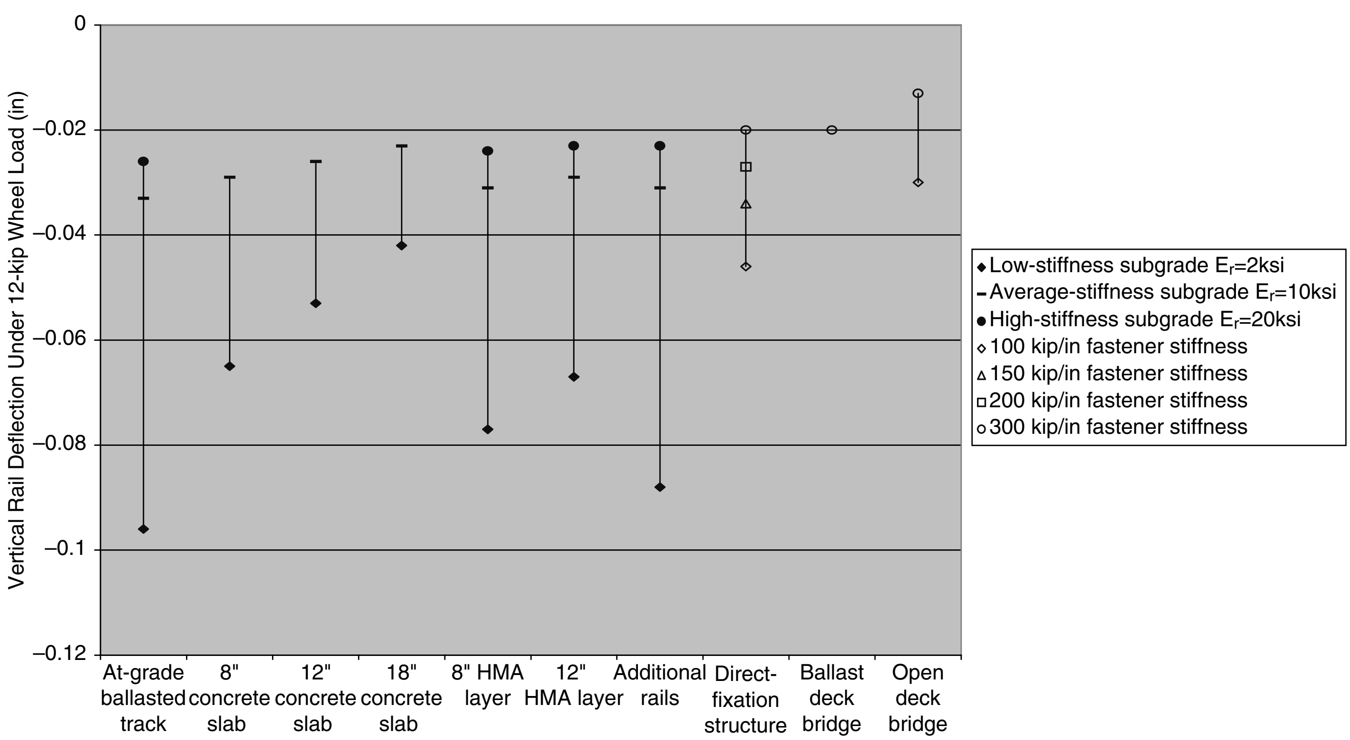

Figure 31 Comparison of rail deflection data for wood-tie track transition configurations under 12-kip wheel loading.

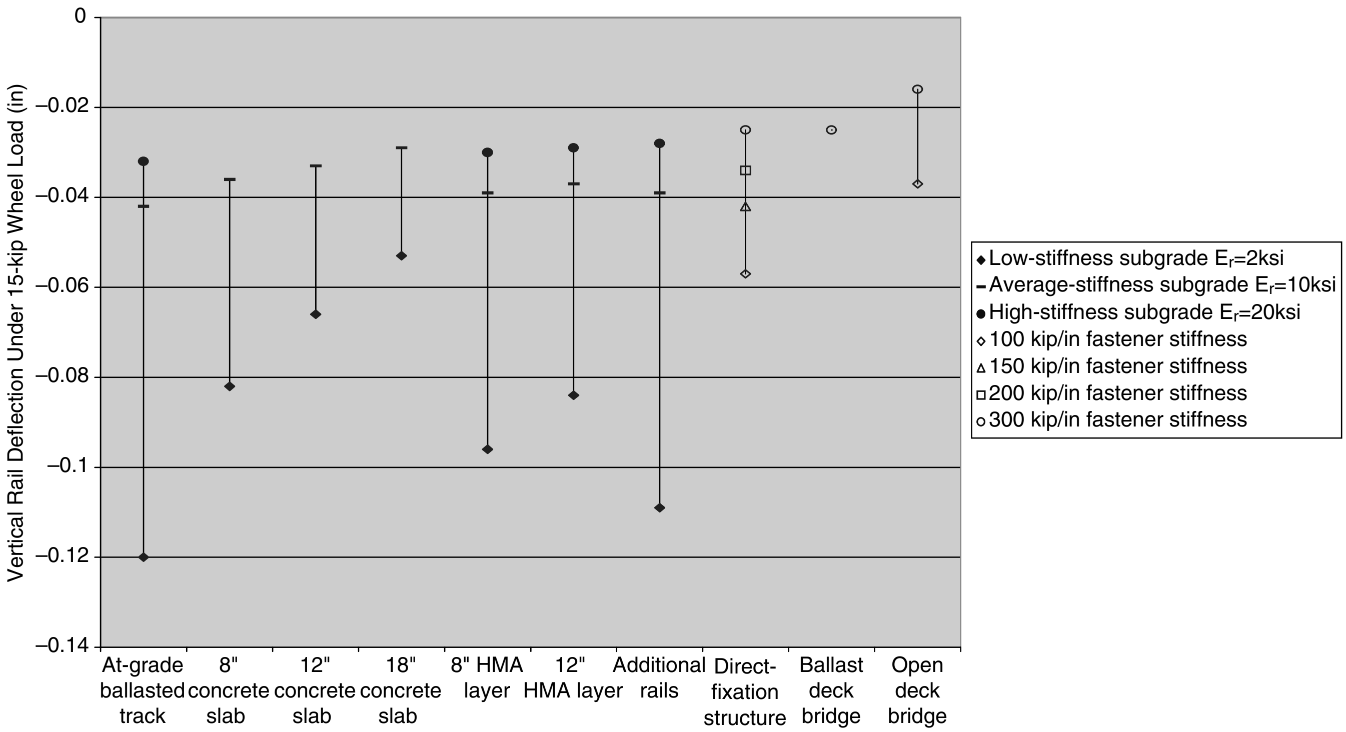

Figure 32 Comparison of rail deflection data for wood-tie track transition configurations under 15-kip wheel loading.

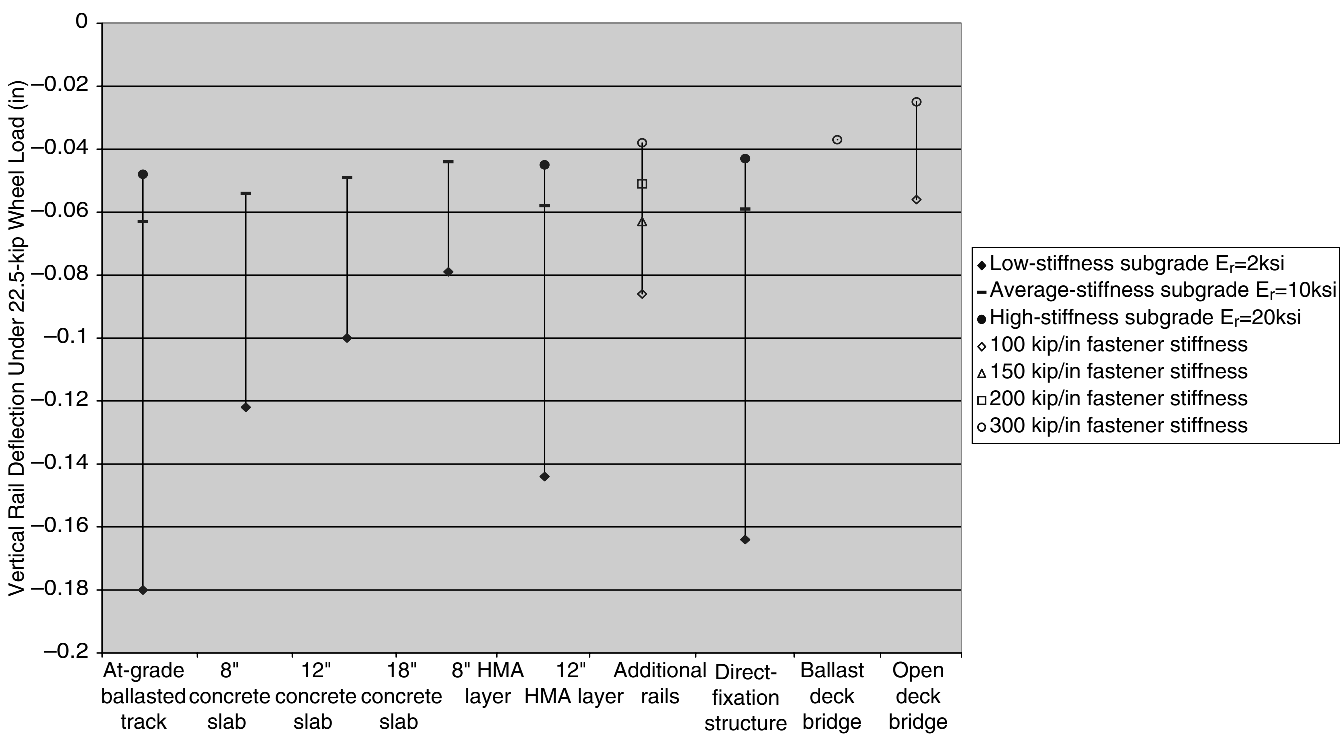

Figure 33 Comparison of rail deflection data for wood-tie track transition configurations under 22.5-kip wheel loading.

Table 10 Matching subgrade resilient modulus to fastener stiffness on structures

Tie Type/ Subgrade E_r (ksi)	Direct-Fixation and Ballast Deck Bridge Fastener Stiffness (kip/in)	Open Deck Bridge Fastener Stiffness (kip/in)*
Wood/6	100	50
Wood/8	150	75
Wood/10	150	100
Wood/12	150–200	100
Wood/15	200	100
Wood/20	300	200
Concrete/5	100	NA**
Concrete/8	150	NA
Concrete/10	150–200	NA
Concrete/12	200	NA
Concrete/15	200–300	NA
Concrete/20	300	NA

*Wood ties with elastomeric pad between the tie plate and tie. **NA = not applicable.

Table 11 Matching subgrade resilient modulus with transition design to fastener stiffness on structures

Tie Type/ Subgrade E_r (ksi)	Transition Type/ Thickness (in)	Direct-Fixation and Ballast DeckBridge Fastener Stiffness (kip/in)	Open Deck Bridge Fastener Stiffness (kip/in)
Wood/2	Concrete slab/18	100	75
Wood/6	Concrete slab/18	200	100
Wood/6	Concrete slab/12	150	100
Wood/6	Concrete slab/8	150	75
Wood/10	Concrete slab/18	200–300	150
Wood/10	Concrete slab/12	200	150
Wood/10	Concrete slab/8	200	100
Wood/15	Concrete slab/12	300	150
Wood/15	Concrete slab/8	200	150
Wood/6	HMA/12	150	75
Wood/6	HMA/8	125	75
Wood/10	HMA/12	200	100
Wood/10	HMA/8	150–200	100
Wood/15	HMA/12	200	150
Wood/15	HMA/8	200	150
Wood/20	HMA/12	200–300	150
Wood/20	HMA/8	200–300	150
Concrete/2	Concrete slab/18	150	NA*
Concrete/2	Concrete slab/12	100	NA
Concrete/6	Concrete slab/18	200	NA
Concrete/6	Concrete slab/12	200	NA
Concrete/6	Concrete slab/8	200	NA
Concrete/10	Concrete slab/18	300	NA
Concrete/10	Concrete slab/12	300	NA
Concrete/10	Concrete slab/8	200	NA
Concrete/15	Concrete slab/8	300	NA
Concrete/6	HMA/12	150	NA
Concrete/6	HMA/8	125	NA
Concrete/10	HMA/12	200–300	NA
Concrete/10	HMA/8	200	NA
Concrete/15	HMA/8	300	NA

*NA = not applicable.

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