# Design of Well-Performing Railway Transitions

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## ABSTRACT
This paper presents a review of railroad track transition behavior, causes of undesirable performance, and existing designs that exhibit desirable transition performance. The first focus of the paper is reviewing common factors leading to reoccurring track geometry deviations. This involves the inherent problem of a train passing from a deformable, earth substructure onto a nearly rigid, man-made structure. This process results in increased dynamic loads from the differential movement between the transition zone and bridge and within the transition zone itself. To avoid these increased dynamic loads, it is ideal to minimize all possible movements between the transition zone and bridge deck. Realistically, emphasis should be placed on reducing both ballast and subgrade settlements in the transition zones along with decreasing the track stiffness on the bridge. Two well-performing bridge transitions are presented along with their key design components to illustrate techniques for minimizing differential movements. Other design techniques and influential factors on ballast degradation are also addressed because of its relevance to ballast settlement in the transition zone.


## INTRODUCTION
Differential settlement at higher-speed railway transition zones represents an expensive and reoccurring maintenance issue for railway companies and potential safety concern because of the continual upgrade to heavier, longer, and faster trains. In 2005, the estimated maintenance cost for transition zones was $200 million annually according the Association of American Railroads and maintenance costs will likely continue to increase (*1*).

To reduce differential movement and the need for frequent recurring track resurfacing, a wide variety of transition zone designs and remediations have been proposed (*2-6*). These typically involve (1) increasing and smoothing the track stiffness in the transition zone and/or (2) lowering the track stiffness of the bridge deck because of the fundamental understanding that differential stiffness and settlement leads to undesirable transition zone performance. Potential solutions in the transition zone have included: increased tie lengths, decreased tie spacing, additional rails, Hot-Mixed Asphalt (HMA), concrete approach slabs, stone columns, piles, geoweb, and soil stabilization. Bridge deck solutions include: ballasted bridge decks, rail and tie pads, and ballast mats. While a few of these solutions have shown promising results, none are all-encompassing and typically work on a site-specific basis.

Improvements in instrumentation and numerical techniques along with recent motivations for developing transition zone design solutions have resulted in new research projects over the past decade. The goal of this paper is to (1) review the multiple causes of differential settlement at transition zones and attempt to expand upon the existing knowledge of how transition zones perform, (2) illustrate two successful bridge transition zone designs, and (3) discuss potential solutions and remediation along with factors influencing ballast settlement.

## CAUSES OF INCREASED AND DIFFERENTIAL SETTLEMENT
Multiple investigations throughout the world have been dedicated to determining the potential causes of increased settlement at transition zones (*2,3,7-9*). Besides the consensus that the causes are typically site specific, increased dynamic loading within the transition zone is often viewed as the mechanical driver that results in increased settlement in the transition zone. Inadequate drainage and undesirable construction practices also contribute to settlement.

Multiple factors potentially increase the dynamic loads applied to the ballast but they can be generally categorized into four causes: (1) rapid changes of axle elevation, (2) uneven load distribution, (3) impact loads, and (4) high-stiffness and low-damping of the bridge. In order to optimize designs, it is important to identify which factors primarily contribute to increased dynamic loads and then focus on reducing the influence of those factors.

The rapid change in axle elevation in transition zones is historically the main emphasized cause of increased dynamic loads in transition zones and it can result from both differential stiffness and settlement between the transition zone and bridge deck. In both cases, the lower track stiffness and/or greater track settlement in the transition zones cause the front train axle of a truck to accelerate upwards when reaching the bridge abutment. The rapid upward acceleration of the front axle will result in not only an increased loading on the bridge abutment but also in the transition zone from the back axle due to coupling of the front and back axles. Numerical modeling results suggest that differential stiffness alone will not significantly increase the dynamic loads in the transition zone. Results by Nicks (*7*) and Wang et al., (*10*) show increased dynamic loads of less than 20%. However, numerical modeling results have displayed significant increased dynamic loads from differential settlement with increases surpassing 100% (*7,10*). This seems valid conceptually because differential settlement produces a larger change in axle elevation than from only differential stiffness. At bridge exits, the opposite effect occurs and can also result in the “bouncing” or “galloping” of the train once exiting the bridge (*11*).

The second and third causes of increased dynamic loads result from the development of tie-ballast gaps within the transition zone (*12*). Tie-ballast gaps, i.e. hanging ties, often develop because the earthen material in the transition zone substructure naturally settles while the man-made bridge deck will remain essentially rigid over time, especially if supported by deep foundations. The transition zone can also experience additional settlement from the increased dynamic loads from rapid changes of axle elevation, producing the “dip” often observed 6 to 12 feet from the bridge abutment because that is the location of the increased dynamic load from the back axle. This results in the rail and ties to hang or cantilever from bridge deck and open track while tie-ballast gaps of varying height develop in the transition zone (Figure 1). Due to the existence and variation of tie-ballast gaps, the load redistributes and concentrates on particular ties (*13*). The load can also increase when the moving ties impact the ballast because of Newton’s Second Law that states force (F) equals mass (m) multiplied by acceleration (a). Load redistribution is currently being investigated using numerical techniques. Also, accelerometers attached to concrete ties in transition zones show increased accelerations during contact with the ballast, suggesting impact (*14*).

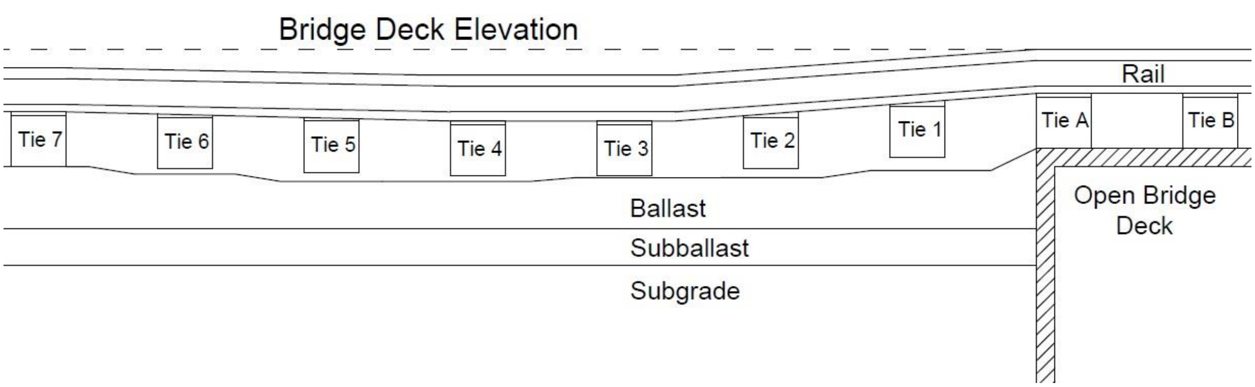


**Figure 1: Example diagrams of bridge transition zones with tie-ballast gaps.**

The fourth cause of increased loading is from the high-stiffness and low-damping of bridges, especially with concrete ties. This effect has been investigated by other authors (*2,4,15*).

Additional factors commonly attributed to increased settlement within transition zones are poor drainage and undesirable construction and maintenance practices. Excess water, typically coupled with fouling, can result in lower stiffness (*16*), increased settlement (*17,18*), and potentially the development of excess pore-water pressures within the ballast, all of which will accelerate the deterioration of the track geometry. Undesirable construction and maintenance practices involve a wide range of factors including:

inadequate geotechnical characterization, inadequate compaction, non-uniform soil, narrow embankment widths and steep slopes, inadequate tamping, and others (*4*).

## TRACK SCORECARD

A major takeaway is that in order to eliminate the increased dynamic loads in the transition zones, the differential transient and permanent displacement must be limited not only between the transition and bridge but also within the transition zone itself. In other words, an ideal transition zone will have a constant rail elevation between the transition zone and bridge during train passage. This is ideal because the differential stiffness and settlement between the transition zone and bridge will increase dynamic loads from rapid changes of axle elevation while differential settlement within the transition will concentrate dynamic loads from load redistribution. Additionally, lowering the stiffness and increasing the damping of the track on the bridge can also reduce dynamic loads and this will likely be accounted for when reducing differential transient displacements between the transition zone and bridge.

To illustrate how to prevent large differential transient and permanent displacements, the concept of a "track scorecard" is used and is presented in Figure 2. It lists many of the potential displacement components in track, including: (1) rail compression, (2) rail-tie gap, (3) tie pad/plate displacement, (4) tie displacement, (5) tie-ballast gap, (6) ballast displacement, (7) subballast displacement, (8) subgrade displacement, and (9) lateral displacement. For the design of an ideal transition zone, all displacement components should be addressed in both the transient and permanent time-frames because once differential transient and/or permanent displacements develop, the dynamic loads will increase and accelerates the track degradation process.

| Transition and Bridge Displacement Component | Noticeable Transient | | Noticeable Permanent | |
|---|---|---|---|---|
| | T | B | T | B |
| Rail compression | | | | |
| Rail-tie gap | | | | |
| Tie pad/plate displacement | | | | |
| Tie displacement | | | | |
| Tie-ballast gap | | | | |
| Ballast displacement | | | | |
| Subballast displacement | | | | |
| Subgrade displacement | | | | |
| Lateral displacement | | | | |

**Figure 2: Example of track scorecard to conceptually compare bridge and transition zone transient and permanent displacements.**

Previously proposed designs have typically focused on the transient track displacements (track stiffness) by decreasing the transient displacement of a single or a few components in the transition zone or by increasing the displacement on the bridge (*2-6*). The main exception is Qian et al. (*19*) which proposed focusing on the permanent displacements by use of a “settlement ramp”, which adjusts the ballast gradation along the approach with the desire of gradually reducing ballast settlement as the track approaches the bridge abutment.

Ideally both transient and permanent time-frames must be addressed because differential movement from either time-frame can increase dynamic loading. The permanent time-frame may be a greater priority because differential settlement produces greater dynamic loads than from purely differential stiffness (*10*). However, once the dynamic loads increase, ballast deterioration initiates and places the track in a self-perpetuating system where the increased dynamic loads from track settlement results in greater track settlement.

Adequate geotechnical and construction practices, proper drainage, and ensuring the ballast is well-tamped to reduce the initial ballast settlement after the first train loadings are also imperative factors. Inadequate construction, drainage, or maintenance, e.g. tamping, can significantly change one of the multiple displacement components in the transient and permanent time-frames and potentially render any solution ineffective.

## WELL-PERFORMING SITES

A significant amount of previous research on transition zone design involved implementing a solution and tracking its potential improvement over time (*3,15*). This method is beneficial by showing a quantitative “before” and “after” comparison and clearly shows the influence of a particular solution. However, because of the costs involved in new transition zone design or remediation, the authors instead decided to investigate two bridge transition zones that have already been installed and have proven records of adequate performance. This provides a “finalized perspective” of what is shown to work and hopefully “before” and “after” measurements of new installations will be the feature of future work.

### Site #1

The first site consists of a bridge transition zone that handles freight trains with velocities of about 25 mph with annual traffic of about 7 MGT and has required only minimal track geometry maintenance since being placed in service in 2009 (5 years). The track site involves the west end of a bridge spanning hundreds of feet on an approach fill over 75 feet high and is displayed in Figure 3. The track is considered Class 3 for operations, has timber ties, and supports both loaded and unloaded freight trains.

To avoid differential movement and the subsequent increased dynamic loads, the bridge transition zone was designed with four main components: (1) ballasted concrete bridge deck, (2) a 6-inch thick hot-mixed asphalt (HMA) layer underneath a 12-inch thick ballast layer on the approach, (3) 27-foot concrete wing walls extending perpendicular to the bridge abutment, and (4) consolidation of the approach fill prior to track construction. These features are important because specifically, (1) the ballasted bridge deck reduces the stiffness or load-displacement differences between the approach and bridge deck and increases the track settlement on the bridge, (2) the HMA layer supports and stabilizes the ballast layer by developing a higher ballast modulus, spreading the train loads, confining the ballast, and provides an infiltration barrier between the ballast and subgrade (*20,21*), (3) the concrete wing walls add confinement to the ballast and subgrade which can reduce settlement and lateral displacement, and (4) waiting 5-years for the 75-ft fill to consolidate reduces the settlement of the subgrade fill from train loadings. In terms of the “track scorecard”, the site does a very good job at equalizing the transient and permanent displacements in the transition zone and bridge.

**Figure 3: West End of Site #1 Bridge Transition Zone**

Using non-invasive accelerometers and high-speed video cameras, the track on the bridge, transition zone, and open track behaved similarly with tie accelerations of about 5g for loaded freight trains and tie displacements of about 0.04 inches or 1 mm (*22*). The low values of both metrics, less than or equal to 5g of tie acceleration and 0.04 inches of tie displacement, indicate good track support when compared against historically poorly supported track where tie accelerations can range from 10 to 100g and tie displacements can reach 0.4 in (10 mm) or greater (*14*). The lack of discernable difference between the seven selected ties at varying locations on the bridge, transition zone (0 to 27 feet from the bridge abutment), and open track (27+ feet from the bridge abutment), suggests that four design/construction techniques significantly reduced differential track behavior and prevent the development of increased dynamic loads.

**Site #2**

The second site involves a similar bridge transition zone (Figure 4) that supports unloaded and loaded freight trains moving at velocities of 25 mph with annual traffic at about 70 MGT and has required only minimal track maintenance since construction in 1998 (16 years). Two main differences between Site #1 and Site #2 are that Site #2 consists of concrete ties instead of timber ties and minimal fill was placed before construction.

As partly shown in Figure 4, three of the four design techniques shown previously were used in Site #2 with (1) a ballasted concrete bridge deck, (2) a 6-inch HMA layer under 12-inches of ballast, and (3) a 24-foot concrete wing walls extending perpendicular to the bridge abutment.


**Figure 4: West End of Site #2 Bridge Transition Zone**

Using the same non-invasive instrumentation as Site #1, the track on the bridge, transition zone, and open track behaved similarly with tie accelerations measuring at about 5g and tie displacements measuring at about 0.04 inches or 1 mm (*22*).

These two sites show a strong correlation between the small amount of total and differential movement in the transient time-frame and of the reduction in the need for track resurfacing. This relation is expected because the small magnitudes of transient movement imply a smooth load transfer between the rail, rail pads, ties, and ballast which prevents the initiation of increased dynamic loads. This lack of dynamic loads will not start the track degradation process and will allow the track to maintain track geometry for extended periods of time, i.e. 5 and 16 years respectively.

## ALTERNATIVE DESIGNS

One of the primary objectives of railway transition zone design is to minimize increased dynamic loads caused from multiple sources, including: (1) rapid changes in axle elevation from differential stiffness and settlement between the transition zone and bridge deck, (2) load redistribution and concentration of loads from tie-ballast gaps in the transition zone, (3) impact from moving ties contacting the ballast from tie-ballast gaps, and (4) high bridge stiffness and low damping. The design techniques presented in the previous section seem to have accomplished this task because the track geometry at both sites has been maintained well since being placed in service and tie accelerations showed no evidence of increased loading (*22*). However, these are not the only available techniques and may not be the optimal options or most cost-effective solution in every situation.

Having the ability to choose from a wide range of transition zone design techniques is beneficial because it allows for cost-effective decisions and site-specific solutions so alternative, potentially more economical techniques that can accomplish the same result should also be explored. Multiple authors have investigated various possible techniques that can be used (*2,4*) and others have measured their effect on track behavior (*3,6,15*). If these techniques can accomplish the same function as those presented, they will likely be viable alternatives. For example, the use of wedge-shaped backfills in a transition zone in Portugal (6) and rail pads and ballast mats in the United States (*15*) have also shown promising results.

## BALLAST SETTLEMENT

As stated in the previous sections, an ideal transition zone will eliminate all differential transient and permanent movements between the bridge and transition zone but accomplishing this can be expensive and may not be considered cost-effective. In these cases, data suggests focusing on reducing settlement within the transition zone ballast layer and decreasing the stiffness of the bridge will be most effective at reducing the increased dynamic loads. This section will review some primary factors that cause ballast degradation and settlement along with proposed suggestions on how to increase ballast life.

One of the main components of ballast settlement is the breakdown of ballast from repeated train loadings and process of mechanical tamping (*23,24*). This, along with fine infiltration from the subgrade, train cars, and degraded ties, can foul the ballast (*23*) and change its gradation which therefore changes its stiffness, settlement, and drainage properties (*17,18,25*). Testing of fouled ballast has displayed increased settlement and wide variations in stiffness, i.e. modulus, depending on whether it is wet or dry. This suggests that efforts solely focusing on eliminating differences in track stiffness may only be applicable after ballast degradation occurs. At that point, the transition zone track stiffness and settlement potential will have changed and can initiate the track degradation process. Efforts to clean and properly drain the ballast can prevent the severe negative effects of fouling and confining the transition zone with concrete wing walls can reduce settlement.

Secondly, stiff ties and large ballast particles can cause the tie to distribute its load to only a few concentrated ballast sections instead of the entire tie-ballast surface. Field measurements of the tie-ballast stress distribution shows 20 to 30% average contact area for new ballast and about 30 to 40% for highly degraded ballast (*26*). This low contact area will translate to higher local stresses acting on the ballast particles which can start the degradation process. These high local stresses can be reduced by decreasing the stiffness of the tie by using alternative materials or under tie-pads (UTPs). For example, while UTPs actually lowers the stiffness in the transition zone and results in greater transient displacements, it can provide beneficial effects by better distributing the load amongst a single tie. UTPs can lower the local stresses on the ballast, reduce ballast breakdown, and studies have shown UTPs to be able to reduce ballast settlement (*27*). To account for the lower track stiffness, a slight overlift in the transition zone region may be necessary to avoid increased dynamic loads from rapid changes in axle elevation.

## SUMMARY

Successfully designing and remediating transition zones are a difficult task because of the multiple factors that can lead to track degradation. This paper summarizes a few causes of increased dynamic loads in transition zones, presents two examples of successful transition zone design, and discusses causes of ballast degradation over time and its effect on transition zone performance. A few summary remarks are listed below:

- Transition zone degradation is often attributed to increased dynamic loads in the transition zone region. Among other factors, these can be produced from: (1) rapid changes in axle elevation, (2) load redistribution, (3) impact loads, (4) high stiffness and low damping of the bridge. Additionally, stiff concrete ties can increase local stresses acting on the ballast while construction practices, maintenance practices, and drainage are also important factors.

- To avoid increased dynamic loads, ideal transition zone design should eliminate both the differential transient and permanent track displacement between the transition zone and abutment and within the transition zone itself.

- Two bridge transition zones that have performed successfully and have required only minimal track maintenance since being placed in to service were instrumented and monitored. The transition zone design, including (1) a ballasted bridge deck, (2) HMA underlying the ballast, (3) and concrete wing walls extending perpendicular to the bridge abutment appear to reduce the differential moment between the bridge, transition zone, and open track. The ballasted bridge deck decreases bridge stiffness and allows greater transient and permanent displacements on the bridge. The HMA layer helped distribute stresses in the transition zone and prevent infiltration between the ballast and subgrade. The concrete wing walls helped confine the ballast and reduce ballast settlement in the transition zone region.

- Additional considerations include: (1) the ballast will likely degrade over time, especially when the ballast degradation is coupled with impeded drainage, and results in changes of ballast stiffness, settlement potential, and drainage and (2) stiff ties may distribute the load over a small contact area producing high localized stresses on the ballast which can increase ballast degradation.

- Solutions such as minimizing or smoothing the track stiffness between the transition zone and bridge may not be the best approach for bridge transition zone design because: (1) many additional factors, e.g. differential settlement and load redistribution, can increase dynamic loads to an even greater degree, (2) track stiffness is largely influenced from construction and maintenance practices, and (3) ballast and track degradation will change in track and ballast stiffness over time. This makes it difficult to develop an all-encompassing solution that is flexible to the wide variation of field conditions, construction practices, and degradation that will naturally be present.

In summary, specifications used for transition design will involve knowledge of how the transition zone is expected to behave from site characteristics and recommending site-specific solutions for that particular location. Once that is accomplished, adequate construction and maintenance practices are necessary to ensure desirable performance once implemented. If a general philosophy is to be used, the authors believe that more emphasis should be placed on increasing track support and reducing high tie-ballast contact loadings, especially impacts, which result in ballast damage and settlement in the transition zone along with reducing the stiffness of the bridges instead of stiffening or “hardening” the transition zone.

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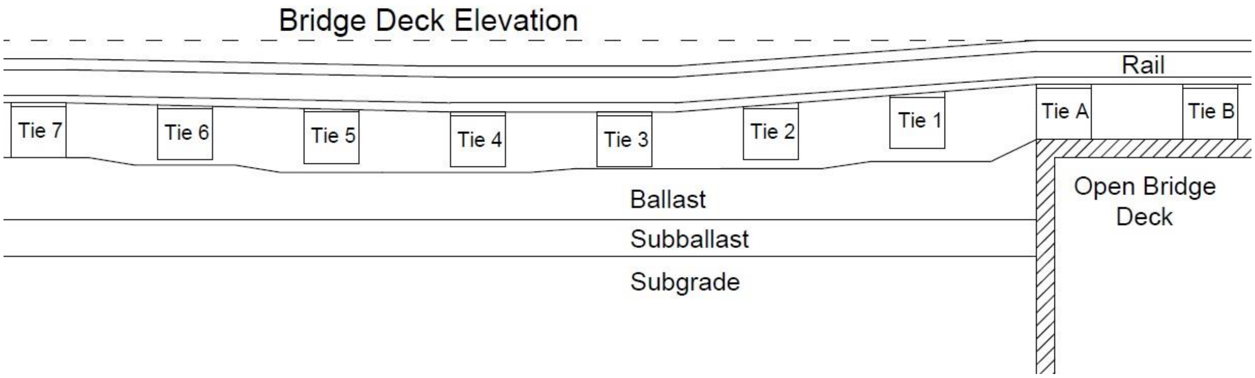


**Figure 1: Example diagrams of bridge transition zones with tie-ballast gaps.**

| Transition and Bridge Displacement Component | <u>Noticeable Transient</u> | | <u>Noticeable Permanent</u> | |
|---|---|---|---|---|
| | <u>T</u> | <u>B</u> | <u>T</u> | <u>B</u> |
| Rail compression | | | | |
| Rail-tie gap | | | | |
| Tie pad/plate displacement | | | | |
| Tie displacement | | | | |
| Tie-ballast gap | | | | |
| Ballast displacement | | | | |
| Subballast displacement | | | | |
| Subgrade displacement | | | | |
| Lateral displacement | | | | |

**Figure 2: Example of track scorecard to conceptually compare bridge and transition zone transient and permanent displacements.**

**Figure 3: West End of Site #1 Bridge Transition Zone**

Figure 4: West End of Site #2 Bridge Transition Zone