EFFECTS OF HEAVY AXLE LOADS ON BONDED INSULATED
JOINT PERFORMANCE

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ABSTRACT

Heavy Axle Load (HAL) coal traffic, with higher speeds and higher traffic densities, places a significant performance demand on bonded insulated rail joints (bonded IJs). This paper reviews bonded IJ failure modes, analysis, and recent design innovations being evaluated by the Transportation Technology Center, Inc., (TTCI), Pueblo, Colorado, a wholly owned subsidiary of the Association of American Railroads (AAR).

Heavy haul railroads, suppliers, and researchers from TTCI are working together to improve the performance of bonded IJs. Significant progress has been made through an AAR sponsored research and development project focused on understanding the HAL service environment, loading conditions, and failure modes of bonded IJs. The industry now has the opportunity to develop improved performance bonded IJs.

Today, bonded IJ service life can be as short as 200-million gross tons (MGT). Bonded IJ performance on heavy haul coal routes has also declined as the load environment has become more severe. Bonded IJs service life is lower than virtually all other running surface components (including turnout frogs and switch points). Only high angle crossing diamond frogs with unsupported flangeway gaps have similarly short service
lives. Bonded IJs pose a significant threat to service reliability and efficiency of railroads operating heavier, faster, and higher traffic rate environments.
1.0 BONDED IJ PROBLEM DESCRIPTION

On heavy traffic coal routes, the relatively short service life of bonded IJs reduces service reliability and increase train delays.

Despite their drawbacks, bonded IJs are essential components for current track circuit based signal systems by dividing the track into short segments (usually 2 miles or less) that detect train presence and activate trackside signals. These signals allow for train separation and improving the safety and capacity of track. Bonded IJ spacing is dependant on the desired capacity of the line and train operating speeds. Figure 1 shows a typical bonded IJ in heavy haul service.

While bonded IJs are essential to the operating department, they also introduce weak points in the track which cause increased maintenance and service disruptions. Bonded IJs are also a potential safety risk.

Bonded IJ performance on heavy haul coal routes has declined as the load environment has become more severe. Today, bonded IJ service life may be as short as 200 MGT. This short service life is lower than virtually all other running surface components including turnout frogs and switch points. Traditionally, turnout frogs have been the shortest lived components in HAL service. Improvements in design and materials, however, have lengthened frog service live to 400 - 600 MGT. Only high angle crossing diamond frogs with unsupported flangeway gaps have similarly short service lives. With many times more bonded IJs in track (compared to other components), bonded IJs contribute significant risks on achieving service reliability and efficiency goals. Data in Figure 2 confirms the long held
belief that bonded IJ life is relatively short as improvements in other track components have
highlighted bonded IJs as the next component to be improved.

On high tonnage routes, bonded IJs may be replaced within as little as 12 to 18
months with direct costs of thousands of dollars per mile per year. Indirect costs such as crew
labor and schedule disruption due to train delay can be higher, especially on lines at or near
capacity. With such short service lives, the economics of developing a longer lived bonded
IJ are compelling.

Understanding bonded IJ failure mechanisms is essential to improving performance.
With funding from AAR, TTCI is working with suppliers and railroads to develop longer
lived bonded IJs. Work completed in 2004 developed an understanding of bonded IJ
performance and documented bonded IJ failure modes in HAL service. Efforts in 2005 are
aimed at developing economic solutions with the railroads and suppliers. TTCI’s present role
is to develop an understanding of current failure modes and the effects of design parameters
on performance.

1.1 Service Life in HAL Track

Figure 2 shows service life data for a group of bonded IJs that were installed on a heavy
intermodal mainline during a signal-upgrading project. The joints are located in a line
that carries mostly higher speed intermodal traffic. Tonnage rates on this line are between
50 to 65 MGT per year per track (the Weibull plot projects a median life of 172 MGT for
the group of 150 bonded IJs).\(^1\) The short service life observed on this HAL line is
corroborated by a recent survey of track component lives.

The industry committee on rail, AREMA 4, has surveyed its members about
bonded IJ performance. The average service life values returned in the survey are 280
MGT for tangent track and 230 MGT for curved track. This includes all track with tonnage rates above 20 MGT per year.

Since most track circuits can operate with only one bonded IJ, there is redundancy in the typical two bonded IJ installation. Thus, the service life reported for bonded IJs (that is, a track circuit life) is probably much higher than the actual service life over which the insulation of the bonded IJ is effective. Data from one railroad includes both current joint condition (from inspections made by the local track inspector) and joints that were removed from track and thus, is closer to the actual usable life on a bonded IJ.

The data in Figure 2 confirms the long held belief that IJ life is relatively short. Improvements in other track components have left IJs as one of the weakest links in the track structure.

Factors adversely affecting service life on HAL routes include:

- Higher average wheel loads from larger capacity cars
- Higher dynamic loads from higher speeds and a stiffer track structure
- Higher longitudinal forces from elimination of other rail joints and better rail anchoring
- Higher traffic density which reduces opportunities to perform bonded IJ maintenance activities such as surfacing and running surface flow grinding

The service life of a bonded IJ is described differently from many other track components because it can deteriorate and fail rapidly. Referred to as “insulation fail-safe occurrences,” electrical failure for a bonded IJ can mean it has ceased to consistently perform its train control function of separating the track into control circuits. In this state, the bonded
IJ can still be structurally sound as a mechanical joint and would not pose any additional risk of derailment.

The bonded IJ can also fail mechanically. In this failure mode, referred to as “mechanical fail-safe occurrences,” the joint may have broken, cracked, or loose components including bolts, joint bars, or rails. A mechanical fail-safe occurrence may not have an increased risk of derailment.

1.2 Effects of Axle Load, Dynamic Load, and Traffic Rates

The effects of static load (axle load), dynamic load, and traffic rates are interwoven in evaluating bonded IJ performance on HAL routes. As the railroads have increased car capacity, they have also:

- Increased traffic rates
- Raised train speeds
- Increased track stiffness
- Increased the tensile stresses in the rail

With these conditions in mind, it was perceived that the heavier loads and higher speeds were generating more mechanical component defects such as out of round wheels. Yet, the true extent of dynamic wheel load issues was not understood until wayside impact load measuring stations were installed to quantify them. Recent sampling of dynamic vertical forces from Wheel Impact Load Detectors (WILD) suggests that the HAL coal fleet does have a higher percentage of wheels that cause high dynamic loads as compared to the general car fleet.²

The effects of all three factors (static load, dynamic load, and traffic rates) have been significant in raising the severity of the service environment experienced by track
components such as bonded IJs. From previous work with frogs, we know that components in high dynamic load environments such as crossing diamonds, switches, and track structure transitions are more affected by increasing wheel loads.\textsuperscript{3}

1.3 Effect of Static Wheel Load on Bonded IJ Performance

The effects of car capacity or static wheel load on bonded IJ performance are significant. As with other special trackwork components, average service lives under HAL traffic have been decreased as compared to service lives under 263 kip car traffic. As loading has increased, a foreshortening of service life has resulted for these track components which typically fail in high cycle fatigue. Yet, the bonded IJ design has remained practically the same during this period of increasing wheel loads. This effect may be more significant in the case of bonded IJs because higher loading is likely causing components to degrade in fewer load cycles. The cracking of epoxy near the end post of the joint may be an example.

The effect of wheel load increases on typical open track component service life decreases is roughly linear. This effect is significantly larger for components in high dynamic load environments such as bonded IJ’s, turnouts, and crossing frogs, which had service life decreases of up to 80 percent with increased car weights from 263 kips to 315 kips.

2.0 FAST EXPERIENCE

The FAST High Tonnage Loop, where 315 kip cars are operated, has been using conventional 36-inch bar bonded IJ plugs for many years. The documented service life of a bonded IJ is 400 MGT at FAST under service conditions that include:
- 315-kips car – always loaded
- 40-mph operations
- Relatively stiff track
- Mostly curved track
- Relatively narrow dynamic load spectrum

This 400-MGT average life is significantly better than the less than 200-MGT lives now seen on some 286 kip car coal routes. Thus, average wheel load is not the only factor in determining performance.

The service environment in revenue service coal routes appears to be more severe than the more controlled load environment at FAST, specifically, the range of vertical dynamic loads and the range of vertical loaded deflections are higher in revenue service. This suggests that the extreme loads, not the average load, are a controlling factor in bonded IJ service life. Figure 3 shows a comparison of the vertical load environment at FAST with a 286 kip car coal route in revenue service.

Another factor affecting the service life of bonded IJs and other track components is the increased rate of traffic on HAL routes. Today, as these lines carry more tonnage, the rate of traffic increases, leaving less time for track maintenance. As a result, there is a shift in maintenance policy, component selection, and even failure definition. As the relative costs of track time versus direct replacement costs for components increases, maintenance policy will tend to gravitate towards track renewal and away from selective component replacement. This enhances service reliability at the expense of average service life – as some components may be replaced before failure.
2.2 Failure Mode Analysis

In order to better understand failure mechanisms, a sample of 20 IJs removed from revenue service was collected and examined by TTCI. The joints were from lines that carry coal traffic predominantly in 286 kip cars. Results of the examination show that most joints have more than one defect. This finding is consistent with the observation that many joints remain in track for some time after insulation fail-safe occurrences. Thus, the evidence of the initial cause may be obliterated by the subsequent damage from continued tonnage. Figure 4 shows a cross section view of one of the bonded IJs examined by TTCI. The joints were destructively examined by cross-section cuts and disassembly.

Figure 5 shows a distribution of failure modes from a group of bonded IJs on a heavy haul coal route. This group is typical of failures seen on other routes with 286 kip cars.

There are several common modes that limit service life for bonded IJs in HAL service. Some of these are related to quality control issues in components and assembly. Problems with batches of joints from a given supplier, batches of epoxy, and batches of bonded IJ kits have been reported by the railroads.

There are also service life-reducing aspects related to the design and capacity of the joint. These occur with structural aspects of the joint or components within the joint. These situations begin with the joint becoming a running surface discontinuity. Figure 6 shows small deformations in the running surface caused by the bonded IJ gap. This discontinuity generates dynamic loads at the joint which damage the foundation. Due to lower stiffness of
joint, the deflection becomes significantly larger than deflections typically found in surrounding track.

Figure 7 shows a typical distressed bonded IJ foundation in track that otherwise generally has good support. We believe the cause of the poor foundation condition in this case is the dynamic loading generated by the running surface discontinuity of the IJ. The combination of high dynamic forces and larger deflections at the IJ cause the foundation to fail here before it does in open track. This foundation condition causes cracking in the glue or epoxy at the top-center of the joint bar to rail interface. Figure 8 shows typical bonded IJ glue cracking near the end post of the joint. The weakened epoxy bond allows moisture intrusion and larger deflections.

Figure 9 shows a disassembled bonded IJ with glue debonding and water intrusion. As the glue debonds, the joint becomes subjected to “pull-apart” because of the longitudinal forces in the rails. “Pull-apart” damages insulating components such as thimbles and end posts as well as mechanical joint components such as bars and bolts. Figure 10 shows a bonded IJ that “pulled-apart” in track. Joints can, however, continue to function as insulators long after the initial deterioration begins. Bonded IJ design has much redundancy so that several defects can be present before safety is compromised. However, once the bonded IJ fails to insulate the track, it is immediately replaced. Pull aparts with broken bolts or beyond the hole drilling tolerance are also replaced upon detection.

The sequence of photographs shown in Figures 6 through 10 depicts the most typical failure scenario of bonded IJs in HAL service. They deteriorate from a loosening of the joint. This is manifested as epoxy “unzipping” from the end post outward, an
electrical short due to fretting or relative component movement, broken bolts, broken joint bars, or joint “pull-apart.”

3.0 LOAD ENVIRONMENT

Severity increase of the service environment has resulted in the degradation of bonded IJ performance. To remedy this situation, TTCI quantified the load environment for HAL routes. This updated information will be used to develop improved performance of bonded IJs for HAL service.

3.1 Revenue Service

- The real-time dynamic data collected from supported and suspended instrumented joints shows that impacts from wheels may be more than two times the static wheel loads. See Figure 11 for a histogram plot of impacts from mainly a test train of 286 kip wheel loads.

- The maximum measured bending stresses in joint bars for both supported and suspended bonded IJs on a good foundation were less than 10 percent of the material yield stress. See Figure 12 for the time history of bending stresses in a typical suspended joint.

- The bonded IJs are generally installed at high neutral temperatures, which result in higher longitudinal loads during winter conditions. As Figure 13 shows, an insulated joint installed at 118 degrees was subjected to tensile force of more than 500 kips during winter conditions.
3.2 Stress Analysis

A typical six-bolt insulated joint of RE136 rail was modeled in the stress analysis program ANSYS®. The load cases were designed to simulate the most likely operational envelope of the bonded IJs. The three service load cases analyzed are: vertical load only, vertical and longitudinal load, and vertical and longitudinal loads with unequal settlement of supports.

The ANSYS® analysis shows that the stress levels in the bolts and bars were well below yield limits of material for the first two cases. However, the bonded IJ bars have a tendency to yield under the loading condition of the third case.

The analysis further shows that wheels running on the rail gauge corner may cause torsion in the suspended joints. This torsion can induce bending stresses in the bolts in addition to axial preload. The analysis also predicts that the contact pressure between bars and rail is highly non-uniform. Figure 14 shows the stress plots of the model.

4.0 REVIEW OF DESIGN INNOVATIONS IN TEST TODAY

Improving the performance of bonded IJs can be accomplished by improving any of the weaknesses in current designs, maintenance, and operations. Working with suppliers, railroads have developed new designs to address the increasingly severe service environment. Most of the effort has focused on the parts that suppliers and designers can be assured of having an effect – the steel components of the bonded IJ. These efforts can be classified as:

- Reducing deflections
- Reducing component relative movement
• Increasing the strength of failure prone components

The main function of bonded IJs is to divide the track into electrical track circuits while maintaining mechanical integrity. Because of a lack of effective insulated tie plates, railroads have settled for a “suspended” foundation. With this configuration, the middle of the bonded IJ is located over a tie crib. Thus, the joint is unsupported where it is weakest. Bonded IJ bending and joint deflections are significantly increased to assure that the tie plates do not short the bonded IJ.

Railroad and supplier efforts have focused on reducing deflections. It is assumed this will also lower the relative movement of components, which is believed to result in epoxy failure at the center of the joint. Several methods have proven to be effective at reducing maximum bonded IJ deflections. These include:

• Supported bonded IJs
• Multiple tie plates
• Longer joint bars
• Larger (cross section) joint bars

Reductions in deflections of up to 50 percent have been measured in the field. These reductions bring the joint closer to the behavior of conventional track. The reductions in deflection are expected to result in an extended service life. Monitoring of bonded IJs with these features is ongoing.

Methods to accommodate relative movement of the rail and joint bars have also been attempted such as the use of more flexible epoxies and variable strength and flexibility epoxies in joints.
More flexible epoxy in the entire joint has not provided improvements in service life. It is too soon to determine if the use of more than one epoxy in the joint provides service life benefits.

4.1 Draft Bonded IJ System Performance Requirements in HAL Service

Table 1 lists performance requirements for bonded IJs. These requirements are a first draft based on the observed problems with existing bonded IJs in HAL service and the service environment measurements made. Table 1 is under review by the railroad track standards engineers and may be altered based from their input.

4.2 Advanced Design Bonded IJ

TTCI has developed an improved performance bonded IJ design for prototype development and testing. The design was developed from observation of current designs, analysis and modeling work, and the requirements of the draft performance guidelines. This design will have the following features:

- Reduce bonded IJ-caused dynamic loads:
  - Uses running surface design from AAR Frog Longitudinal Profiles: Proven successful in No. 20 fixed point frogs
  - More damping: Mitigates effects of dynamic loads
- Lower deflections:
  - Foundation with larger bearing area on ties and ballast
  - Continuous support, but tampable: Frame ties and multi-tie plates
- Components:
  - Stronger insulator and more environmentally stable epoxy
• Assembly
  o Improved rail and bar surface preparation: to eliminate surface contamination

5.0 THE NEXT GENERATION IJ

The next generation IJs for HAL service will not resemble currently used bonded IJs. The ultimate goal is removal of all bonded IJs from mainline track.

In order to eliminate bonded IJs, other effective means of controlling train traffic and detecting broken rails must be developed and implemented. Train control systems, which rely entirely on radio communications, are well into the field demonstration stage. These replacement systems require significant capital investment, but can also provide significant operational savings.

Development of an effective alternate way to detect broken rails is needed to eliminate conventional track circuits and bonded IJs from HAL service tracks. This will also improve the economics of communications based train control.

Under the AAR Technology Scanning program, Virginia Tech (VT) is looking at potential technologies to replace the conventional IJ. VT is looking at non-mechanical joints for train control track circuits as well as unconventional methods of detecting broken rail, which would allow elimination of track circuits. By the end of 2005, VT will have a report on potential methods of eliminated mechanical bonded IJs.
REFERENCES


LIST OF FIGURES

Figure 1. Typical Mainline Bonded Insulated Joint
Figure 2. Mainline Insulated Joint Service Life Projection
Figure 3. Comparison of Revenue Service and FAST Vertical Forces
Figure 4. Bonded Insulated Joint Cross-Section View
Figure 5. Failure Modes Analysis of Bonded IJ’s on HAL Track
Figure 6. IJ with Running Surface Deformation due to Gap
Figure 7. Distressed IJ Foundation in Good Mainline Track
Figure 8. IJ with Glue Bond Fail-Safe Occurrence Near End Post
Figure 9. IJ that has Failed-Safe Electrically after Disassembly
Figure 10. Typical IJ Pull-Apart In Track
Figure 11. Frequency and Value of Wheel Impacts
Figure 12. Time History of Bending Stresses in a Test IJ
Figure 13. Temp – Force Relationship
Figure 13. Force – Temperature Relationship for Typical Mainline Track IJ
Figure 14. Stress Distribution in IJ Finite Element Model

LIST OF TABLES

Table 1. Draft Bonded IJ System Performance Requirements in HAL Service
Table 2. Draft Bonded IJ System Performance Requirements in HAL Service
Figure 1. Typical Mainline Bonded Insulated Joint
Probability Plot for IJ LIFE
Weibull Distribution - ML Estimates - 95.0% CI
Censoring Column in IJ STATUS

Shape 10.83
Scale 178.00
MTTF 169.91
StdDev 18.919
Median 172.09
IQR 24.743
Failure 22
Censor 136
AD* 336.91

Figure 2. Mainline Insulated Joint Service Life Projection
Figure 3. Comparison of Revenue Service and FAST Vertical Forces
Figure 4. Bonded Insulated Joint Cross-Section View
Figure 5. Failure Modes Analysis of Bonded IJ’s on HAL Track
Figure 6. IJ with Running Surface Deformation due to Gap
Figure 8. IJ with Glue Bond Fail-Safe Occurrence Near End Post
Figure 9. IJ that has Failed-Safe Electrically after Disassembly
Figure 11. Frequency and Value of Wheel Impacts
Figure 12. Time History of Bending Stresses in a Test IJ
Figure 13. Force – Temperature Relationship for Typical Mainline Track IJ
Figure 14. Stress Distribution in IJ Finite Element Model
<table>
<thead>
<tr>
<th>Performance Requirement Name</th>
<th>Performance Requirement Value</th>
<th>Current Requirements</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Service</td>
<td>HAL – 315K GRL cars</td>
<td>HAL – 315K GRL cars</td>
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</tbody>
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| Service Life                  | 400 MGT (min.)               | 1 year warranty      | - Double the current HAL life  
- Long term goal is life of rail |
| Dynamic Load generated by Insulated Joint | 1.3 x impact loads in open track | None                | - Loads a good car would see going over IJ  
- Recommended for ride quality  
- Comparable to open track |
| Dynamic Vertical Load Capacity | 160,000 lbs                  | None                 | - Expected loading generated by car with wheel or suspension defects  
- Cars are removed from service beyond this load |
| Longitudinal Load Capacity    | 800,000 lbs (min.)           | 650,000 lbs          | - Increase needed due to larger rail sections carrying larger loads.  
- Avoid failure of rail before IJ |
| Track Modulus & Deflection    | Same as surrounding track    | None                 | - Typical track Modulus:  
Wood Ties-2,500 to 4,000 lbs/in./in.  
Conc. Ties- 4,000 to 6,000 lbs/in./in.  
Deflections: 0.1-0.25 in. |
| Track Damping                 | Range 100-200 lbs/in./sec/tie/rail | None             | Require to attenuate impacts |
| Electrical                    | AREMA recommended practices  | AREMA recommended practices | 10 Mega Ohms |
| Lab “Proof” Test              | ?                             | None                 | Similar to rail weld slow bend test |
| Relative movement of rail head to joint bars | Epoxy properties dependent – should not crack epoxy | None | Rail to bar relative movement should be minimized, but acceptable value depends on epoxy |