CASE STUDIES USING GAGE RESTRAINT MEASUREMENT TO DETECT WEAK TRACK CONDITIONS ON CONCRETE TIE TRACK

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ABSTRACT
Gage Restraint Measurement System (GRMS) technology was developed in the 1980s and informally adopted by parts of the industry to detect locations of decreased gage restraint capabilities related to ineffective ties or fastening systems. These conditions may lead to gage widening derailments with serious consequences.

Current GRMS guidelines, standards, and limits were developed as a performance standard based on extreme loading conditions resulting from acceptable geometry irregularities. The limits were compared with data collected by GRMS on a range of classes of track predominately with wooden ties and cut spike fasteners. These guidelines are for minimum structural strength and may not be sufficient for finding locations of concern on concrete tie track or locations requiring greater geometry control. This paper presents findings from efforts currently being conducted by Federal Railroad Administration’s Office of Research, Development and Technology (FRA RDT) and ENSCO, Inc. to improve the understanding of GRMS behavior on concrete ties in the form of case studies. These efforts include tests using the FRA’s DOTX 218 research vehicle both at the Transportation Technology Center (TTC) in Pueblo, CO, on concrete track with manufactured track weaknesses and on revenue service concrete track.
INTRODUCTION

Concrete crossties and elastic fasteners in North America were first utilized on a large scale in the 1970s and use has continued to expand in recent years. Concrete crossties offer the promise of greater geometry control, durability, and restraint capability over wooden ties that have been a standard in the railroad industry.

Gage Restraint Measurement System (GRMS) technology was developed in the 1980s and informally adopted by parts of the industry to detect locations of decreased gage restraint capabilities related to ineffective ties or fastening systems. These conditions may lead to gage widening derailments with serious consequences. Current GRMS guidelines, standards, and limits were developed as a performance standard based on extreme loading conditions resulting from acceptable geometry irregularities. The limits were compared with data collected by GRMS on a range of classes of track predominately with wooden ties and cut spike fasteners (1), (2), (3). These guidelines are for minimum structural strength and may not be adequate on concrete tie track due to the different nature of rail deformational behavior when equipped with elastic fastening systems. Current standards and maintenance/safety limits may not be able to identify locations of concern on concrete tie track or locations requiring more restrictive limits on variation in track geometry.

Rail seated on concrete ties with elastic fasteners has a different deformational response to vertical and, in particular, lateral loading compared to that seen on wooden ties with cut spike fasteners due to differences in the nature of force interactions at the rail-tie interface. Elastic fasteners introduce “toe-load” to the base of the rail, which is a clamping force resulting from flexing of the fastener. The toe-load serves as an important component of lateral and longitudinal rail restraint capacity by increasing the normal forces on the rail-tie interface resulting in decreased rail deflections and increased gage restraint capacity of elastic fastening systems. These facts will also be reflected in different response of the GRMS when testing on concrete ties with elastic fasteners.

This paper presents findings from efforts currently being conducted by the FRA RDT and ENSCO, Inc. to improve the understanding of GRMS behavior on concrete ties in the form of case studies. These efforts have included tests using FRA’s DOTX 218 research vehicle - both at the TTC in Pueblo, CO on concrete track with manufactured track weaknesses and on revenue service concrete track.

GRMS OVERVIEW

The current GRMS was developed and installed on the DOTX 218 in 2004. In general, a GRMS uses a split-axle to apply a lateral force to both rails. On the DOTX 218, the split-axle does not replace one of the axles in the vehicle’s trucks, but is a separate deployable axle that is lowered to the track when making measurements and raised during vehicle transits or when a potential problem with the lowered axle is detected. In addition to the split-axle, the GRMS includes two gage measurement beams suspended from the vehicle, one close to the split axle to measure loaded gage and the other 19 feet ahead of the split axle to measure unloaded gage.
The GRMS split-axle applies a nominal lateral load of 14,000 pounds (14 kips) to each rail, a load that was determined through experience and testing to be adequate to overcome the inertia and friction inherent in the rail/tie plate/fastener/tie mechanical system as well as to fully and rapidly load the track structure. A nominal vertical load of 20,000 pounds (20 kips) was selected to yield an overall lateral-to-vertical ratio (L/V) of 0.7. As a safety precaution, the GRMS will automatically retract the axle if the L/V ratio exceeds 1.25 at either wheel or the loaded gage exceeds 58.25 inches.

During gage restraint testing, the GRMS calculates gage widening strength indices, the Projected Loaded Gage (PLG24) index and the Gage Widening Projection (GWP) index in real time and reports the locations along the track where either calculated index exceeds the user-specified maintenance or safety thresholds.

In addition to the two gage widening strength indices, the amount of rotation and lateral translation of both rails induced by the combined lateral and vertical loads applied by the split axle is calculated by a rail roll application. Profiles of the gage side of both the left and right rails captured by the two gage measurement beams are aligned by shifting and rotating the sets of the captured profile measurements. The amount of shift and rotation necessary to align the two sets of rail measurements represent the rail base lateral translation and the rail roll, respectively. Rail roll is also the change in rail cant. Further information about the rail roll application is provided in (4).

**Projected Loaded Gage (PLG24)**

The PLG24 index uses known minimum rail restraint criteria and measurements of loaded gage, unloaded gage, and wheel forces to estimate gage in specific track locations. PLG24 allows for the
identification of locations that would allow wheel drop if the track were subjected to severe loads. The index is expressed as:

\[ PLG24 = GAGE_{UNLOADED} + (A_{FACTOR} \cdot \Delta GAGE) \]

where:
- \( PLG24 \) = estimated gage, in inches, under a designated severe lateral and vertical load scenario
- \( GAGE_{UNLOADED} \) = gage of the track, in inches, with no loads applied
- \( A_{FACTOR} \) = factor used to extrapolate from test loads to severe loading conditions
- \( \Delta GAGE = GAGE_{LOADED} - GAGE_{UNLOADED} \) = delta gage = difference between the unloaded gage and the gage where the test load is applied, in inches.

The extrapolation factor, \( A_{FACTOR} \), scales the deflection measured under test loads to a severe loading configuration. The Federal Track Safety Standards (FTSS) are based on assuming minimally adequate track strength and a severe loading of 24 kips lateral force and 33 kips vertical force. For this track strength and loading, the extrapolated gage (called PLG24) is calculated using the following equation for \( A_{FACTOR} \):

\[ A_{FACTOR} = \frac{13.513}{(L - 0.258 \cdot V) - 0.009 \cdot (L - 0.258 \cdot V)^2} \]

where:
- \( L \) = actual GRMS applied lateral force, in kips.
- \( V \) = actual GRMS applied vertical force, in kips.

According to the FTSS, a track location with an extrapolated gage (PLG24) of 59.0 inches is a “first level exception” - a high risk for a gage widening derailment, requiring immediate corrective action. The FTSS further specifies that a location having a PLG24 of 58.0 inches is a “second level exception” - a maintenance area that would likely grow to an exception of 59.0 inches without corrective action. In the GRMS, the PLG24 safety and maintenance thresholds are settable parameters.

**Gage Widening Projection (GWP)**

The GWP was developed based on the mechanical concept of track compliance, which is a measure of the spring rate the track exhibits as it deflects outward under an applied lateral load. At any given location, the measured track compliance equals the difference between the loaded and unloaded gage divided by the instantaneous lateral load severity applied to cause the deflection; its units are inches of deflection per kilo-pound of applied force.

If track is treated as a spring with a constant stiffness, the deflection measured is directly proportional to the load severity applied. An increase in deflection only indicates a higher load was applied, not a change in stiffness. The GWP normalizes the track deflection measured by a GRMS to the deflection expected if 8.26 kips had been the actual test load severity. GWP is calculated as follows:

\[ GWP = \frac{\Delta GAGE}{L - 0.258 \cdot V} \]

where
- \( GWP \) = estimated gage widening under 8.26 kips load severity.
- \( \Delta GAGE = GAGE_{LOADED} - GAGE_{UNLOADED} \) = delta gage = difference between the unloaded gage and applied, in inches.
- \( L \) = actual GRMS applied lateral force, in kips.
- \( V \) = actual GRMS applied vertical force, in kips.
- 8.26 = normalizing load severity, in kips.
The term “Projection” is used to indicate that a normalization/extrapolation operation has been performed and the actual deflection which occurred in the field may have been greater than or less than the reported GWP, depending on the actual applied test load at the reported location.

The GWP was developed to accommodate varying vertical loads from the previous parameter Gage Widening Ratio (GWR) as detailed in (5). According to the FTSS, a track location with a GWR of 1.0 inches or greater is a “first level exception” - a high risk for a gage widening derailment, requiring immediate corrective action. The FTSS further specifies that a location having a GWR of 0.75 inches is a “second level exception” - a maintenance area that would likely grow to a GWR of 1.0 inches without corrective action. GWP was designed to use the same thresholds as GWR.

CASE STUDIES

In order to improve the understanding of GRMS behavior, FRA conducted several tests with the DOTX 218 in recent years. Two of these tests focused on GRMS response on concrete tie track.

Case Study 1: Simulated Restraint Defects

In March 2013, DOTX 218 conducted a comprehensive GRMS test in a controlled environment at the TTC facility on the Facility for Accelerated Service Testing (FAST) High Tonnage Loop (HTL) section with concrete ties. Three separate locations of weak track were “manufactured” by removing the tie clips and insulators on the gage and field side of both rails for 3, 5, and 7 consecutive ties otherwise in very good condition. The three locations were located in a tangent track and separated from each other by approximately 60 feet of unaltered ties. The FTSS (49CFR §213.109) consider a concrete tie effective when, in addition to other requirements, it is configured with no less than 2 fasteners on the same rail except where fastener placement impedes insulated joints from performing as intended. Therefore, the manufactured test zones technically consist of non-effective ties. The weak location with 7 consecutive altered ties also represents a limiting case before such a configuration would become a tie defect on Class 4 and 5 tangent track, regardless of effective tie distribution or other factors such as an apparent geometry condition.

The FTSS require any 39-foot segment of track to be supported by the following number of effective ties that are distributed effectively to support the entire section:

<table>
<thead>
<tr>
<th>FRA track class</th>
<th>Tangent track, turnouts, and curves</th>
<th>Tangent track and curved track less than or equal to 2 degrees</th>
<th>Turnouts and curved track greater than 2 degrees</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class 1</td>
<td>5</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>Class 2</td>
<td></td>
<td>8</td>
<td>9</td>
</tr>
<tr>
<td>Class 3</td>
<td></td>
<td>8</td>
<td>10</td>
</tr>
<tr>
<td>Class 4 and 5</td>
<td></td>
<td>12</td>
<td>14</td>
</tr>
</tbody>
</table>

Based on a nominal tie spacing of 24 inches (2 feet) for concrete ties, a 39-foot segment of track can contain 19 ties. The following table provides the hypothetical maximum number of consecutive non-effective ties in a 39-foot track segment that would not constitute a tie defect assuming that sufficient support remains such that gage, surface, and alignment are maintained within the limits specified in the FTSS.
Table 2: Extreme Case of Maximum Allowable Number of Consecutive Non-Effective Ties

<table>
<thead>
<tr>
<th>FRA Track Class</th>
<th>Tangents, Curves less than or equal to 2°</th>
<th>Turnouts and curves greater than 2°</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class 1</td>
<td>14</td>
<td>13</td>
</tr>
<tr>
<td>Class 2</td>
<td>11</td>
<td>10</td>
</tr>
<tr>
<td>Class 3</td>
<td>11</td>
<td>9</td>
</tr>
<tr>
<td>Class 4 and 5</td>
<td>7</td>
<td>5</td>
</tr>
</tbody>
</table>

DOTX 218 traversed the test zone multiple times varying the lateral and vertical loads on the GRMS axle. A total of 26 test runs were performed with L/V ratios between 0.36 and 1.00. The purpose of this test was to investigate the GRMS response to known concrete tie conditions under different test loading scenarios, assess the normalization/extrapolation operation to adjust for various test loads used in the GWP and PLG24 parameters, and identify desired lateral and vertical forces and GWP thresholds for use in finding deteriorated restraint conditions for GRMS testing on concrete ties.

Analysis of collected data showed that GWP and PLG24 measurements match each other very well for runs with GRMS loading within the recommended American Railway Maintenance-of-Way Association (AREMA) region for GRMS test loads (6). The runs outside the recommended AREMA region result in erratic GWP and PLG24 signatures that do not match well with corresponding data from the other runs. This indicates less reliable performance of the GWP formula for varying test loads outside of the recommended region of test load for GRMS.

Overlays from three runs that encompass the entire range of loading conditions during the test are presented in Figure 4 and Figure 5:

- DOTX 218 Run #1; representing normal GRMS test loads, L=13.8 kips, V=20.2 kips, L/V=0.68
- DOTX 218 Run #2; representing lowest L/V GRMS test loads, L=8.0 kips, V=22.0 kips, L/V=0.36
- DOTX 218 Run #3; representing highest L/V GRMS test loads, L=14.0 kips, V=14.0 kips, L/V=1.00

Figure 3 illustrates the test forces used for the three selected DOTX 218 runs with respect to AREMA guidelines for standard GRMS test loads. The region in green is considered acceptable for GRMS testing. Run #2 is clearly outside the recommended AREMA test configuration for GRMS.

Figure 3: Forces at Selected DOTX 218 runs with Respect to AREMA Guidelines from TTC Testing March 2013

Figure 4 presents overlays of loaded and unloaded gage, PLG24 and GWP from the three DOTX 218 runs. The gage overlays indicate larger lateral rail head movement with increasing load severity throughout the test zone, especially at the locations of weakened track. The larger GWP measurement observed was 0.7 at the weakened location of 7 altered ties, below the current GWP maintenance level of 0.75.
Rail roll angles, head displacements derived from rail roll angle, and base translations are shown in Figure 5. When base translation and head displacement from rail roll are added together, total gage widening is obtained. The presented data suggests that a large portion of gage widening at the weakened track locations originates from lateral rail translations (over 60% in case of loads applied in Run #3, roughly 80% in the case of loads applied in Run #1) as lateral gaps are present when insulators are removed. Base displacement did not exceed 0.5 inches even with increasing lateral loads as the lateral gaps in the rail seat get used up and further lateral translation is restrained by the rail seat shoulder. Base displacement, as provided by the rail roll application, is a good indicator of missing rail clips and insulators on the field side of the rail. The signature of the base displacement channel reflects a resolution of only one decimal point of the measurement channel. The resolution has since been increased to three decimal points.

Figure 4: Gage, PLG24, GWP from TTC Testing March 2013
The results show that standard GRMS test loads clearly produce elevated GWP and PLG24 metrics for weakened ties on concrete track. Therefore current GRMS test loads are suitable for testing on concrete tie track. The current GWP safety and maintenance thresholds, however, were not sufficient to detect serious track weaknesses (per 49CFR §213.109) – in this case 7 consecutive ties with removed rail restraint – even at the maintenance level threshold.

**Case Study 2: Revenue Service Track**

Following the test in the controlled environment at TTC, DOTX 218 conducted a GRMS test on a revenue service track in April 2014. The purpose of this test was to characterize concrete tie track conditions associated with GRMS readings at various magnitudes, specifically below the current maintenance and safety thresholds. The vehicle tested approximately 130 contiguous miles on a heavy haul, mostly Class 4 track territory with concrete ties and elastic fasteners of various manufacturers – predominantly Pandrol Safelock I – carrying close to 200 million gross tons (MGT) per year of traffic. The GRMS thresholds were temporarily lowered on DOTX 218 to generate GRMS events with peak values below the current safety and maintenance threshold levels during the test. In the following week, ENSCO personnel visited and documented selected track locations where the GRMS generated events with peak values below the current threshold levels.

A total of 16 track locations were documented, 15 GWP event locations with peak values ranging between 0.34 and 0.49 and one PLG24 event location at a magnitude of 57.57 inches. The GWP value 0.49 and PLG24 value of 57.57 inches represent the largest GRMS indices values encountered during the test. The 113 mile test zone had an average GWP value of 0.1 and standard deviation of 0.05, which indicates strong and consistent lateral restraint that is generally associated with well-maintained concrete tie track.

The one investigated PLG24 event was related to a slightly worn curve with worn rail head on the
gage side and worn insulators. The GWP value at this location was 0.17. This location was not a place of concern. In contrast, the higher GWP values at the 15 visited locations were related to broken ties and the magnitude of the GWP event was correlated to the number of consecutive ties that were damaged or defective. The tie conditions were very localized: two or more consecutive broken ties and sometimes several surrounding ties affected with insulator wear. The locations with peak GWP values as low as 0.34 were easily discernable from the surrounding track. The GWP locations can be divided into four groups based on the GWP magnitude and track and tie conditions present. The four groups in order of increasing severity of encountered track and tie conditions are as follows:

**GWP range: 0.34 - 0.41 – 11 locations**

All locations in this group contained two consecutive broken ties on one or both sides, with one exception where only one broken tie with increased tie spacing was present. The adjacent ties were not broken but in some cases contained worn insulators leading to lateral slack in the rail seat. The ties were mostly broken in the rail seat and/or shoulder regions and in few cases contained center cracks and or center breaks in addition. Typical conditions encountered in this group are shown in Figure 6. Three separate locations are represented in the example. Red arrows mark cracked ties.

![Figure 6: Example of Concrete Tie Conditions at GWP Range 0.34-0.41](image)

**GWP: 0.42 – 1 location**

The one location in this group contained two consecutive ties broken in the shoulder region with one clip field side loose followed by two good ties with worn insulators leading to 1/8 inch lateral gaps in the rail seat and then followed by another two broken ties, one of them broken completely the other broken in the rail seat region. All the described damage was found on one side of the ties under the same rail. Two ties in this location also contained center cracks. The surrounding ties had only slightly worn insulators. The tie conditions at this location are shown in Figure 7.
GWP: 0.45 – 1 location

The one location in this group contained two sets of two consecutive ties broken in the rail seat and shoulder region under one of the rails. One tie containing minor center cracks but with intact rail seats and shoulders was located between them, providing enough lateral gage restraint to prevent higher GWP readings at this location. Three of the broken ties also had a broken shoulder under the opposite rail. The middle tie with intact rail seats and shoulders, and several adjacent ties, contained worn insulators. The tie conditions at this location are shown in Figure 8; a plot of foot-by-foot GWP readings is also provided. The GRMS was able to discern the locally improved gage restraint provided by the center ties.

3.2.4 GWP: 0.49 (highest reading) & 0.42 – 2 locations

Both locations contained three consecutive ties broken in the rail seat under one rail. One of the ties at the location with the higher GWP value of 0.49 also contained a broken rail seat under the opposite rail. Several ties at both locations also contained center cracks. Surrounding ties had only slightly worn insulators.

It is interesting to note that from the point of view of a hi-railing track inspector there would not be many indicators to discern these locations from the rest of the track as weak spots. The broken rail seats...
do not become apparent until inspected closely, however the locations are easily identifiable by the GRMS. Tie conditions at the two locations are illustrated in Figure 9.

Figure 9: Example of Concrete Tie Conditions at GWP 0.49 & 0.42

CONCLUSIONS
The first presented Case Study 1: Simulated Restraint Defects revealed the following:

- GRMS was able identify three artificially manufactured weak spots in the track, created by removing the tie clips and insulators on the gage and field side of both rails for 3, 5, and 7 consecutive ties that were otherwise in very good condition.
- The GWP over these test sites never exceeded 0.7 inches, which is below the current GWP maintenance level of 0.75, even at the location of 7 consecutive ties with removed rail restraint. The current GWP thresholds did not detect such serious track deficiencies even at the maintenance level threshold.
- Standard GRMS test loads were suitable for testing on concrete tie track and the normalization/extrapolation operation to adjust for various test loads used in the GWP and PLG24 parameters worked correctly as designed for forces within the AREMA guidelines for standard GRMS test loads.
- Base translation parameter as provided by the rail roll application on DOTX 218 was clearly elevated at locations with missing rail clips and associated insulators on the field side of rail.

The second presented Case Study 2: Revenue Service Track revealed the following:

- The tie conditions associated with GWP levels between 0.34-0.49 were very localized with two to three consecutive broken ties and sometimes several surrounding ties affected with insulator wear. GWP events with a peak as low as 0.34 were easily discernable from the surroundings track.
- GWP events with peaks at 0.42-0.49, which are significantly below the current GWP thresholds, can identify locations of maintenance interest where railroads may want to remediate immediately.
- The GRMS can detect types of weak track locations that are often difficult to identify from a hi-railing inspection.

The conducted tests showed that GRMS is a useful tool to help assess conditions of concrete ties with elastic fasteners. The results, however, also demonstrated the need to develop better thresholds for GWP values for detecting deteriorating restraint conditions on track requiring greater geometry control such as track where railroads have deployed concrete ties and elastic fasteners.
FUTURE WORK

The above observations are valid on concrete ties unaffected by rail seat deterioration (RSD). In the case of ties affected by RSD, the GRMS response is likely different. This is the current focus of further research and DOTX 218 testing.

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