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Development of Gage Widening Projection Parameter for the Deployable Gage Restraint Measurement System

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13. ABSTRACT

Recent gage restraint measurement system (GRMS) developments include the redesign of GRMS vehicles to conduct testing from a deployable axle instead of using freight truck mounted axle and GRMS on hi-rail vehicles. This new test configuration results in boundary condition changes in the applied loads and split axle location; both of which influence the results. To ensure equivalent safety considering these significant changes, a comprehensive evaluation of the mechanistic basis for previous GRMS rulemaking, coupled with a fundamental investigation of factors influencing GRMS performance and inspection accuracy, was conducted along with field-testing to verify conclusions. Results of the investigation to date suggest a need for reconsideration of the gage widening ratio (GWR) equation, which treated vertical load as a constant parameter. With the new GRMS testing capability at a wider range of test loads, it is necessary to include vertical load in the GWR equation. GWR has been the leading source of discrepancies between the inspections conducted by original GRMS design and redesigned vehicles over the same territory. This report describes the analysis and recent field-testing to provide the fundamental basis for a proposed gage widening projection formula.

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1 mile (mi)	= 1.6 kilometers (km)	1 meter (m)	= 1.1 yards (yd)
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1 square yard (sq yd, yd^2)	= 0.8 square meter (m^2)	1 square kilometer (km^2)	= 0.4 square mile (sq mi, mi^2)
1 square mile (sq mi, mi^2)	= 2.6 square kilometers (km^2)	10,000 square meters (m^2)	= 1 hectare (ha) = 2.5 acres
1 acre = 0.4 hectare (he)	= 4,000 square meters (m^2)		
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1 fluid ounce (fl oz)	= 30 milliliters (ml)	1 liter (l)	= 1.06 quarts (qt)
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1 pint (pt)	= 0.47 liter (l)		
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1 gallon (gal)	= 3.8 liters (l)		
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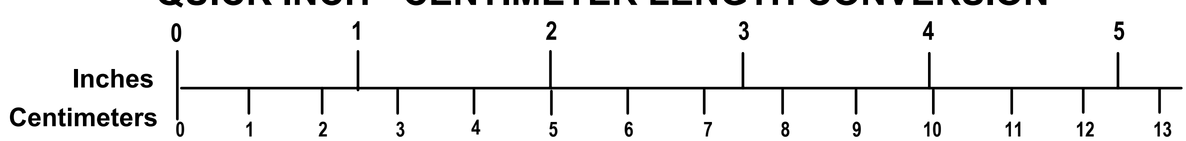

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°C	-40°	-30°	-20°	-10°	0°	10°	20°	30°	40°	50°	60°	70°	80°	90°	100°

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Table of Contents

List of Figures

List of Tables

Preface

Gage widening derailments have been a challenge to the continued improvement of rail safety. Once the single leading cause of derailments, research and development projects on equipment and procedures have dramatically improved rail safety by targeting improved track gage widening performance. Specific developments that have contributed to the enhanced safety of track relative to gage widening risk include:

1. The gage restraint measurement system (GRMS), an automated mechanical inspection system that identifies locations with poor gage widening characteristics by exercising the gage strength of the track using a split axle in place of one of the standard axles on the freight truck.

2. The lightweight track loading fixture, which is a handheld device used to test the track gage by applying loads to confirm GRMS identified exceptions.

3. Track safety standards accommodating the application of GRMS technology.

The original GRMS technology developed in the 1980s and adopted by the industry through the 1990s. Recent advances in GRMS technology include the adaptation of the technology by Holland Company to a hi-rail GRMS using a single deployable split axle targeting reduced cost and GRMS inspections that are more convenient. Using the hi-rail concept, Holland Company has provided GRMS inspections to the industry for maintenance planning. Further, the Federal Railroad Administration developed a new rail bound inspection vehicle utilizing a deployable split axle design to improve safety, as well as operational cost and efficiency.

The newly designed vehicles operate substantially the same as the original technology. The new improvements, however, appear to identify gage widening exceptions at substantially different loading magnitudes and configurations than originally conceived, thereby requiring modifications in Track Safety Standards to ensure an equivalent level of safety. This report summarizes the efforts made to investigate and improve the track safety standards GRMS provisions.

Executive Summary

This report describes the development of the new Gage Widening Projection (GWP) formula as a replacement for the Gage Widening Ratio (GWR) parameter that has been used as an index of weak or strong tie and fastener condition. Gage restraint measurement systems (GRMS) use GWR and the Projected Loaded Gage (PLG) index to assess the risk of freight train derailment due to gage widening. Development of new GRMS systems and their subsequent evaluations, however, have identified inconsistency in the current GWR equations on the treatment of different loading conditions and different vehicle characteristics. A comparison test in October 2002 between the Holland TrackSTAR, a deployable single split axle, hi-rail GRMS, and the FRA T-6, a railbound GRMS with a truck-mounted split axle, showed a significant difference in defect numbers reported by these vehicles. Analyses and field evaluations indicated that these discrepancies were attributed to various factors, including the GWR equation, measurement accuracy problems, and differences in the physical configuration of the vehicles.

The Federal Railroad Administration (FRA) has procured the T-18 as a replacement of the T-6, and it is the first railbound GRMS vehicle to have a deployable loading axle, giving it much more flexibility than its predecessor. The evaluation and verification testing in November 2004 in Front Royal, VA, on the Norfolk Southern Railroad (NS) included a set of tests with 25 different loading configurations within the acceptable load range for GRMS testing. The results of this test indicated that the current GWR calculation does not treat different loading configurations similarly, even for the same vehicle due to treatment of vertical load as a constant not as a variable in the GWR equation. A new form for the GWR equation was developed keeping all these factors in mind, and it was tested using the T-18 with two different loading configurations on the Maryland Midland Railroad (MMIR) in February 2005. The correct extrapolation loads were arrived at using the results of this test. The resulting equation was named GWP and has extrapolation loads of L = 16 kips and V = 30 kips. A final conclusive comparison test between the FRA T-18 and the Holland TrackSTAR was performed in St. Louis, MO on the BNSF Railway (BNSF). The GWP and Projected Loaded Gage at 24 kips lateral load (PLG24) comparison was found to be excellent between both the GRMS vehicles. The GWP, which is a two variable dependent parameter, was also found to compare well with the finite element TRKLOD model. Results from these analyses indicated that the GWR equation in the Track Safety Standards (TSS) should be replaced with the GWP equation to accommodate the different applied vertical loads.

1. Introduction

FRA Office of Research and Development (R&D) has initiated and maintained its research effort in GRMS technology development to improve detection of railroad track gage defects that cause derailments. In the rail transportation industry, due to heavy lateral loads being applied to the rails, it has been a problem to maintain the established distance between the rails. Lateral restraint or the strength to withstand these loads comes from ties, tie plates, rails, spikes, and the supporting track foundation. The ties and fasteners play vital roles in maintaining the track gage. If the loads applied to the rails are high enough to overcome the rail restraint, it is possible to move the rails sufficiently apart to have the wheels of the car drop between the rails, causing a gage widening derailment. GRMS has used GWR and PLG index to assess the risk of train derailment. Both of these indices were developed based on research conducted with deflections resulting from different vertical and lateral loading configurations on rails that represented the minimum restraint criteria allowed on track.

Comparative testing was conducted on the MMIR in October 2002 to evaluate the GRMS capabilities of FRA T-6 and Holland TrackSTAR. The FRA T-6 is a railbound vehicle, and the Holland TrackSTAR is a hi-rail GRMS. Based on initial test results, it was determined that the current GWR calculation did not produce comparable results between the two vehicles. The comparison testing was conducted by monitoring the testing capabilities of each vehicle over the same track, repeatability over particular sections, and accuracy comparisons. The TrackSTAR produced substantially more defects than the FRA T-6. The main differences between these two vehicles are the loading conditions: the FRA T-6 applies a lateral load of 14 kips and a vertical load of 21 kips (L/V = ~0.7) whereas the Holland TrackSTAR applies a lower load of 10 kips and a vertical load of 14 kips (L/V = ~0.7). The applied load severity, which is a measure of the effective lateral load when the restraining effect of the vertical load and friction combination is removed, is different for both vehicles. Other differences included the gage measurement system, structure of the cars, and load control used to apply the loads. The current GWR equation does not consider the effects of different vertical loads; it is extrapolated only to a limiting lateral load. Another major difference between the T-6 and TrackSTAR is that the T-6 GRMS axle is a truck axle and the TrackSTAR has a single axle GRMS. A simulation using the TRKLOD, a finite element model, indicated that the T-6 would measure 12 percent less deflection when compared to the deflection from the same loads in a TrackSTAR configuration, due to the effect of the vertical load applied through the adjacent axle in the truck onto the rails. The current GWR was developed for a vehicle that applies a vertical load 18-21 kips; if the vertical load changes, the GWR value is not consistent. All these problems constituted the need for a new GWR parameter that is consistent for different vehicle configurations and normalized for different load configuration. This report describes the development of the new GWR computations, along with description of field-testing conducted to confirm analytical conclusions.

The new GWR parameter will satisfy the following criteria:

1. It should be loading configuration (load severity) independent.

2. It should be extrapolated to working loads since GWR is an indicator of weak or strong tie and fastener condition rather than the ultimate strength of the track.

3. The same equation would be used for truck-mounted and single split axle GRMS vehicles.

4. The threshold for the safety and maintenance exceptions should remain the same, 1.0 inch and 0.75 inches, respectively as those found in TSS.

2. Background

Since railroads were first used to move heavy equipment, maintaining the track gage by a system of ties, fasteners, and ballast has been a great challenge. Ties are typically made of wood, concrete, or steel, and they perform three major functions. They hold the rails at the correct gage, distribute the loads applied by the train to the track foundation, and anchor the track against lateral movement. The fasteners attach the rails to the ties and are typically cut spikes, screw spikes, or some type of spring clip. When the forces generated by the train exceed the rail holding capacity of the ties and fasteners, the rails move apart either through rotation or translation, allowing the wheels to drop between the rails. This is known as gage widening derailment. Gage widening-related accidents have been one of the top five causes of track-related accidents based on FRA's Railway Accident/Incident Reporting System (RAIRS) since FRA started monitoring railroad accident statistics in the late 1960s. A program was developed at the Volpe National Transportation System Center (VNTSC) in 1980 to investigate minimum rail restraint characteristics of typical track. Field and laboratory tests were performed to develop performance-based rail restraint standards that eliminate the worst case scenarios of the applied trainloads and local track conditions that would lead to rail restraint failure. In conjunction with the field and laboratory tests, two prototype devices were developed that provide quantitative measurements of the rail restraint capacity: GRMS and the lightweight track loading fixture (LTLF).

2.1 GRMS Technology

GRMS is a vehicle that runs on the track with a split axle applying vertical and lateral loads while continuously measuring the change in gage. The prototype GRMS system developed by FRA used a spilt axle mounted in the truck of a 100-ton hopper car and used FRA's instrumentation car T-6 to record the data as described by Carr and Stuart (1995). The two vehicle consist was commonly referred to as the T-6, and a locomotive towed it. The loads were applied through the split axle, which was mounted on a standard three-piece truck in the rear of the hopper car. The split axle applied the loads through its 33 inches flanged steel wheels and housed the sensors that detect the track deflection under loads. A passive load control used in the original GRMS vehicle combined with high internal friction, limited its response to rapid track changes. The LTLF is manually operated and applies the lateral load through the theoretical shear center of the rail cross-section while using a gage bar to measure the change in gage. LTLF and its successor, the portable track-loading fixture (PTLF) use a manual hydraulic pump and cylinder to produce a test load of 4 kips. The LTLF/PTLF provide a method to verify defects identified by GRMS.

Holland Company's TrackSTAR vehicle is a hi-rail based GRMS and is capable of measuring other track parameters like rail profile and track geometry. It utilizes a single deployable split axle between the vehicle driving axles for applying vertical and lateral loads and has an optical rail measurement system to measure gage as described by McCarthy (1995). TrackSTAR uses an active load control to apply loads on the track and is able to rapidly respond to the changes in track conditions.

FRA procured a new GRMS vehicle, the T-18, which utilizes a state-of-the-art deployable single split axle capable of applying variable lateral and vertical load combinations. The evaluation testing of the T-18 on NS in Riverton, VA, indicated repeatable unloaded and loaded gage measurements as well as low standard deviations of the applied lateral and vertical loads. The T-18 uses a mechanical gage measurement approach compared to the optical system being used in the Holland TrackSTAR.

2.2 GRMS Mechanics

The initial development of GRMS technology was based on field experience with a variety of derailments which indicated that gage widening failure had occurred under common track loading scenarios. A field study near Logan, OH, defined the track characteristics of minimally adequate in-service track to define the boundary between acceptable and unacceptable track, tie, and fastener conditions (Jeong and Coltman, 1983). Unacceptable conditions were noted as those where the track, tie, and fastener conditions were not adequate to safely support track loads. The main characteristic of an unsafe tie is an inability to restrain the spike or fastener from movement under load. Load-deflection characteristics of minimally adequate track conditions were developed from data analysis at various test sites. Knowledge of track failure modes indicated that rail restraint characteristics and track forces were critical parameters. A series of vehicle-track interaction tests was conducted in Bennington, NH, to define the limits of tolerable track geometry irregularities based on the response of a common vehicle type. Lateral and vertical loads were measured to determine the lateral to vertical load ratio (L/V), and it was found that peak wheel-rail forces reached 22 kips and were relatively insensitive to vehicle speed (5 to 20 mph) (Coltman and Weinstock, 1988). Lateral loads of 24 kips on the high rail and 16 kips on the low rail have been measured on track with geometry that passed FRA TSS during the test according to Blader (1983). Track maintained to minimum levels should be able to withstand 24 kips ultimate lateral load without gage change adequate to cause wheel drop. The loads from the field study in Bennington, NH, defined the target load regime for the development of GRMS to detect track, tie, and fastener conditions not meeting the minimally adequate criteria used by Jeong and Coltman (1983).

2.2.1 Track Response to Applied Loads

A new track structure with appropriate ballast and good geometrical alignment can support typical train loading. As each track component is worn and degraded over time, however, subsequent loading, deformation, and environmental effects diminish the restraint capacity. Track with a high percentage of structurally degraded ties typically exhibits geometry perturbations, particularly gage, cross-level, and alignment. These geometry imperfections create dynamic interactions between the train and the track that can produce high lateral wheel-rail forces. When combined with a weakened track structure, high lateral loads can cause sufficient spreading of the rails to allow wheel drop. This occurs when the loaded gage exceeds the critical safety limit defined by the physical dimensions of a wheel set. The critical safety limit is defined by the minimum acceptable flange thickness, minimum acceptable back-to-back wheel dimension, standard tread dimension, and a notch in the rim including half of the rim tread radius. The combination of these dimensions is a critical safety limit of 59 inches, as shown in Figure 1.

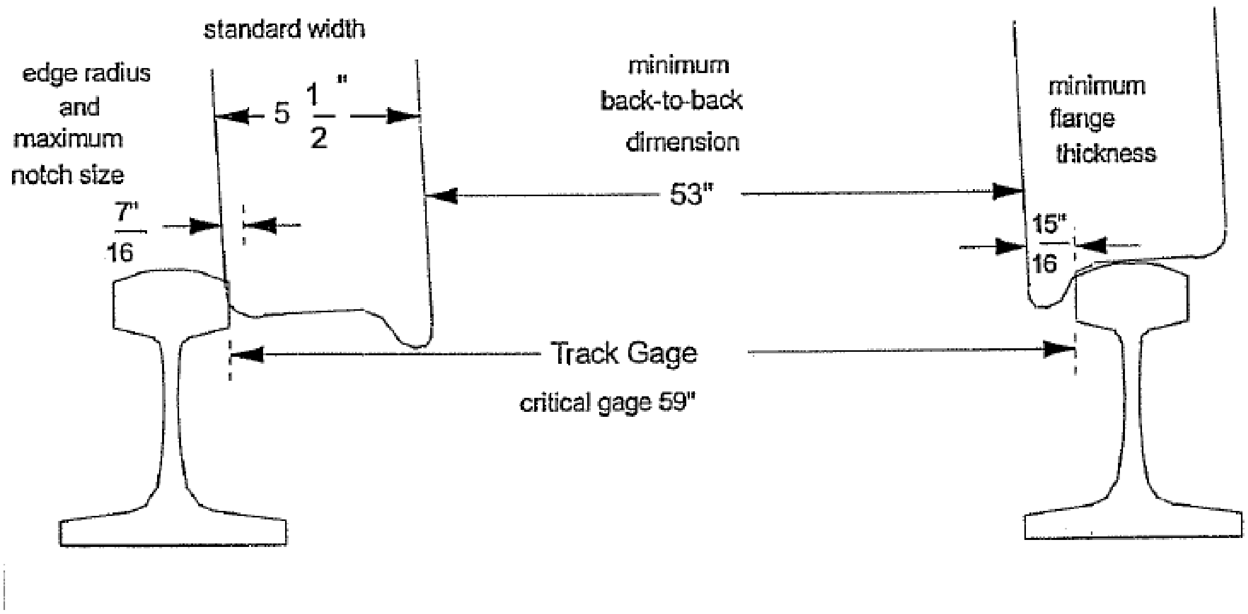


Figure 1. Risk of gage widening derailment when gage exceeds critical gage, 59 inches

The gage can approach this limit if the high rail, low rail, or both rails move under load. This motion can be separated into two components: translation and rotation, as shown in Figure 2(a). Poor performing ties, fasteners, or large dynamic forces cause each motion. Rotation is controlled by the location and magnitude of the applied loads, the fastener holding stiffness, the rail section geometry and torsional stiffness, and the wheel-rail interface geometry. Translation is controlled by the lateral stiffness of the tie and fasteners, rail section geometry and lateral bending stiffness, and the frictional force induced by the applied vertical load.

The overall railhead deflection is influenced much more by the track properties (ties, fasteners, ballast) than by the rail mechanical properties (material properties, rail geometry, rail weight). This is significant when evaluating a measured head deflection under load and relating it to the rail restraint capacity. The resulting railhead deflection is caused by foundation deficiencies, not rail material or geometry defects.

Figure 2(b) shows a rail segment under vertical and lateral loading on a strong tie. Since the tie is assumed to be strong, all the rail, tie plate, and spike gaps are taken up by the initial rail movement. On the other hand, Figure 2(c) shows the rail under loading on a weak tie. As with the strong tie, all the initial gaps are removed. In this diagram, the tie plate has translated laterally, as the tie can no longer support the spikes. This weakened restraint capacity can vary from the worst case, represented by missing ties or spikes, to light degradation with small plate movement and no spike pull.

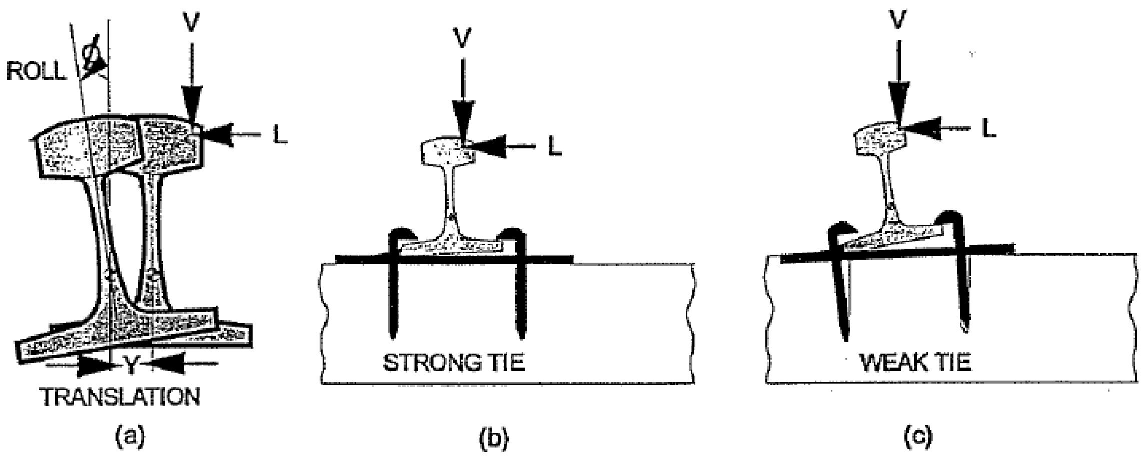


Figure 2. Rail translation and rotation under weak and strong ties

2.2.2 Load Severity

Load severity is a representation of the effective lateral force applied to the rail that removes the resistance offered by the combination of the vertical force and friction between the rail and tie plate (Manos, at al., 1982), given by:

$$S = L - \mu V \qquad [1]$$

Where:

S = track load severity (kips)
L = applied lateral force (kips)
V = applied vertical force (kips)
μ = coefficient of friction between tie and rail, approximated as 0.4.

The load severity concept is a useful tool to estimate the net load applied to the track that is not balanced by friction at the rail-tie interface and must therefore be restrained by the fastener.

2.3 Current Rules and GRMS Application

2.3.1 Projected Loaded Gage 24 (PLG24)

The PLG at 24 kips ultimate loading condition (PLG24) parameter considers the combination of the rail deflection and unloaded gage and is indicative of the overall ability of the tie and fastener system to maintain gage under severe loads of L = 24 kips and V = 32 kips. The extrapolation loads were derived from an investigation by VNTSC (Kish et al., 1984), which surveyed loads experienced by high and low rails during various tests and analysis of cars in severe curve conditions. PLG24 is computed according to:

$$PLG24 = ULG + A \cdot (LDG - ULG) \qquad [2]$$

Where:

ULG = unloaded gage (in),
LDG = loaded gage (in), and
A = an extrapolation factor computed from:

$$A = \frac{13.513}{(L - 0.258 \cdot V) - 0.009 \cdot (L - 0.258 \cdot V)^2} \qquad [3]$$

L = applied lateral force (kips)
V = applied vertical force (kips).

2.3.2 GWR

The current definition of GWR is based on two concepts:

1. The track gage compliance originally proposed as the deflection rate, which was the inverse of stiffness and indicated the allowable deflection per unit load and thus conveyed the response of track gage to load.

2. GWR used the deflection rate concept, multiplied by a factor corresponding to the ultimate load condition, to develop limiting deflection criteria at an ultimate load condition.

These concepts indicate that GWR is a limiting condition representing the amount of movement in the track under working loads. The current GWR equation is stated as:

$$GWR = \frac{LDG - ULG}{L} \cdot 16 \qquad [4]$$

Where:

ULG = unloaded gage (in)
LDG = loaded gage (in)
L = applied lateral force (kips)

Rearranged in a similar manner to the PLG24 equation, GWR can equivalently be represented as:

$$GWR = (LDG - ULG) \cdot \left(\frac{16}{L}\right) \qquad [5]$$

In a manner similar to PLG24, GWR thus uses the factor 16/L as an extrapolation factor to a higher load condition from the test load. In this manner, 16 may represent the GWR ultimate lateral load condition.

The current TSS set the exception thresholds to 0.75 inches for maintenance and 1.00 inch for safety. The scale factor 16 kips in the GWR equation was determined as being the extrapolation load at which the deflection of minimally acceptable track at a nominal FRA's T-6 applied lateral force would yield a GWR value of 1.00 inch. Field tests reported by Jeong and Coltman (1983) indicated that for low lateral loads (up to 15 kips), rail-base displacements account for 70 percent to 90 percent of the total railhead displacements. A high rail-base displacement would indicate that the tie, tie-plate, or the spikes are not in good condition, and hence the GWR value closely indicates the rail fastening condition at a specific location.

2.4 Vehicle Design Requirements

The minimum design requirements specified by FRA TSS, Part 213, for a GRMS vehicle specify that gage restraint should be measured between the heads of rail at an interval not exceeding 16 inches. The applied vertical load should be no less than 10 kips per rail, and the lateral and vertical test load combinations should be such that they provide an L/V ratio between 0.5 and 1.25. An L/V ratio of greater than 0.8 has been found by experience to be more prone to derailment; hence, vehicles operating in this zone of lateral load and vertical load combination exercise caution. The American Railway Engineering and Maintenance-of-Way Association (AREMA) Manual for Railway Engineering is more detailed, and it specifies the gage measurement requirements, as shown in Figure 3. Unloaded gage should be measured at least 5 feet behind or 10 feet ahead of any load applying source greater than 350 pounds in either lateral or vertical directions. The loaded gage measurement should take place within 1 foot of the applied load. Lateral and vertical load applied by a GRMS vehicle should fall in zone II or zone IV as illustrated in Figure 3. Caution should be used during testing as risk for derailment is higher in zone IV due to high L/V ratio.

Ambiguity in the vehicle requirements has led to different designs. An evaluation of the hi-rail and railbound designs to assure consistency in load and displacement measurements is necessary. This evaluation is a major step in the advancement of new GRMS design, as described in this report, for the current design change to single split axle with variable test loading combinations from truck split axle with constant vertical test load.

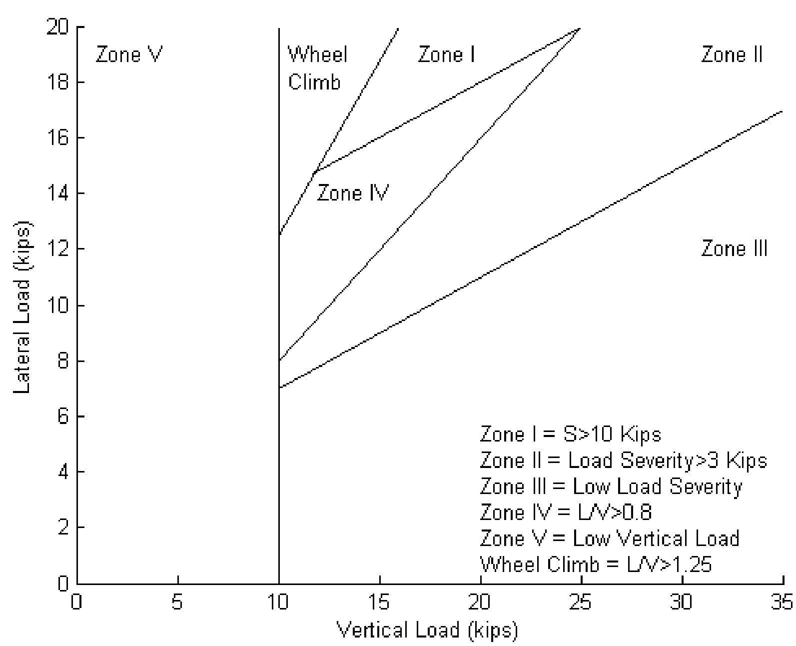


Figure 3. Permitted test loadings for gage restraint as per the AREMA guidelines

2.5 GRMS Technology Summary

Recent changes in the design of GRMS vehicles include the Holland TrackSTAR and the FRA T-18, which are single axle GRMS systems as opposed to the truck mounted split axle devices used for GRMS testing. The TrackSTAR used a laser-based non-contact gage whereas the T-6 and the T-18 used a contact-based gage measurement system. The T-6 and T-18, as well as other GRMS vehicles used in the railway industry, apply a nominal lateral load of 14 kips and a nominal vertical load of 21 kips whereas the TrackSTAR applies a lateral load of 10 kips and a corresponding vertical load of 14 kips. The L/V ratios of the different load combinations used are approximately 0.7. The applied load severity is different for TrackSTAR when compared to the T-6 and the T-18.

Loading conditions during measurement of gage restraint play a critical role in obtaining accurate and repeatable data. Track gage widening load-deflection behavior is nonlinear and is controlled by many factors, including rail size, tie type, and condition. Confirmation of the capabilities of different systems with distinct test loads to accurately measure gage restraint is important to ensure track safety.

3. GRMS Field Investigation

Good comparison between present GRMS vehicles and their repeatability, as well as reliability, is very important in making GRMS a good tool to test gage restraint. A comparison test was carried out between the FRA T-6 and the Holland TrackSTAR in October 2002 on MMIR. Substantial differences between the two vehicles in design and performance led to considerable disparity in the test results. The TrackSTAR found more safety and maintenance exceptions than the FRA T-6 in the GWR and PLG24 category. Both vehicles have some measurement errors. For example, the T-6 was slow in reacting to gage changes, and the TrackSTAR had a drifting lateral load sensor. It was concluded that investigation of GWR and PLG24 was needed to ensure accuracy for varying load conditions. A detailed report on the MMIR comparison test was developed, which included the analysis of the test results (Choros et al., 2003).

Development of the FRA T-18 and its qualification testing was conducted in November 2004 on NS. The ability of the T-18 to test at different loading configurations was used to investigate the relation between GWR and load severity. A length of about 50 miles of track was tested at two different load severities: one loading configuration being the FRA T-6 nominal loads and the other being the TrackSTAR's nominal loads. Repeatability of the T-18 was found to be excellent when the two loading configurations were compared over subsequent runs. Based on the investigation of the influence of load severity on GWR, a new equation, GWP, was developed. Using the GWP equation, a comparison of the TrackSTAR and the T-18 was conducted on the River Subdivision of BNSF between St. Louis, MO, and Cape Girardeau, MO, during, March 7-11, 2005. Excellent repeatability was found between both the vehicles in terms of the new form of GWR (which is called GWP) and PLG24.

3.1 Summary of Test Conditions

The MMIR track was predominantly Class II with 115 American Railway Engineering Association design (RE) rail section with a few exceptions where lighter rail was used, usually less than one rail length. Timber ties were used predominantly for the track structure, with the exception of a few sections where steel ties were used. Timber tie condition varied from new to degraded, typical of Class II track. When MMIR was retested with the T-18 in February 2005, the tie and rail conditions were found similar to those when tested in October 2002. Detailed information about the track for the October 2002 tests can be found in Choros et al. (2003) report.

The November 2004 test with the T-18 was conducted at NS on Class II track with 136 RE rail section. The track length was about 2,600 feet and had a few weak locations due to weak timber ties and some lost spikes. Locations of weak gage restraint capacity were created by removing the spikes of a tie for both rails and using a flat steel plate with the same thickness as the regular tie plate instead of a regular tie plate. These spots were created with an objective of obtaining the same coefficient of friction between the rail and the tie for all the created defects. The number of consecutive ties with flat steel plates instead of normal tie plates determined the relative severity of the poor gage restraint condition. The GRMS vehicle applied loads through five such locations of increasingly poor gage restraint using additional flat steel plates.

Similarly, the comparison test between the T-18 and the TrackSTAR in March 2005 carried out on the BNSF River Subdivision between St. Louis and Cape Girardeau, MO, had a repeatability phase of testing where defects were created using the same procedure followed at the evaluation testing at NS. The repeatability comparison testing was carried out on 132 RE rail section, and the over the road run comparison was conducted on a combination of 115 RE, 132 RE, and 136 RE rail sections.

3.2 Data Analysis

Results from the first comparison test at MMIR between the FRA T-6 and the TrackSTAR indicated that both vehicles were repeatable at their respective nominal loads. The Holland TrackSTAR, however, identified a greater number of reportable exceptions, GWR and PLG24, for safety and maintenance. The principal difference between the numbers of exceptions from the two GRMS vehicles was GWR safety. The TrackSTAR found 10.17 times more GWR safety exceptions than the T-6. For GWR maintenance, PLG24 maintenance, and the PLG24 safety, the TrackSTAR's numbers of reported exceptions were higher by 2.63, 6.33, and 7.89 times, respectively, as shown in Table 1.

Table 1. Comparison of the exception count between the FRA T-6 and the Holland TrackSTAR from the test conducted in October 2002 on MMIR

Exception Type	Safety		Maintenance	
	T-6	Holland	T-6	Holland
GWR	78	814	329	125
PLG24	9	71	42	266

Some measurement errors existed in both the vehicles, which the comparison report details. Accounting for measurement errors still did not bridge the gap between the two vehicles. A simulation using the TRKLOD model shows that the T-6 would measure 12 percent less deflection when compared to the deflection from the same loads in a TrackSTAR configuration due to the effect of the vertical load applied through the adjacent axle in the truck onto the rails. The current GWR was developed for a vehicle that applies 18-21 kips vertical load, and if the vertical load changes, the GWR value is not consistent.

3.3 GWR Computation

Development of new design GRMS and distinct loading configurations has spurred the need to improve the GWR's reliability between vehicles. The current GWR equation is computed using Equation 4 and does not currently include a vertical load term. New vehicle designs and operating loads make it necessary to include the vertical load to get good repeatability between two different GRMS equipment for the GWR parameter.

The T-18 repeatability testing over the same stretch of track at different speeds on NS (November 2004) found the GWR to be 0.045inches at the five different speeds. After the preliminary results, a stretch of track (about half a mile) was tested at 25 different load combinations of acceptable vertical and lateral loads. Figure 4 shows the change in GWR with respect to applied load severity at three different weak locations (locations where no tie-plates were substituted). The coefficient of friction chosen was 0.258, and it is equal to the c value derived by Blader (1983) to approximate the minimal rail restraint curve. These locations were chosen such that they were roughly about 0.8 inches GWR at nominal T-6 load severity of 7 kips, therefore closely representing minimally acceptable track. It is clearly observed that the GWR graph has a positive slope; hence, it is not normalized for different loading configurations, and hence the GWR equation is inconsistent for vehicles that apply different nominal load combinations.

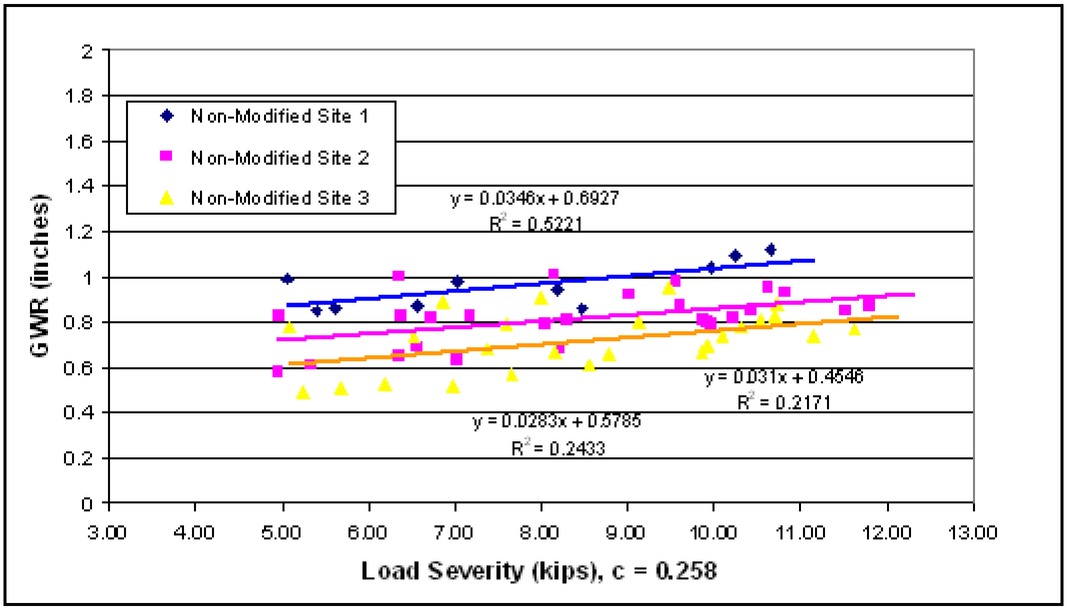


Figure 4. T-18 GWR values for three different non-modified sites at different load configuration runs

4. Analytical Investigation

The present GWR computation does not take into account the applied vertical load; thus it was found not to perform well in vehicle comparison tests. Therefore, a thorough analysis of the fundamental GWR computation was conducted with the goal of developing a new computation procedure that would perform equally well for a variety of load configurations representing the new generation GRMS systems and provide an equivalent level of safety. The applied load severity, a good representation of the effective lateral load resistance, results in different GWR values when loads vary even at the same location. The form of the new GWR equation was developed using three different approaches involving various physical and analytical track models, along with consideration of established conditions of minimally acceptable track conditions. The result of the analysis was a new equation termed the GWP index to avoid confusion with the earlier GWR, which it is intended to replace.

4.1 Derivation of GWP

Since the PLG24 equation performed better than GWR in the comparison test between the different GRMS vehicles, the PLG24 analysis procedures were investigated to determine if the extrapolation procedure could improve the performance of the current GWR equation. The PLG24 equation includes an extrapolation factor to estimate gage for extreme loading situations, which would be detrimental to track conditions if the loading was applied in the field during testing. Due to the potential track damage at the higher loads, the A-factor was developed as the ratio of two non-linear equations with the numerator being the limiting conditions (L = 24 kips and V = 32 kips) and the denominator being the applied conditions. The A-factor is given as follows:

$$A = \frac{(L_c - 0.258 \cdot V_c) - 0.009 \cdot (L_c - 0.258 \cdot V_c)^2}{(L - 0.258 \cdot V) - 0.009 \cdot (L - 0.258 \cdot V)^2} \qquad [6]$$

Where:

L_c = critical lateral load set at 24 kips

V_c = critical vertical load set at 32 kips

0.258 = coefficient of friction, identified from the lines of constant deflection as the slope of the lateral load-vertical load graph, termed $m_{L,V}$

Based on the lines of constant deflection developed for the PLG A-factor from TRKLOD analysis, shown in Figure 5, the E-factor was developed as the extrapolation factor for estimating gage widening under GWR ultimate load. The slope of the lines of constant deflection relating lateral load and deflection govern the relationship together with the spacing between the constant vertical load lines. The slope of the deflection versus lateral load lines is 0.0663 in/kip on average as shown on the graph. The slope of the plot of deflection versus vertical load for the single axle loading condition was found to be -0.167 in/kip of vertical load on average. The negative value of this ratio appeared reasonable since less deflection would be expected for an increase in vertical load. The deflection equation was then developed as:

$$D = m_{L,D} \cdot L - m_{V,D} \cdot V \quad [7]$$

Where:

D	=	deflection
$m_{L,D}$	=	slope of the lateral load, deflection plot, (0.663 in/kip lateral load)
L	=	lateral load
$m_{V,D}$	=	slope of the vertical load, deflection plot, (-0.167 in/kip vertical load) and
V	=	vertical load

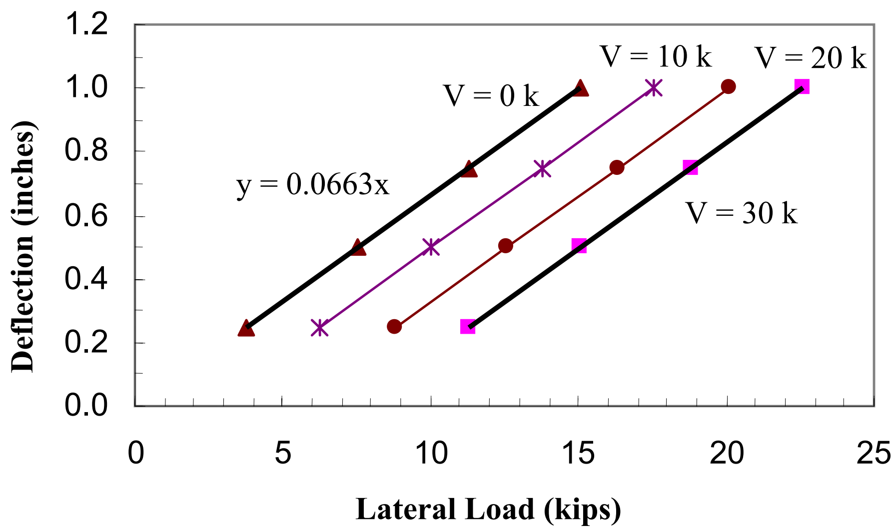


Figure 5. Lateral load-deflection trends for different vertical loads

Since the PLG24 and GWR are ratios of deflection at a limiting condition to the deflection at the test load conditions, similarly the E-factor was computed as a ratio of the deflection computed for the ultimate load to the field test load conditions. The limiting conditions for GWR analysis were assumed as 16 kips lateral and 32 kips vertical; the 1 inch deflection at the limiting condition is a constant in the E-factor equations. The E-factor for a single axle test load condition can be computed according to:

$$E = \frac{D_c}{D} = \frac{m_{L,D} \cdot L_c - m_{V,D} \cdot V_c}{m_{L,D} \cdot L - m_{V,D} \cdot V} = \frac{0.512}{(0.066L - 0.017V)} = \frac{7.75}{L - 0.257 \cdot V} = \frac{16 - 0.257 \cdot 32}{L - 0.257 \cdot V} \quad [8]$$

Where

D_c is the critical deflection, and then GWR would be computed as:

$$GWR = \Delta Gage \cdot E \quad [9]$$

Where

ΔGage = LDG-ULG

Another approach using the PLG A-factor resulted from simplifying the A-factor by neglecting the higher order terms:

$$A_1 = \frac{L_c - 0.258 \cdot V_c}{L - 0.258 \cdot V} \qquad [10]$$

Where

$$GWP = \Delta Gage \cdot A_1$$

The equation simplifies to a ratio of load severities for the given coefficient of friction, denoted in this analysis as $m_{L,V}$ of 0.258:

$$A_1 = \frac{S_c}{S} \qquad [11]$$

Where

S_c = critical load severity
S = test load severity

Neglecting the higher order terms results in a difference between the original A-factor and the A-factor without higher order terms (A_1) of 12 percent for the condition of reduced load severity where the GWR does not perform well, as shown in Table 2. Otherwise, A_1 could properly extrapolate to the ultimate load conditions within 10 percent error.

Table 2. Analysis of A-factor dependence on higher order terms

L_c kips	V_c kips	L kips	V kips	A-factor	A_1	Percent Error
24	33	14	21	1.68	1.80	7
24	33	10	21	3.03	3.38	12
24	33	17	21	1.28	1.33	4

Two other methods were investigated to verify the nature of the GWP equation, namely the Simple Rail Spring Model and the TRKLOD analysis, which Appendix A describes in detail.

4.2 Summary of Analytical Investigation

For all the three approaches, the values of the critical vertical load V_c are not known. The critical lateral load L_c is set to 16 kips, the same as used before in the original GWR equation. The forms of the equations are:

$$E = \frac{D_c}{D} = \frac{m_{L,D} \cdot L_c - m_{V,D} \cdot V_c}{m_{L,D} \cdot L - m_{V,D} \cdot V} \qquad [12]$$

which is previous equation 8 and

$$A_1 = \frac{S_c}{S} = \frac{L_c - m_{V,L} \cdot V_c}{L - m_{V,L} \cdot V} \qquad [13]$$

This is previous equation 10, again with $m_{V,L}$ equal to the coefficient of friction of 0.258. These computation procedures fall into two categories, the application of a ratio of deflection for equation 12 and a ratio of load severity for equation 13 to extrapolate from field test load to ultimate load condition.

4.3 Field Verification

One criterion not achieved yet is that the GWP equation should keep the safety limits set in TSS the same. A test was conducted again on MMIR in February 2005 with the T-18 being operated at two different loading configurations, one with the nominal T-6 loads (L = 14 kips and V = 21 kips) and the other with nominal TrackSTAR loads (L = 10 kips and V = 14 kips). The exceptions were computed using equation 13 with L_c = 16 kips and V_c = 32 kips. Forty-nine of these exceptions were tested using the PTLF loaded to 4 kips and a gage bar to measure rail deflection. Good correlation was observed on the plot of GW32 (32 refers to V_c) versus PTLF delta gage (loaded at 4 kips) for both the load configurations, as shown in Figure 6.

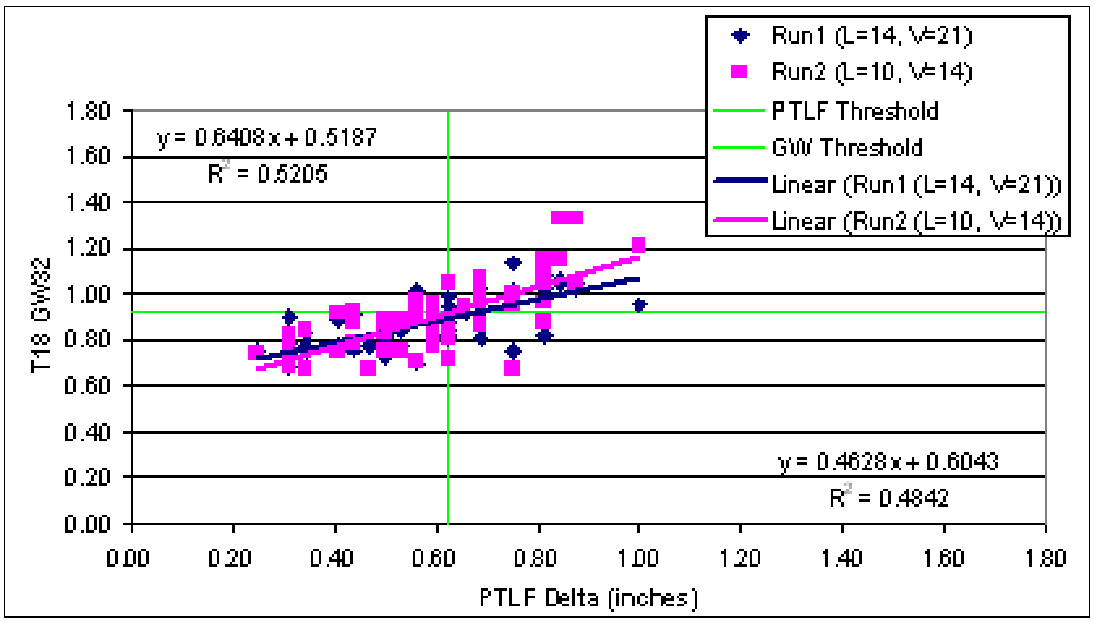
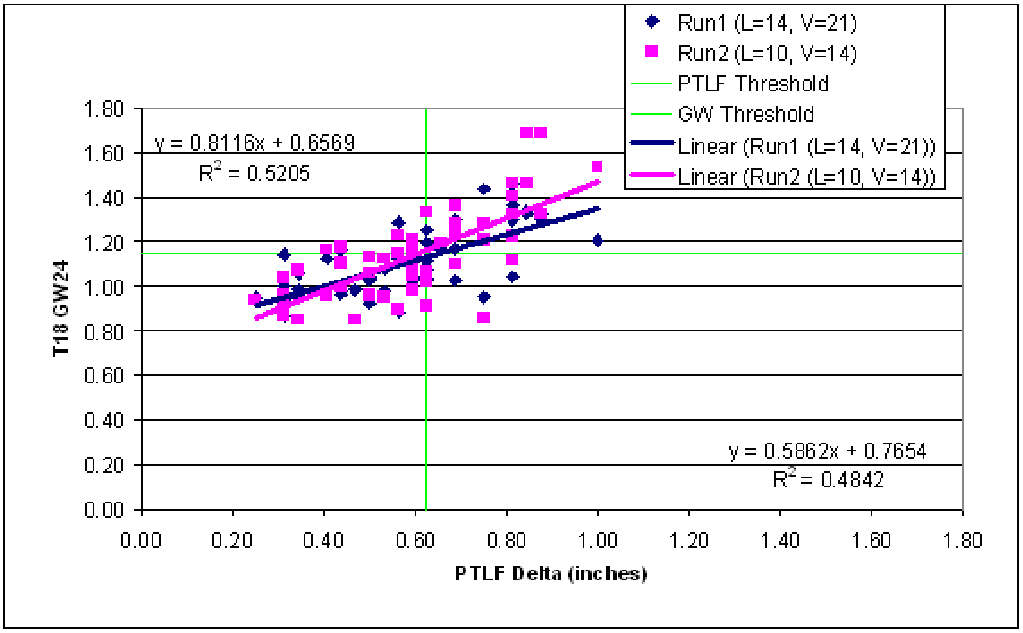


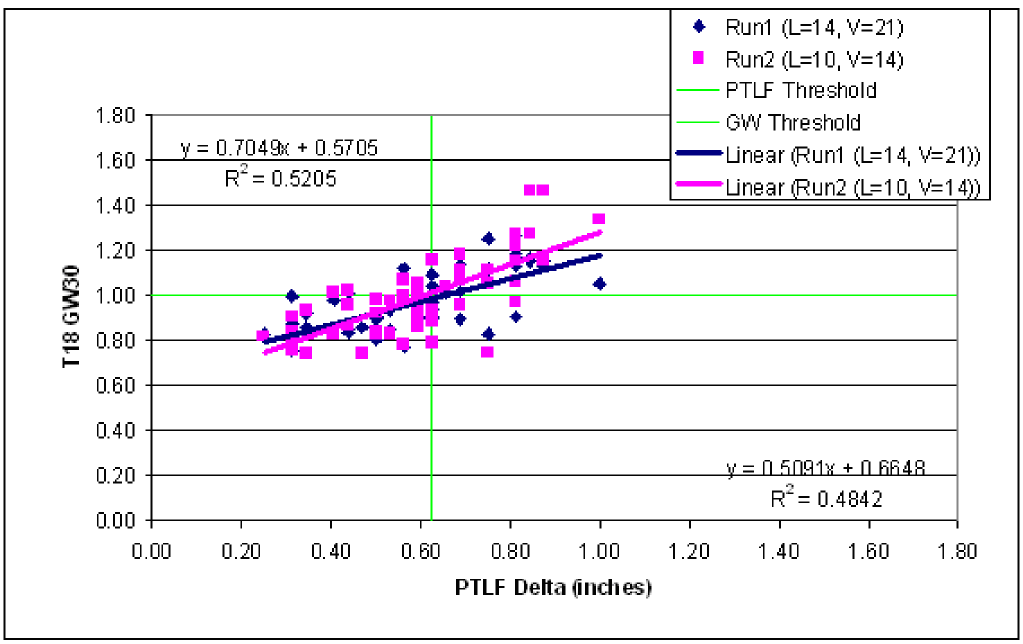
Figure 6. GW32 versus PTLF delta gage comparison for T-18 results from MMIR

It is noticed that the 0.625 inches PTLF delta gage line intersects the two load configuration runs at about 0.9 inches of GW32. The 0.625 inches delta gage for a 4 kips PTLF loading has been considered a safety exception for comparison purposes. Therefore, 32 kips is not the critical vertical load since the threshold would have to be changed to 0.9 inches from 1.0 inch. Two more critical vertical loads, 24 kips and 30 kips, were also plotted, and it was found that GW30 provided the best results in keeping the thresholds the same as the old GWR thresholds. Figure 7 (a) and (b), respectively, show these two plots.

Normalization was also investigated by plotting GW30 versus load severity for the same three locations, which were used in Figure 4 when plotting GWR versus load severity. Figure 8 shows that GW30 is independent of load severity and hence the different loading configurations applied by the different vehicles. The combination of maintaining the threshold the same as GWR and normalization achieved by GW30 makes it satisfy all the requirements for a parameter that identifies weak tie fastener system efficiently for a variety of test configurations and load magnitudes.



(a)



(b)

Figure 7. GW24 (a) and GW30 (b) versus PTLF delta gage comparison for T-18 results from MMIR

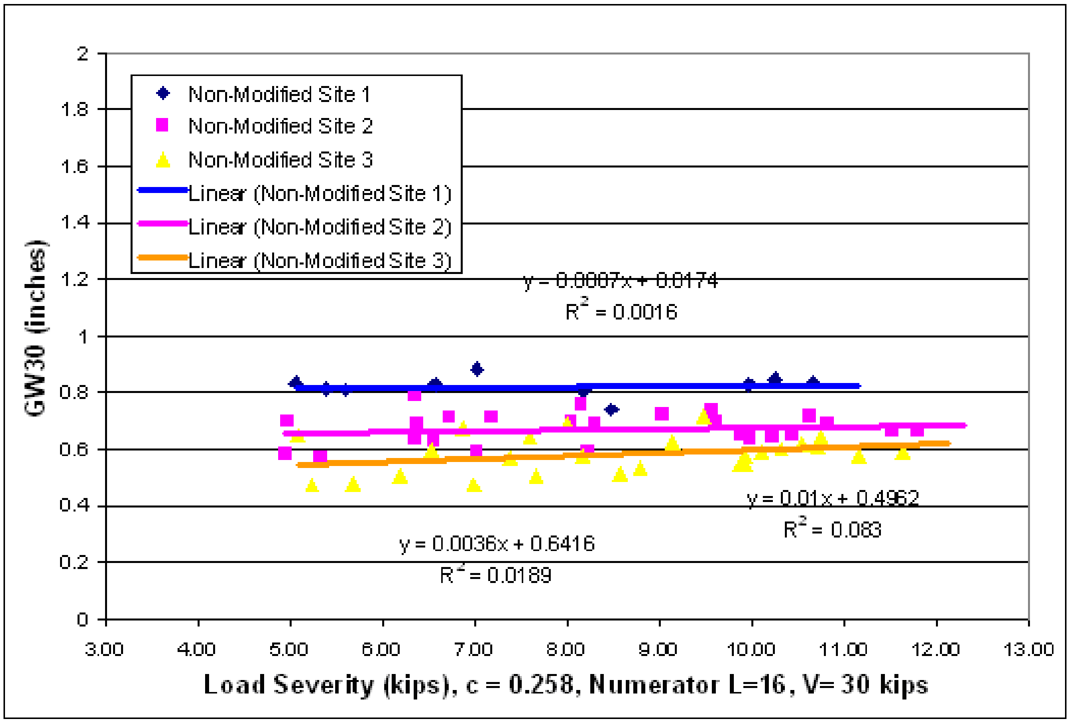


Figure 8. Normalization of GWP showing that GWP is not dependent on the load severity

4.4 Gage Widening Projection

The form of the GWP equation is based on a ratio of load severity according to equation 13 with critical lateral and vertical loads of 16 kips and 30 kips, respectively, and is stated as follows:

$$GWP = \Delta Gage \cdot \frac{16 - 0.258 \cdot 30}{L - 0.258 \cdot V} = \Delta Gage \cdot \frac{8.26}{L - 0.258 \cdot V} \qquad [14]$$

Selecting the vertical load at 30 kips instead of 33 kips used in the derivation of the A-factor will allow the TSS safety limits to remain the same, 0.75 inches for maintenance and 1.00 inch for safety defects.

5. Evaluation of GWP Performance

5.1 Comparison between GWR, GWP, and PTLF

The GWP equation results were compared to GWR values and PTLF results to evaluate the changes resulting from the new equation. The analysis was conducted to determine if the new equation addressed the previously identified problems with the GWR equation. It was found that the GWP equation compared well with the PTLF limit of 5/8-inch deflection when the applied force is increased from 0 to 4 kips. The PTLF was applied to two locations during the BNSF test to obtain an estimate of the accuracy of both the T-18 and TrackSTAR to measure gage strength. Figure 9 shows one of these locations, where the PTLF 4 kips deflection was a 0.5 inches and thus not an exception according to the TSS, CFR 213.110(m). The GWR flags it a safety exception where the GWP value does not deem it a safety exception.

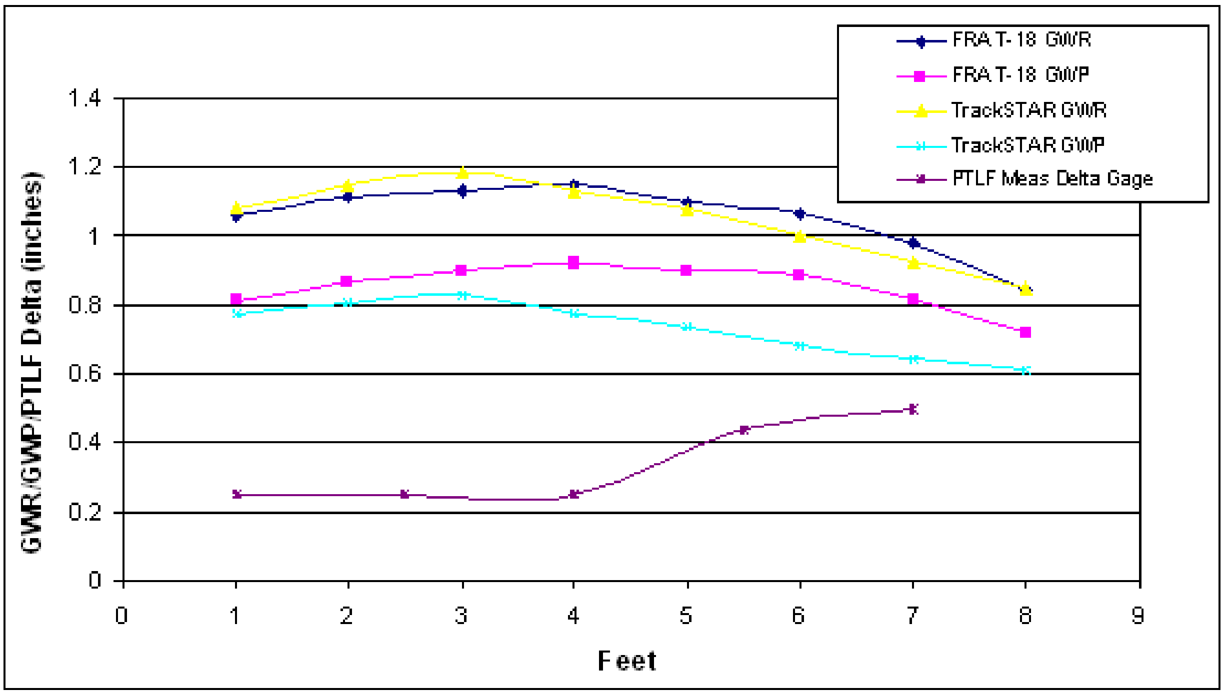


Figure 9. Comparison of the GWP with the GWR where the PTLF and the GWP agree with each other and the GWR does not

The T-18, as well as the TrackSTAR, gage measurements were compared to wayside measurements to ensure correct measurements by the sensors on the vehicles. Wayside instrumentation was set up on three out of the five weakened spots to compare the measurements of the GRMS vehicles. String potentiometers were instrumented to the rail to facilitate the displacement measurements on both sides of the rails. Figure 10 shows a sample measurement by one of the potentiometers. Both the vehicles showed good comparison (tabulated in Table 3) with the wayside instrumentation of TrackSTAR being the better of the two on average.

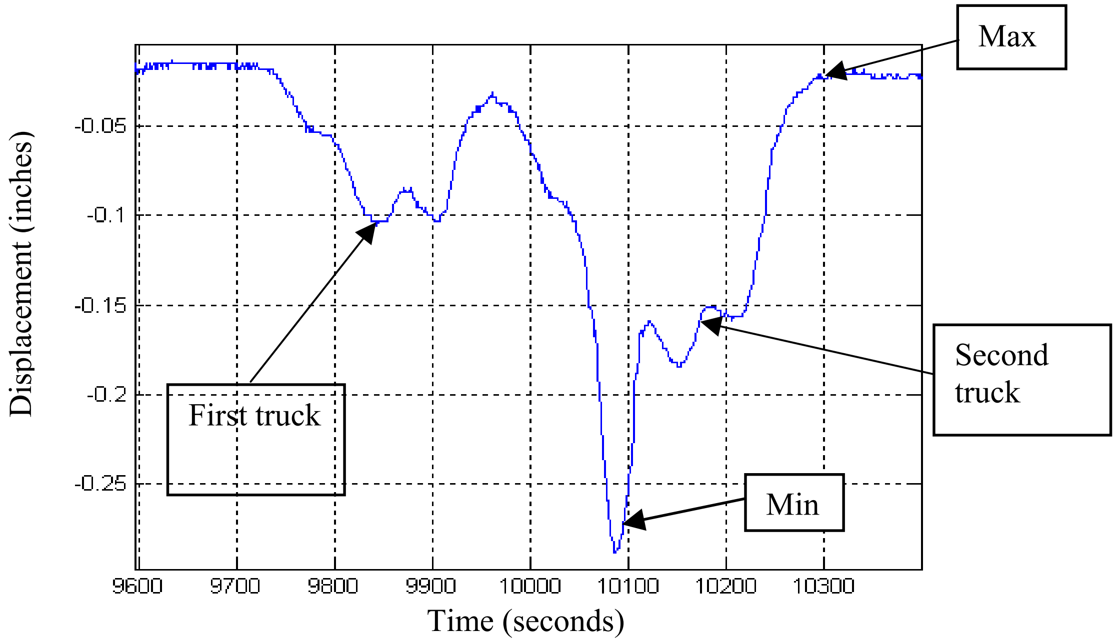


Figure 10. Sample wayside measurements used to measure the maximum deflection of a run for a particular location

Table 3. Percentage error of the delta gage measured by the GRMS vehicles compared to the wayside instrumentation measurement

GRMS Test Results	Loads (kips)	Average Error	Std Dev
T-18 All Runs Combined Error		-9.08%	13.79%
T-18 Day 1 Average Error	10L 14V	-18.99%	8.32%
T-18 Day 2 Average Error	14L 21V	4.13%	6.05%
TrackSTAR Average Error	10L 14V	-6.05%	14.59%

5.2 Field Data Comparisons

The comparison test between the T-18 and the TrackSTAR at St. Louis, MO, consisted of the following three phases of testing.

5.2.1 Verification and Calibration

Verification and calibration of both vehicles were performed for all GRMS fundamental measurements, namely unloaded gage, loaded gage, left and right vertical and lateral loads, and distance measurement. A load cell fixture was used to verify and calibrate the load measurements. A gage bar was used at 20 different locations to calibrate and verify GRMS loaded and unloaded gage measurements. A measured 1,000-foot section was used to calibrate the distance encoders used by each GRMS vehicle. Both the FRA T-18, as well as the Holland TrackSTAR, showed good calibration of the basic GRMS measurements.

5.2.2 Repeatability

After the calibration was performed and the measurement capabilities of both the vehicles were verified, a repeatability test was conducted for both the vehicles. A test section of about 1,500 feet was chosen, and the T-18 was tested at five different speeds and the TrackSTAR at three different speeds, all within the operating track speeds. Weak spots were generated by removing tie plates in increasing number and replacing the tie plates with flat steel plates. Four weak spots were created in tangent section and one weak spot in the curve section; Figure 11 shows the layout of weak spots.

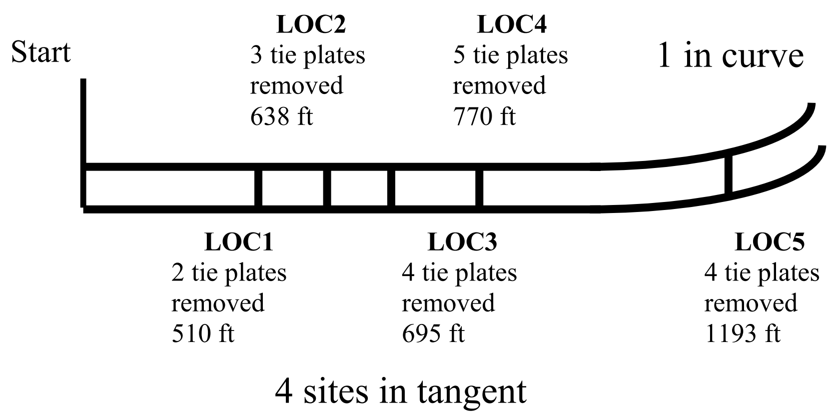


Figure 11. Layout of the weak spots on the repeatability zone

Both vehicles were found to be highly repeatable. Figure 12 shows the GWP values for both the vehicles over a 400-foot section of the repeatability zone. No exceptions were found on the repeatability segment that the vehicles tested.

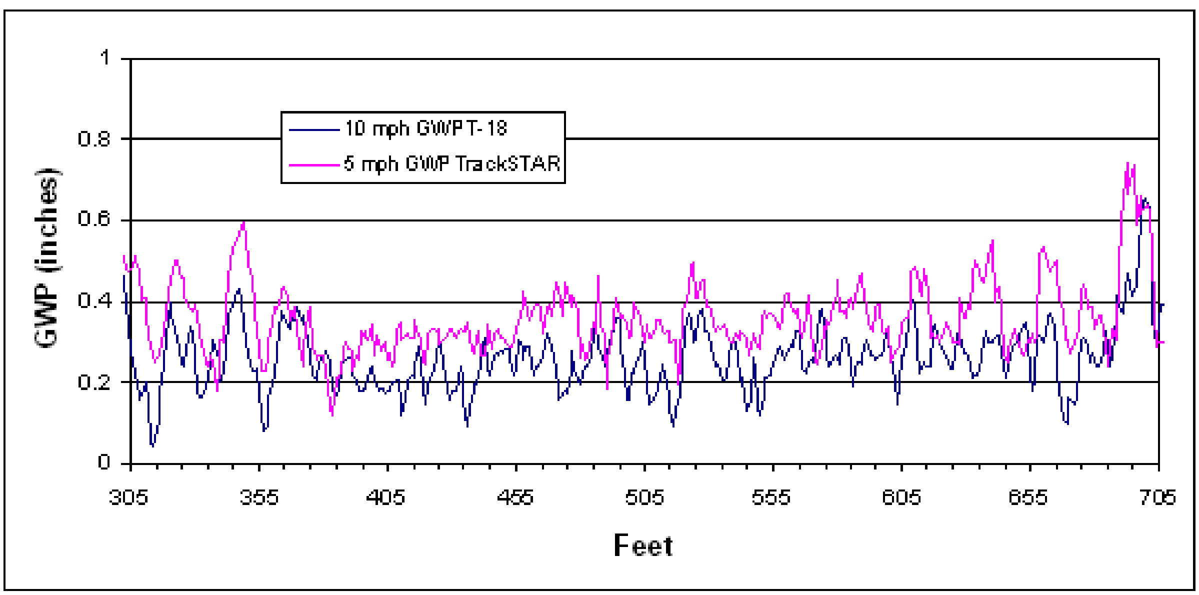


Figure 12. GWP repeatability tests comparison a zone of approximately 400 feet for the TrackSTAR and the T-18

5.2.3 Over the Road Test

The last phase of the comparison testing included testing both GRMS vehicles over about 40 miles of Class III track with both vehicles applying their respective nominal loads. Figure 13 shows the loads applied by the both vehicles on the AREMA plot. It can be seen that both the vehicles adhere to the AREMA specifications of applying test loads to the track. The acceptable zones on the AREMA plot are Zone II and Zone IV for test load application.

Figure 14 shows a plot comparing GWP from the TrackSTAR, as well as the T-18, and it is observed that the comparison is very good. PLG24 safety exceptions were based on a PLG24 threshold of 59 inches, and GWP safety exceptions were based on a GWP threshold of 1.00 inch. The exception count for both the vehicles compared very well and is tabulated in Table 4. GWP comparison between the two GRMS systems in terms of exceptions counted by location and feet were found to be very good (five for TrackSTAR and eight for T-18 when counted by location). Consecutive feet exceptions were counted as one exception by location. Table 5 shows the exception count considering the previous equation of GWR and safety threshold of 1.00 inch. It is observed that the maintenance and safety exception counts show greater disparity than the GWP numbers.

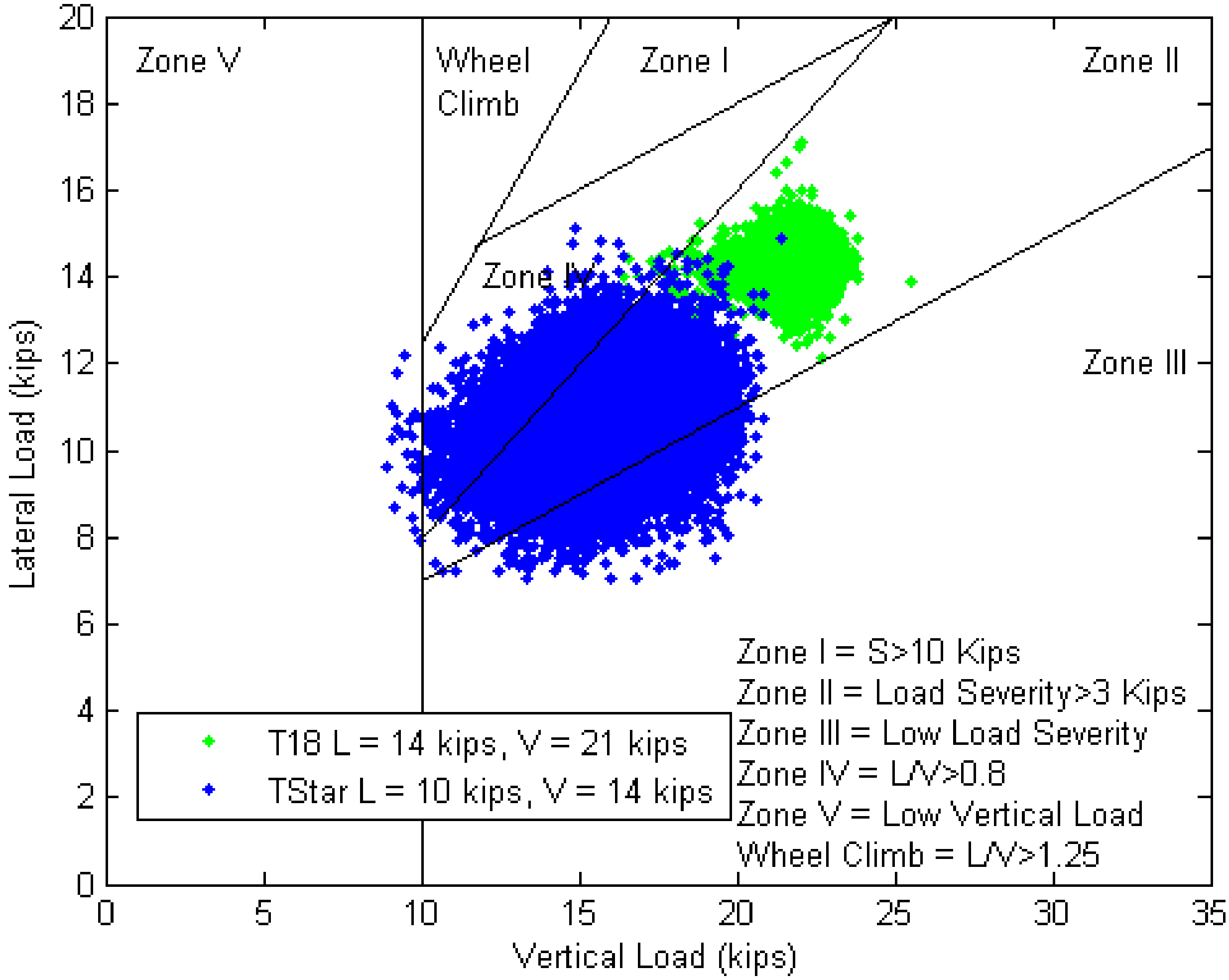


Figure 13. AREMA load plot for FRA's T-18 and TrackSTAR

GRMS Vehicles	Standard deviation (kips)	
	Lateral	Vertical
TrackSTAR	0.76	1.04
T-18	0.27	0.47

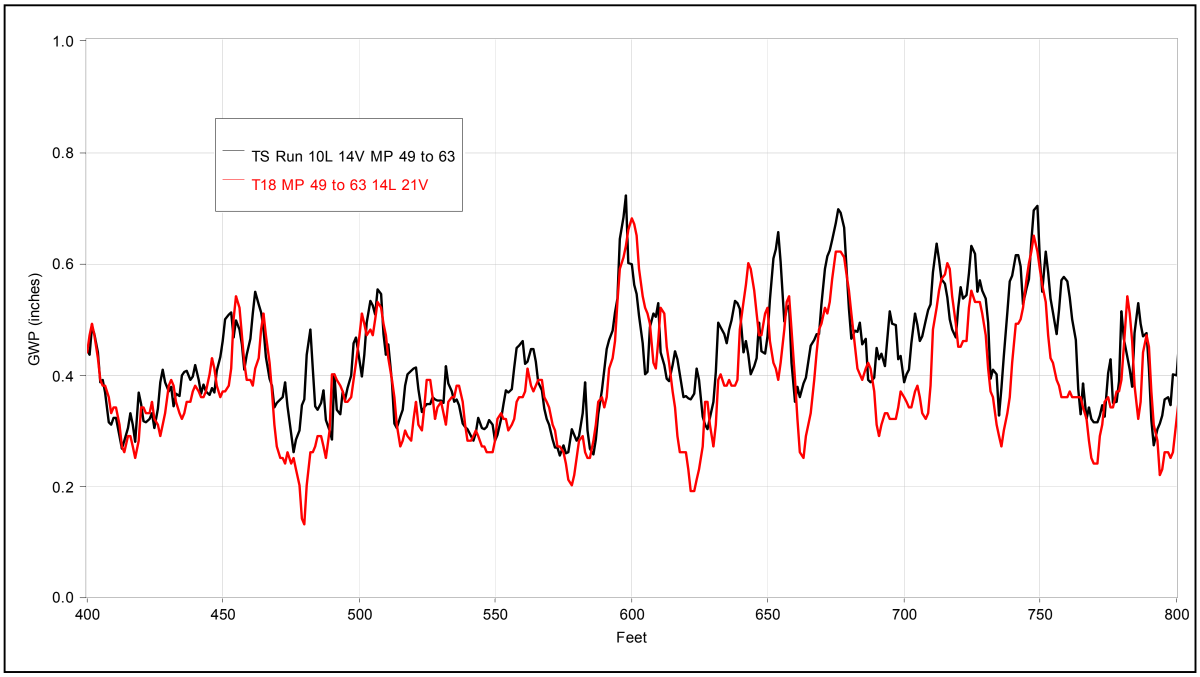


Figure 14. Comparison plot of GWP from the T-18 and TrackSTAR over a length of 400 feet during the Phase 3 tests, March 2005

All three phases of the comparison testing between the FRA T-18 and the Holland TrackSTAR concluded that the GWP was an excellent measure to use when testing with GRMS vehicles with different loading configurations and systems. Further, by utilizing the GWP equation, both GRMS vehicles are capable of performing gage widening strength tests to determine the integrity of the track structure to withstand applied service loads.

Table 4. Exception count for both the GRMS vehicles using the GWP equation

GRMS Vehicle	GWP Safety	GWP Maintenance	PLG Safety	PLG Maintenance	Loaded Gage
Exceptions by Feet					
TrackSTAR	13	225	5	1154	0
T-18	23	244	5	2480	163
Exceptions by Location					
TrackSTAR	5	85	3	280	0
T-18	8	75	3	439	46

Table 5. Exception count for both the GRMS vehicles using the GWR equation

GRMS Vehicles	GWR Safety	GWR Maintenance	PLG Safety	PLG Maintenance	Loaded Gage
Exceptions by Feet					
TrackSTAR	245	1277	5	1154	0
T-18	154	907	5	2480	163
Exceptions by Location					
TrackSTAR	69	322	3	280	0
T-18	45	225	3	439	46

By comparing the two exception numbers obtained from the GWP and the GWR, it is observed that the cumulative (safety and maintenance combined) of GWP numbers for TrackSTAR are 90, and for the T-18, it is 83 with the TrackSTAR identifying 8 percent more exceptions. The same cumulative numbers for the GWR are 391 for the TrackSTAR and 270 for the T-18, providing a ratio of 1.45. In addition, in the case of GWP, it is observed that the safety exceptions are greater for the T-18 whereas the maintenance numbers are greater for the TrackSTAR. It is noticed that the GWR favors the vehicle applying a lower load severity (TrackSTAR) over the vehicle applying a higher load severity (T-18). In contrast to that, the GWP is a much better comparison between two different vehicles applying different load combinations. The GWP exceptions from the St. Louis test noted by both the vehicles were overlaid with the TRKLOD model for the minimally acceptable track conditions. The GWP exceptions compare excellently with the TRKLOD model, and Appendix B describes the analysis in detail.

6. Summary and Conclusions

The GWP equation was developed as a two variant dependent parameter that aims to satisfy the requirements from which the original GWR was developed. Shortcomings of the original GWR were analyzed in depth, and analysis and field verification were used to determine the form of the present GWP equation. A test with the FRA T-18 was conducted on MMIR with different loading configurations to arrive at the exact value of the critical vertical load, which was determined to be 30 kips. The GWP achieves normalization of gage widening values at different loading configurations. It also keeps the original threshold of 1.00 inch as the safety exception limit and the maintenance limit, is retained at 0.75 inches. Excellent correlation exists between the GWP and the delta gage measured using the PTLF loading up to 4 kips. The theoretical TRKLOD model was also found to have good comparison with the GWP values from the comparison test between the FRA T-18 and the Holland TrackSTAR. GWP is a better extrapolation equation than the GWR, which normalizes the differences in applied loads common in the various designs of the GRMS vehicles present today. Advantages of the GWP over the GWR and its merits as an excellent tool for measuring track gage widening warrant its inclusion in the TSS.

7. Recommendations

It is recommended to apply the GWP equation described in this report in place of GWR for all GRMS analysis. Specifically, the GWP should be used in place of GWR for any redesigned GRMS operating at a loading different from the originally applied nominal 14 kips lateral, 21 kips vertical load combination, or for GRMS systems where the split axle is not located in the position of the leading axle of the trailing truck. The recommended GWP equation is:

$$\mathrm{GWP} = \Delta\mathrm{Gage} \cdot \frac{8.26}{\mathrm{L} - 0.258 \cdot \mathrm{V}} \qquad [15]$$

8. References

AREMA (1999). Manual for Railway Engineering, American Railway Engineering and Maintenance of Way Association, Landover, MD.

Blader F. (1983). "Analytic Studies of the Relationship Between Track Geometry Variations and Derailment Potential at Low Speeds," FRA/ORD-83/16, September.

Carr, G. and C. Stuart (1995). "Performance-Based Tie/Fastener Inspection Technique Using the Gage Restraint Measurement System," Nondestructive Evaluation of Aging Railroads, International Society for Optical Engineering (SPIE), Proceedings, Vol. 2458, June.

Choros, J., Fateh, M., Sussmann, T., and E. Curtis (2003). "Gage Restraint Measurement System Comparison Tests: Railbound and Hi-Rail Vehicles," FRA/ORD-03/29, December 2003.

Coltman, M. and H. Weinstock (1988). Vehicle/Track Interaction Test at Bennington, NH, DOT/FRA/ORD-87/1, revised.

Coltman, M., Dorer, R., and P. Boyd (1988). "The Development of Automated Survey Techniques for Evaluating Tie and Rail Fastener Performance," Applied Mechanics Rail Transportation Symposium, American Society of Mechanical Engineers, AMD-Vol. 96, RTD-Vol. 2.

Jeong, D. and M. Coltman (1983). "Analysis of Lateral Rail Restraint," U.S. Department of Transportation, Federal Railroad Administration, Report No. FRA/ORD-83/15, September.

Kish, A., Jeong, D., and D. Dwonczyk (1984). "Experimental Investigation of Gauge Widening and Rail Restraint Characteristics," DOT/TSC/FRA-84-05, FRA/ORD-84/12.

Manos, W. P., Scott, J. F., Choros, J., and A. M. Zarembski (1982). "Development of an Improved Vehicular Loading Characterization, Associated with Gage Strength of Track," American Railway Engineering Association, Bulletin 686, Volume 83.

McCarthy, W. (1995). "TSAR High-Rail System for Measurement of Rail Lateral Restraint," Nondestructive Evaluation of Aging Railroads, International Society for Optical Engineering (SPIE), Proceedings, Vol. 2458, June.

Appendix A. Rail Spring Model and TRKLOD Derivations

A-1. Derivation of Rail-Spring Model Factor

A simple physical model of the rail was also used to derive an equation for predicting rail deflection and hence a form for the GWP equation. The rail is assumed to be restrained against lateral movement by a single lateral spring with stiffness K. Furthermore, interaction of the rail with the tie plate due to the vertical force will cause a frictional force that reduces the effective lateral force by a factor depending upon the frictional coefficient between the tie and the tie plate. The value of the frictional coefficient can be found from the constant deflection lines for tests performed in the past on rail deflections with varying application of lateral and vertical force combinations.

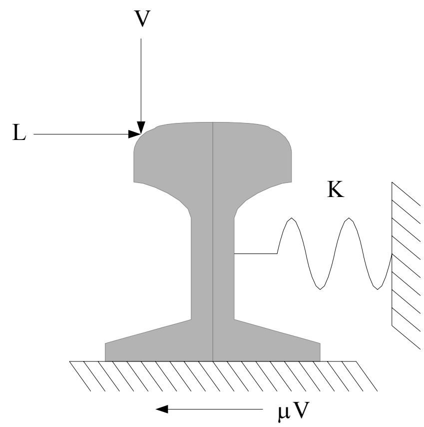


Figure A-1. Simple rail-model represented by the rail restrained by a single lateral spring against a lateral and vertical force combination

Based on analysis of this model, an equation for an extrapolation factor was developed that is given by equation 10 and similar to equation 11, thus confirming the nature of the analysis of the PLG A-factor development.

$$F = K \cdot x$$

$$F = L - \mu \cdot V$$

$$x = \frac{L - \mu \cdot V}{K}$$

$$x_{gw} = \frac{L_{gw} - \mu \cdot V_{gw}}{K}$$

$$I = \frac{x_{gw}}{x}$$

$$I = \frac{(L_{gw} - \mu \cdot V_{gw})}{(L - \mu \cdot V)}$$

In the above derivation, it is assumed that the rail deflections are equal for both rails. The extrapolation factor, I, for this model is the ratio of the deflection expected at the target load severity, noted with the sub, gw, in the equations, to the deflection obtained by the GRMS vehicle for the applied load severity and thus is equivalent to equation 10, the ratio of load severities for the ultimate and test load conditions.

A-2. Derivation Based on the TRKLOD Analysis

TRKLOD is a finite element model with each node representing a tie and the rail modeled as a beam element using three piecewise linear springs. The restraints are one lateral spring and two vertical springs, which adequately represent the displacements and rotations experienced by the rail under the any loading conditions, as shown in Figure 5 (a). More information about the TRKLOD model and its working can be obtained from the TRKLOD manual (Jeong and Coltman, 1982).

Both vertical and lateral springs are considered to be piecewise linear, as illustrated in Figure A-2 (b) and A-2 (c). The TRKLOD model takes inputs for the breaking points of the springs in the form of F and δ combinations.

The TRKLOD model was run for a series of load combinations representing the load spectrum of interest for GWR and spring constants representing minimally acceptable track conditions developed by analysis presented in Manos, W. P., Scott, J. F., Choros, J., and A. M. Zarembski (1982); Coltman, M., Dorer, R., and P. Boyd (1988); and Jeong, D. and M. Coltman (1983). The model was then used to obtain predicted deflections. The deflections shown in Figure 5 are the deflection for a single rail presented by Coltman, M., Dorer, R., and P. Boyd (1988) and used in the development of PLG24. The total gage change is obtained by doubling the single rail deflection.

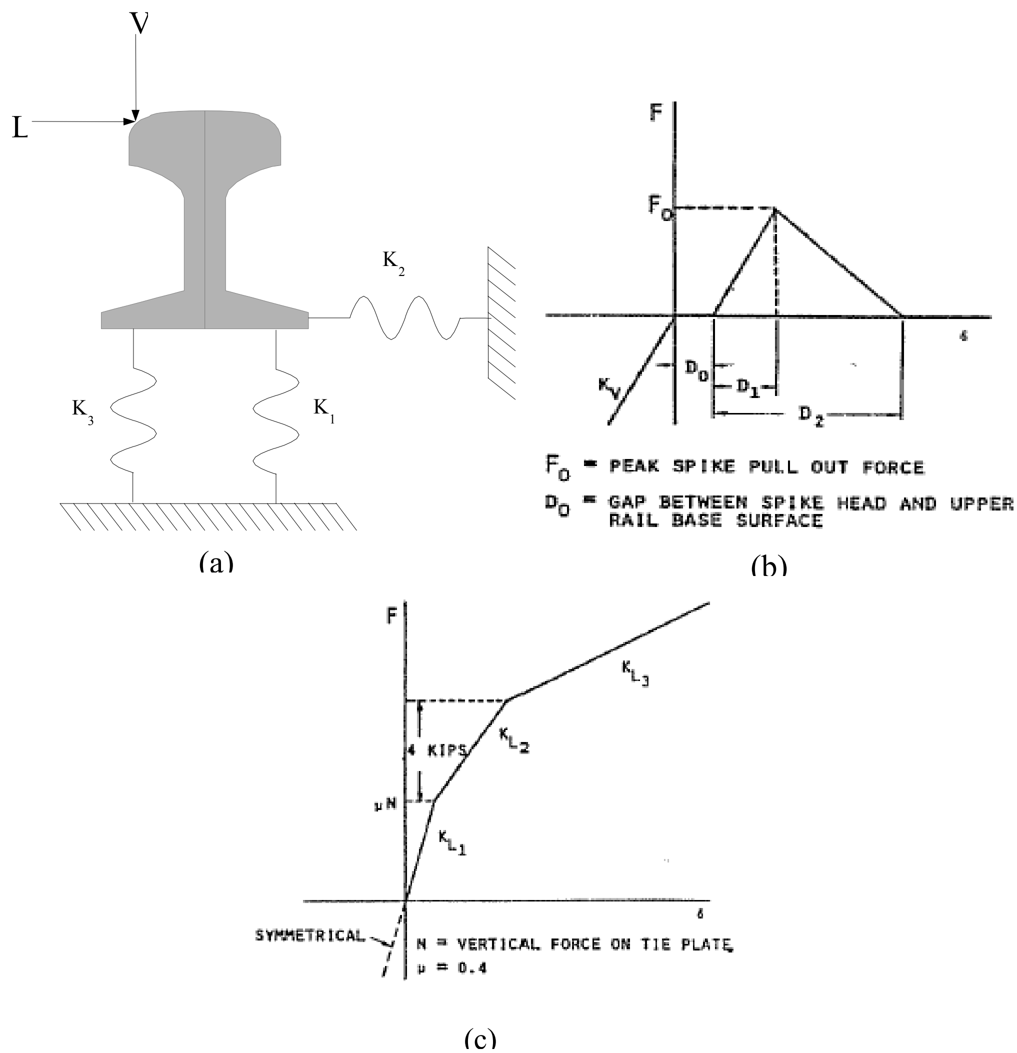


Figure A-2. Schematic of the TRKLOD model element and its cross-section (a), lateral piecewise linear spring (b), and vertical piecewise linear spring (c)

Given the deflection values from TRKLOD, an extrapolation factor E_{TRKLOD} was defined as the ratio of the deflection at the critical loads to the deflection at the applied loads, Equation 8 where D is the expected deflection at the test load for the minimally acceptable track conditions used for the spring constants in TRKLOD. The analysis procedure is similar to the analysis of the data from Figure 5 and was used to develop the E-factor in Section 4.1.

Appendix B. GWP and TRKLOD Model Comparison Analysis

The GWP results were compared to the TRKLOD model using a series of simulation runs of the model using soft springs as the definition of minimally acceptable track with 115 lb rail, 18 inches tie spacing, and load application using a single axle GRMS vehicle. Table B-1 gives the breaking points of the soft spring model, and the parameters of the 115 lb rail were taken from the TRKLOD manual.

Table B-1. Coordinates of breaking points of the soft spring used for the TRKLOD model

K_1, K_3 Vertical Springs (Five Breaking Points)

δ	F
-100.0	-2500.0
0.0	0.0
0.2	2.0
1.5	0.0
100.0	0.0

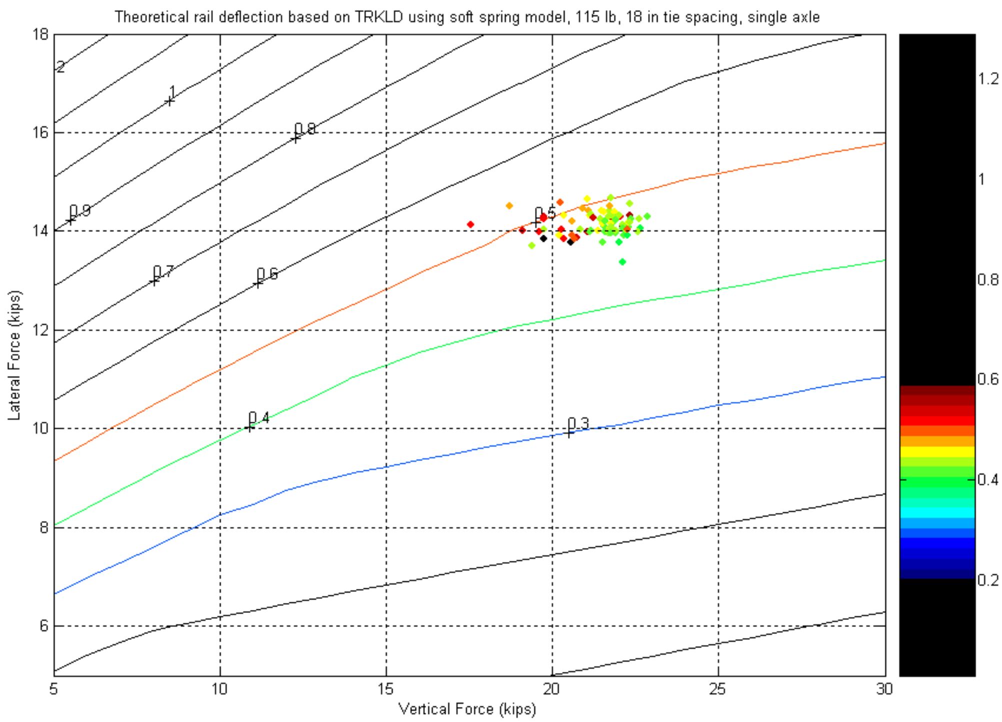
K_2 Lateral spring (Seven Breaking Points)

δ	F
-110.67	-484.00
-10.67	-404.00
-10.00	-400.00
0.00	0.00
10.00	400.00
10.67	404.00
110.67	484.00

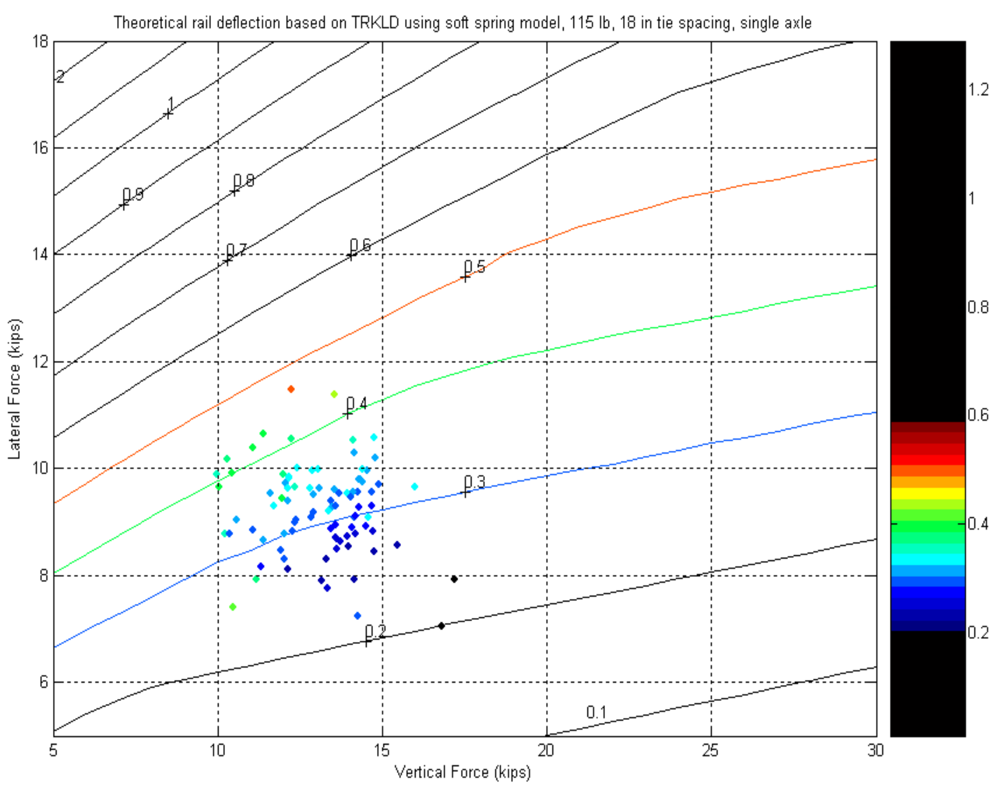
Figure B-1 (a) and B-1 (b) show data from safety and maintenance GWP exceptions from T-18 and TrackSTAR, respectively overlaid on top of constant deflection lines of the TRKLOD model. The colors of the data points are indicative of the deflection measured of a single rail during the GRMS testing. The mean and standard deviation of the difference between actual measured delta gage and the TRKLOD predicted delta gage based on the applied lateral and vertical loads were calculated and are tabulated in Table B-2.

Table B-2. Average and standard deviation of the difference between the measured and TRKLOD predicted delta gage for T-18 and TrackSTAR

T-18		
	Safety	**Maintenance**
Mean	0.20	-0.05
Standard Deviation	0.12	0.06
TrackSTAR		
	Safety	**Maintenance**
Mean	0.18	-0.03
Standard Deviation	0.11	0.04


Theoretical rail deflection based on TRKLD using soft spring model, 115 lb, 18 in tie spacing, single axle
Lateral Force (kips)
Vertical Force (kips)
2
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3

(a)


Theoretical rail deflection based on TRKLD using soft spring model, 115 lb, 18 in tie spacing, single axle
Lateral Force (kips)
Vertical Force (kips)
2
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1

(b)

Figure B-1. TrackSTAR data points from exception locations overlaid with the TRKLOD models constant lines of deflection

A positive value of the average difference between the predicted and the measured is noticed for both the vehicles for the safety exceptions, and a slightly negative value (less than zero) is observed for both the vehicles for maintenance exceptions. A positive value of the difference indicates that the measured delta gage is higher than the expected or predicted delta gage. Hence the track at that location is weaker than minimally acceptable track and therefore a safety exception. A slightly negative value of the difference, which is observed with the maintenance exceptions, indicates that the track at that location is a slightly stronger than minimally acceptable track but is still weak and requires maintenance. The GWP value consistently shows the difference between the safety and maintenance exceptions for different vehicles with different loading configurations.

Acronyms

AREMA	American Railway Engineering and Maintenance-of-Way Association
BNSF	BNSF Railway (formerly Burlington Northern Santa Fe Railway)
Delta gage	Gage change between loaded and unloaded gage measurements
FRA	Federal Railroad Administration
GRMS	Gage Restraint Measurement System
GWP	Gage Widening Projection
GWR	Gage Widening Ratio
LTLF	Lightweight track loading fixture
MMIR	Maryland Midland Railroad
NS	Norfolk Southern Railroad
PLG	Projected Loaded Gage
PLG24	Projected Loaded Gage at 24 kips lateral load
R&D	Research & Development
RAIRS	Railway Accident/Incident Reporting System
RE	American Railway Engineering Association rail section design
T-18	FRA GRMS test vehicle with deployable split axle, commissioned May, 2004
T-6	FRA GRMS test vehicle with truck mounted split axle, replaced by T-18
TrackSTAR	Holland’s Company hi-rail GRMS with deployable split axle
VNTSC	Volpe National Transportation System Center