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Gage Restraint Measurement System Comparison Tests: Railbound and Hi-Rail Vehicles

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13. ABSTRACT

Comparative tests were conducted to evaluate the gage restraint measurement system (GRMS) testing capabilities of a railbound GRMS vehicle, Federal Railroad Administration's (FRA's) T-6, and a hi-rail vehicle, Holland Company's TrackStar GRMS system. The test objectives were to compare the performance of the two vehicles by monitoring the testing capabilities over the same section of track; evaluate repeatability and accuracy; and assess comparative vehicle performance over known defects. The tests were conducted on track owned by Maryland Midland Railroad, classified as FRA Class 2 track. Test data for both vehicles were analyzed with respect to FRA loading and gage restraint standards for GRMS testing and the requirements stated in the American Railway Engineering and Maintenance of Way Association (AREMA) Manual. Loaded and unloaded gage, delta gage, gage widening ratio, and projected loaded gage at 24 kips (PLG24), along with the left and right vertical and lateral loads, were the primary values analyzed and compared for the two vehicles. Results from these tests and related analyses indicate that both vehicles meet FRA and AREMA testing requirements. Accuracy and repeatability for both vehicles were acceptable. Data as recorded from each vehicle, analysis procedures, and conclusions are described in this report.

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Preface

Derailments due to wide gage under dynamic loading are a safety concern. Based on an extensive research program sponsored by the Federal Railroad Administration (FRA), a gage restraint measurement system (GRMS) has been developed. The GRMS vehicle is used to evaluate the track's ability to maintain gage under service load conditions. Based on improved understanding of gage widening derailments and an improved level of safety provided with the use of GRMS data, as well as improved maintenance efficiency from unbiased evaluation of tie condition, GRMS technology has been widely adopted. Today, all of the Class 1 railroads and the Canadian Railroads own or rent some type of GRMS vehicle or service. Due to the rapid adoption of this technology, two measurement systems are currently in use: a railbound system and a hi-rail truck-based system.

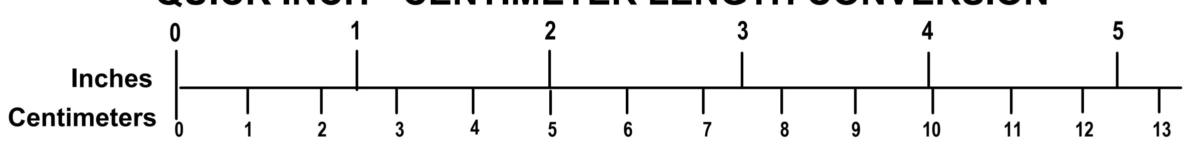
FRA's track safety standards have been appropriately revised to include GRMS testing as a performance-based alternate standard. This alternate standard is based on data provided by the FRA's railbound GRMS vehicle. The FRA GRMS vehicle is used to evaluate the ability of the track structure to maintain gage under service load, as indicated above.

The tests described in this report compare the testing performances of FRA's railbound prototype and Holland Company's TrackStar hi-rail GRMS systems. The major difference between the two systems is the magnitude of the applied loads vertical and lateral loads, and the associate lateral-to-vertical (L/V) load ratio due to dynamic variance in the applied loads. The difference in applied loads could lead to differences in loaded gage measurements, hence it is important to confirm the capability of the two systems with different test loads to accurately assess track gage widening conditions, to ensure track safety. Test procedures were designed to assure that the systems meet the American Railway Engineering and Maintenance of Way Association (AREMA) Recommended Practice and provide an accurate evaluation of potential track safety problems.

METRIC/ENGLISH CONVERSION FACTORS

ENGLISH TO METRIC		METRIC TO ENGLISH	
LENGTH (APPROXIMATE)		**LENGTH** (APPROXIMATE)	
1 inch (in)	= 2.5 centimeters (cm)	1 millimeter (mm)	= 0.04 inch (in)
1 foot (ft)	= 30 centimeters (cm)	1 centimeter (cm)	= 0.4 inch (in)
1 yard (yd)	= 0.9 meter (m)	1 meter (m)	= 3.3 feet (ft)
1 mile (mi)	= 1.6 kilometers (km)	1 meter (m)	= 1.1 yards (yd)
		1 kilometer (km)	= 0.6 mile (mi)
AREA (APPROXIMATE)		**AREA** (APPROXIMATE)	
1 square inch (sq in, in^2)	= 6.5 square centimeters (cm^2)	1 square centimeter (cm^2)	= 0.16 square inch (sq in, in^2)
1 square foot (sq ft, ft^2)	= 0.09 square meter (m^2)	1 square meter (m^2)	= 1.2 square yards (sq yd, yd^2)
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)		
MASS - WEIGHT (APPROXIMATE)		**MASS - WEIGHT** (APPROXIMATE)	
1 ounce (oz)	= 28 grams (gm)	1 gram (gm)	= 0.036 ounce (oz)
1 pound (lb)	= 0.45 kilogram (kg)	1 kilogram (kg)	= 2.2 pounds (lb)
1 short ton = 2,000 pounds (lb)	= 0.9 tonne (t)	1 tonne (t)	= 1,000 kilograms (kg) = 1.1 short tons
VOLUME (APPROXIMATE)		**VOLUME** (APPROXIMATE)	
1 teaspoon (tsp)	= 5 milliliters (ml)	1 milliliter (ml)	= 0.03 fluid ounce (fl oz)
1 tablespoon (tbsp)	= 15 milliliters (ml)	1 liter (l)	= 2.1 pints (pt)
1 fluid ounce (fl oz)	= 30 milliliters (ml)	1 liter (l)	= 1.06 quarts (qt)
1 cup (c)	= 0.24 liter (l)	1 liter (l)	= 0.26 gallon (gal)
1 pint (pt)	= 0.47 liter (l)		
1 quart (qt)	= 0.96 liter (l)		
1 gallon (gal)	= 3.8 liters (l)		
1 cubic foot (cu ft, ft^3)	= 0.03 cubic meter (m^3)	1 cubic meter (m^3)	= 36 cubic feet (cu ft, ft^3)
1 cubic yard (cu yd, yd^3)	= 0.76 cubic meter (m^3)	1 cubic meter (m^3)	= 1.3 cubic yards (cu yd, yd^3)
TEMPERATURE (EXACT)		**TEMPERATURE** (EXACT)	
[(x-32)(5/9)] °F	= y °C	[(9/5) y + 32] °C	= x °F

QUICK INCH - CENTIMETER LENGTH CONVERSION



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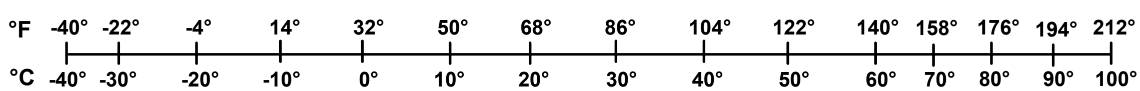

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Executive Summary

Concurrent testing of Maryland Midland Railroad tracks in October 2002 by the Federal Railroad Administration (FRA) T-6 gage restraint measurement system (GRMS) consist and the Holland Company TrackStar GRMS vehicle was conducted. Test results indicate that both vehicles identify gage widening track problem areas, with some significant differences in vehicle performance, and both vehicles meet FRA (CFR49, §213.110c) and American Railway Engineering and Maintenance of Way Association (AREMA) requirements for GRMS testing. The two systems are representative of the two classes of available GRMS systems: railbound and hi-rail truck-based systems. The FRA maintains and operates T-6, a railbound GRMS system, which differs significantly from the Holland Company TrackStar, a hi-rail GRMS, in operation, load application, and sensor systems. Due to these differences, the need to compare their testing performances with respect to identifying dynamic gage widening problem areas had been deemed necessary.

An analysis of the applied test loads found that both vehicles apply gage-widening loads that meet AREMA and FRA requirements for GRMS testing. The applied test load was a primary concern since previous research indicated that the magnitude of the test load controls the track gage widening deflection mode. Due to the application of a load control system on the split axle, the TrackStar-applied loading did not vary significantly from the acceptable load range specified by AREMA, although the load magnitudes are lower than the nominal loads for the T-6. The GRMS loads specified in the FRA standards (CFR49, §213.110c)—the minimum applied load, the lateral to vertical load ratio, and the load severity—were met by both vehicles.

The performance of the GRMS load and gage sensors were also evaluated. It was found that the measurements for both the T-6 and TrackStar were accurate and repeatable, with several exceptions. During the evaluation of the sensors, TrackStar inaccurately measured unloaded gage in curves and recorded wider loaded gage in weak track zones when compared to T-6. The cause of the inaccurate unloaded gage in curves has not been determined. The larger loaded gage value was unexpected because the nominal applied loads for the TrackStar were lower than the T-6. The narrower loaded gage recorded by the T-6 was found to be caused by an applied load reduction (within the AREMA acceptable range for GRMS testing), as the T-6 split axle encountered a weak zone and extended to the wider gage. The TrackStar load control system maintained constant lateral load. The cause of the overall difference in loaded gage measurement was possibly due to a combination of three factors: difference in nominal load between the vehicles, influence of the second axle of the truck on the T-6, and the load reduction on the T-6 in weak zones. The last factor could possibly be due to T-6's passive load control system in contrast to the active load control system of the TrackStar.

When applied to the specified limits in the Track Safety Standards, the wider loaded gage measured in weak zones by the TrackStar identifies a higher number of track safety exceptions. The wider loaded gage leads to a higher gage widening ratio (GWR) and projected loaded gage (PLG24) for the TrackStar, that when compared to the same limits, identifies safety exceptions where T-6 did not. This was confirmed by comparing noted T-6 safety exceptions to the TrackStar. The comparison further indicated that all T-6 safety exceptions were detected by the

TrackStar as safety exceptions along with many other exceptions that were either T-6 maintenance exceptions or not identified by the T-6. This finding indicates that further work is required to:

1. refine GWR and PLG24 parameters to ensure that they accurately account for the different load conditions;
2. evaluate the influence of the TrackStar wider loaded gage measurements; and
3. ensure that both systems identify exceptions at locations of similar track condition.

1 Introduction

Gage widening under dynamic loading has historically been a significant cause of track-related derailments. Due to this safety concern, track gage widening behavior has been a topic of Federal Railroad Administration (FRA) sponsored research for over 20 years. During the research program, several techniques to measure gage strength (the resistance of rail to dynamic gage-spreading loads) were developed and tested. Due to the improved understanding of these types of derailments and the controlling factors, all Class 1 freight railroads currently operate test equipment to measure gage strength as a safety measure and as an indicator of required maintenance to guide tie renewal strategies. In addition, gage restraint measurement system (GRMS) specifications are included as performance-based alternate standards in the Track Safety Standards (TSS) 213 and were adopted in the high-speed standards (Subpart G). The American Railway Engineering and Maintenance of Way Association (AREMA) Manual of Recommended Practice provides vehicle performance recommendations for GRMS testing. The desire to measure track gage strength has led to the development of two different types of measurement vehicles: railbound and hi-rail. This report discusses comparison tests of a railbound vehicle (one that can travel over only railroad track) and a hi-rail vehicle (a vehicle designed for travel on both road and railroad track that can also test track), the two current vehicle types for GRMS testing.

Loading conditions during measurement of gage strength have been found to be a critical element for 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, and the rail fastening system. Vehicle differences in test conditions must be accounted for to ensure accurate identification of problem areas during testing with different systems. The two track gage strength measurement systems that have been developed operate at significantly different test loads. Confirmation of the capabilities of the two systems with different test loads to accurately assess track gage strength is important to ensure track safety.

This series of tests was conducted to collect data for desired performance comparisons of the two GRMS prototypes. Test procedures were designed to validate the performance of the hi-rail GRMS for use in track gage widening evaluations to assure that the system meets the AREMA Recommended Practice [1] and FRA standards for GRMS testing (CFR49, §213.110c). Testing was conducted in accordance with a draft specification developed by AREMA Committee 2, Subcommittee 3. There were three primary test phases: Phase I, over the entire Maryland Midland Railroad and Phases II and III, over selected test sections. All tests were conducted in the same direction from west to east.

Gage restraint evaluation requires measurement of four basic parameters—vertical load, lateral load, loaded gage, and unloaded gage—at a given point along the track. Each parameter should be measured with an understanding of its errors, repeatability, statistics, and calibration procedures. These parameters are used to compute delta gage, gage widening ratio (GWR), and projected loaded gage at 24 kips (PLG24) to assess track condition.

2 Track Information

2.1 Maryland Midland Railroad Track Description

The test track section selected for these tests is located in Union Bridge, Maryland, on the Maryland Midland Railroad (MMR). FRA's GRMS has surveyed this area extensively; MMR was selected since it could provide sufficient track time for the test completion without serious traffic interruptions. The mainline track of the MMR is FRA Class 2 track. The entire track length, approximately 48 miles (MP 22 to 70), was surveyed by both vehicles. Selected sections were then used for system evaluation and defect detection tests.

Rail size over the entire test section is predominantly 115 RE, with a few exceptions of lighter rail, usually less than one rail length. Joint bars were used for the majority of the track with a few exceptions where welded rail was used. Double-edge plates with two spikes per plate at tangent track and up to five spikes per plate were used, depending on the track curvature and tie condition. Rail anchors, every other tie or every tie, were used only in curves.

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 "poor," typical of Class 2 track.

Track alignment from Highfield to Emory Grove, Maryland, is shown in Figure 1. Curves up to 10 degrees comprise approximately half of the railroad, with grades up to 2 percent at the western section of the railroad near Highfield, Maryland. Four typical locations of track where both vehicles have detected defects are shown in Figure 2.

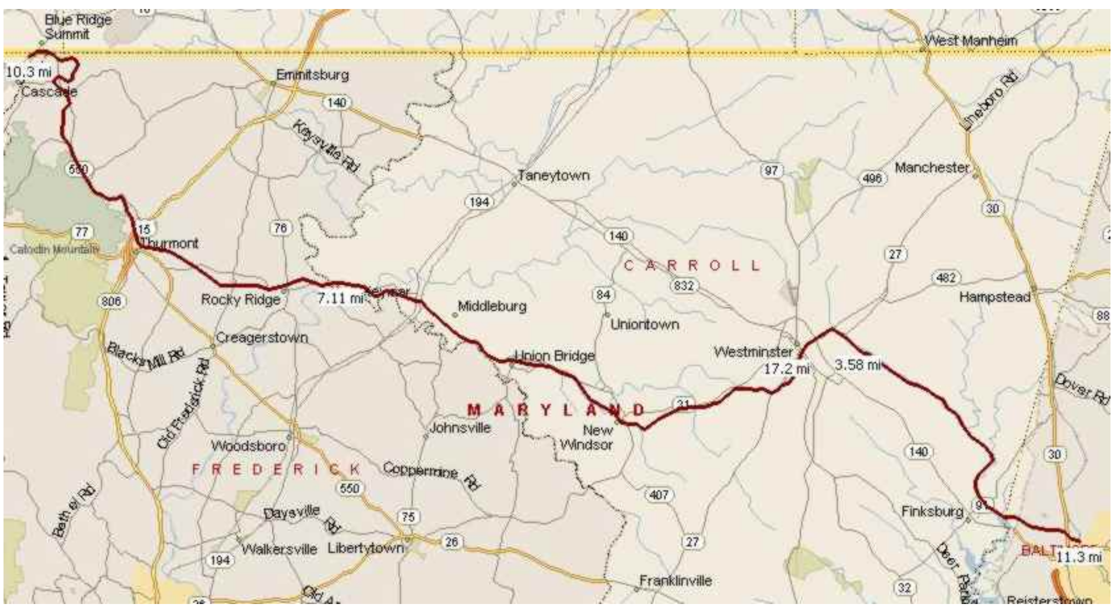

Figure 1. Maryland Midland Railroad Map

Figure 2. Typical Track Sections Where Both Test Vehicles Detected Defects

2.2 Track Requirements

The track described above met the track requirements for conducting the GRMS comparison tests stated in the test plan [2]. These requirements were:

1. FRA Class 2 or better track geometry conditions. At least a 3-mile section of wood-tied track with no switches
2. Left- and right-hand curves of 2 degrees or more
3. 1-mile section of tangent track
4. Cut spikes, and
5. No major maintenance within the last 3 months (i.e., surfacing, tie replacement, rail replacement, etc.)

2.3 Test Zones for Phase I, II, and III

The entire track length from Highfield to Emory Grove, Maryland, was tested by both vehicles under Phase I testing. Phase II testing was conducted on a tangent section of track east of Union Bridge, Maryland, from milepost 44.7 to 43.5 and Phase III testing was conducted from milepost 47.6 to 47.3 west of Union Bridge.

Phase I tests compared the test data of the two GRMS vehicles during normal operation. To accomplish this task, the entire MMR track was tested. For an unbiased comparison, each system tested a section of track that was not disturbed by the other vehicle and one that was previously tested. "Undisturbed" is defined as a section of track that recently (within a day or two) had not been tested with a GRMS and a tested section is defined as track that was recently tested with a GRMS.

To meet Phase I criteria, the TrackStar began testing from Union Bridge, Figure 1, east to MP 22, Emory Grove, and concurrently the T-6 consist started from MP 70, Highfield to Emory Grove, the east end of the railroad. While T-6 was testing from Union Bridge to Emory Grove, the TrackStar traveled by road to Highfield and tested east to Union Bridge to complete Phase I testing. Using this sequence, tested and undisturbed track were provided for both vehicles.

Test sections for Phase II and III tests were identified based on test plan requirements, track condition, and gage widening data obtained during Phase I. The exact location for Phase II and III tests was determined from the Phase I data and previous gage widening data. Figure 3 shows the Phase II test section.

Figure 3. Tangent Track Section East of Union Bridge Used for Phase II Testing

Phase II tests were designed to evaluate the system measurement capabilities and performance under static conditions and at various speeds. A series of tests evaluated the three basic subsystems of each GRMS vehicle:

- Static and dynamic loaded gage measurements,
- Dynamic unloaded gage measurements, and

- Evaluation of applied loads.

Both vehicles were tested over the same section for Phase II. These tests were conducted to determine the characteristics of each vehicle and were not affected by previous testing.

Phase III includes tests to compare the repeatability of the test results of the two GRMS vehicles, compare their measurements with the lightweight track loading fixture (LTLF), and evaluate their ability to identify zones with known track dynamic wide gage characteristics. The LTLF is a device that applies a lateral gage widening load of 4,000 lb to the theoretical shear center of both rails, while measuring the gage widening deflection. The portable track loading fixture (PTLF), a predecessor to the LTLF, was also used during the test. (The acronyms PTLF and LTLF are used interchangeably in this report as they represent the same loading conditions and similar test results.) Two sections of tangent track, approximately 150 ft long, were selected based on data from Phase I tests. Selection criteria were that each section has a GWR, as measured by T-6, of 0.35 and 0.50 in. to indicate a "strong " and "weak" condition. Automatic load detectors (ALD) were placed at these locations to accurately identify the specific track locations. Based on Phase I data and time constraints, the two sections were adjacent to each other, between milepost 47.6 and 47.3. Both GRMS vehicles surveyed these sections after visual inspection and LTLF testing to determine the characteristics of the section and to diagnose the nature of the gage widening condition.

3 Vehicle Information

The two GRMS vehicles compared in this series of tests were FRA's GRMS system, T-6 research car (DOTX206) coupled to a Union Pacific (UP) 100-ton hopper car (UP37183), and Holland Company's TrackStar vehicle 478 (TrackStar). The T-6, FRA's GRMS, is defined as a railbound system while the TrackStar is defined as a hi-rail system. The T-6 vehicle was converted to a research vehicle to study the affects of dynamic gage widening and provide data for the development of standards to mitigate derailments caused by gage widening. The TrackStar was designed to provide gage widening testing services to the railway industry based on the FRA's Track Safety Standards and AREMA Recommendations.

To perform GRMS measurements a vehicle is required to be able to apply to the track and measure vertical and lateral loads and measure loaded and unloaded gage while in motion. Using the measured values, derived parameters are generated and compared to existing FRA Track Safety Standard (TSS) [3]. Table 1 lists these measured and derived parameters.

3.1 FRA's GRMS, T-6 Consist

The T-6 consist is made up of three distinctive vehicles, a locomotive usually provided by the host railroad, the UP hopper car in which the split axle and the unloaded gage measuring system are located, and FRA's research car where the data acquisition system is located. The hopper car and the research car are permanently coupled together. During testing, the locomotive will couple to the hopper car to pull the consist: locomotive, hopper car, and research vehicle. This arrangement allows recording of the unloaded gage measurement first, then the loaded measurement.

Table 1. Measurements and Derived Parameters for Conducting Gage Restraint Measurement Evaluations

Measurements Parameters
Left and right vertical loads (V) Left and right lateral loads (L) Loaded and unloaded gage (LTG and UTG)
Derived Parameters
Δ_g (Change in gage) Eq. 1. Gage widening ratio (GWR) Eq. 2. Projected loaded gage (PLG24) Eq. 3.
$\Delta g = LTG - UTG$ (1) $GWR = \frac{16{,}000\Delta g}{L}$ (2) $PLG24 = UTG + \frac{13.514\Delta g}{(0.001L - 0.000258V) - 0.009 \cdot (0.001L - 0.000258V)^2}$ (3)

Vertical and lateral loads are applied using a standard 36-in. wheel mounted on a split axle. The split axle assembly, used to measure the loaded gage, is the leading axle of the trailing truck, Figure 4, when the vehicle is in test mode. An encoder mounted to the axle is used for distance measurements. Under non-testing moves, the split axle is locked for regular rail movement.

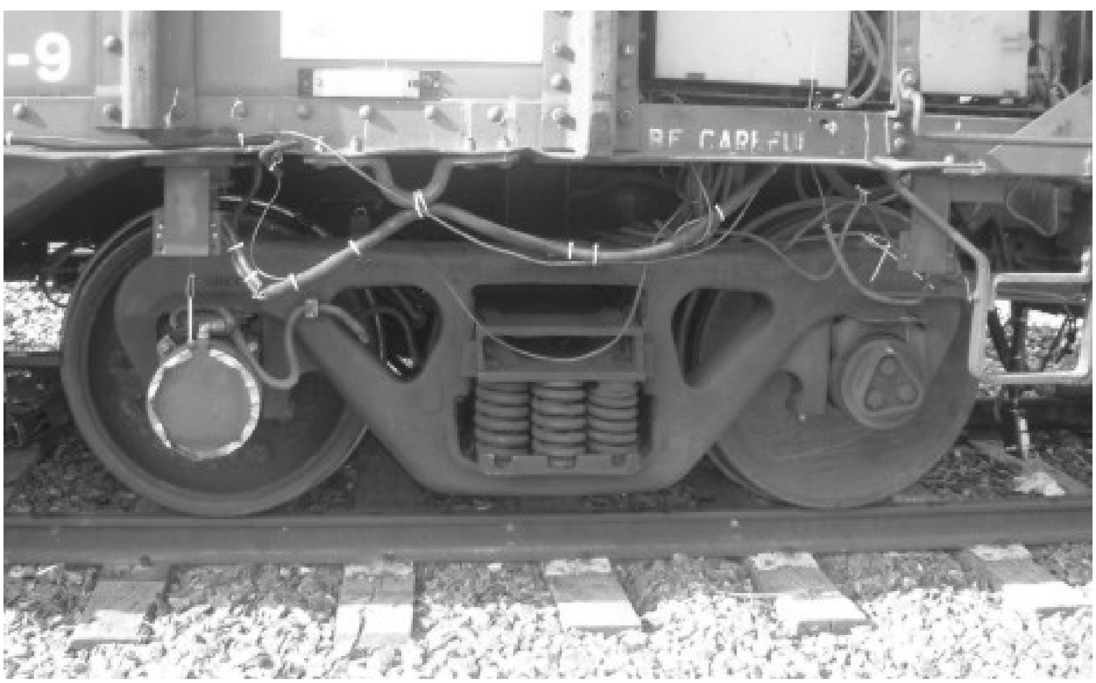

Figure 4. Hopper Trailing Truck With the Split Axle Assembly

To eliminate the influence of the gage-spreading load, the unloaded gage is measured approximately 10 ft from the split axle using a small split axle trolley with 12-in. diameter wheels. Air pressure lowers and retracts the axle and provides a nominal vertical and lateral load to keep the wheel on the rail during testing. Figure 5 shows the unloaded gage measurement wheels in the retracted position.

Figure 5. FRA's GRMS Unloaded Gage Measuring Axle Assembly in the Retracted Position

Computer-based load control and data acquisition for the split axle device and the unloaded gage measurement system are handled from the research vehicle. Cameras mounted under the hopper car allow the operator in the research car to monitor the position of the loading wheels. All data is collected, analyzed, displayed, and/or stored in real time, marking the location of any maintenance or safety defects. A paint spraying system mounted close to the split axle marks the defect locations.

3.2 Holland's Hi-Rail, TrackStar

The TrackStar vehicle is a hi-rail-based track measurement system capable of GRMS measurements and measurement of other track parameters like rail profile and track geometry, which could be useful in gage strength evaluation and track inspection.

Track geometry is measured using a combination of an optical rail measurement system and a fiber-optic gyro and accelerometer-based real-time inertial navigation package. Geometry measurements can be set to FRA or Transport Canada standards. Unloaded gage, loaded gage, and delta gage are measured and derived from the geometry system measurements every foot. Due to time delay in data processing, the marking of defects during these tests is out of phase by 237 ft, i.e., the track defect is 237 ft behind the marked section of track. The length of the defect is unaffected; the distance painted on the track is the actual size of the defect area.

A vertical load axle deployed vertically from the frame of the vehicle just forward of the rear tandem axles is used to apply vertical and lateral loads. The load axle consists of a hydraulically controlled split-axle capable of applying servo-controlled lateral forces to the track structure. The axle loads and software thresholds are adjustable to maintain a nearly constant lateral load. Vertical load is tied to the vehicle frame and is adjustable to a given preset load using hydraulic pressure. However, the vertical control system is not a high-performance servo valve system, thus the vertical loads are susceptible to changes from track anomalies and vehicle dynamics. Figure 6 is a schematic of the TrackStar showing the location of load application (deployable center axle of the vehicle), gage measurement, and paint spraying system location with respect to the vehicle.

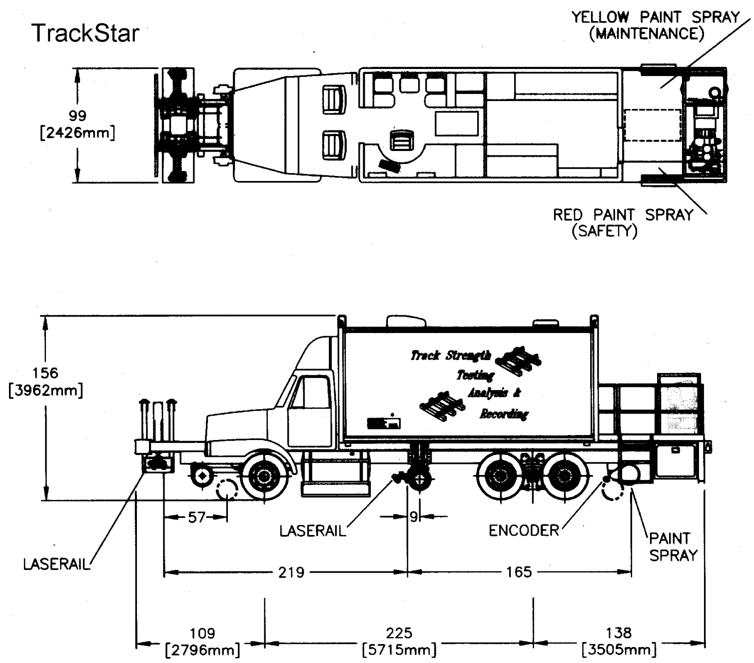

Figure 6. Schematic Diagram of the TrackStar

3.3 Mechanistic Vehicle Distinctions

The mechanistic differences between the two GRMS vehicles are due to applied load and configuration. The 100-ton capacity hopper car is ballasted to apply a vertical load of 21 kips to each wheel of the truck with the split axle. The TrackStar loading is significantly less: vehicle weight is approximately 60 kips, with 14 kips concentrated on the test wheel. Both vehicles test at a nominal L/V ratio of approximately 0.7. The nominal test loads and L/V ratio fall within the recommended applied load and L/V range provided in FRA's Track Safety Standard and AREMA Manual of Recommended Practice; therefore, the loads and L/V range do not constitute a problem for conducting GRMS testing with either vehicle.

The difference in load configuration is mainly the presence of a second heavily loaded axle relatively close to the T-6 test axle, with no significant load near the TrackStar test axle. The influence of the second axle on the T-6 measurement was evaluated using TRKLOD finite element analysis software [4]. Based on the 6-ft axle spacing and 19.5-in. nominal tie spacing, the second axle resulted in approximately 12-percent reduction in measured loaded gage [8].

4 Data Analysis

Data analysis was performed for each of the three phases of testing. Results were used to determine if the TrackStar provides gage widening measurements comparable to FRA's T-6 GRMS vehicle, on which the current track safety standards for gage widening are based. In addition, data collected with the LTLF during Phase II testing were analyzed and compared to test results of both vehicles. Exception reports and logs generated by the vehicle operators during the conduct of the tests are included in the Appendices.

4.1 Phase I Tests and Analysis

The objective of this phase of testing was to compare the two vehicles under normal operating conditions, over the same track. Exception tables (maintenance and safety), load variation, unloaded and loaded gage widening on tangents and curves were the criteria used.

Data from both vehicles were aligned before any analysis was performed using the Automatic Track Data Alignment System (ATDAS) [5]. The software uses a Fast Fourier Transform (FFT) correlation approach allowing a dataset to be automatically aligned with another set. For the data from these tests, the unloaded gage traces for both vehicles gave the best correlation for alignment and were subsequently used to align the data from the two vehicles. T-6 unloaded gage was used as the basis for alignment and TrackStar unloaded gage was aligned to it. Once these two datasets were aligned, the entire dataset was shifted by the difference of the unloaded gage to produce two datasets that were aligned with each other. Both vehicles recorded all data at 1-ft increments, which allowed for shifting of the data based on the unloaded gage rather than aligning every channel in the dataset.

The first item checked for each system was the load application as it compared with the recommended AREMA specification. Sections of track of approximately 4 miles, 4.2 for T-6, and 4.6 for the TrackStar were selected and the loads were plotted for both vehicles, as shown in Figure 7 and Figure 8. AREMA requirements state that the GRMS test load should fall within Zone II, Figure 7, which indicates a vertical load greater than 10,000 lb and severity index [6] greater that 3,000 lb. Severity Index is defined by equation (4):

$$S = L - cV \tag{4}$$

where S = Severity Index
L = Lateral Load
V = Vertical Load
c = Apparent coefficient of friction (0.40)

The figures indicate that both vehicles meet the load criteria. T-6 vertical loads were approximately 21 kips with a standard deviation of 0.71 kips while the lateral loads were 14.52 kips with a standard deviation of 1.35 kips. Nominal load for the T-6 was set at 21 kips vertical and 14 kips lateral. A lateral load cluster between 0 and 5 kips was caused by the release of the applied lateral test load at road crossings, switches, sliding joints, etc., to ensure safe operation.

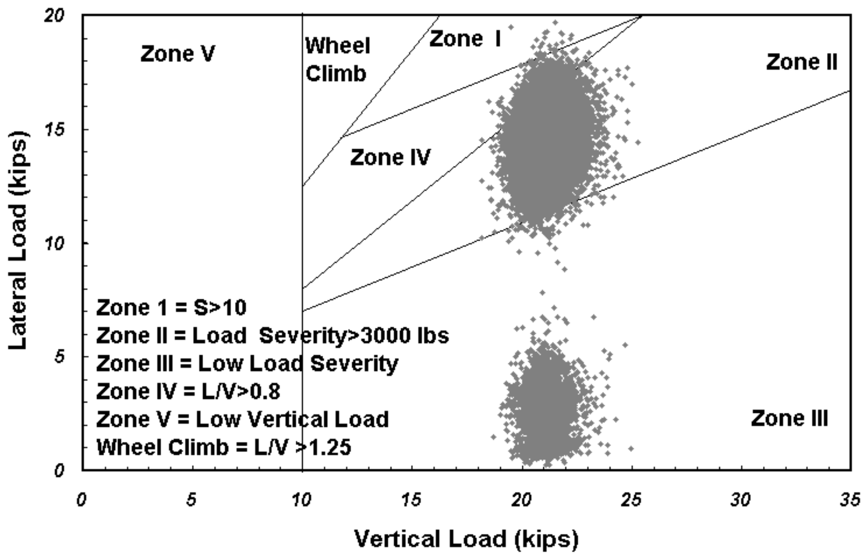

Figure 7. T-6 Vertical and Lateral Test Loads Plotted on AREMA's Recommended Test Load Chart

The TrackStar vertical load data in Figure 8 is predominately in Zones II and IV, with very few exceptions where the load dropped below 10 kips. There are few lateral load values in Zone III, probably due to the removal of applied lateral test load at crossings, switches, sliding joints, etc. Since the lateral load for the TrackStar is controlled by a servo feedback system, the cluster is more distinct than that observed for the T-6. Nominal loads for the TrackStar were set at 15 kips vertical and 10 kips lateral. The actual loads for this section of track were 14.32 kips vertical with a standard deviation of 1.19 kips and 10.38 kips lateral with a standard deviation of 0.79 kips. With the exception of a few vertical loads falling below 10 kips, the TrackStar meets AREMA's requirements for GRMS testing.

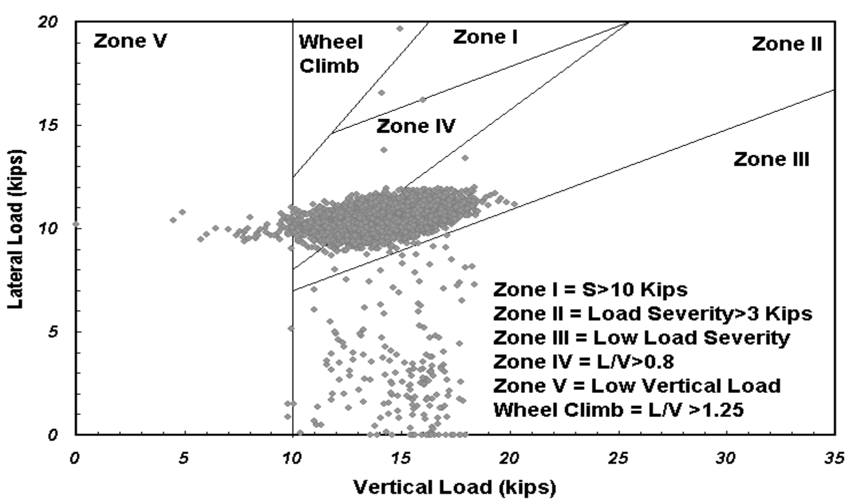

Figure 8. TrackStar Vertical and Lateral Test Loads Plotted on AREMA's Recommended Test Load Chart

The loads appeared to be accurately recorded on both vehicles since both magnitudes corresponded to documented vehicle weights and expected load application variations. No specific evaluation of load measurement accuracy was undertaken. Load sensor drift on the TrackStar was observed during testing. The drift magnitude appeared small and was corrected by the operator during interruptions in testing.

Once the applied loads for both vehicles were evaluated and found to meet AREMA and FRA load requirements, the maintenance and safety exceptions recorded by each vehicle were analyzed for the entire 48 miles tested in Phase I. The limits set for maintenance and safety exceptions were based on FRA's TSS, and are shown in Table 2.

Table 2. Track Safety Standard Limits for GRMS Exempt Track

GRMS Parameters	Measurement Limit (in.)	
	Maintenance	Safety
UTG		58.00
LTG	58.00	58.00
GWR	0.75	1.00
PLG24	58.00	59.00

When the measured or computed GRMS parameters exceeded the maintenance or safety limits, the location was marked as an exception. Table 3 is a list of all exceptions recorded from both vehicles. Figure 9, Figure 10, and Figure 11 are comparisons of the total number of exceptions and number of maintenance and safety exceptions recorded in each mile by the T-6 and the TrackStar, respectively. It is apparent that the TrackStar measured many more safety and maintenance exceptions (798 GWR and PLG24 and 73 LTG safety and 428 maintenance) than the T-6. Further analysis of the data was conducted to investigate the potential cause of these differences. Note that for maintenance exceptions, only 5 miles of data were used for both GRMS vehicles since there were no available maintenance exceptions reported from the TrackStar for the remaining test miles.

Table 3. GWR and PLG24 Maintenance and Safety Exceptions for Both Vehicles

	GWR Maintenance, Locations		PLG24 Maintenance, Locations		GWR Safety, Locations		PLG24 Safety, Locations	
MP	FRA T-6	TrackStar	FRA T-6	TrackStar	FRA T-6	TrackStar	FRA T-6	TrackStar
72	13	0	11	0	1	0	0	0
71	0	0	0	0	0	0	0	0
70	0	0	0	0	0	0	0	0
69	13	0	6	0	0	13	0	2
68	39	0	17	0	2	45	0	2
67	23	0	2	0	6	39	1	3
66	13	0	16	0	3	13	0	0
65	8	0	10	0	1	24	0	4
64	14	0	4	0	0	26	0	2
63	51	0	14	0	3	7	0	0

62	41	0	21	0	12	22	1	1
61	36	0	6	0	4	11	0	1
60	4	0	1	0	0	17	0	0
59	8	0	1	0	0	14	0	0
58	0	0	0	0	0	7	0	0
57	44	0	26	0	3	15	0	0
56	0	0	0	0	0	14	0	4
55	0	0	0	0	0	45	0	1
54	16	0	0	0	0	43	0	2
53	24	2	8	0	0	40	0	1
52	63	118	15	77	6	35	0	7
51	7	118	5	95	0	69	0	8
50	8	51	1	56	0	13	0	0
49	0	0	0	0	0	16	0	2
48	12	0	1	0	2	34	0	1
47	24	0	14	0	1	47	0	5
46	0	0	0	0	0	8	0	1
45	30	0	27	0	7	5	4	1
44	23	40	13	38	5	17	0	9
43	15	0	0	0	0	0	0	0
42	33	0	18	0	3	0	0	0
41	17	0	21	0	1	0	1	0
40	27	0	10	0	3	0	0	0
39	24	0	1	0	0	0	0	0
38	4	0	1	0	0	0	0	0
37	19	0	18	0	0	0	0	0
36	4	0	1	0	1	0	0	0
35	19	0	22	0	1	0	0	0
34	0	0	0	0	0	0	0	0
33	0	0	0	0	0	8	0	2
32	15	0	20	0	2	30	0	2
31	0	0	0	0	0	41	0	4
30	35	0	14	0	4	6	1	3
29	0	0	0	0	0	21	0	1
28	11	0	7	0	2	18	0	0
27	6	0	10	0	0	5	0	0
26	1	0	0	0	1	0	0	0
25	20	0	4	0	1	0	0	0
24	0	0	0	0	0	3	0	0
23	0	0	0	0	0	8	0	0
22	21	0	1	0	1	10	0	0
21	13	0	1	0	1	13	0	0
20	13	0	7	0	1	10	1	0
19	0	0	0	0	0	2	0	2

Note: TrackStar's maintenance exception function was turned off except for 5 miles.

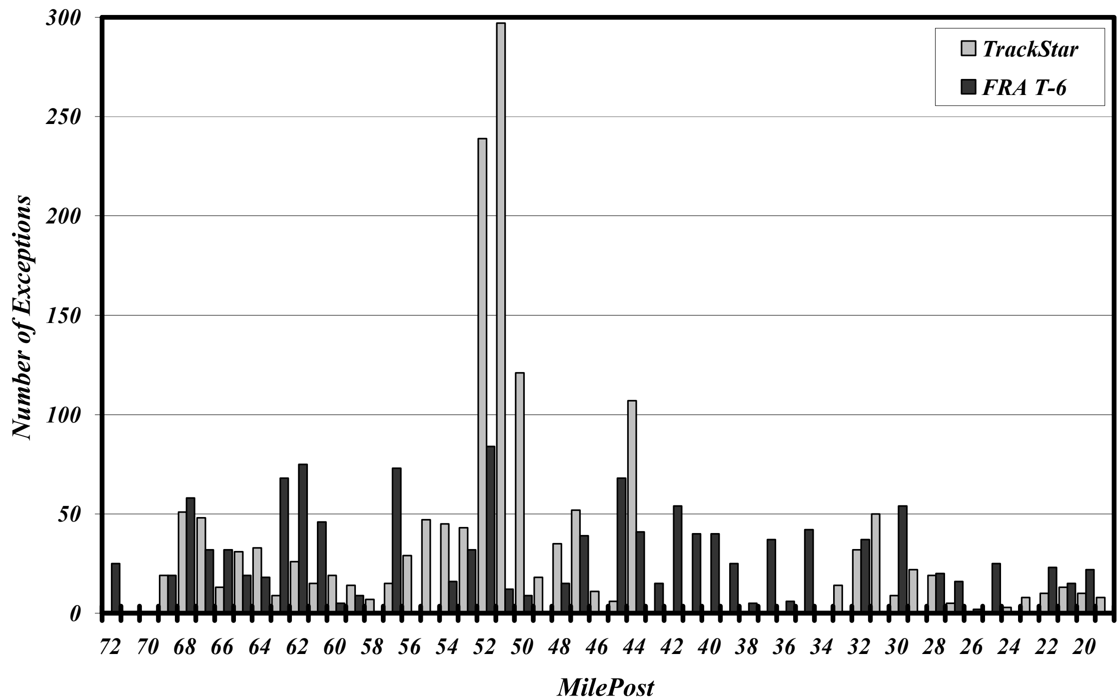

Figure 9. Total Safety and Maintenance Exceptions Comparison by Milepost Between T-6 and TrackStar

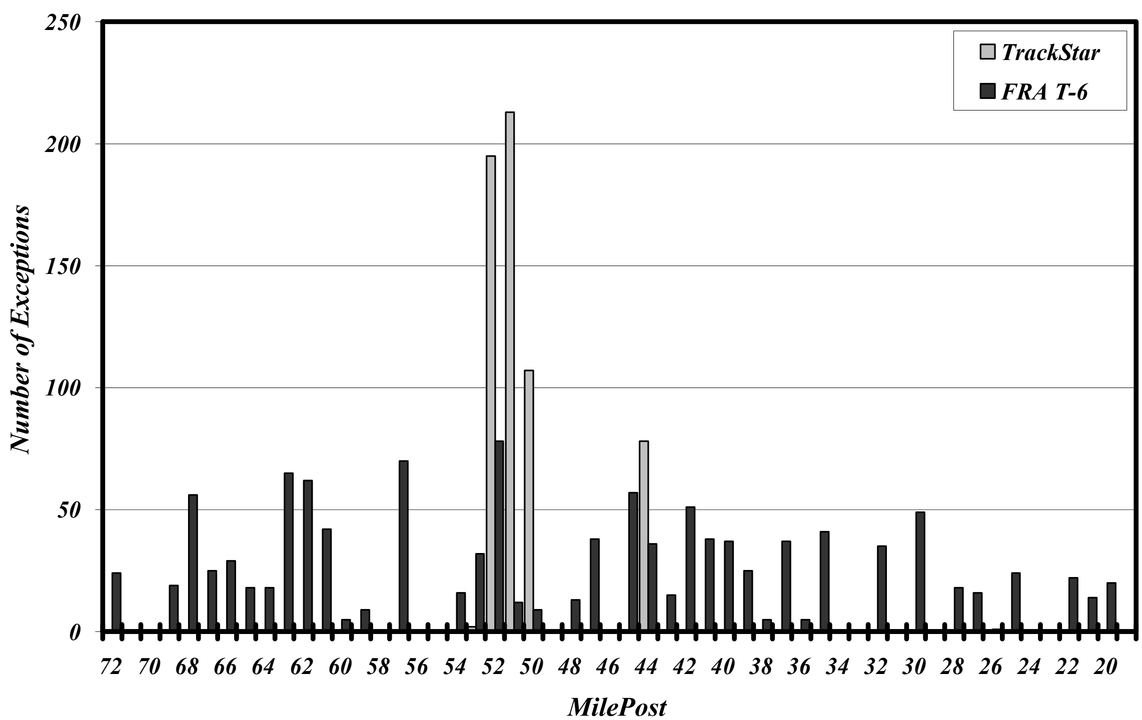

Figure 10. Maintenance Exceptions Comparison by Milepost Between T-6 and TrackStar

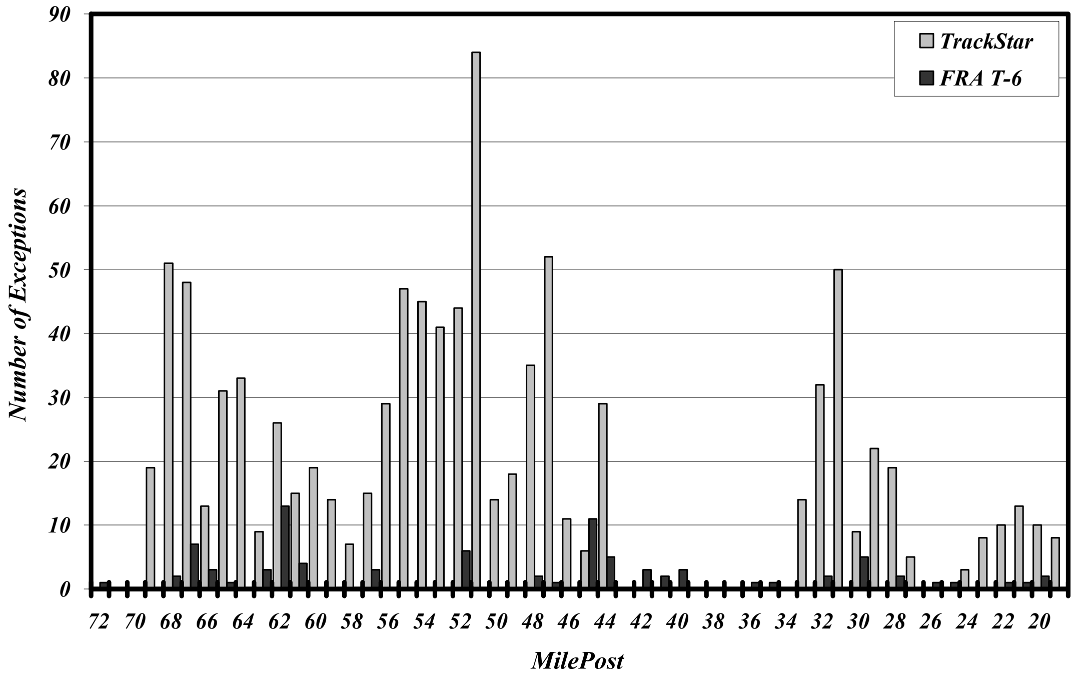

Figure 11. Safety Exceptions Comparison by Milepost Between T-6 and TrackStar

The number of reportable exceptions—GWR and PLG24 for safety and maintenance and loaded gage safety as recorded by each vehicle—were compared as shown in Figure 12. The principal difference between the numbers of exceptions from the two GRMS vehicles is in GWR safety, with 10.17 more exceptions recorded by the TrackStar relative to the T-6. For GWR maintenance, PLG24 maintenance, and PLG24 safety the TrackStar's number of reported exceptions was higher by 2.63, 6.33, and 7.89 times, respectively. Loaded gage safety exceptions were not identified by the T-6, thus no comparison can be made; however, the number of exceptions recorded by the TrackStar is given in the figure as 73.

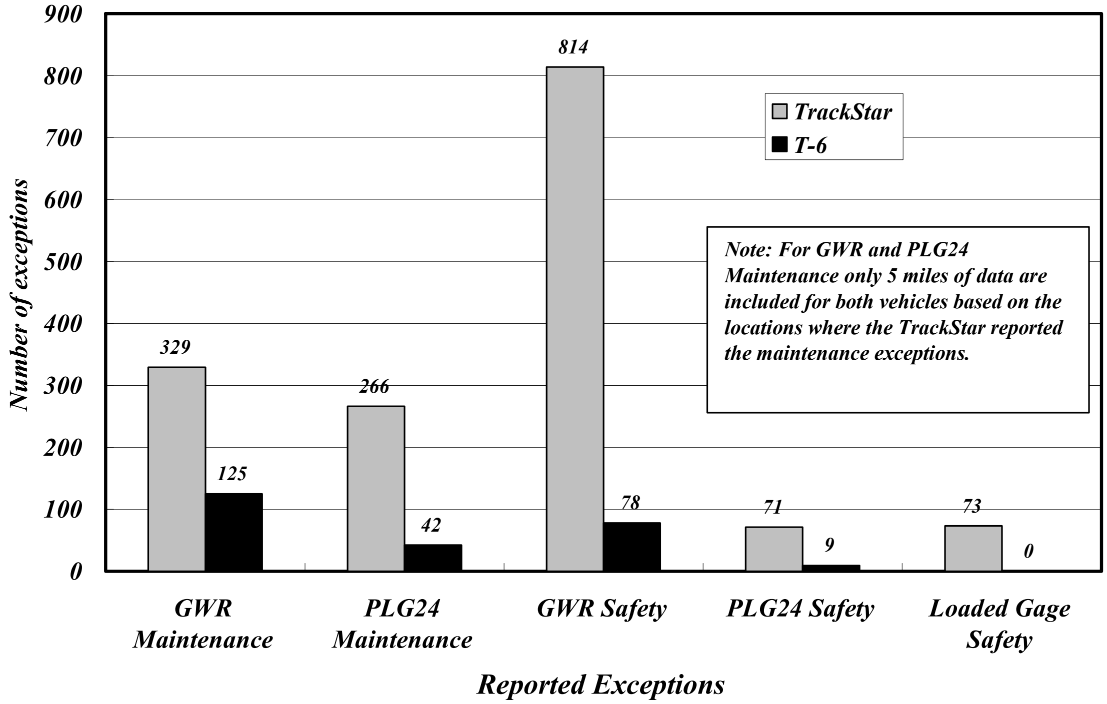

Figure 12. Gage Widening Safety and Maintenance Exception Comparison Between the T-6 and the TrackStar

Table 4 provides a statistical comparison of the measured and derived parameters from both vehicles at two different zones with left- and right-hand curves. An analysis was conducted to investigate a possibility of a bias in the data measured by either vehicle; this data indicates a significant difference between the vehicles due to curving, further investigated in Phase II.

Table 4. Statistical Comparisons for Measured and Derived Parameters at Two Selected Sections of Track

Section 1(MP 58 - 53)					
		FRA T-6		TrackStar	
		Mean	STD[1]	Mean	STD[1]
Unloaded Gage (in.)1	Tangent (MP 57.5)	56.546	0.117	56.612	0.118
	1 Degree Curve (MP 57.2)	56.734	0.248	56.648	0.175
	2 Degree Curve (MP 57.8)	56.657	0.152	56.875	0.200
	3 Degree Curve (MP 55.2)	56.858	0.187	56.986	0.200
	4 Degree Curve (MP 53.5)	56.312	0.202	56.483	0.212
	5 Degree Curve (MP 56.4)	57.069	0.225	57.282	0.230
Loaded Gage (in.)	Tangent (MP 57.5)	56.871	0.099	56.974	0.155
	1 Degree Curve (MP 57.2)	57.040	0.235	56.980	0.190
	2 Degree Curve (MP 57.8)	56.962	0.144	57.213	0.233
	3 Degree Curve (MP 55.2)	57.254	0.160	57.295	0.202
	4 Degree Curve (MP 53.5)	56.712	0.186	56.838	0.237
	5 Degree Curve (MP 56.4)	57.383	0.198	57.566	0.262
GWR (in.)	Tangent (MP 57.5)	0.357	0.073	0.584	0.155
	1 Degree Curve (MP 57.2)	0.350	0.068	0.537	0.167
	2 Degree Curve (MP 57.8)	0.340	0.087	0.544	0.189
	3 Degree Curve (MP 55.2)	0.462	0.101	0.498	0.179
	4 Degree Curve (MP 53.5)	0.424	0.321	0.574	0.203
	5 Degree Curve (MP 56.4)	0.373	0.102	0.460	0.178
PLG24 (in.)	Tangent (MP 57.5)	57.069	0.126	57.447	0.248
	1 Degree Curve (MP 57.2)	57.259	0.268	57.416	0.269
	2 Degree Curve (MP 57.8)	57.162	0.187	57.653	0.339
	3 Degree Curve (MP 55.2)	57.564	0.224	57.693	0.276
	4 Degree Curve (MP 53.5)	56.987	0.363	57.299	0.336
	5 Degree Curve (MP 56.4)	57.642	0.248	57.935	0.349
Section 2(MP 40)					
Unloaded Gage (in.)	Tangent (MP 39.1)	56.604	0.236	56.605	0.218
	1 Degree Curve (MP 39.4)	56.580	0.119	56.627	0.110
	2 Degree Curve (MP 38.9)	56.365	0.123	56.481	0.173
Loaded Gage (in.)	Tangent (MP 39.1)	57.089	0.218	57.058	0.326
	1 Degree Curve (MP 39.4)	56.958	0.122	56.833	0.146
	2 Degree Curve (MP 38.9)	56.769	0.102	56.725	0.141
GWR (in.)	Tangent (MP 39.1)	0.554	0.126	0.741	0.353
	1 Degree Curve (MP 39.4)	0.421	0.085	0.336	0.183
	2 Degree Curve (MP 38.9)	0.440	0.078	0.396	0.179
PLG24 (in.)	Tangent (MP 39.1)	57.439	0.304	57.655	0.554
	1 Degree Curve (MP 39.4)	57.207	0.177	57.112	0.275
	2 Degree Curve (MP 38.9)	57.011	0.135	57.052	0.206

[1]Note: STD indicates standard deviation.

4.2 Phase II Tests

4.2.1 Measurement Evaluation

The Phase II evaluation of the GRMS systems consisted of repeated runs over the same 1-mile section of track with a long tangent section followed by a curve and then a single pass-through of the same section, where the loaded and unloaded gage values were compared to hand measurements from a gage bar. Prior to the day of the test, a 500-ft tangent track section of the site was tested using the PTLF to provide a baseline reference for both vehicles. After review of the data from the entire Phase II test zone, it was determined that the 500-ft section of track with PTLF data available was suitable for evaluation of the vehicles and summarization of the Phase II test findings. Therefore, this 500-ft section of track is the main data reported in this section of the report.

4.2.1.1 Repeatability

The repeatability of both GRMS systems was found to be excellent during the Phase II testing. Both vehicles provided loaded and unloaded gage measurements that were very repeatable for the same test direction and vehicle. The unloaded gage data is indicative of the trend and is shown in Figure 13. The four passes at different speeds indicate the same variations for each vehicle. The track location in this figure varies for the 4 passes by up to 20 ft since these short test runs for Phase II were not aligned. The data from the TrackStar was manually shifted to align it with the T-6 data.

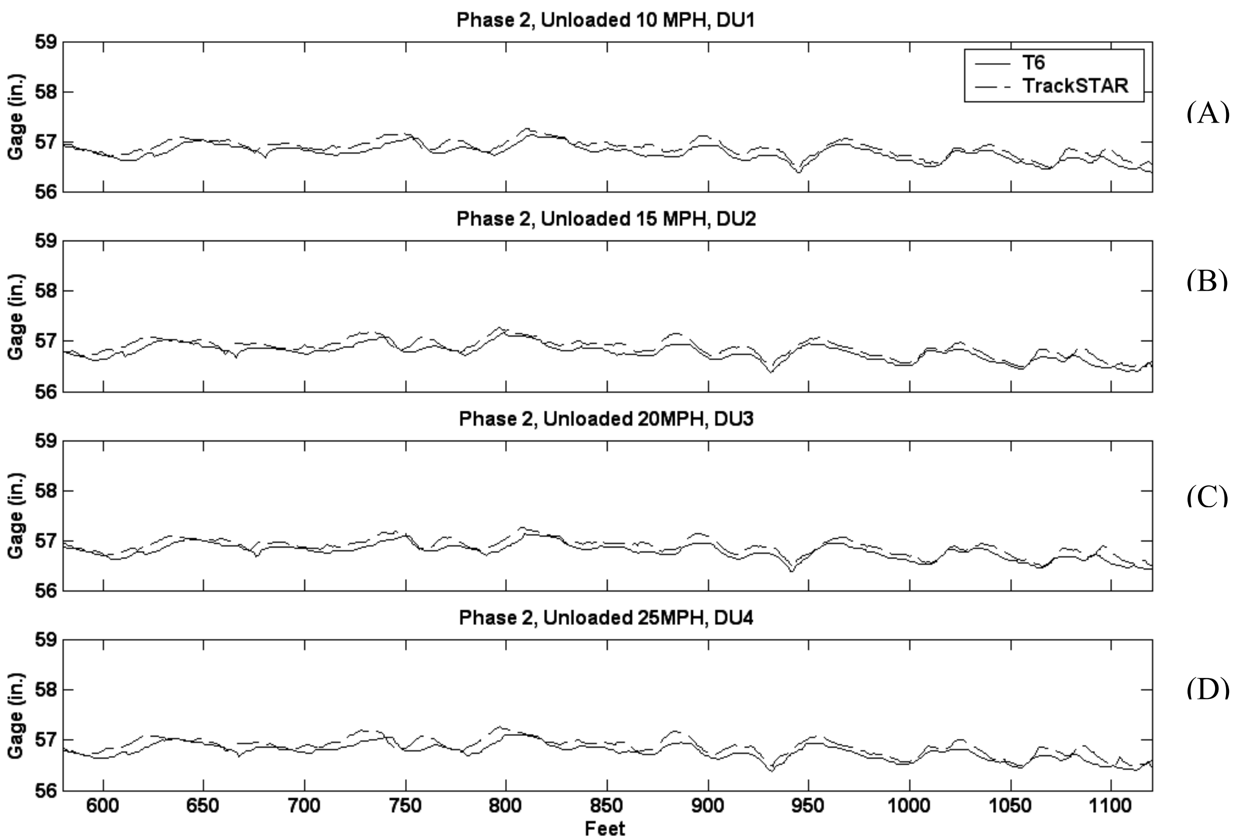

Figure 13. Unloaded Gage Measurement Variation With Speed

Figure 13 shows some very repeatable distinctions between the unloaded gage measurements made by the T-6 and the TrackStar. For example, at approximately 875 to 900 ft, the TrackStar repeatedly measures a peak in the data with higher amplitude than the T-6. By inspection, it also appears that all TrackStar unloaded gage measurements are higher in magnitude than the T-6 data.

All test parameters (unloaded gage, loaded gage, GWR, and PLG24) for a 10 mph pass for both vehicles are presented in Figure 14 for which the data from the TrackStar were manually shifted to align it with the T-6 data. The data indicates the previously observed higher unloaded gage for the TrackStar and a higher dynamic range (peaks higher and valleys lower than the T-6 measurements) of loaded gage, but with distinctly higher peaks than the T-6. This trend holds for both the GWR and PLG24 data. As an example, one of the largest peaks in loaded gage in both the T-6 and TrackStar data occurs at approximately 1,030 ft. The relative magnitudes of the loaded gage, GWR, and PLG24 are generally consistent.

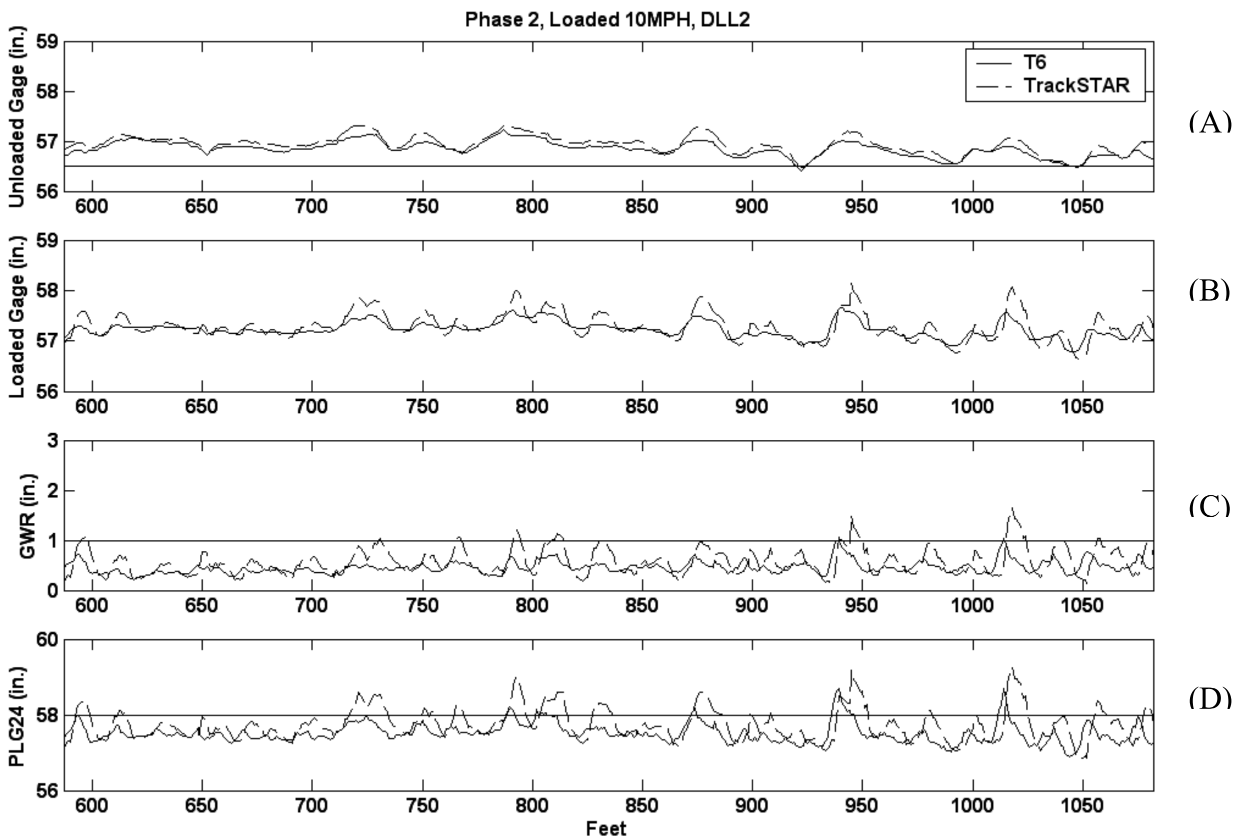

Figure 14. Test Parameters From 10 mph Phase II Test

In the entire dataset from Phase II, a very repeatable difference in unloaded and loaded gage was observed between the vehicles. The difference is characterized by larger magnitude peak unloaded gage values measured by the TrackStar and a larger dynamic range for loaded gage with higher peaks. Therefore, the differences in the data are attributed to systematic differences in the measurement systems (such as the applied loads and gage measurement systems), and not attributed to random errors.

4.2.1.2 PTLF Comparison

The PTLF and predecessor designs were the first measurement techniques employed to investigate dynamic wide gage conditions on track and were used to document occurrences of dynamic wide gage prior to the development of test vehicles. Experience with the PTLF testing method provides a strong basis for evaluating the performance of the two GRMS vehicles.

A comparison of a 10 mph test pass from the T-6 and the static LTLF data is presented in Figure 15. The data in the plot are the loaded and unloaded gage measurements with the unloaded values lower in magnitude than the loaded gage. The LTLF data were collected every 3 ft through the 500-ft long tangent track test zone. The trends in the data for both the LTLF and the T-6 are remarkably similar considering that the LTLF provides a very different load condition. In general, the overall magnitude and trends are very consistent between the two measurement systems with some zones of distinct trends, particularly around 150 ft. Potentially, the differences in this zone are due to the applied load or very poor track and tie conditions. The comparison of the LTLF data and the TrackStar data is presented in Figure 16, which indicates higher magnitude unloaded and loaded gage measurements by the TrackStar, but with remarkably similar trends to the LTLF data. In addition, the distinction between the T-6 and LTLF data at 150 ft is also noticeable in the TrackStar data where similar trends are observed, but with a distinct increase in magnitude of both the unloaded and loaded TrackStar gage data. This shows that both vehicles measure track conditions indicative of dynamic gage widening problems since the differences between the LTLF and both vehicles are similar to the differences previously observed and the trends in all three datasets (LTLF, T-6, and TrackStar) are similar.

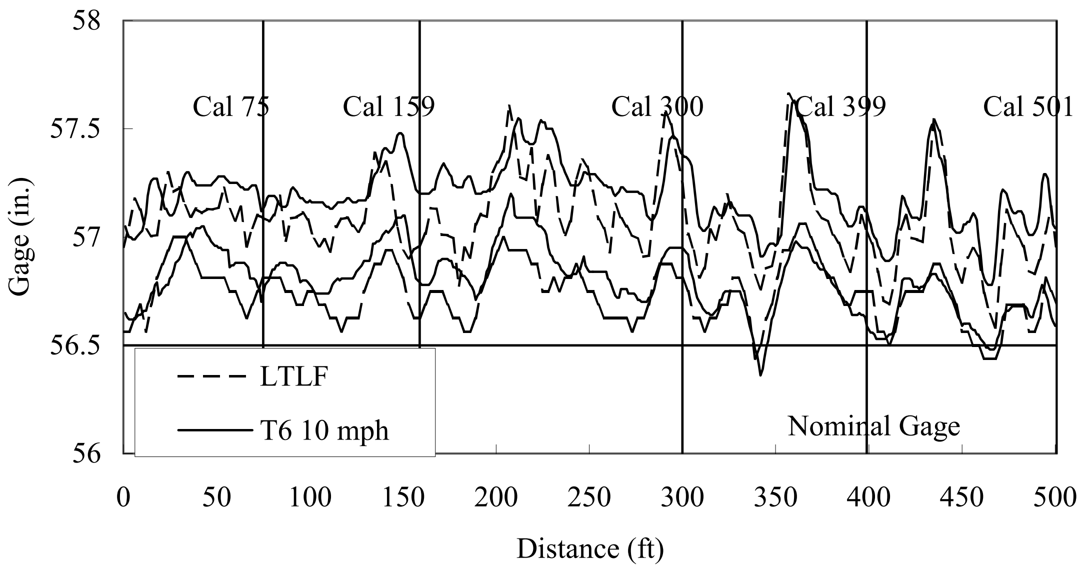

Figure 15. Comparison of T-6 10 mph Data With LTLF

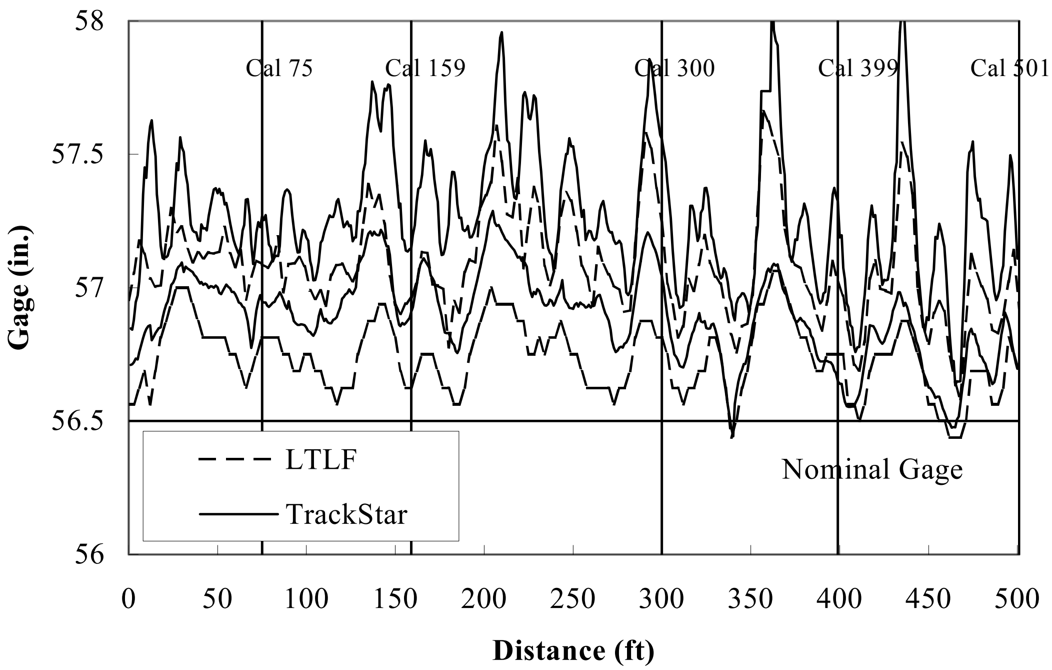

Figure 16. Comparison of TrackStar 10 mph Data With LTLF

4.2.1.3 Accuracy

To estimate the accuracy of the measurements made by both vehicles, gage was measured using a standard track gage bar with a resolution of 1/32 in. (The resolution taken as 1/2 the smallest increment on the gage bar, with 1/16 in. divisions on the gage bar.) These measurements were taken during a separate Phase II test zone pass. The gage bar comparisons were made at random locations through the entire 1-mile test zone and the data are presented in Table 5. The unloaded gage measurements from the TrackStar were all greater than the gage bar indicated value, especially in the curve. The T-6 unloaded gage data varied, with both greater and lesser values than the corresponding gage bar values. The TrackStar loaded gage measurements varied both greater and less than the gage bar data, with an average difference of 0.04 in. However, one anomalously large value of 0.17 in. dominates the dataset. Considering this 0.17-in. value as an outlier and removing it from the dataset provides an average error of 0.01 in., indicating very good agreement between the loaded gage measured by the gage bar and the TrackStar. The loaded gage measurements for the T-6 had an average difference of 0.07 in. and all but one measurement indicated gage measured by T-6 greater than the gage bar reference value.

The TrackStar measured unloaded gage generally wider than the gage bar and loaded gage was measured nearly the same as the gage bar reference. A potential cause of the TrackStar unloaded gage error has been hypothesized by the manufacturer to be the result of the large offset of the gage measurement system and the track, especially in curves, due to the overhang of the unloaded gage system in front of the vehicle.

The T-6 measured unloaded gage with nearly the same values as the gage bar on average, but loaded gage tended to be measured wider than the gage bar reference. The unloaded gage measurement trolley on the T-6 was subject to increased friction in the gage measurement mechanism due to gage trolley damage during recent shipment. This friction resulted in the gage wheels not being in the flanged position several times during this test.

Table 5. Accuracy Evaluation Data

Static Unloaded	Gage (in.)						Track Characteristic
Test Identification	Gage Bar	Trackstar	Error (in.)	Gage Bar	T-6	Error (in.)	Tangent/Curve
SU-1	56.56	56.58	0.02	57.09	57.2	0.11	Tangent
SU-2	56.88	56.95	0.08	56.66	56.67	0.01	Tangent
SU-3	57.13	57.18	0.05	57.03	57	-0.03	Tangent
SU-4	57.13	57.24	0.12	57.03	57.05	0.02	Curve
SU-5	56.97	57.11	0.14	56.59	56.51	-0.08	Curve
SU-6	57.50	57.64	0.14	56.50	56.42	-0.08	Curve
SU-7	56.56	56.63	0.07				Curve
Average			0.09			-0.01	

Static Loaded	Gage (in.)						Track Characteristic
Test Identification	Gage Bar	Trackstar	Error (in.)	Gage Bar	T-6	Error (in.)	Tangent/Curve
SL-1	57.19	57.25	0.06	56.94	57.1	0.16	Tangent
SL-2	57.13	57.18	0.05	57	57.1	0.10	Tangent
SL-3	57.00	56.98	-0.02	58	57.88	-0.12	Tangent
SL-4	57.63	57.66	0.03	57.56	57.62	0.06	Curve
SL-5	57.38	57.33	-0.05	57.16	57.24	0.08	Curve
SL-6	57.75	57.92	0.17	56.66	56.79	0.13	Curve
Average			0.04			0.07	

Note: Gage bar resolution is approximately 0.03 in. (1/32 in.)

The error between the gage bar measurements, which was considered the standard, and the measurements from the two GRMS vehicles, are plotted in Figure 17. As illustrated in the figure, there is no discernable error trend with loaded and unloaded gage for either GRMS vehicle.

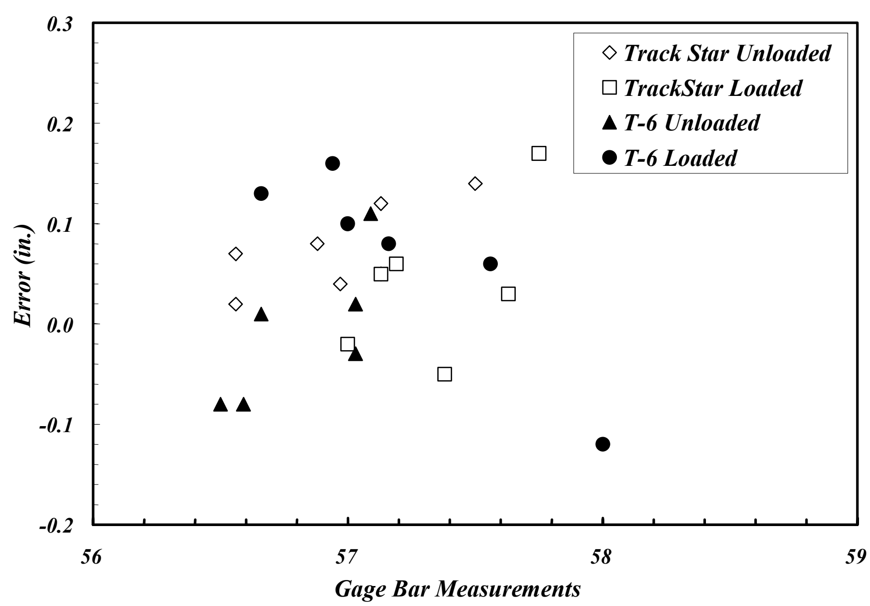

Figure 17. Error Plot Between the Gage Bar Measurements and the Two GRMS Vehicle Readings

4.2.2 Load Response

To investigate the systematic measurement differences between the T-6 and the TrackStar, data from 10 mph passes by each vehicle were analyzed. Figure 18 presents the measured load and loaded gage for both vehicles. Based on inspection, a distinct trend was observed at locations of approximately 150, 210, 300, 360, and 430 ft, which are identified by vertical lines drawn between the two plots. These locations highlight TrackStar measured peaks in loaded gage. At these locations, the T-6 load is at a minimum. In addition, a TrackStar measured loaded gage value minimum, such as at approximately 230 ft, corresponds to a local peak in the T-6 load.

These differences can be explained by the differences in the load control system for the two vehicles. The TrackStar has very good load control due to a feedback control circuit, which was used to overcome friction in the split axle, axle mass and dynamic track changes that impact lateral loads. When the TrackStar approaches a weak track gage location, the load is maintained at the test level with only minor variation. However, the passive load-control by the T-6 allows the load to drop as the axle extends to the wider loaded gage position in the weak track location. Therefore, in short sections of weak track, the T-6 load is significantly lower than the nominal test load (approximately 30 percent; the load drops to nearly 10 kips, indicating a 4 kip drop from the nominal 14 kip load). This results in the weak section (potentially as short as a single tie) being evaluated at a load level up to 30 percent less than the specified test load. This affected loaded gage, but in the computation of GWR and PLG24 the actual load conditions are used to extrapolate to theoretical loads of 16 and 24 kips, respectively. In addition, when strong track locations are encountered, the load increases for the T-6 as the axle retracts to accommodate the narrower gage as shown at approximately 400 ft in Figure 18 where the load is slightly more than 15 kips. However, the observed load variations are lower in magnitude than for weak zones, creating a less critical variation, which is not critical to the safety evaluation of track.

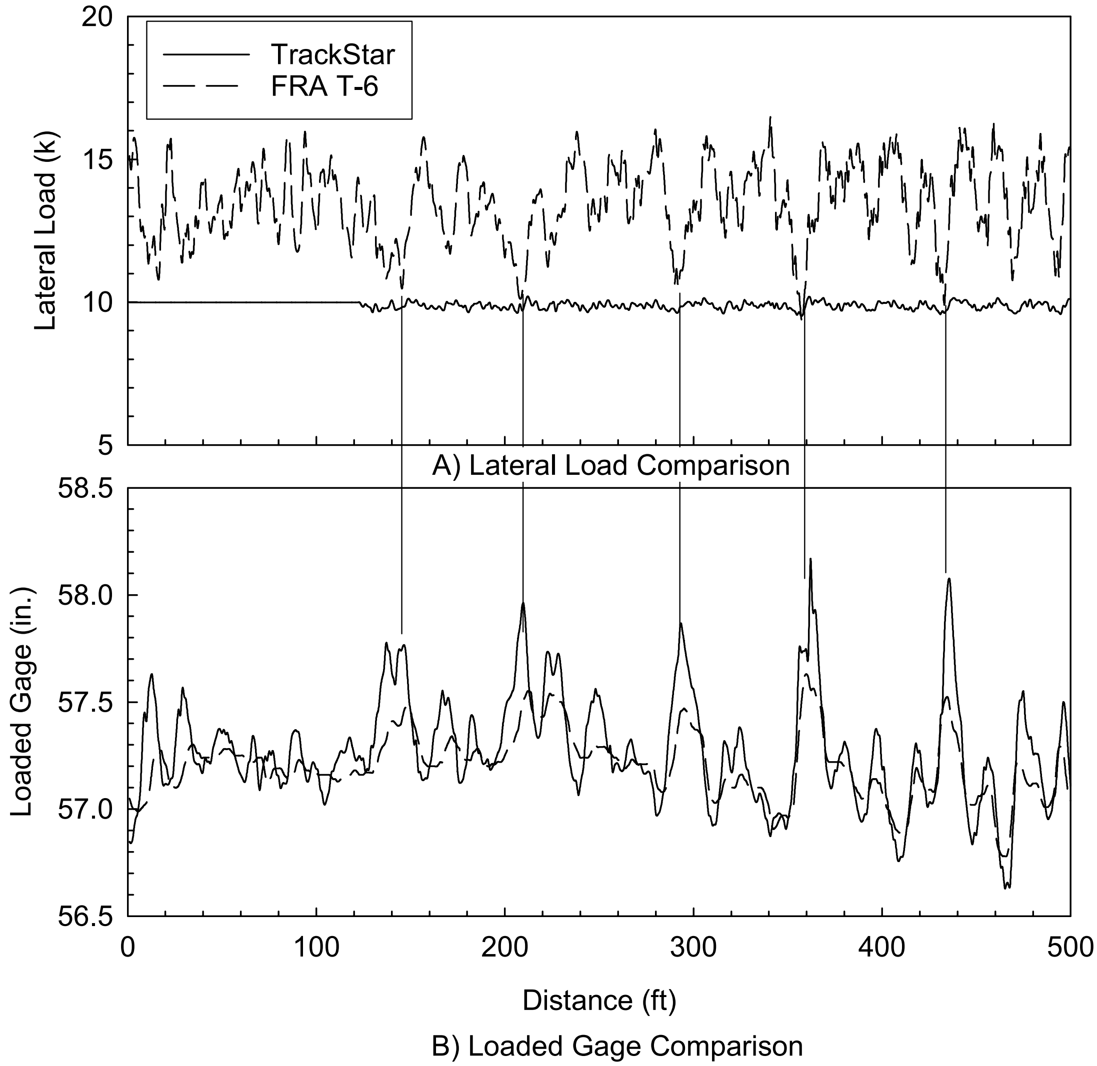

Figure 18. Load-Response Analysis

4.3 Phase III Tests and Analysis

4.3.1 Phase III Tests

The repeatability of the two GRMS vehicles, the LTLF, and their ability to identify zones with known track gage widening characteristics were all tested in this phase. A section of tangent track between milepost 47.3 and 47.6 was selected based on data collected from the T-6 under Phase I testing. In this section, two locations were chosen with a GWR as measured by T-6 of approximately 0.35, and two with a GWR of 0.50 in., to indicate both a "strong" and "weak" gage widening condition. At each zone, an ALD was placed to mark the exact location in order to compare the recorded data from each vehicle and at the different test speeds. The speed over this section varied for both vehicles from 10 to 25 mph in 5 mph increments.

4.3.2 Phase III Data Analysis

The data from Phase III is presented in Table 6. Locations 1 and 2 as defined in the table are considered to have a "weak" gage widening condition, with LTLF readings of 0. 44 and 0.50, while Locations 3 and 4 represent the "strong" condition, with LTLF readings of 0.25 and 0.31, respectively. The maximum values of loaded track gage, GWR, and PLG24 are given for each vehicle, speed, and location. The LTLF reading at 4,000 lb, based on initial unloaded gage prior to vehicle testing are also given in the table. The LTLF data for all four locations are within the safety limit of 0.625 in.

Table 6. Speed vs. Measured and Calculated Values Between the T-6, TrackStar, and LTLF

Speed mph	Location	Loaded Gage FRA T-6[1] (in.)	GWR FRA T-6 (in.)	PLG24 FRA T-6 (in.)	Loaded Gage TrackStar[1] (in.)	GWR TrackStar (in.)	PLG24 TrackStar (in.)	LTLF at 4,000 lb (in.)
10	1	0.690	0.540	1.130	0.627	0.545	1.079	0.438
	2	0.820	0.600	1.380	0.816	0.564	1.256	0.500
	3	0.630	0.330	0.850	0.604	0.282	0.829	0.250
	4	0.400	0.360	0.610	0.361	0.375	0.696	0.313
15	1	0.700	0.520	1.120	0.642	0.379	0.969	0.438
	2	0.660	0.390	0.920	0.773	0.569	1.217	0.500
	3	0.640	0.320	0.820	0.602	0.298	0.850	0.250
	4	0.420	0.430	0.770	0.433	0.385	0.767	0.313
20	1	0.750	0.400	0.970	0.687	0.338	0.963	0.438
	2	0.640	0.360	0.870	0.755	0.628	1.237	0.500
	3	0.690	0.350	0.890	0.644	0.295	0.853	0.250
	4	0.380	0.360	0.590	0.391	0.440	0.742	0.313
25	1	0.810	0.500	1.130	0.705	0.376	1.023	0.438
	2	0.730	0.490	1.100	0.758	0.602	1.270	0.500
	3	0.680	0.510	1.060	0.674	0.457	1.023	0.250
	4	0.460	0.400	0.660	0.409	0.464	0.753	0.313

[1] Loaded gage data for both vehicles is shown as the difference from nominal 56.50-in. track gage.

A comparison of all the pertinent factors at Location 1 for all test speeds is shown in Figure 19. Loaded gage values for both vehicles are plotted as actual value minus nominal gage, 56.50 in. This format is used for all bar charts in this section. The data indicates that for PLG24, GWR, and loaded gage there is no significant change due to speed for both vehicles. A slight change due to speed variation is noted for both vehicles but not sufficient to conclude that there is any speed dependency difference between the vehicles at this location. Hence, it can be concluded that the data from both vehicles is not significantly speed dependent above 10 mph.

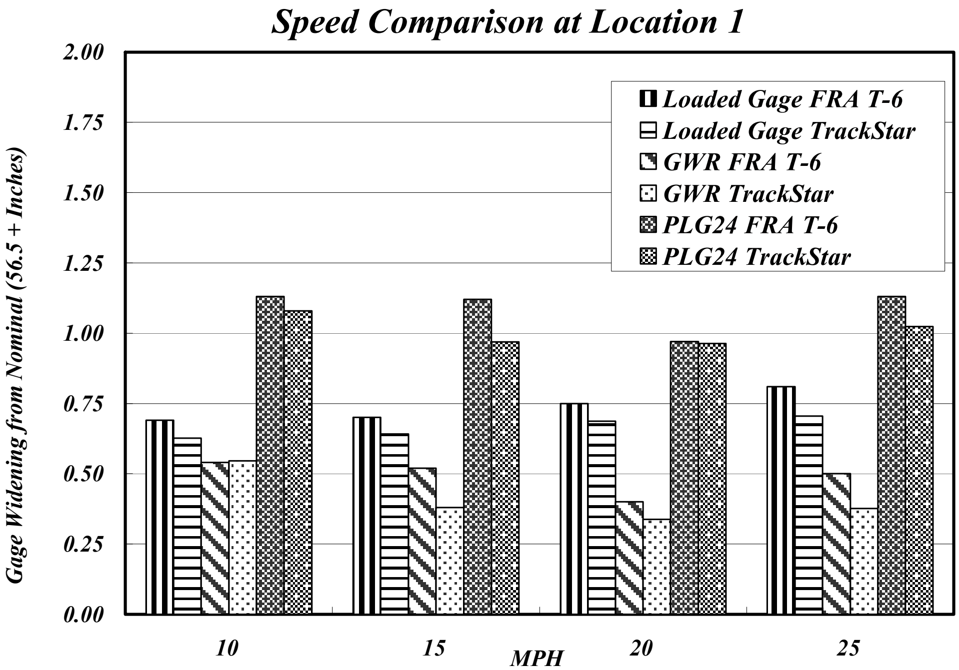

Figure 19. Loaded Gage, Gage Widening Ratio and Projected Loaded Gage 24 at Location 1 for TrackStar and T-6

A comparison of the recorded and derived information from the two GRMS vehicles at 20 mph and the LTLF are given in Figure 20. At all four locations containing "weak" and "strong" track, both vehicles recorded higher loaded gage than the LTLF; there was not a distinguishable pattern to explain the difference in the recorded value at all locations other than that both vehicles showed greater loaded gage widening. The loaded gage range was 25 percent to 157 percent higher for the TrackStar, while for the T-6 the range was 21 percent to 176 percent higher. Although there was variation when looking at the data for all locations, this variation was more consistent at each location between the LTLF and the two vehicles.

As expected, both vehicles recorded higher PLG24, GWR, and loaded gage at Locations 1 and 2, considered the "weak" tracks, than at Locations 3 and 4, considered the "strong" locations. With the exception of Location 4, where the TrackStar recorded higher GWR than loaded gage, none of the other data show any distinguishable patterns.

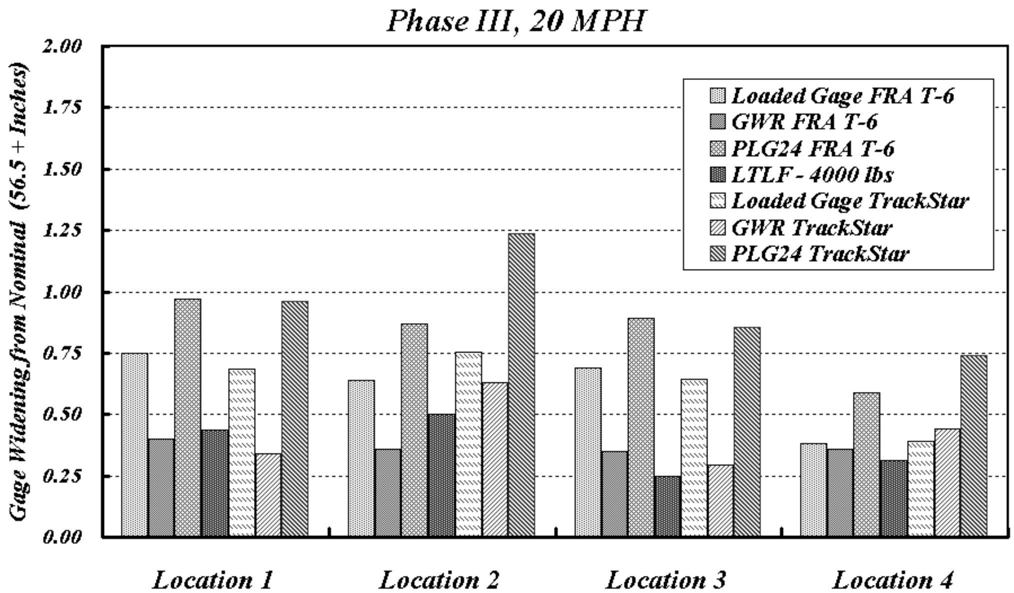

Figure 20. Parametric Comparison between the TrackStar, T-6, and LTLF at Phase III Selected Locations

5 Discussion of Results

Based on the testing, it appears that both vehicles can meet the minimum requirements for performing GRMS safety measurements. However, some of the gage measurements and derived parameters have been found to be different, which will require refinement of testing techniques and safety limits to ensure comparable inspection results. For both vehicles, data repeatability was found to be excellent with one exception: the applied gage-spreading load for the TrackStar had a tendency to change slightly over time. Accuracy of both vehicles was good, within the range of accuracy of the gage bar verification, with the exception of the TrackStar unloaded gage in curves. The variation in loaded and unloaded gage measurements from the LTLF compared well with both vehicles, but the T-6 and TrackStar magnitudes differed.

5.1 Loaded Gage

The TrackStar loaded gage had a higher dynamic range than the T-6, which was mostly higher magnitude but with lower values also. However, both vehicles accurately locate loaded gage variations. The TrackStar loaded gage data may be more accurate than the T-6 data when compared to a gage bar placed near the point of load application, based on the data in Table 5. In general, the accuracy of the TrackStar loaded gage relative to the gage bar was very close and the observed error was dominated by one large anomalous value. In addition, the TrackStar loaded gage measurements at each location compared well with the LTLF measurements from Phase III testing.

The main difference in the loaded gage measurement systems on the T-6 and TrackStar is that the T-6 measures loaded gage with sensors on the split axle, while the TrackStar uses a laser gage measurement external to the axle targeting a rail location near the point of load application. Mechanical vibration, bending, and wheel position contribute to the potential error in the loaded gage measurement on the T-6, all of which do not influence the TrackStar laser measurement.

5.2 Unloaded Gage

Based on the analysis of the Phase I test data it was concluded that relative to the T-6, the TrackStar generally recorded higher unloaded gage than the T-6, with the exception of one 1-degree curve that was analyzed. From Phase II testing and data analysis, it was confirmed that the TrackStar recorded higher magnitude unloaded gage than the T-6. During verification tests with the gage bar, the gage measured in curves by the TrackStar was higher than that measured using the gage bar in the same location at the same time. Specifically, the TrackStar average unloaded gage error was about 1/8 in. compared to the gage bar in the curve. T-6 unloaded gage data was generally within the measurement accuracy of the reference gage bar, except for the sporadic occurrence of a flanging problem due to friction in the gage trolley and wheels.

The observed differences in unloaded gage in curves were analyzed by Holland Company staff to evaluate potential causes and determine possible solutions. Holland Company proposed that the location of the gage measurement in front of the forward hi-rail gear results in the measurement of gage not perpendicular to the rails. The measurement of gage not perpendicular to the rails could result in an error of 0.01 in. for a 5-degree curve and 0.06 in. for a 15-degree curve as estimated by Volpe staff; significantly less than the observed approximately 0.12 in. error on the

5-degree curve in the test section from Phase II. The error explanation that the gage error is due to measurement not perpendicular to the rails cannot account for the observed error magnitude, although it is likely a contributing cause.

Based on Holland Company data analysis, a method to force the TrackStar unloaded gage to match the unloaded gage measurement of the T-6 was developed [7]. The equation was developed empirically by overlaying the measured TrackStar data over the T-6 data. Equation (5) was proposed to correct the unloaded gage data:

$$\mathrm{ULG}_{\mathrm{Corr}} = \mathrm{ULG}_{\mathrm{Measured}} - 2.6\sin\left|\mathrm{Curvature}\right| \tag{5}$$

where $\mathrm{ULG}_{\mathrm{Corr}}$ is the corrected unloaded gage, $\mathrm{ULG}_{\mathrm{Measured}}$ is the measured unloaded gage, and Curvature indicates the measured degree of curvature. Based on this equation, Holland Company corrected the 0.5-mile long section of data shown in Figure 21. The result of the correction is in Figure 22, which shows improved agreement between the TrackStar and the T-6.

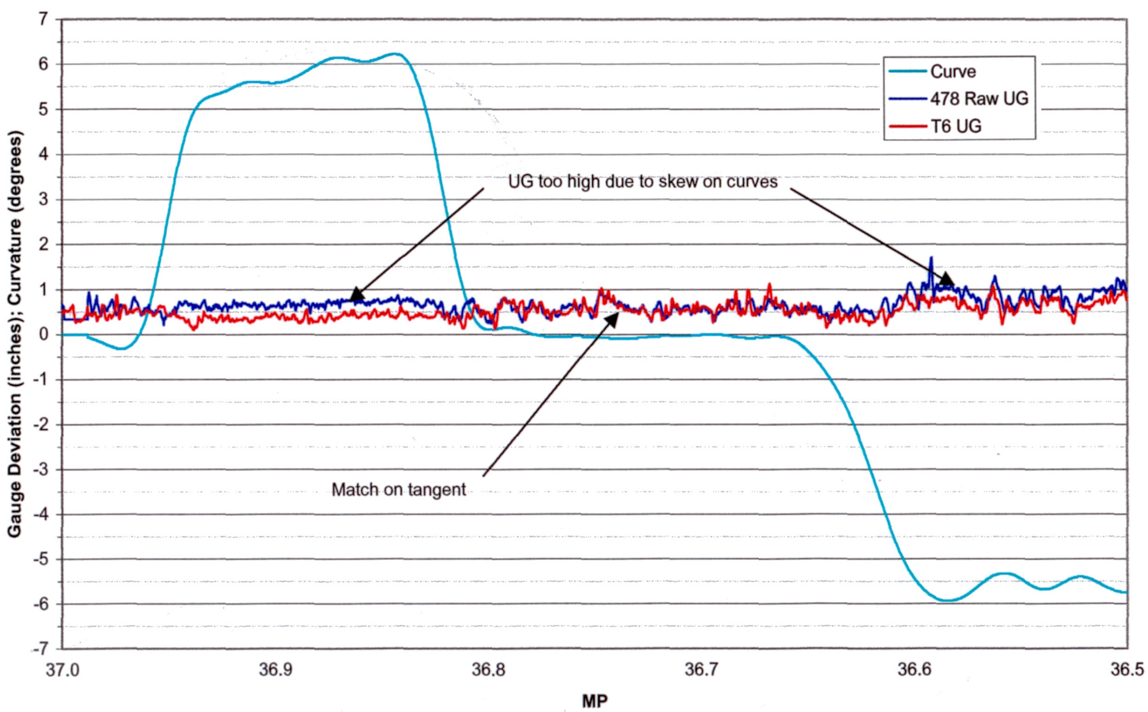

Figure 21. Uncorrected TrackStar Unloaded Gage [7]

Although the reason given for the unloaded gage error is not the cause of the error, the correction provided improves the agreement between the TrackStar and the T-6. Although further effort is required to identify and understand the error, it appears that the error is systematic and not random, indicating that system modification or calibration could correct the measurement error.

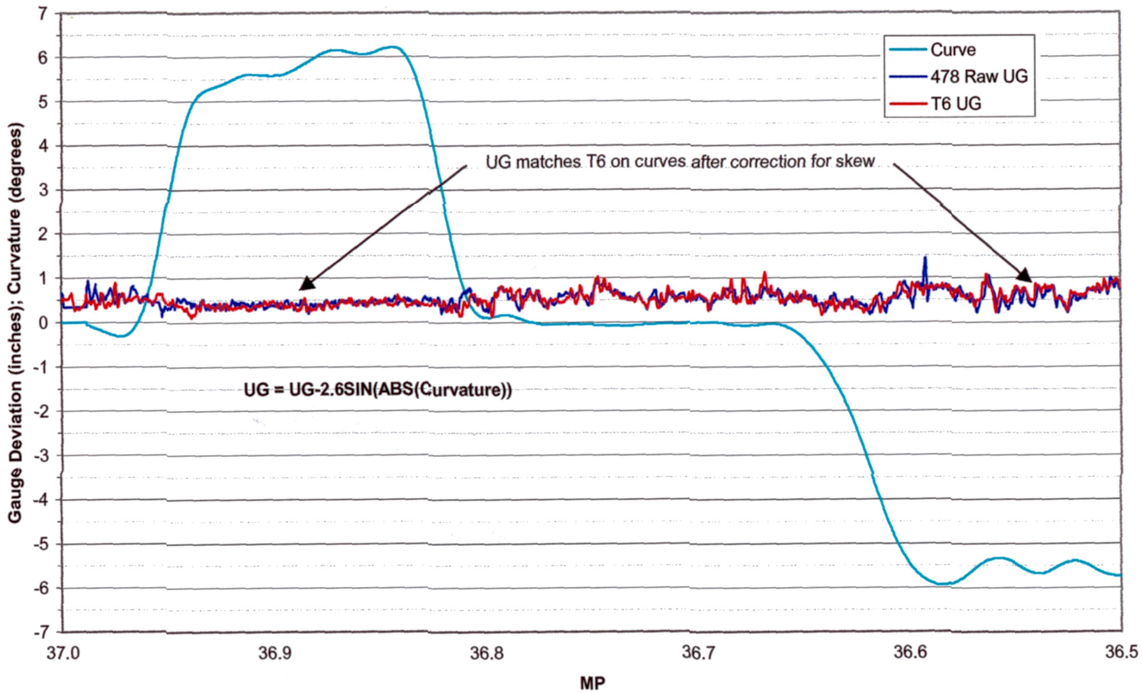

Figure 22. Corrected TrackStar Unloaded Gage [7]

5.3 Test Load

The nominal applied loads for the T-6 are 21 kips vertical and 14 kips lateral providing a L/V of 0.67 and 14 kips vertical and 10 kips lateral giving a L/V of 0.71 for the TrackStar. The lateral load applied by the TrackStar was more uniform (standard deviation of 0.22 kips) than the T-6 lateral load (standard deviation of 1.32 kips). The standard deviation for the TrackStar was computed for loads in the range of 5 to 15 kips, whereas the standard deviation for the T-6 was computed for all test data. The vertical load varied more in the TrackStar, likely due to the short wheelbase and vehicle motion during testing. The applied loading is significantly less for the TrackStar than the T-6. This results in a requirement for better load control by the TrackStar to maintain the load in the desired Zone II region in Figure 7 and Figure 8 to meet AREMA specification for applied load. The applied loads for both vehicles met AREMA and FRA specifications.

The applied load magnitude influence on the measured lateral deflection was estimated based on Figure 23, which was recreated from [10]. The plot shows the lateral-vertical load relationship for constant single rail deflection estimated for minimum acceptable track strength conditions. For the minimum track strength conditions from [10], the deflection associated with the applied loading was estimated from Figure 23 and tabulated in Table 7. To estimate Δ gage, the individual rail deflection for each lateral, vertical load pair was doubled. Based on this analysis it is estimated that the T-6 under nominal load conditions of 21 kips vertical and 14 kips lateral load would measure 1.11 in. Δ gage, compared with the TrackStar which would be expected to measure 0.82 in., representing a 26 percent lower value measured by the TrackStar as compared to the T-6 for the same conditions.

The lateral load control was better for the TrackStar relative to the T-6, resulting from the need to maintain a narrow load spectrum to meet AREMA test load requirements. As described in Section 4.3.2, the improved load control appears to result in wider loaded gage measurements as load is maintained at test levels more uniformly than the T-6. When the T-6 tests through a section with poor ties, the lateral load drops as much as 30 percent (14 k to 10 k, Figure 18) due to passive load control, while the axle extends to the wider gage. The observed 30 percent drop in lateral load at weak zones corresponds to an approximately 0.49 in. Δ gage reduction (44 percent) estimated by interpolation from Figure 23 and a reduction in applied load severity from 5,600 lb to 1,600 lb. More precise evaluation of the influence of the lateral load variation can be developed through more detailed modeling and analyses. However, the order of magnitude estimate from available data indicates that the load severity reduction during testing using the T-6 in weak gage strength zones likely is the most significant single cause of the measurement differences between the T-6 and TrackStar.

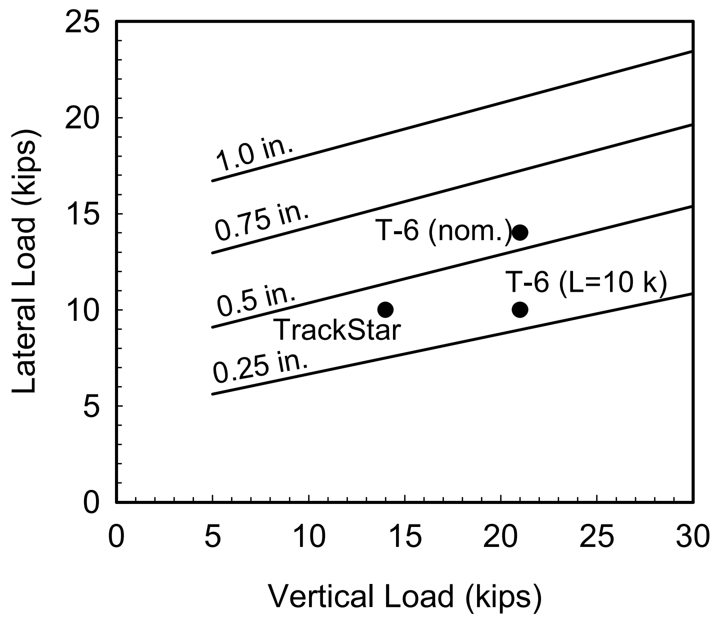

Figure 23. Constant Deflection Lateral to Vertical Load Relationships for Minimum Track Strength Conditions [after 10] (Coltman, Dorer, and Boyd, 1988)

Table 7. Influence of Test Load Variation on Minimum Track Strength Deflection

Test Condition	Load (kips)		Δ Gage (in.)	Change from Nominal (%)	Load Severity (lbs)	PLG 24 A Factor
	Lateral	Vertical				
T-6 Nominal	14	21	1.11	0	5600	1.71
T-6 Low Load	10	21	0.62	44%	1600	3.08
TrackStar	10	14	0.82	26%	4400	2.24

5.4 Derived Parameters

The parameters derived from the GRMS measurements are GWR and PLG24, described in equations 2 and 3, respectively, and described in more detail in [11]. GWR characterizes overall tie condition by quantifying the gage change allowed under a load of 16 kips. PLG24 quantifies the gage allowed under a maximum lateral load of 24 kips (PLG24) to characterize the safety limit behavior under allowable ultimate load as an indicator of derailment potential at ultimate load conditions of 32 kip vertical load and 24 kip lateral load on the flanging rail and 16 kips on the non-flanging rail.

Assuming the unloaded gage measurement of the TrackStar can be calibrated to provide an accurate measurement, the main difference between the TrackStar and T-6 that will affect GWR and PLG24 is the loaded gage difference due to the applied loading. The loaded gage variation resulted from the different nominal load magnitude, loading conditions (truck versus single wheel), and load-response characteristics of the test systems. The overall load magnitude influence would result in approximately 26 percent greater lateral deflection to be measured by the T-6 compared to TrackStar. The single wheel loading results in approximately 12 percent less lateral railhead deflection for truck loading than with one axle for similar track, tie, and test load conditions [9]. This indicates that a 12 percent less lateral deflection would be expected with the T-6 split axle, compared to a single axle load application system. The applied load drop of approximately 30 percent when the T-6 encountered weak track results in 44 percent less lateral deflection measured than if the T-6 maintained nominal load conditions. The combination of these errors (+26 load, -12 single/truck, -44 load drop) indicates an overall difference of approximately –30 percent, indicating the T-6 measures about 30 percent less lateral deflection than the TrackStar considering these main differences between the vehicles. This compares well with the observed differences between the two vehicles, for example in Figure 15 (tangent track, no unloaded gage error) the observed delta gage (loaded gage - unloaded gage) difference at the weak track anomaly at 150 ft was approximately 38 percent on average for the 10 data points from 145 ft to 155 ft (to account for data misalignment since these datasets were not aligned using ATDAS).

In the data analysis from Phase II, it was noted that loaded gage from the TrackStar was both higher and lower in magnitude than the T-6. The larger observed data range for the TrackStar loaded gage likely results from the vehicle differences on the order of 30 percent in weak zones due to differences in loading magnitude, axle configuration, and load control. The difference in loaded gage could cause the observed variation in delta gage that was noted in the GWR data from the Phase II test site shown in Figure 24. The GWR data is mainly dependent upon the Δ gage (loaded gage – unloaded gage) measured during testing, Equation 2. The GWR data show the expected higher dynamic range (both higher and lower magnitude) for the TrackStar data relative to the T-6. However, the overall magnitudes in a weak track location, such as the zone at approximately 150 ft, show the much larger values provided by the TrackStar. This large difference in GWR values in weak zones likely resulted in the many GWR safety defects identified by the TrackStar, but not the T-6. For instance, in the zone at 150 ft, the T-6 GWR value was 0.51 in. and the TrackStar value was 1.03 in., which represents a difference of over 100 percent.

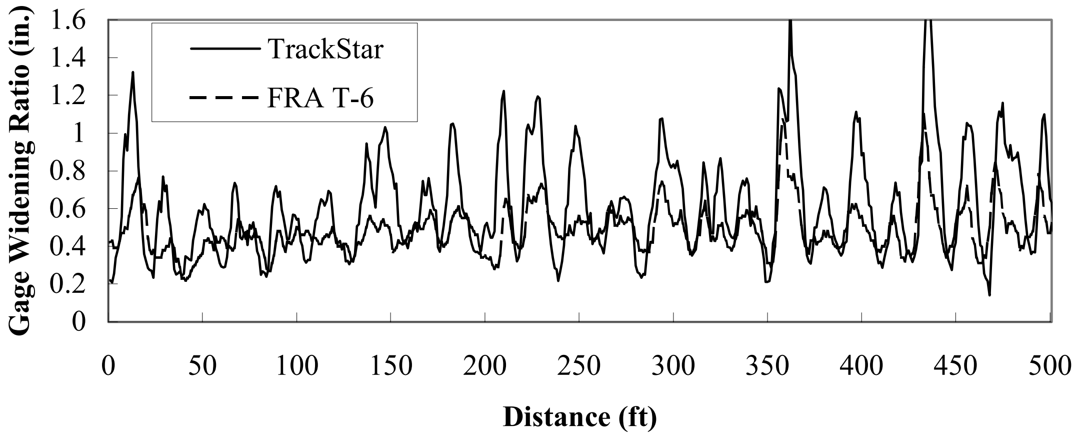

Figure 24. GWR Comparison, Phase II Test Site

The larger data range of the delta gage data from the TrackStar compared to the T-6 will also affect the projected loaded gage (PLG) data. Projected loaded gage is an indication of the behavior of the track under ultimate acceptable load conditions. Equation 3 presents the formulation for PLG and the data recorded by both the TrackStar and T-6 at the Phase II test site is shown in Figure 25. The data indicate the previously observed trend of TrackStar higher dynamic range compared to the T-6, but with a tendency for overall higher magnitude values especially in weak track zones. In the weak zone at approximately 150 ft, the PLG derived from the TrackStar data was 58.5 in. and 57.9 in. from the T-6.

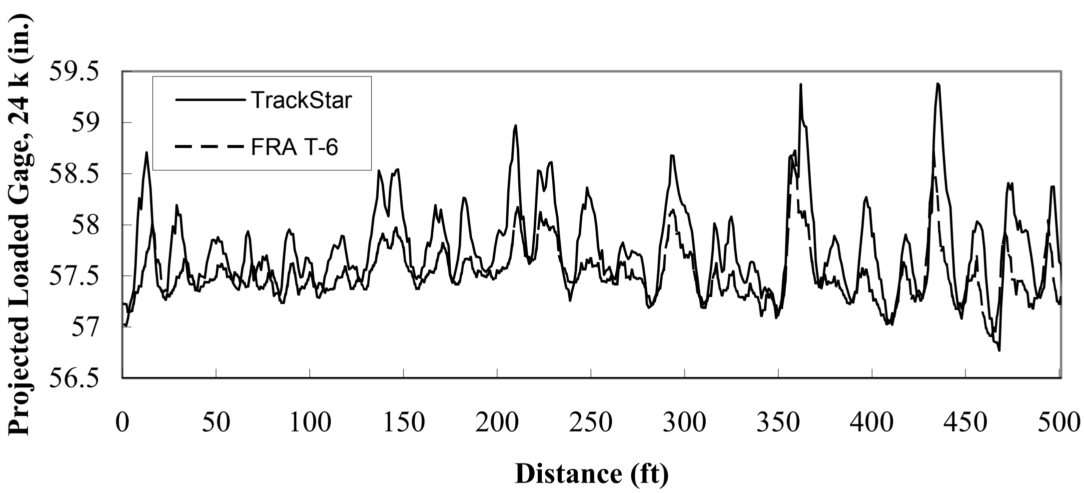

Figure 25. Projected Loaded Gage Comparison, Phase II Test Site

5.5 Exceptions

Based on the Phase I analysis, the TrackStar noted a higher number of safety exceptions per mile than the T-6. Since the safety exception limits are based on derived parameters, GWR and PLG24, and measured loaded gage, the differences in the load application and deflection measurements discussed in Section 4.1 account for the majority of the differences noted. Vehicle dynamics effecting the deflection measurements of the TrackStar or the T-6 could have a minor effect on the number of deflections noted by each vehicle. This hypothesis could not be confirmed with the existing test data.

A large discrepancy in the number of maintenance exceptions between the vehicles was also noted. The differences in the measurements and derived parameters in Section 4.1 likely result in some of the maintenance exceptions. The differences in the maintenance exceptions cannot be readily explained except that the method of counting these exceptions must have been different for each vehicle. Some of the maintenance exceptions were counted as safety exceptions by the TrackStar, possibly due to difference in the deflection measurements, as explained above, and partly due to the method that the TrackStar accounted for these exceptions.

6 Summary and Conclusions

Based on an extensive research program, a GRMS was developed and implemented to help reduce the number of annual derailments due to wide gage through better inspection of track condition. Two measurement systems are now available for evaluation of track conditions indicative of dynamic wide gage problems: the railbound FRA T-6 GRMS system and Holland Company's TrackStar hi-rail truck-based system. The tests described in this report compared the performance of the two systems since the applied loads are much different. The tests were designed to determine whether the two systems meet the minimum requirements of the AREMA Recommended Practice and if both systems provide an accurate evaluation of potential track safety problems. They were conducted in three phases: Phase I to evaluate performance under typical track survey conditions; Phase II to evaluate accuracy and precision of the measurements; and Phase III to evaluate the ability of the two systems to repeatedly measure and identify a documented problem location.

The two test vehicles have distinct load application and measurement systems. The T-6 uses a split leading axle on the trailing truck to apply the nominal gage-spreading force of approximately 14 kips and gage is measured on the axle for the loaded condition and in the center of the vehicle using a mechanical buggy for the unloaded condition. The TrackStar uses a split axle deployed near the center of the vehicle to apply the nominal gage-spreading force of approximately 10 kips and gage is measured using a laser sensor system just in front of the split axle for the loaded condition and in front of the front hi-rail gear for the unloaded condition.

The test was conducted in Union Bridge, Maryland, on the Maryland Midland Railroad (MMR), which has been extensively surveyed by FRA's GRMS. The entire 48-mile-long mainline FRA Class 2 track was surveyed by both vehicles. The track structure with several localized exceptions is jointed 115 RE and timber ties varying from "new" to "poor" condition. The track alignment includes curves up to 10 degrees with grades up to 2 percent.

Load application differences between the two vehicles was one of the primary concerns. The TrackStar, a lighter vehicle, required a load control system to maintain the vertical and lateral loads within AREMA recommended limits. The loads measured by both vehicles during these tests meet AREMA requirements. The variation of the test load was evaluated by determining the standard deviation over a mile of track. The 0.79 kips standard deviation for the TrackStar indicated better load control compared to the 1.32 kip standard deviation for the T-6. Drift in one of the load sensors on the TrackStar was noted during testing but did not appear to adversely affect the data since the nominal gage-spreading load was maintained, the drift resulted in a difference between left and right loads which was corrected intermittently. The vertical load variation between the two vehicles was approximately the same with a standard deviation of approximately 1.07 kips for the T-6 and 1.27 kips for the TrackStar. The applied loads met AREMA requirements for GRMS testing.

During Phase I, the maintenance and safety exceptions were compared for the two vehicles. The TrackStar recorded safety exceptions at a rate of 5.7 to 1 compared to the T-6 [9]. This high number of safety exceptions results in many paint marks on the track and made it difficult to visually confirm many of the safety exceptions from the TrackStar. The safety exceptions from the T-6 appeared to correspond with noted TrackStar safety exception locations. The TrackStar recorded maintenance exceptions only over 5 miles, making it difficult to evaluate the relative performance of the two vehicles.

During Phase II, the accuracy and precision of the two systems were evaluated. Both systems provide very repeatable data indicating suitability for GRMS testing. The accuracy of the two systems was evaluated by stopping the vehicles and measuring loaded and unloaded gage with a gage bar as a reference. The unloaded gage for both vehicles in tangents compared well with the gage bar and was suitable for GRMS testing. In curves, the TrackStar measured approximately 1/8 in. wider gage than the gage bar, which is a significant problem since this error can dominate any gage widening under load. Holland Company has evaluated this problem and provided a calibration, but the problem should be investigated in more detail since the cause of the problem postulated by Holland does not appear to cause the magnitude of unloaded gage error measured during the test. The T-6 measured unloaded gage accurately in curves compared to the gage bar. Loaded gage in both curves and tangent track compared well with the gage bar for both vehicles. Further evaluation of the systems in Phase II indicated that the loaded gage measured by the TrackStar was up to ½ in. wider than the T-6 and the PTLF. An examination of the load and gage data from this track section indicated that the active lateral load control applied by the TrackStar maintained the load at prescribed test conditions even when entering weak track zones where the axle must extend. When the axle extends at weak track zones, the applied lateral load on the T-6 drops up to 30 percent resulting in lower measured loaded gage compared to the prescribed test conditions at nominal load. Further examination of this problem revealed it was due to a combination of differences between the systems: nominal load conditions, influence of the second truck axle on the T-6 which is not present for the TrackStar, and the load drop at weak zones up to 30 percent. These factors were evaluated using available data and found to account for an approximately 30 percent greater loaded gage measured by the TrackStar, which was confirmed with data from the test and analysis.

During Phase III, the two systems' ability to identify zones of good and poor track conditions relative to gage widening problems was evaluated.

Assuming Holland Company can fix the noted problems with the test vehicle: load sensor drift and unloaded gage error in curves, it appears to provide an accurate indication of the basic parameters needed to safely conduct GRMS surveys. The derived parameters from the TrackStar of GWR and PLG24 tend to be significantly higher in weak track locations than the T-6. This results partially from the up to 30 percent difference in loaded gage due to differences in the applied load and test conditions. The unloaded gage error would also contribute to the difference in curves, but detailed analysis of data from tangent track was conducted to develop some insight about the relative differences between the two systems that would remain if Holland Company can calibrate the unloaded gage system for accuracy in curves. If the measurement error and load differences are correctly addressed, a large difference could still exist between GWR and PLG24 data from the TrackStar and T-6 due to the nonlinearity of the load dependency. PLG24 accounts for this nonlinearity explicitly, although further analysis to evaluate if this accurately reflects the load differences between the T-6 and TrackStar is required. GWR does not account for the nonlinearity of the load dependency and some effort to establish a suitable means to calculate GWR for the different load conditions of the T-6 and TrackStar should be investigated.

Based on the evaluation, both vehicles meet AREMA requirements for GRMS testing. Holland Company should address the significant problem of the unloaded gage error in curves to ensure safety and the load sensor drift should also be addressed. Differences in the load application between the two systems results in up to 30 percent higher loaded gage measured by the TrackStar. This results in higher GWR and PLG24 values and identifying many more locations as safety exceptions. The safety exception locations appear to identify T-6 noted safety exception locations, indicating that TrackStar performs the GRMS function adequately by noting the T-6 safety exception plus others. In no instance did the TrackStar indicate a safety exception that was not correctly evaluated by the T-6 based on current standards and minimally acceptable conditions. Using the current standards limits, the TrackStar appears to identify track conditions that are less critical to safety defects than the T-6. The main challenge remaining is to develop standards and limits that provide for any acceptable measurement system to safely and efficiently evaluate similar minimally acceptable track conditions equally.

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