Federal Railroad Administration

Report to Congress:
Committee on Transportation and Infrastructure of the House of Representatives

Committee on Commerce, Science, and Transportation of the Senate

---

FAST Act Report on Vertical Track Deflection

August 2016

U.S. Department of Transportation

Federal Railroad Administration

METRIC/ENGLISH CONVERSION FACTORS

ENGLISH TO METRIC

LENGTH (APPROXIMATE)

1 inch (in) = 2.5 centimeters (cm)
1 foot (ft) = 30 centimeters (cm)
1 yard (yd) = 0.9 meter (m)
1 mile (mi) = 1.6 kilometers (km)

AREA (APPROXIMATE)

1 square inch (sq in, in^2) = 6.5 square centimeters (cm^2)
1 square foot (sq ft, ft^2) = 0.09 square meter (m^2)
1 square yard (sq yd, yd^2) = 0.8 square meter (m^2)
1 square mile (sq mi, mi^2) = 2.6 square kilometers (km^2)
1 acre = 0.4 hectare (he) = 4,000 square meters (m^2)

MASS - WEIGHT (APPROXIMATE)

1 ounce (oz) = 28 grams (gm)
1 pound (lb) = 0.45 kilogram (kg)
1 short ton = 2,000 pounds (lb) = 0.9 tonne (t)

VOLUME (APPROXIMATE)

1 teaspoon (tsp) = 5 milliliters (ml)
1 tablespoon (tbsp) = 15 milliliters (ml)
1 fluid ounce (fl oz) = 30 milliliters (ml)
1 cup (c) = 0.24 liter (l)
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 yard (cu yd, yd^3) = 0.76 cubic meter (m^3)

TEMPERATURE (EXACT)

[(x-32)(5/9)] °F = y °C

METRIC TO ENGLISH

LENGTH (APPROXIMATE)

1 millimeter (mm) = 0.04 inch (in)
1 centimeter (cm) = 0.4 inch (in)
1 meter (m) = 3.3 feet (ft)
1 meter (m) = 1.1 yards (yd)
1 kilometer (km) = 0.6 mile (mi)

AREA (APPROXIMATE)

1 square centimeter (cm^2) = 0.16 square inch (sq in, in^2)
1 square meter (m^2) = 1.2 square yards (sq yd, yd^2)
1 square kilometer (km^2) = 0.4 square mile (sq mi, mi^2)
10,000 square meters (m^2) = 1 hectare (ha) = 2.5 acres

MASS - WEIGHT (APPROXIMATE)

1 gram (gm) = 0.036 ounce (oz)
1 kilogram (kg) = 2.2 pounds (lb)
1 tonne (t) = 1,000 kilograms (kg)
= 1.1 short tons

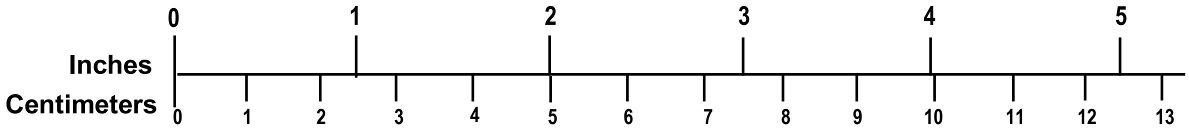
VOLUME (APPROXIMATE)

1 milliliter (ml) = 0.03 fluid ounce (fl oz)
1 liter (l) = 2.1 pints (pt)
1 liter (l) = 1.06 quarts (qt)
1 liter (l) = 0.26 gallon (gal)
1 cubic meter (m^3) = 36 cubic feet (cu ft, ft^3)
1 cubic meter (m^3) = 1.3 cubic yards (cu yd, yd^3)

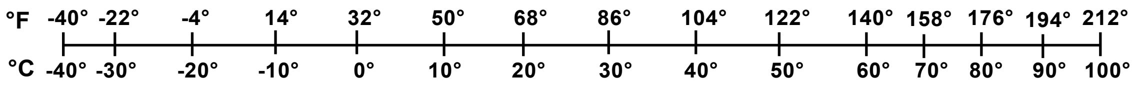
TEMPERATURE (EXACT)

[(9/5) y + 32] °C = x °F

QUICK INCH - CENTIMETER LENGTH CONVERSION



QUICK FAHRENHEIT - CELSIUS TEMPERATURE CONVERSIC



For more exact and or other conversion factors, see NIST Miscellaneous Publication 286, Units of Weights and Measures. Price $2.50 SD Catalog No. C13 10286 **Updated 6/17/98**

Contents

Illustrations

Tables

Executive Summary

On December 4, 2015, President Obama signed into law the Fixing America's Surface Transportation Act (FAST Act) (Pub. L. 114-94). Section 11414 of the FAST Act, "Report on Vertical Track Deflection," requires the Secretary of the Department of Transportation (Secretary) to submit a report to Congress on various topics related to vertical track deflection (VTD). This report addresses the four items specifically identified in the FAST Act: (1) the findings and results of testing of VTD instrumentation during field trials on revenue service track; (2) the findings and results of subsequent testing of VTD instrumentation on a Federal Railroad Administration (FRA) Automated Track Inspection Program (ATIP) geometry car; (3) recommendations for developing quantitative inspection criteria for poor track support using existing VTD instrumentation on ATIP geometry cars; and (4) an assessment of whether a recommendation for installing VTD instrumentation on all remaining FRA ATIP geometry cars no later than 3 years after the date of enactment of the FAST Act is warranted.

FRA is aware of the safety risks posed by poorly supported track. A number of recent accidents have had primary or secondary causes related to track support. Inadequate support can result in joint bar failures, tie deterioration, and poor track geometry. FRA has been working with universities and the railroad industry to develop approaches and technologies capable of measuring VTD under typical service loads. The VTD system discussed in this report is one element of the program FRA is developing to better understand the significance of track deflection and support. While VTD research is particularly challenging, the University of Nebraska-Lincoln (UNL) has deployed a prototype system on FRA's DOTX 218 track inspection car in 2015.

This report addresses the four FAST Act requirements as follows:

1. During field trials on revenue service track, the UNL VTD system identified some conditions that required immediate attention because they posed or created a potential safety hazard, i.e., "safety level conditions." However, the majority of the conditions identified by the system did not pose an immediate safety risk, such as derailment, yet required some corrective maintenance to slow further deterioration. These locations are referred to as "maintenance level conditions" and are left to the railroad industry to address based on the characteristics of their particular operation. The raw measurement produced by the UNL system has not been shown to differentiate between safety level and maintenance level locations. VTD may need to be coupled with other inspection data to effectively identify safety hazards and determine the specific track failure modes;

2. The current version of the UNL system is installed on a FRA ATIP car. This system is being used to collect additional data to: (a) better understand how it performs when installed on different vehicle types (weights, suspensions, placement in consist, etc.); (b) better understand the correlation between the measurements produced by the system and safety risks; and (c) help develop and validate thresholds that accurately identify safety risks;

3. FRA plans to develop quantitative inspection criteria for poor track support using existing VTD instrumentation on its ATIP geometry cars. Parametric analyses, which examine the relationship between track deflection and failure of track components, are needed to establish safety limits on VTD that can be used to identify high-risk track locations with poor or inadequate support. Such analyses will evaluate the effect of deflection amplitude and wavelength on rail stresses, tie integrity, and other failure-related modes associated with track and its components; and

4. The VTD measurement system is not ready to be implemented throughout the full ATIP fleet due to the need for further research to establish a set of criteria to positively identify unsafe track conditions.

1 Introduction

Since the early 1970s, FRA has been funding research that focuses on developing systems that can measure VTD due to applied load. Several systems have been developed with limited application (see Appendix A). Recently, FRA initiated a research project with UNL to develop a system that can measure VTD from a moving rail car. FRA and the railroad industry are currently evaluating this VTD system to determine its capabilities, particularly its ability to identify areas with variation in the characteristics of the track structure that require remedial action from the railroad. As a result of FRA's research, the principals at the University of Nebraska formed MRail Inc. (MRail) to commercialize the VTD system. The original FRA prototype is known as the UNL/MRail system. Recently, MRail agreed to provide Harsco Rail with exclusive worldwide sales and marketing of their VTD system.

This report is in response to a statutory mandate in section 11414 of the FAST Act. That section requires the Secretary, no later than 9 months after enactment of the FAST Act, to prepare a report on the research conducted or procured by FRA in developing a system that measures VTD from a moving rail car. This report discusses the four items required by the FAST Act: (1) the findings and results of testing of VTD instrumentation during field trials on revenue service track; (2) the findings and results of subsequent testing of VTD instrumentation on a FRA program geometry car; (3) recommendations for developing quantitative inspection criteria for poor track support using existing VTD instrumentation on FRA ATIP geometry cars; and (4) recommendation for installing VTD instrumentation on all remaining FRA ATIP geometry cars no later than 3 years after the date of enactment of the FAST Act.

A team of researchers and industry partners was assembled to gather data and conduct the research for this report. In gathering the data, a questionnaire was developed and sent to industry partners that have used or are currently using VTD technology. The responses to these questionnaires were incorporated into the findings presented in this report.

2 Background

Railroad vehicles introduce vertical, lateral, and longitudinal forces while operating over track. The track structure is responsible for transmitting these service loads to the ground. Since the 1800s when railroad transportation started, the track structure has been a focus of research. The general design of the track structure, as shown in Figure 2-1, consists of the two rails, ties, fasteners, ballast, subballast, upper subgrade soil, and lower subgrade soil.

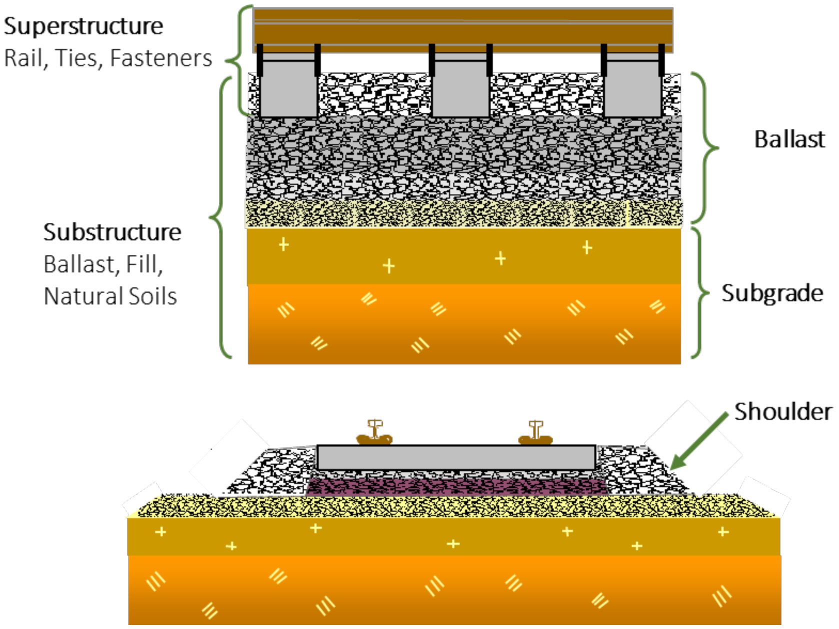


Figure 2-1 Track Structure (Source: Selig and Waters, 1994)

When a train travels over the track, the track deflects due to the applied vertical force as shown in Figure 2-2. Researchers quantify the track deflection using different measures such as track stiffness, track modulus, and track dynamic compliance. Track stiffness is used to define the amount of the track deflection due to applied static (low-frequency) load at a certain location. Track modulus is used to account for the nature of the track structure as it is supported along the track. Hence track modulus is used as an average of the track stiffness per length of the track. Track dynamic compliance is used to account for the variation in the track deflection due to the variation of the frequency and the amplitude of the applied vertical force.

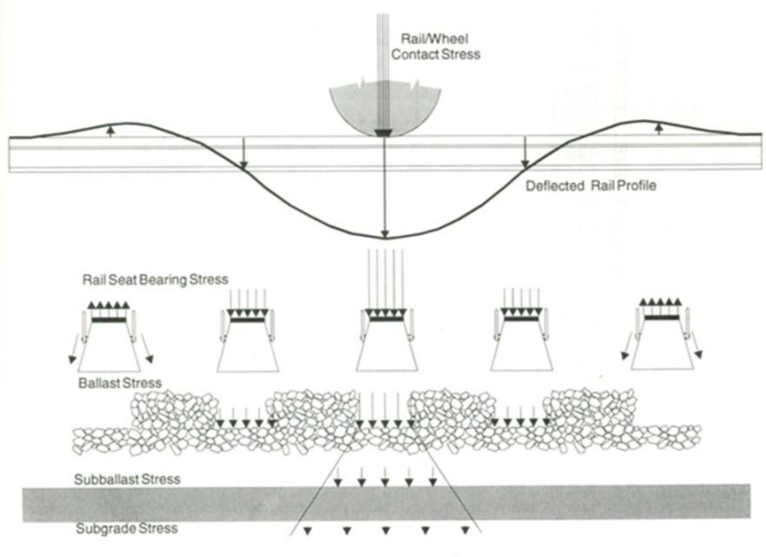
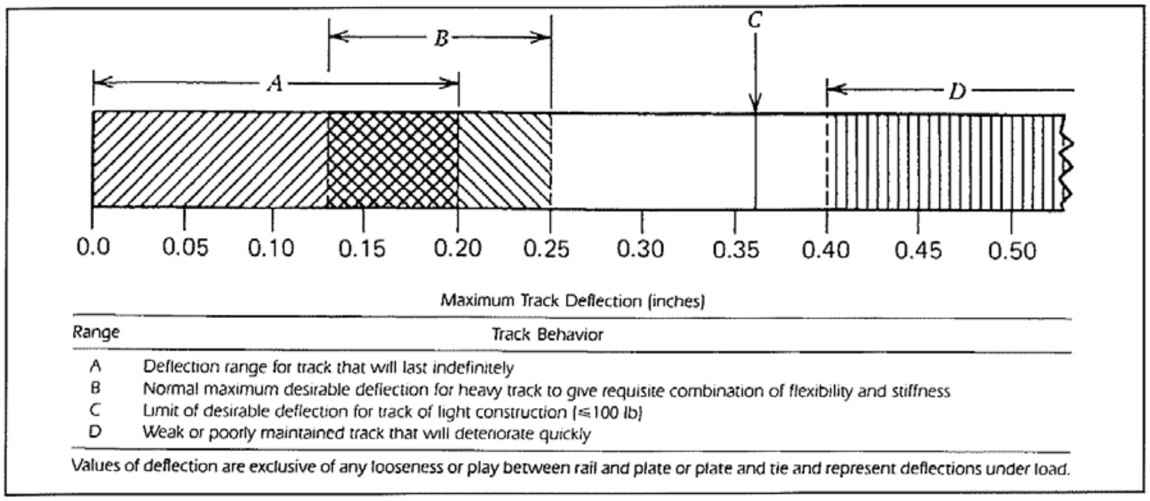


Figure 2-2 Track Deflections Under Wheel Load (Selig and Waters, 1994)

Railroad track is a relatively simple system to construct using ties, fasteners, and rails often supported on ballast (gravel or crushed stone) and subballast. The simplicity of the system belies the relative complexity and interaction of the components and the importance of the components to appropriately distribute the traffic loads. The deterioration of any component or layer can be viewed to have a detrimental effect on other components of the system. Large track deflections often indicate some combination of degraded ties and fasteners and poor ballast and subgrade layers. The degraded components often do not adequately distribute the load in the structure leading to further component deterioration.

The American Railway Engineering and Maintenance-of-Way Association (AREMA) Manual of Recommended Practice identifies VTD as a key parameter indicative of the performance of track. Track deflection is described in the AREMA manual with the recommendations that deflection should be less than 1/4 inch and greater than 1/8 inch to minimize strain and fatigue in the rail or wheels (AREMA, 2011). The small range indicates that track that is either too soft or too stiff may be problematic, as shown in Figure 2-3.



Range	Track Behavior
A	Deflection range for track that will last indefinitely
B	Normal maximum desirable deflection for heavy track to give requisite combination of flexibility and stiffness
C	Limit of desirable deflection for track of light construction (≤100 lb)
D	Weak or poorly maintained track that will deteriorate quickly

Values of deflection are exclusive of any looseness or play between rail and plate or plate and tie and represent deflections under load.

Figure 2-3 Deflection Ranges Associated with Track Life (Source: Choros, 1985)

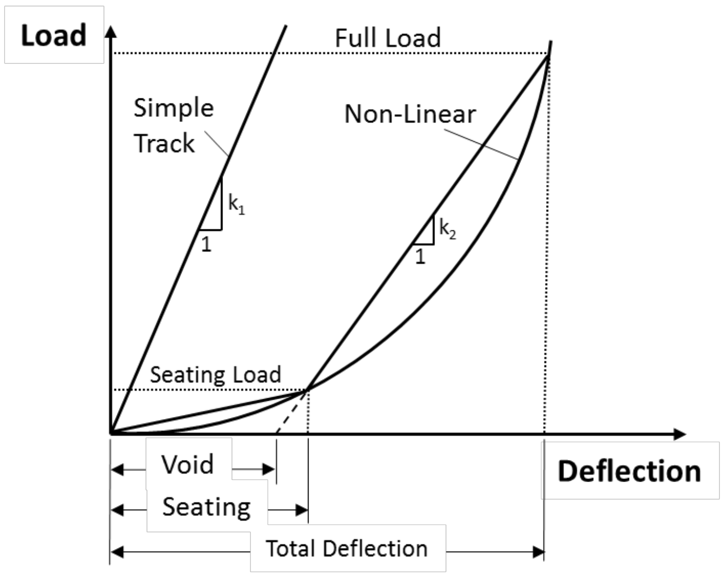
Since large vertical track deflection is thought to increase the stress on all track structure components, and cause more rapid deterioration of the track superstructure and support layers, VTD systems are designed to identify segments of the track with large vertical deflection under the axle loads as indicators of weakened structures.

2.1 Impacts On Track Structure

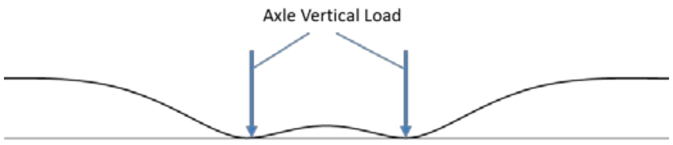
A new track structure that is properly constructed with appropriate ballast and good geometrical alignment often supports train loads with little deflection or deterioration. As each track component wears and degrades over time from traffic loads and environmental effects, the track gradually deforms. When this deformation is uniform and small, the track is considered to be exhibiting normal settlement. When these deformations are not uniform, track support is changed and can lead to greater non-uniform deformation and more stress on track components.

Most railway track can be described as stable, meaning that little track settlement occurs and track geometry does not deteriorate significantly. However, as track structure and subgrade problems develop, while only affecting a small percentage of total track mileage, these locations require maintenance and these areas may pose an increased derailment risk.

The structural behavior of well performing track can often be characterized by the track stiffness, k (units of force/length), which is represented by the slope of the load-deflection curve for simplified linear track as shown in the left portion of the illustration in Figure 2-4a. When the track stiffness is uniform longitudinally, with the same support at each tie, the track will deflect in a characteristic shape shown in Figure 2-4b. This shape is often called the track deflection basin and the magnitude and longitudinal shape are a function of the individual tie support stiffness.



a) Load-Deflection Behavior



b) Track Deflection Basin Below One Truck

Figure 2-4 Track Load-Deflection Characteristics (Sussmann et al., 2001)

Since the track structure deteriorates over time due to the development of voids and/or areas of reduced strength in support layers, a non-linearity in the load-deflection curve can develop as shown to the right of the illustration in Figure 2-4a. The longitudinal distribution of this stiffness characteristic influences the distributions of reaction force at each supporting tie resulting from traffic. The presence of voids or areas of reduced strength can result in increased VTD.

Variable track stiffness, often resulting from non-uniform tie support, can be a source of higher concentrated loads and increased dynamic loads associated with tie degradation, ballast degradation and track geometry deviation growth (Lundqvist and Dahlberg, 2003).

If a gap develops at any of the structural layer interfaces, each passing wheel will result in an impact load as the gap is closed. Although passing traffic may not be directly or noticeably influenced by these gaps, the loads transmitted through the structure may increase (Lundqvist and Dahlberg, 2003). Another concern with track slack related to these gaps is whether all components return to their previous positions following the passage of the train, such as the rail not seating in the tie plate properly.

Open-graded hard rock ballast provides the necessary resilience to support and distribute applied loads from the tie to the ballast. When the ballast becomes fouled, the resiliency is reduced along with the inter-particle contact stress, which can allow relative movement of the ballast particles, settlement of the tie (Selig and Waters, 1994 and Ebersohn, 1995), and may lead to the formation of a gap between the tie and ballast layers. Subgrade settlement can also results in a gap between the ballast and tie. Tie-ballast gaps may not be uniform laterally across the tie or along the track, further exacerbating the load distributing capacity of the structure. Problems related to inadequate track support, often manifested as tie-ballast gaps, may include rapid deterioration of track geometry due to saturation related rearrangement of ballast and roadbed materials and advanced deterioration of track structure components.

Examples of track structure deterioration due to excessive loads on concrete ties include abrasion of the tie bottom as well as the area where the rail seats on the tie, cracking and structural failure, as well as deterioration of the elastic fastener that is used to secure the rail to the tie. Ties can crack in the center when overloaded, especially if ballast support is non-uniform and high in the center of the tie. Vibration of the fastener may affect its ability to maintain its load carrying capability as its hold on the rail loosens. On track with wood ties, spike pull, plate-cut ties, and wood tie bottom abrasion are examples of deterioration and failure modes that may occur under high loads, especially with the vibration that may develop when slack is present in the track.

2.2 History of VTD Measurement Technologies

Since its inception in the 1970s, FRA's Office of Research, Development, and Technology (ORDT) has pursued multiple projects related to VTD measurement technology. During this period, FRA's research focused on the challenges of developing such a system on moving cars where a fixed and accurate reference frame necessary to measure the absolute VTD is hard to establish. In the 1970s, FRA designed and manufactured its first prototype VTD measurement system. The main objective of this research was to build a prototype of a test vehicle that can be used to measure VTD under vertical dynamic loads. The relation between vertical dynamic load and VTD was investigated to establish the track dynamic stiffness as one of the parameters to characterize the track structure. Following this research, FRA extended the development of the VTD measurement system by employing different technologies that were well established by the late 1990s. In this research, FRA developed a new system called the walking beam, where measuring deflection was based on tracking the position of a heavily loaded car relative to an adjacent lightly loaded car. Due to the requirement of using two cars to achieve the required VTD measurements, FRA started a second research effort that relied on measuring the accelerations of two axles with different applied vertical load. The measured vertical accelerations of the two axles were processed to determine VTD due to the difference between the two axle vertical loads. Although this approach showed promising results, the reliability of the system was poor due to the short life expectancy of the sensors that were affected by the high vibration introduced by the required applied vertical load. In 2002, FRA started its most recent VTD development research initiative with UNL.

FRA has continued research into the use of VTD to support the diagnosis of track performance problems and develop quantifiable track structural characteristics. Initially, better diagnosis of safety risks at locations that appear in existing datasets, such as track geometry, was the goal. The FRA Office of Railroad Safety maintains the Railway Accident/Incident Reporting System (RAIRS) for tracking derailment causes and trends. Consideration of data available in RAIRS loosely associated with ballast and subgrade problems, shown in Figure 2-5, along with the limited information on the track structural characteristics associated with these derailments, pointed to the need to better quantify track support variations. While the number of track support-related derailments per year is relatively low, the damage associated with derailments resulting from structural failure of the track can be significant. Recently, FRA's VTD system developed by UNL was installed on the FRA's DOTX 218 Gage Restraint Measurement System (GRMS) vehicle. FRA envisions that having a system on its ATIP vehicles will provide a large set of data it can analyze to help establish the safe levels of VTD.

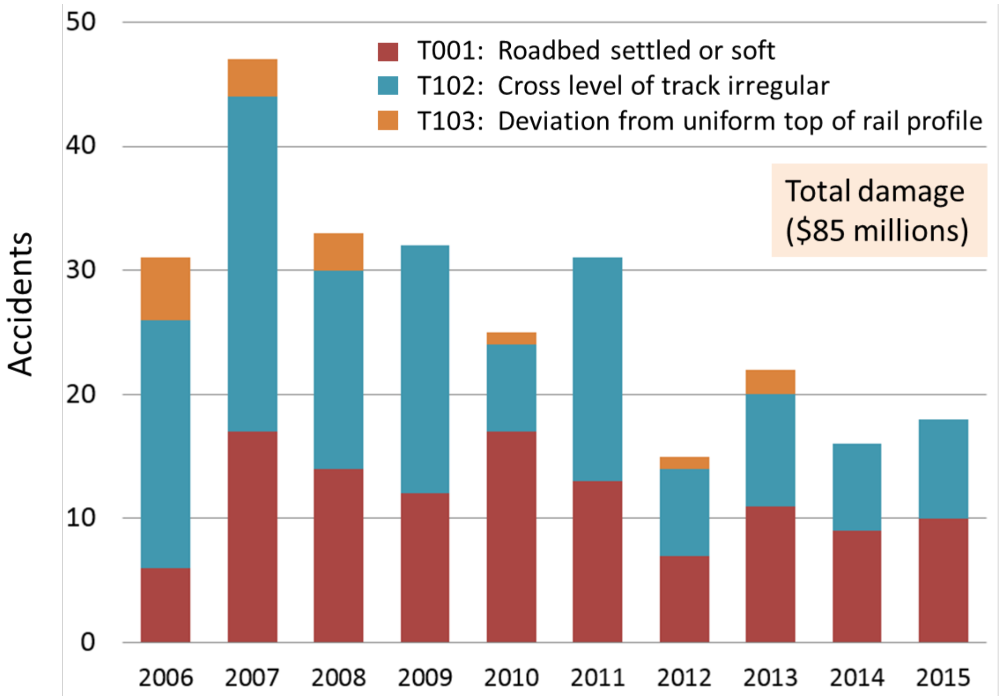


Figure 2-5 Ballast and Subgrade Related Accidents per Year

(FRA Office of Railroad Safety Railway Accident/Incident Reporting System)

2.3 Potential Safety Risks Associated with VTD

As discussed in Section 2, the track structure provides the required resistance to the forces applied by the railroad vehicle when operating over the track. When the track structure is vertically loaded, VTD will occur. This VTD is the sum of the bending of the rail, the compression of the substructure (ballast, etc.), and any gap located between the ties and the ballast. The amount of the VTD due to the vehicle load should be limited to the value the track can restore to after the vehicle passes. If the VTD value is too large, a permanent alteration to the track shape may exist after passage of the vehicle. This alteration is commonly seen as a change in the track geometry or failure of a track component. The geometry of the track has a significant impact on rail vehicle dynamics and thus is one of the key parameters for identifying safety risks. VTD may be an important indicator of locations where track geometry may change at a rate that could quickly lead to a safety risk. In addition, a large VTD may be the result of a gap between rail and ties and/or between ties and ballast (void). This gap can cause high-impact vertical force that can damage the vehicle or the track components causing the vehicle to derail or provide poor ride quality.

In addition, VTD can cause additional indirect track structure problems in the lateral and longitudinal directions. This can happen when ties are not fully surrounded by ballast. For instance, when the track starts to move in the vertical direction and the vehicle applies a lateral force, the track can shift laterally. Lateral track shift can cause vehicle derailment. FRA, through ORDT, is investigating other potential safety risks associated with VTD. These safety risks may be categorized as follows:

1. Failure or rapid deterioration of track superstructure components, including ties, fasteners, rail, and joint bars, due to increased load or stress;

2. Unrestrained track or rail due to settlement of the track supporting layers allowing the formation of gaps between the rail and tie or tie and ballast;

3. Inadequate ballast strength resulting in increasing risk of ballast related instability, including track buckling and track shift; and

4. Foundation failure resulting in an unsupported track structure.

Safety Risks 1 and 2 are most directly related to VTD. For example, research performed by FRA's ORDT to find the incipient condition for broken joint bars showed some preliminary correlation between a visual estimate of track deflection and broken joint bars (Bruzek and Jamieson, 2014). While the mechanism of failure seems clearly linked to VTD, thresholds are still required. Threshold development will require a scientific basis for assessing failure, such as identifying load limits for Safety Risk 1 and particular examples that demonstrate Safety Risk 2 and help to link the risk to VTD magnitude. The remaining safety risks require development of a clearer link between the track failure mode and VTD. For instance, testing will be required to develop a deflection range for track with loose or unconsolidated ballast to fully assess the relationship between unconsolidated ballast and lateral track strength, and the possibility that VTD might help mitigate Safety Risk 3. In addition, developing a link that connects Safety Risk 4 to increased track deflection will require working with the industry to identify a location susceptible to foundation failure and developing a test to evaluate if VTD might be a leading failure indicator.

The following sections do not describe all aspects of track structural issues, but rather provide examples of problems that may be identified by considering VTD along with other available information.

2.3.1 **Failure or Rapid Deterioration of Track Superstructure Components**

Track structure deterioration due to excessive loads and or excessive movement causes concerns for overall rail integrity, rail joints, welds, ties and fastener systems including tie plates, pads, insulators and clips, and ballast. For concrete ties, the risks include tie bottom abrasion, rail seat abrasion, cracking and structural failure, as well as deterioration of the elastic fastener. Ties can crack in the center when overloaded, especially if ballast support is non-uniform and high in the center of the tie. Vibration of the fastener may affect the clips ability to maintain restraining load (toe load) as well as vibrating clips loose. On wood tie track, spike pull, plate cut ties, and wood tie bottom abrasion are examples of deterioration and failure modes that may occur under high loads, especially with the vibration that may develop when slack is present. Of particular concern are the influence of large track deflection on rail crack growth and superstructure integrity. Furthermore, as components degrade and fail, the rail may become unrestrained leading to the second safety risk condition.

2.3.2 **Unrestrained Track or Rail**

Large track deflections associated with gaps in the support structure have the risk of the rail not seating as designed and allowing foreign objects to move between the tie and rail. For instance, track ballast, or spikes could move between the rail and tie interfering with the rail seating in the preferred position and creating potentially large concentrated loads that can lead to rail breaks. If the rail does not return to the required alignment position, track safety can be compromised.

2.3.3 **Inadequate Ballast Strength**

Locations with large VTD have reduced capacity to laterally and longitudinally restrain track. Inadequate ballast strength associated with poor ballast consolidation is characterized by reduced stiffness, resulting in increased VTD which might be captured using a VTD measurement technique. Ballast with inadequate strength cannot restrain the track, allowing it to move in vertical, longitudinal and lateral directions. If the track can move longitudinally under thermally induced longitudinal loads, the neutral temperature (the temperature where the longitudinal force is zero) can be reduced, increasing the rail buckling force in track. The reduced track lateral strength will reduce track resistance to lateral buckling.

2.3.4 **Foundation Failure**

The pressure transmitted to the subgrade must be significantly lower than the strength of the subgrade soils to ensure the track is supported without excessive deformation under repeated loading. In cases where applied stress exceeds subgrade strength, the subgrade generally deforms in one of three modes: (1) massive shear; (2) progressive shear; and (3) plastic deformation (Selig and Waters, 1994). Massive shear failure is a shear type failure below the track similar to that associated with slope instability, and is the least common but most catastrophic failure mode and potentially the most challenging to detect based on VTD measurement. Progressive shear failure, generally termed subgrade squeeze, is characterized by remolding of the soil at the subgrade surface, squeezing of the remolded soil into the track shoulder, and surface manifestation as a track shoulder heave. The result can be a variation in VTD from one end of the tie to the other end. Plastic deformation, generally termed ballast pockets, is caused by settlement of the subgrade soil with little or no lateral deformation. The surface manifestation is initially profile variations with variable track support from tie to tie and in advanced stages may be indicated by track slack or gaps between components.

2.4 Current Development Status of the VTD Measurement

This section discusses the technical details of the UNL/MRail VTD measurement system. It summarizes how the measurement is made, the UNL-developed criteria, a description of loaded geometry based end-chord offset (ECO) measurement, and the VTD metrics as they relate to the previously described potential safety risks.

2.4.1 Technical Approach

The UNL/MRail VTD system measures a component of the total vertical deflection of a rail from a moving platform at revenue service speeds. This is accomplished through lasers and a camera mounted onto a side frame of a standard railroad truck assembly. The loaded rail car transfers the forces through the side frame to the wheels into the track. A line projected through the loaded wheel contact points on the rail is used as an instantaneous reference. The UNL design relies on a laser line striking the rail at a specific distance, normally 4 feet, from the nearest axle and a camera to capture an image of that line on the rail. The angle of the lasers is such that the laser lines shift position as the rail moves up and down. A video camera records the projection of the laser line on the head of the rail. These images are then processed to determine the instantaneous vertical location of the rail at the camera location (H_L) as shown in Figure 2-6. The vertical height of the deflected rail (y_{rel}) is determined by subtracting the measured (H_L) from the predetermined vertical location of the camera with respect to the line connecting the contact points of the truck wheels (H_R) as shown in Figure 2-6. Each rail has its own camera and lasers to determine its deflection independently. To this end, it is important to mention that y_{rel} represents the rail deflection plus the existing rail space curve profile geometry.

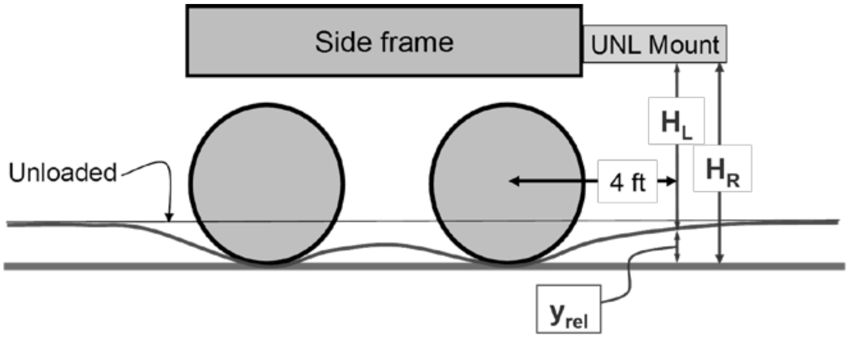


Figure 2-6 University of Nebraska-Lincoln Measurement Approach

The measured vertical height of the deflected rail (H_L) is affected by the rail space curve profile geometry, the motion of the frame where the system is installed (because this motion will affect the estimated constant (H_R)), and the dynamic load of the wheel and the adjacent car (because its load can affect the shape of the deflected rail (basin)).

To eliminate the effect of the existing rail space curve profile geometry, the track geometry needs to be measured and removed. To do so, a measurement known as the end chord offset (ECO) is used. The ECO is a vertical distance from a given point from the nearest axle to the UNL/MRail system (L_1) on a loaded measured geometry of the space curve representing the rail to the theoretical line projected through two additional points located at the wheel/rail contact points on the same loaded space curve; the general representation of the ECO is shown in Figure 2-7. The determined ECO is then subtracted from the determined vertical height of the deflected rail (y_{rel}) to calculate the rail vertical deflection.

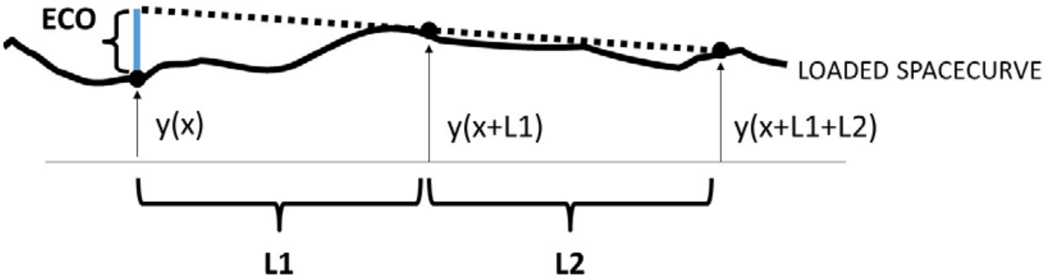


Figure 2-7 Illustration of End Chord Offset

2.4.2 **VTD Metrics**

When FRA took the initiative to develop the UNL/MRail system, the initial goals were:

1. To develop a system that can accurately measure vertical track deflection from a moving car at revenue speeds; and

2. To run the system autonomously so that data can be collected automatically.

In 2010, FRA determined the UNL/MRail system had achieved these two goals. To examine the achievement of the second goal, UNL/MRail conducted several field measurements. These field measurements were later examined and an initial categorization of the severity of the vertical track deflection was set by UNL/MRail based on the value of y_{rel}. This categorization was examined by field visits to assess the condition of the track. In most cases, FRA found the measurements did not always increase with the increasing severity of the track condition. In some instances, a y_{rel} measurement of 0.5 inch had more perceived safety risk than a y_{rel} measurement of 1.0 inch (see Farritor and Fateh, 2013). y_{rel} was found to locate zones affected both by track geometry and reduced track support stiffness. By subtracting the ECO from y_{rel}, the VTD system was able to identify specific locations with weak or soft support. Therefore, FRA concluded combining this data with other track data, such as track geometry to help discriminate specific risks from other locations with data of similar magnitude, may be needed to determine the condition of the track structure. In addition, FRA recently concluded the use of the magnitude of the measured y_{rel} is not the correct approach to determine VTD safety metrics and these values may need to be normalized to the other factors such as dynamic wheel load and segment length.

In general, the magnitude of localized track deflection (i.e., deflection in short distance along the track) can be associated with failure or rapid deterioration of track superstructure components and unrestrained track or rail (Safety Risks 1 and 2 as discussed in Section 2.3). However, the longer the track has been exposed to this repetitive loading, the higher the severity of the risk due to wear and fatigue to the track and components. This highlights one challenge in this research: interpretation of this data is not dependent on only deflection magnitude. The length of track over which the deflection occurs also has some bearing on the severity of the track problem. Thus, a general concept for interpretation of VTD data is to identify high-magnitude track deflection zones and assess the severity of the problem. Coupled with this field investigation are analyses of critical loading and deflection cases for rail and ties. This coordinated effort is a part of a planned and ongoing FRA ORDT research program investigating track support and substructure requirements. This plan includes correlation of track geometry degradation rates to track support characteristics like VTD, and developing an analytical basis for reduced component life supported by VTD data for rail, joint bars, ties, and ballast.

Work to analytically characterize the safety risks that might appear in VTD data for inadequate ballast strength and foundation failure (Safety Risks 3 and 4 as discussed in Section 2.3) is planned. Until mechanistic links between these safety risks and VTD data are observed, speculation about a potential safety metric is likely premature. Canadian National Railway (CN) and the University of Alberta have made substantial progress in correlating UNL/MRail y_{rel} data averaged over long wavelengths to the identification of substructure track support problems. The current FRA research project that employs DOTX 218 is examining several techniques to process y_{rel} data adjusted for track geometry in real time in terms of characteristic track lengths. This will facilitate field investigations of locations of concern. Whether other effects such as dynamic wheel load or segment length are important to the measurement and issues of repeatability or directionality remain to be investigated.

3 Revenue Service Testing

During research conducted to develop the UNL/MRail system, over 39,000 miles were tested with a variety of cars and in partnership with different railroads as described in Table 3-1. The initial concept developed by UNL was evaluated using a tank car and caboose. Shortly after demonstrating the concept and finalizing the test load and data collection requirements, a Union Pacific Railroad (UP)-owned hopper car was provided to UNL for revenue service testing under more stable loading conditions at revenue service speeds.

Table 3-1 MRail Test Summary

Designation & Vehicle Type	Deployment	Years of Service	Railroads or Territories Tested	Mileage of Reported Measurements
Tank car/caboose*	UNL Research	2004-2005	BNSF, UP, OPPD	555
UNLX002 Hopper Car	UNL Research and Testing Service	2006-present	BNSF, UP, CP, Indiana Railways	24,000
CN-NOK1322034 Gondola Car	CN Test Vehicle	2013-present	CN	4,000
DOTX 218** Manned Inspection Vehicle	FRA Research and Testing	2014-present	Continental United States	7,200
TUVX001 Hopper Car	TUV Rhineland Testing Service	2013-present	BNSF, Alabama Gulf Coast	3,600
Totals				**39,355**

* Manned operation
** Mounted on truck with primary suspension. Unmanned system operating on manned car.

3.1 Hopper Car

The UP hopper car UNLX002, shown in Figure 3-1, tested approximately 24,000 miles primarily on UP and BNSF Railway (BNSF) track. Most of this testing was sponsored by FRA between 2006 and 2012 and consisted of system evaluation and repeat tests for analysis of measurement reproducibility and investigation of track changes related to traffic-caused deterioration and seasonal climatic variations. Additional testing was conducted on Indiana Railways and Canadian Pacific Railway (CP). The Omaha Public Power District (OPPD) track of Indiana Railways was a major focus area where the system was routinely evaluated. This track had limited traffic, which was beneficial for system evaluation and modification allowing the car to stop at specific locations and evaluate the track conditions leading to specific measurements and system performance characteristics.

Figure 3-1 UNLX002 Hopper Car and Measurement System (Farritor and Fateh, 2013)

Figure 3-2 shows all y_{rel} measurements above 0.5 inch recorded during a survey of UP's South Morrill Subdivision. In this example, there were more than 275 locations exceeding 0.5 inch on each of the rails of main track 2. However, the majority of the conditions identified by the system did not pose an immediate safety risk. The results shown in this example survey are typical of other surveys.

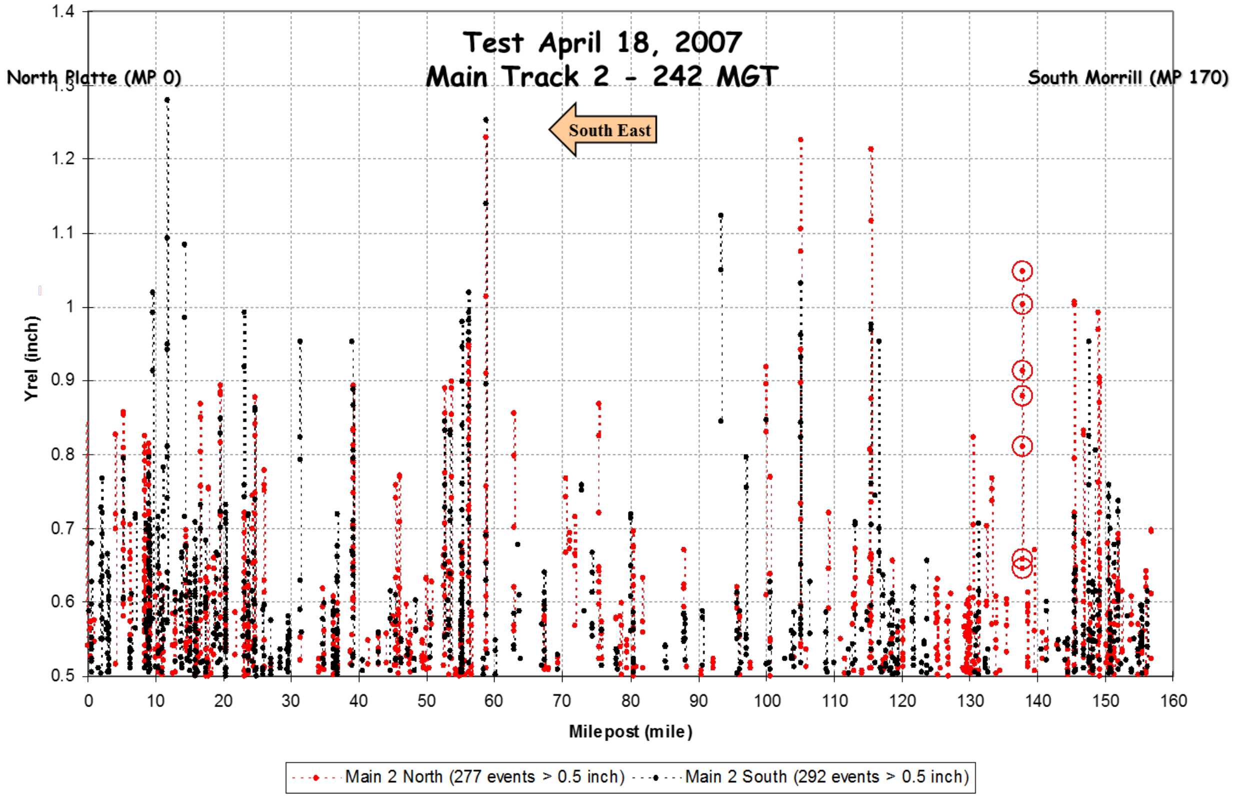
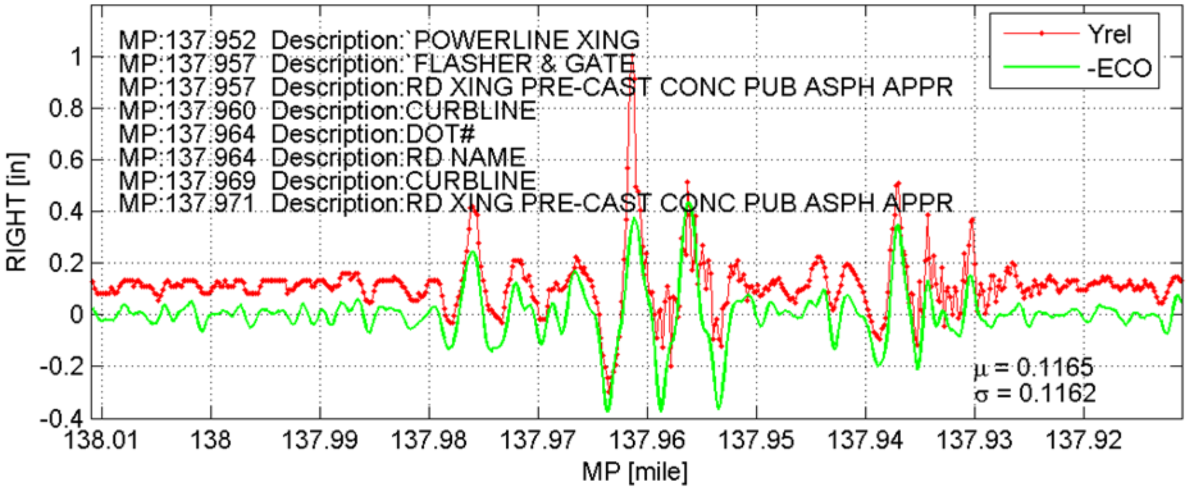


Figure 3-2 Example Yrel Survey Results on UP's South Morrill Subdivision

The hopper car consist was used to test high-tonnage track for UP several times a year for 6 years. Selected sites were used to evaluate trends that might help assess track deterioration. In most instances, y_{rel} peaks identified changes in track support. However, during one test, a particularly large peak y_{rel} value was observed, as shown in Figure 3-3a. This peak resulted from a highway-rail grade crossing location adjacent to a zone of poor concrete ties where a rail defect was found and a plug rail installed with 2-bolt joint bars. The poor track support condition had a small impact on track geometry shown by the peak in ECO of approximately 0.3 inch. The particularly poor track conditions and the combination of potential problems highlights the type of sites and the associated risks potentially identified by this system.



a) Data

b) Site Photo

Figure 3-3 Measurement System Data (y_{rel}) and Site Photos

The UNL hopper car was also used by BNSF to evaluate the jointed track over which the Amtrak Southwest Chief travels in Kansas and Oklahoma. BNSF employed the UNL/MRail system to assess track support conditions and help improve how the railroad prioritizes joint maintenance. Previous findings that show track support is a critical element for proper joint performance indicate that this location would be expected to fail prematurely.

3.2 Industry Testing

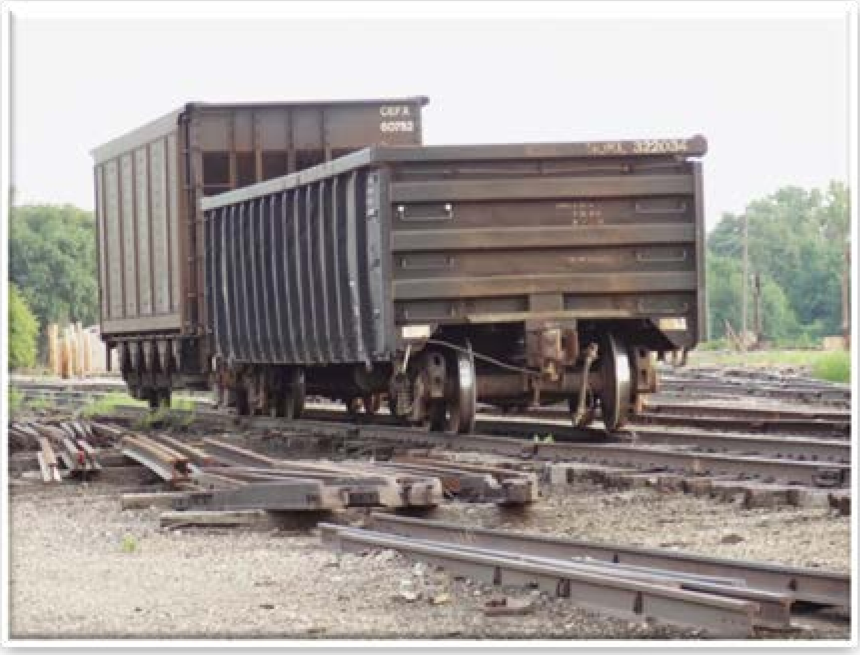
The railroad industry has conducted a wide variety of testing with the MRail system. UP and BNSF both supported the FRA-funded UNL research including a thorough evaluation of the system on the UP's Yoder Subdivision in 2008. As FRA-sponsored testing was winding down and FRA support to commercialize the system took priority, UP continued to support MRail by sponsoring a year of monthly testing to demonstrate annual trends and degradation rates of VTD data. During this time, MRail built an additional system for testing on BNSF and other railroads.

A third system placed on a gondola car was constructed to support testing requested by CN (Hendry et al., 2016). The CN system is currently being considered for migration onto a CN track geometry car, although other technology for obtaining track deflection data may be ultimately used by CN.

BNSF responded to a request for information about MRail testing by indicating that it is still evaluating the system and it will take at least a few more months to assess the correlation between MRail data and fouled ballast, deteriorated ties, and other conditions. To date, no railroad has indicated that it will discontinue MRail testing.

Testing of the MRail system during industry supported projects represents a significant effort in the development of track support evaluation measurement technology. The single largest effort in this area was conducted by CN which collected over 4,000 miles of data with a dedicated gondola car (Figure 3-4). This effort was in response to a 2004 derailment on the Levis Subdivision in Alberta where a progressive maintenance problem requiring addition of ballast and surfacing ended in an embankment failure illustrated in Figure 3-5. The progressive nature of the maintenance and the ultimate failure culminated in CN's evaluation of the MRail technology to improve understanding of track support and help identify safety risks due to unseen track support problems.

The data resulting from the CN testing was evaluated by researchers at the University of Alberta who concluded that the MRail measurement data can be filtered to remove the effects of track geometry while leaving the effects of variations in track support over longer distances. If confirmed, this finding could establish a way to assess the development of unseen weaknesses in track support as they develop. The challenge will be to pinpoint the particular layer and type of substructure weakness, and use this knowledge to assess the potential risk of an embankment failure.



a) CN MRail Measurement Car

b) MRail System on CN Measurement Car

Figure 3-4 CN MRail Measurement Car (Hendry et al., 2016)

Figure 3-5 CN Levis Subdivision Derailment (Source: Transport Canada, 2004)

3.3 FRA DOTX 218

A different version of MRail system is installed on a FRA DOTX 218 GRMS vehicle where it is attached to the truck side frames behind the inboard axle of one of the trucks (Figure 3-6). The DOTX 218's truck side frames are located above the suspension springs, allowing independent movement of each axle. Therefore, for the DOTX 218 installation, the system relies on four Linear Variable Differential Transformer (LVDT) assemblies, one above each wheel, to monitor the relative displacement of the axles with respect to the vehicle. These measurements are necessary to account for relative motion between the truck fame and the wheel to update the constant distance (H_L) as discussed in Section 2.2.4.

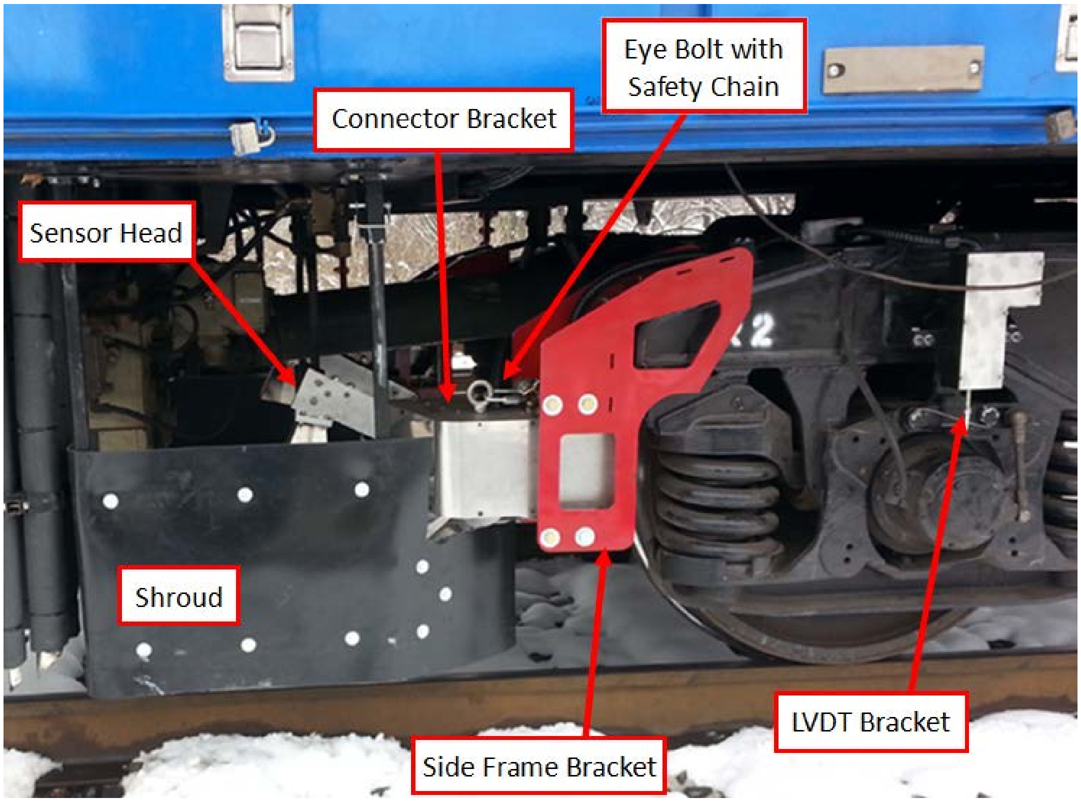


Figure 3-6 Vertical Track Deflection Measurement System Assembly on DOTX 218

The system's two sensor assemblies housing a camera and a class 3b laser are mounted directly above the rails and oriented so the laser and camera are focused on the rail 4 feet from the wheel-rail contact point. Shrouds have been installed in the system to block direct sunlight on the laser line. An enclosure containing the system's data collection and processing computer, cellular modem, and communication hub for all components of the system is located inside DOTX 218. An antenna assembly mounted on top of the vehicle allows for transmitting recorded data as well as remote access into the system for diagnostic purposes.

Since the installation of the system in early 2014, FRA has used the VTDMS to measure VTD in selected sites to evaluate the system. The system was originally configured to automatically start and stop recording along with other measurement systems installed on DOTX 218 and transmit recorded data required for post processing to yield y_{rel} values along the track. FRA is currently in the process of integrating the VTDMS with other measurement systems on the DOTX 218 to produce processed y_{rel} measurements and report them along with other track measurements in real time.

4 VTD Quantitative Inspection Criteria Development Plan

FRA’s ORDT is currently evaluating using VTD as an inspection tool. FRA presently has not developed formal inspection criteria associated with installation of the VTD system on the DOTX 218. This is because FRA is currently evaluating the system for functionality, repeatability, and the relationship of VTD track assessment data collected by other inspection systems such as track geometry, GRMS, Ground Penetrating Radar, and track bed imaging systems. This ongoing research and system evaluation will include application of VTD measurement and track support evaluations of track-caused derailments to help better understand the causes leading to potential track support failure, and how these telltale signs of safety risk might possibly be detected using VTD in concert with the full suite of inspection technologies available to FRA and industry.

A major aspect of the development of VTD-based inspection criteria will be to review the conditions under which track geometry may not be stable for the periods of time between inspections and develop hypotheses for specific failure modes that will be sought out in a review of technical literature, tested in the lab, and assessed in the field by FRA regional track inspectors. As part of this research project, FRA’s ORDT will work with regional inspectors to develop a more comprehensive evaluation of track support at derailment locations possibly linked to track support problems as well as assess what safety risks are most appropriate for detection with VTD technology.

There are, however, several aspects of potential inspection criteria that have been considered based upon similar applications of VTD in countries such as Canada and Australia. Inspection criteria needs in those countries focus on a more complete assessment of the track structure including characteristics of track support layers not typically included in U.S. derailment reports. FRA expects to investigate how to include this data in inspection reports when appropriate.

VTD measurement has shown utility in diagnosing causes of variations in track support that appear to be linked to safety related failure modes as discussed in section 2.3 of this report. As these failure modes are further clarified, it may be useful to have more than one measurement system available. A phased implementation may be warranted during the research phase of the FRA ORDT program to provide researchers with the data necessary to develop this measurement system into a more mature inspection technology as well as expose FRA track inspectors and the industry to this technology. A phased implementation will also provide the opportunity for FRA inspectors to critically comment on whether the data is helpful in improving track safety. Critical feedback from inspectors on how this technology could be most useful will be crucial to the success of the implementation of VTD criteria since the inspectors will be the users of this inspection technology and they have the most direct link to current and emerging safety concerns.

5 VTD Implementation Plan on ATIP Fleet

Prior to installing VTD instrumentation on the entire ATIP fleet, FRA will need to develop a VTD metric that can differentiate between a safety level defect location that needs immediate repair and a location that is degraded but is still serviceable and safe (see Section 2.3). Without this metric, the VTD system would produce many false positives that do not pose a safety risk. In addition, a small number of safety conditions would be buried in the output, making it difficult for railroad to verify and remediate. Once developed, that metric would then need to be included in a rulemaking so that it could be incorporated into FRA's regulations.

The current program has installed a version of the system on an ATIP car (DOTX 218 described in Section 3.3) and data is being collected during ATIP surveys. The processing algorithms are being developed and refined to operate on the car. The information collected by the VTD system will be integrated with the track geometry data to aid in developing the required safety metric. In addition, while the data is being collected and processed in real time, locations that exceed a predefined threshold will be evaluated and documented by field personnel. This approach, over a period of time, will allow the metric developed to be refined resulting in appropriate thresholds that are considered a safety risk in need of immediate repair.

Analytical modeling will be conducted in parallel to the hardware testing. This modeling will evaluate each of the failure modes described in Section 2.3. From this modeling, the appropriate safety metric algorithm will be developed, evaluated, and implemented on DOTX 218.

Installing VTD instrumentation on the entire ATIP fleet utilizing the UNL/MRail system will require a laser to be mounted in a manner that targets the rail at a location 4 feet from loaded axle. Clearances would have to be made to allow the appropriate swing required by the VTD system mounting brackets. This will require that the cars be redesigned, modified, or replaced to incorporate the VTD technology. The funds needed to install VTD systems on the ATIP fleet are not included in the Congress' current FY 2016 appropriation for FRA ATIP.

A future recommendation for implementation will be generated upon successful completion of the VTD modeling, metric development, and evaluation program.

6 Conclusions

In this report, FRA has addressed the items in the FAST Act regarding Vertical Track Deflection. The FAST Act requirement for this report corresponds to a number of recent accidents that had primary or secondary causes related to track support.

FRA is aware of the safety risks posed by poorly supported track. Inadequate support can result in joint bar failures, tie deterioration, and poor track geometry. FRA has been working with universities and the railroad industry to develop approaches and technologies capable of measuring vertical track deflection under typical service loads. Significant effort has been expended over the years to develop methods and techniques to measure track deflection including the VTD system developed by UNL. This system, which was initially funded through a grant by FRA's ORDT in 2011, measures an approximation of track deflection from a moving vehicle.

The VTD system discussed in this report is one element of the program that has been underway to better understand the significance of track deflection and support. While VTD research is particularly challenging in terms of both measurement system development and safety limit thresholding, the desirability of both a measurement system and safety limits has been demonstrated by strong support from the railroad industry. The industry continues to evaluate the utility of the system to identify safety critical track locations and as a maintenance planning tool. This cooperative effort has advanced the research to the point that a prototype system has been deployed.

The conclusions of this report are:

1. During field trials on freight corridors, the UNL VTD system identified some conditions that required immediate attention because they posed or created a potential safety hazard, i.e., safety level conditions. However, the majority of the conditions identified by the system did not pose an immediate safety risk, such as derailment, yet required some corrective maintenance to slow further deterioration. These locations are referred to as maintenance level conditions and are left to the railroad industry to address based on the characteristics of their particular operation. The raw measurement produced by the UNL system has not been shown to discriminate between safety level and maintenance level locations. VTD may need to be coupled with other inspection data to effectively identify safety hazards and determine the specific track failure modes.

2. Parametric analyses, which examine the relationship between track deflection and failure of track components, are needed to establish safety limits on VTD that can be used for identifying high-risk track locations with poor or inadequate support. Such analyses will evaluate the effect of deflection amplitude and wavelength on rail stresses, tie integrity, and other failure-related modes associated with track and its components.

3. The current iteration of the UNL system has been installed on an FRA ATIP car. This system will be used to collect additional data to better understand how the system performs

when installed on different vehicle types (weights, suspensions, placement in consist, etc.), to better understand the correlation between the measurements produced by the system and safety risks, and to help develop and validate thresholds that accurately identify safety risks.

4. Implementation throughout the full ATIP fleet is not recommended at this time due to the need for further research to establish a set of criteria to positively identify unsafe track conditions.

7 References

AREMA (2011). Manual for Railway Engineering, American Railway Engineering and Maintenance-of-Way Association, Volume 4, Chapter 16, Part 10, "Economics of Railway Engineering and Operations – Construction and Maintenance Operations", Landover, MD.

Bruzek, R and D. Jamieson (2014). "Joint Bar Failure Study Field Investigations – Final Report," ENSCO Report SERV-REPT-0000718, Draft report for FRA, December 2014.

Choros, J. (1985). Laboratory Tests on Three Alternative Track Structures, Association of American Railroads, Report Number R-614, September.

Ebersohn, W. E. (1995). *Substructure Influence on Track Maintenance Requirements*. Doctoral Dissertation, Civil Engineering, University of Massachusetts Amherst, Geotechnical Report AAR95-423D, February.

Farritor, S. and M. Fateh (2013). Measurement of Vertical Track Deflection from a Moving Railcar, U.S. DOT, Federal Railroad Administration Report No. DOT/FRA/ORD-13/08.

Hendry, M., Roghani, A., and M. Zhang (2016). Assessment of a Technology for the Measurement for Rail Track Deflection. Draft report for Transport Canada, RDIMS 9113219.

Lundqvist, A. and Dahlberg, T. (2003). "Dynamic forces in railway track due to unsupported sleepers," Twelfth Nordic Seminar in Railway Mechanics, June 1-3, 2004, Luleå.

Selig, E. T., and J. M. Waters (1994). *Track Geotechnology and Substructure Management*. Thomas Telford, London.

Sussmann, T. R. and Ebersohn, W. E., and Selig, E. T. (2001). "Fundamental Non-Linear Track Load-Deflection Behavior for Condition Evaluation," Journal of the Transportation Research Board, Transportation Research Record No. 1742, Intercity Passenger Rail; Freight Rail; and Track Design and Maintenance, pp. 61-67.

Transport Canada (2004). Main Track Derailment, Canadian National Railway Train U-781021-17, Levis Subdivision, Railway Investigation Report R04Q0040.

Abbreviations and Acronyms

AREA	American Railway Engineering Association
AREMA	American Railway Engineering and Maintenance-of-Way Association
ATIP	Automatic Track Inspection Program
BNSF	BNSF Railway (formerly Burlington Northern Santa Fe Railway)
BOEF	Beam on Elastic Foundation
CN	Canadian National Railway
DOT	Department of Transportation
ECO	End chord offset
FAST	Fixing America’s Surface Transportation
FRA	Federal Railroad Administration
GRMS	Gage Restraint Measuring System
LVDT	Linear Variable Differential Transformer
MCO	Mid-chord offset
MP	Milepost
ORDT	Office of Research, Development and Technology
RAIRS	Railway Accident/Incident Reporting System
TLV	Track Loading Vehicle
UNL	University of Nebraska-Lincoln
UP	Union Pacific Railroad
VNTSC	Volpe National Transportation System Center
VTDMS	Vertical Track Deflection Measurement System
y_{rel}	UNL measurement of relative vertical height of the deflected rail between wheel contacts and rail 4 feet from applied load

Appendix A: History of VTD Measurements

The most widely known early American measurements of VTD date back to the 1918–1940 Talbot reports on "Stresses in Railroad Track," which were recorded in committee reports for the American Railway Engineering Association (AREA), the predecessor organization to AREMA. These documents were compiled into a single report published in 1980 by AREA. These measurements linked the vertical track support condition to rail stress and included measurement of both the unloaded and loaded rail profile to develop measurements of the deflection basin. A.D. Kerr in his 2003 text Fundamentals of Railway Track Engineering describes the deflection basin method from the Talbot reports to develop the rail support modulus, often called track modulus, required for validation of the beam on elastic foundation (BOEF) estimates of rail stress (Hetenyi, 1946). However, variability in support from tie to tie often makes determination of the equivalent uniform support over a length of track as required for this calculation very challenging. Kerr (2003) describes an alternate method of evaluating track support by defining the track stiffness, which is simply the applied load divided by track deflection at a single tie. Selig and Waters (1994) describe this technique in more detail and describe the limited applicability of BOEF to realistic assessment of rail stress due to variability in track stiffness. Acknowledging that rail stress can increase substantially when track is not uniformly supported, several agencies have worked to develop track surface based measurements of track deflection. Both the magnitude of track deflection as well as variability along the track are critical to the identification of weak track support zones and locations susceptible to track superstructure component failure or substructure deformation and failure.

Association of American Railroads Track Loading Vehicle

The Association of American Railroads Track Loading Vehicle (TLV) is a specially designed rail car with a deployable axle with hydraulic actuators for loading the track structure and measuring the response in both vertical and lateral deformation modes. This vehicle is often setup for VTD testing to assess track support concerns using the difference between a loaded and unloaded track geometry measurement. As a dedicated vehicle, this measurement system can provide comprehensive data on track response to load.

Walking Beam by FRA/ENSCO

The walking beam system for measuring deflection was based on tracking the position of a heavily loaded car relative to an adjacent lightly loaded car. This system used a series of cameras and targets to track position. The roughly 20-foot length of the measurement across the two trucks and coupler created a strong influence of track geometry and limited the response of the system to rapid changes in track support. Most importantly, the required two-car consist made deployment challenging.

Accelerometer Based Deflection Assessment by Volpe/FRA/ENSCO

In cooperation with Amtrak, an accelerometer based profile measurement was developed for a loaded axle and an unloaded axle on the Amtrak Gage Restraint Measurement Vehicle. The accelerometers were directly mounted near the center of rotation of the axles. The resulting acceleration profiles were processed to develop a measure of the position of the unloaded and loaded rail profiles. The subtraction of these profiles yielded a measure of track deflection. The harsh vibration environment resulted in short sensor life, making this approach a challenge.

Profilometer

A profilometer is based on the dynamic response of the track and was investigated in the 1970s by FRA to develop a measurement for track compliance (inverse of stiffness). More recently, Banverket developed a dedicated railcar with a sprung mass dynamic system that could be used to deflect the track and measure the vertical response. This system has the capability to provide a nearly full load-deflection curve for each tie while moving continuously, providing one of the most useful assessments of track support. However, the measurement system requires a dedicated test car.

MRail

The MRail system was developed by UNL under FRA research funding. The system was developed to assess vertical track deflection based on the relative change in position from wheel/rail contact to a point 4 feet in front of the wheel, thus measuring the central portion of the deflection basin created by a load on the track. The general concept is that the weaker the support, the more the rail will deform making the response of this system larger in weaker track locations. However, the system does not measure the full deflection and due to the 10-foot length over which the measurement is made (including the wheel base of the truck), the system is affected by track geometry variations including pitch of the side frame of the truck to which the measurement system is mounted. This system is still being evaluated to assess system response to vertical track deflection, but has the potential to identify high-risk short wavelength variations in track deflection such as rail-tie and tie-ballast gaps, which are missed by other systems such as the TLV, which is focused on assessment of strength under track load.

Track Vertical Stiffness Measurement by ENSCO/Chinese Ministry of Railways

Starting in 1992, ENSCO and the Academy of Railway Sciences under the Chinese Ministry of Railways embarked on an initiative to determine track vertical stiffness on a continuous basis using loaded and empty rail vehicles. The system was comprised of two flat cars of identical dimensions; each car was supported by two single axles. One car was heavily loaded while the other car was left empty. Follower wheels were added on either side of one axle on each car to allow the measurement of vertical rail geometry in the form of a three-point chord. When the two vehicles were towed in tandem over a section of track, left and right vertical profiles of the track were measured under the two different loads. The difference between the profile measurements captured under the different loads was obtained by subtracting one set of measurements from the other after shifting and aligning the two sets of data. In doing so, inherent variations in track geometry were largely cancelled out; remaining differences were thought to be caused by differences in deformation under different loads. The resulting data was to be filtered and averaged to arrive at a “track stiffness indicator.” This indicator was to be correlated with measured stiffness using other known methods. The system was built and data was collected over selected track sections. There were observable differences between chord-based profile measurements captured under the heavy and light cars and the observed difference exhibiting variations over different track segments. These observations indicated that a stiffness indicator could be derived through this process. However, the Academy of Railway Sciences did not complete the study by correlating the observed differences with actual track stiffness measured by other means.