Abstract

The Transportation Technology Center Inc. (TTCI) and Kelsan Technologies Corp. have undertaken a collaborative effort under FRA funding to assess the suitability of dynamic Rail Deflection Gauge (RDG) instrumentation and associated post-processing algorithms as a means to verify Top of Rail (TOR) friction modifier performance on a territory-wide basis. This work has included the manufacture of a prototype instrument, as well as extensive testing across a range of track structures and lubrication conditions at TTCI’s FAST test loop in Pueblo, CO. In addition, in-field correlation and verification has been conducted at a North American Class 1 freight mainline test site. The resulting data shows good correlation with lateral force measurements, suggesting that the technique has merit as a means to assess TOR friction management.

Introduction

Top of Rail (TOR) friction control through train-mounted or trackside based application of thin-film friction modifiers has been shown to produce several key benefits including reductions in lateral forces [1,2,6,11,14,16], rail wear [6,11,14,16], fuel consumption [2,3,4], corrugation growth [5,8], squeal and flange noise [8]. Detecting the presence of an applied friction modifier can be difficult in the field, as the film distribution and thickness preclude simple observation. Other conventional friction measurement techniques, such as portable hand operated tribometers (used to measure railhead friction), have provided variable results. The use of these instruments is particularly challenging in territory-wide trackside application settings, where wheel conditioning appears to dominate the film distribution mechanism [7]. As such, verification of friction modifier coverage and performance over an extended territory is a challenging task.

The most common method utilized to date for verifying TOR friction modifier performance is to monitor changes in lateral curving force performance over a period of time. This is generally done utilizing strain gauge based lateral/vertical load sites [1,2,6,11,14,16]. These sites provide an accurate, calibrated measure of absolute loads exerted on the track structure. The cost of installing the sites, however, makes numerous and widely spaced locations or frequent relocation (required to examine performance over an extended area) unattractive. As such, the development and use of a more portable and lower cost comparative instrument which provides similar information would be advantageous.

To this end, a new instrument and associated software algorithms have been developed for measuring and analyzing rail deflection data. The Linear Voltage Displacement Transducer (LVDT) based instrument measures motion of the rail head relative to the tie, providing an indirect measure of lateral forces. The analysis software uses a running estimate of the relaxed state of the rail to calculate peak dynamic deflection on a per-axle basis.

Relationship between Lateral Forces and Rail Deflections

For the purposes of the work presented here, “Rail Deflection” is defined as lateral motion measured at centre of the field side of the railhead relative to the tie. The relative rail head to tie movement is brought about by the combination of translation, rotation and deformation of the rail relative to the tie surface, and is a function of tie condition, fastener strength, rail size, longitudinal rail stress and other local, site specific conditions. While additional movement of the rail and tie relative to the ground does occur, this movement is magnified by vertical load and support conditions, and is less sensitive to changes in curving forces generated by alternative friction patterns.

While the relationship between lateral forces and rail deflection (as defined above) is direct, it is made up of a combination of both linear and highly non-linear components. Elastic bending, shearing and rotation of the rail in
response to applied loads can be assumed to be (roughly) linear. Translation of the rail relative to the tie plate and tie plate relative to the tie, however, are also largely governed by (non-linear) sliding friction at these interfaces. Friction forces resisting movement vary with vertical load, which varies simultaneously with lateral load as each axle passes over the measurement site. The net result is a non-linear, stochastic motion that can result in quasi-steady state shifts of the rail’s resting position. This is particularly prevalent with “soft” track structures, as can be seen in the deflection signals shown in Figure 3 (results section of this paper).

**Rail Deflection Measurement Equipment**

The measurement and analysis of rail deflection has been carried out in the past using a range of trackside measurement equipment ([12,13] are among numerous examples). In some cases this has required driving of stakes into the ballast and setting up high precision non-contact measurement equipment, reducing the portability of the approach. Also, ground based measurement accuracy can be confounded by large vertical deflections that are not associated with lateral movement. As the primary goals of the instrumentation are portability and simplicity, tie mounted measurement equipment was considered.

The prototype Rail Deflection Gauge (RDG), shown in Figure 1, collects lateral rail deflection measurements through LVDT based displacement probes. Metal base plates are rigidly fixed to the tie to establish a measurement datum, and the LVDT probes are then mounted using adjustable brackets such that the probes make contact at the center of the vertical rail head surfaces on the field-side. The measurement probes have a travel of 30mm, independent linearity of 0.2%, repeatability of 2 µm and operating bandwidth of 18Hz.

![Figure 1. Typical lateral rail deflection measurement site layout](image)

All signals are collected by the RDG digital data acquisition system at a sampling frequency of 100Hz, after passing through analog 4th-order Butterworth anti-aliasing filters with break frequencies tuned to 50Hz (spectral analysis of rail deflection signals at typical freight speeds has shown that the meaningful characteristic frequencies are typically less than 10Hz). Analog-to-digital conversion resolution is 10 bits, resulting in a measurement resolution of 24 µm.

The signal from an active magnetic wheel sensor is used to trigger the system and track passing axles. Once triggered, the system collects data for a fixed period of time (corresponding to the maximum expected length of a single train), and then goes into a sleep-mode until the subsequent train is detected. Recorded sequences are stored in 8MB of on-board non-volatile memory for subsequent RS-232 based download. In order to allow for practical installation in a range of locations on a given territory, a rechargeable 12V lead-acid battery is incorporated (providing approximately one week of operation under normal operating conditions). When measurement durations longer than this are required, an external deep cycle battery is used to power the system.
Data Analysis Methodologies and Software

Figure 2 shows a simplified representation of the RDG data collection and analysis process. As shown, LVDT displacement and wheel sensor signals are collected by the data acquisition system at 100Hz and stored in on-board non-volatile memory. Subsequently, the raw data is downloaded from the DAQ system and post-processed using a PC-based software tool that has been developed specifically for the application.

The PC-based software performs two main functions. The first is peak recognition, and the second is non-linear compensation. The peak recognition software component uses the wheel sensor signal to obtain “start-points” for a search algorithm, which locates the extreme value of deflection (positive or negative) associated with each axle. Wheel sensor data is also used to establish axle groupings, which are then used to differentiate between cars and locomotives, leading/trailing/shared trucks and leading/trailing axles. Additionally, the relative timing of subsequent wheel sensor and LVDT peaks can be used to establish direction of travel and approximate speed.

The non-linear compensation component of the software is intended to provide a correction for the quasi-static stochastic shifts in rail position that are present in the raw deflection signal (these types of shifts are particularly prevalent in “soft” track structures, e.g. wood tie / cut-spikes as can be seen in Figure 3 below). When these quasi-static shifts are present in the signal, there is no “stable” reference position from which relative deflections can be calculated. As such, an algorithm is implemented to construct a running estimate of the “relaxed” position of the rail head, from which peak deflection values are calculated.

Experimental Demonstration/Test Programs

The experimental test program was divided into two phases. The first of these was conducted on the TTCI FAST-Heavy Axle Load (HAL) test loop in Pueblo, CO [14]. The second was conducted at an instrumented test site located on a mainline section of an eastern Class 1 freight railroad. In both cases, Rail Deflection Gauge (RDG) measurement equipment was installed immediately adjacent to Lateral/Vertical force measurement sites to allow for a direct comparison between measurement types. The following sections provide a detailed description of the test sites, track structures, traffic, lubrication / friction management capabilities and test plans.

Phase 1 Testing: FAST Test Loop

The FAST-HTL program at the Transportation Technology Center near Pueblo, Colorado operates on a dedicated 4.3 km (2.7 mile) loop of track. The FAST loop is constructed with a large range of track components, with conventional track that includes wood ties using both cut spike and direct fixation fasteners, and segments of concrete ties. Tonnage is applied with a 75-80 car train of loaded 113t (125 ton) cars pulled by 4 locomotives. Train operations are generally limited to 4 – 10 hour shifts per week, leaving daytime hours for track inspection, measurements and maintenance. This program is a cooperative effort with funding from AAR and FRA, and significant donations of equipment and materials from the railroads and suppliers.

A unique feature of the FAST program is that once the train starts operating; speed is maintained to a constant 64 +/- 3 kph (40 +/- 2 mph) for most of the shift. For this reason curving forces and other items leading to track degradation remain relatively constant at any one specific location throughout the shift unless something changes on the track or train. In the case of lubrication, changes in friction at the rail/wheel interface will generally alter truck steering and subsequently change curving forces at a specific location.

FAST operations are conducted with the outside rail of the loop protected by two standard wayside based gauge face lubricators (Portec Protector® IV) applying Lithium based, MoS2 grease. This keeps the outside rail of the loop fully...
lubricated facilitating long term rail fatigue tests, and controls rail and wheel flange wear in non test areas. The inside rail of the FAST loop does not receive direct gauge face lubrication, primarily to create a higher level of friction on the gauge face of the single 305m (1000ft) R350m (5 degree) reverse curve. This facilitates increased rail wear rates, allowing rapid evaluation of wear performance to be conducted. As some lubricant applied from the gauge face lubricators tends to migrate from the gauge side to the head of rail, a small amount of oil is applied to the inside rail to create a balanced top of rail friction. This unique lubrication process is conducted to create friction conditions on the rail that emulate what would be found in the field at a variety of curve locations.

During the FAST demonstration/test stage the RDG system was installed at locations considered to be “soft” and “stiff” to determine variations in sensitivity, resolution and correlation (recall than non-linear deflection components are more prevalent in “soft” track structures). At FAST, “soft locations” are comprised with conventional wood ties and cut spikes, with ties exhibiting a variety of splits, having been respiked and plugged over a number of rail replacement maintenance cycle. “Stiff” locations are on newer wood ties with direct fixation (DF) fasteners held down by screw spikes.

With the RDG system installed at each location, the following cycle of lubrication conditions was followed to produce a range of lateral loads for verification and correlation of RDG data:

1. Normal FAST lubrication (outside/high rail GF grease, inside/low rail TOR oil), used to produce balanced friction conditions and baseline lateral loads.
2. Inside/low rail oil turned off, to create a dry low rail TOR surface and increased lateral loads.
3. Return to normal lubrication.
4. Inside/low rail oil flooded, to improve truck steering and produce reduced lateral loads.
5. Return to normal lubrication.

**Phase II Testing: North American Class 1 Freight Railroad**

While results from the FAST demonstrations (presented below) were encouraging, the lack of variability in this environment requires that a field test be conducted to ensure that results could also be used to determine friction when a larger set of variables was introduced. The intent of a portable RDG system would be to determine if top of rail friction applicators were being deployed and adjusted to maximize results.

Key sources of variability in field evaluations include train speed, weight and makeup. A load station measures vertical as well as lateral loads, allowing calculation of L/V ratios and/or sorting of lateral forces by car weights. In its current form, RDG instrumentation can only determine lateral deflections (i.e. automatic sorting by car weight is not possible). While it is feasible to conduct post data collection sorting based on other database information (dispatcher or AEI reports), the intent is to limit the need for such information. Note that sorting by train speed is possible in both types of systems.

A site was offered by an eastern Class 1 freight railroad to conduct a limited field demonstration of the RDG technology. The test location is within a 32 km (20 mile) section of track, which is being monitored by the railroad and AAR/TTCI to document effects of increased axle loads. This area includes 28 wayside TOR applicators (14 on each of the 2 main tracks). This program is intended to supplement some of the limitations from closed loop testing at FAST, and therefore includes a number of similar monitoring techniques, including a load measuring station.

An ongoing effort by the railroad to implement and optimize wayside TOR at this site offered an opportunity to purposely alter application rates for a specific, but short, time period. As part of an overall assessment of TOR issues, the AAR was to document changes in curving forces when a wayside applicator becomes partially disabled or damaged, resulting in a left/right rail differential in friction control effectiveness. One concern is that if only one rail received TOR treatment the result may show increased curving forces on one side of a reverse set of curves.

By adjusting a wayside TOR applicator from “normal” to one (left) rail on, the other (right) rail off, then reversing the left/right bias, it would be possible to monitor:

1. Changes in curving performance on adjacent, reverse curves
2. Changes in RDG performance at the same locations and time.
The test location selected is on a back to back set of R285m – R255m (6.2 – 6.8 degree) reverse curves, with data monitored on the Mainline 1 track, which carries predominantly eastbound loaded coal unit trains and mixed intermodal traffic.

The nearest wayside TOR applicator is about 0.8 km (½ mile) west of the first reverse curve. Track in this area is predominantly wood tie, cut spike construction with 46 cm (18 inch) tie plates. A segment of plastic ties is being evaluated within one curve; however the load station is installed on standard timber ties.

To obtain differential application of TOR materials, the applicator piping was adjusted to cut delivery to both blades on one rail or the other. The sequence followed during this one week demonstration included:

| Day 1 | Normal TOR application rates on both rails. |
| Day 2 | Disable south rail application entirely, maintain slightly reduced rate on north rail. |
| Day 3 | Disable application to both rails. |
| Day 4 | Disable north rail application entirely, maintain slightly reduced rate on south rail. |
| Day 5 | Return to baseline, normal application rate. |

Results

Results from the demonstration/test program described above are presented here in three sections. The first (Part I) examines the characteristics of “raw” rail deflection signals (stiff and soft track structures) in both the time and frequency domains and compares/contrasts these signals with the data obtained from a strain gauge based lateral force measurement site. Part II presents the peak/peak correlation obtained in both FAST loop and field test settings. Part III examines the feasibility of assessing TOR friction modifier coverage with RDG measurements (again, in both FAST and field evaluation settings).

Part I: Lateral Force and Rail Deflection Signal Characteristics

Figure 3 shows an overlay of three 10-second signal traces corresponding to lateral force, RDG (stiff track) and RDG (soft track) measurements. Note that these traces are from separate measurement runs at FAST, and are overlaid to allow a qualitative comparison of signal characteristics. As shown, the rail deflection signal collected in a “stiff” direct fixation track structure has characteristics similar to those seen in lateral force measurements. Distinct peaks and a relatively stable zero-point are seen in both signals. In contrast, rail deflection measurements obtained in a “soft” wood tie / cut-spike structure contain additional low frequency components and gross shifts in the deflection signal produced by quasi-static rail movements. The presence of these gross shifts produces a “wandering” zero point, which makes analysis of dynamic rail deflection non-trivial.

![Figure 3. Characteristics of lateral force and rail deflection signals in “soft” and “stiff” track conditions. Note that the three traces shown are from three different train laps (i.e. the figure is intended to show qualitative differences in signal characteristics).](image)

In order to obtain further insight into the relationship between lateral force and rail deflection signals, a frequency domain (i.e., Fast-Fourier Transform) analysis was performed on raw time-series data from the FAST lateral load
and RDG measurement sites. Figure 4 shows the frequency spectra from lateral force and RDG signals recorded at a stiff track (direct fixation, wood ties) measurement location. Lateral force and rail deflection signals are shown on the left and right of the figure, respectively.

The fundamental frequency of ~1.2Hz in both signals corresponds to the “car-passing frequency”, i.e. the basic periodicity of the train. As seen in the frequency spectra, both the L/V and RDG signals contain peaks at the same fundamental and harmonic frequencies. Higher frequency peaks in the RDG data are attenuated, as can be expected from the mechanical transfer function that maps lateral force to deflection.

Figure 5 shows the frequency spectra from lateral force and RDG signals recorded at a soft track (cut-spikes, wood ties) measurement site. In this case, the RDG spectra contain additional content at frequencies near and below the car-passing frequency. This corresponds to the non-linear gross lateral shifts of the rail seen in Figure 3. The noise introduced by these shifts overlaps with the deflection data in the frequency domain. This further highlights the challenge in analysis of RDG data to produce meaningful results, particularly in soft track structures.
Part II: Correlation of Rail Deflection with Lateral Forces

As illustrated in Figure 2, after the raw deflection data described in the previous section has been collected and stored by the data acquisition system, it is downloaded and post-processed to calculate peak values of deflection relative to the (estimated) relaxed position of the rail. This allows for comparison with the peak values of lateral force, which are typically reported by lateral force measurement sites. Correlations between peak lateral force and rail deflection for leading axles are presented in this section (note that leading axles tend to produce significantly higher forces than trailing axles, making them the focus for analysis in friction management studies).

“Stiff” Track Structure at FAST

Figure 6 and Figure 7 show the correlation between per-axle peak lateral force and peak deflection for leading axles, obtained at a stiff track measurement location on the FAST test loop. Each data point in the figures represents the average values of per-axle peaks calculated for one test train lap. As might be expected from Figure 3, an excellent correlation between lateral force and rail deflection ($R^2=0.83$ to 0.99) is observed in the stiff track structure.

Non-zero intercepts in the correlation equations suggest that the correspondence between percent reductions in lateral force and rail deflections will not be purely proportional. It is expected that stiff track structures will perform better than soft structures in this regard. In addition, analysis of loaded cars will minimize the impact of nonzero intercepts via higher lateral forces and deflections in relation to the intercept values. This represents an opportunity for further improvement to the rail deflection post processing algorithms.

“Soft” Track Structure at FAST

Figure 8 and Figure 9 show the correlation between per-axle peak lateral force and peak deflection for leading axles, obtained at a soft track measurement location on the FAST test loop. Again, each dot in the figures represents the average values calculated for one test train lap. Despite the challenges in processing deflection data from this track structure, the peak detection and non-linear compensation algorithm resulted in a strong correlation ($R^2=0.89$ to 0.92) between peak lateral force and peak deflection.
Figure 8. Correlation between average lateral forces and deflections (leading axles, low rail) calculated per-lap at FAST RDG measurement site 1 (290m (6°) LH curve, soft track).

Figure 9. Correlation between average lateral forces and deflections (leading axles, high rail) calculated per-lap at FAST RDG measurement site 1 (290m (6°) LH curve, soft track).

Class 1 Freight Railroad Field Testing (“Soft” track structure)

Figure 10 and Figure 11 show the correlation between per-axle peak lateral force and peak deflection for leading axles, obtained at the Class 1 freight railroad test site. Each dot in the figures represents the average values calculated for one loaded eastbound train. As shown, the soft track structure and higher degree of variability in the field setting resulted in a somewhat weaker correlation ($R^2=0.48$ to 0.70) than was observed at FAST. While this represents an opportunity for further development in post-processing algorithm performance, the trend is encouraging and (as described in the next section) represents a relationship that can be used to determine TOR friction management conditions.

Figure 10. Correlation between average lateral forces and deflections (leading axles, low rail) for loaded trains in the 255m radius curve at the Class 1 field test site.

Figure 11. Correlation between average lateral forces and deflections (leading axles, high rail) for loaded trains in the 255m radius curve at the Class 1 field test site.

Part III: Verifying TOR Friction Control through Rail Deflection Monitoring

Having illustrated the correlation between peak values of lateral force and rail deflection in the section above, the utility of rail deflection measurements in assessing TOR friction modifier coverage and performance can be considered.

“Stiff” Track Structure at FAST

Figure 12 and Figure 13 show the time series per-axle peak lateral force and rail deflection data collected at the FAST loop (stiff track structure), with the lubrication test phases described in the Experimental Demonstration/Test Programs section (above) overlaid. Transitions between normal lubrication, “dry” low rail and “flooded” low rail
are clearly visible in both the lateral force and rail deflection data, with the data sets following a very similar trend. Lateral forces from approximately 50% to 200% of normal values were produced, with a corresponding range of rail deflection averages on the order of 1mm. Note that the secondary y-axes (rail deflection) are adjusted to produce an overlay based on non-zero intercepts in the correlation. In practical terms, this means that changes in rail deflection should not be interpreted on a percent change basis. Rather, they should be viewed in terms of an absolute shift in the deflection distribution.

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Figure 12. Average lateral forces and deflections (leading axles, low rail) calculated per-lap at RDG measurement site 2 (290m (6°) LH curve, stiff track).
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Figure 13. Average lateral forces and deflections (leading axles, high rail) calculated per-lap at RDG measurement site 2 (290m (6°) LH curve, stiff track).
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“Soft” Track Structure at FAST

Figure 14 and Figure 15 show the time series peak lateral force and rail deflection data collected at the FAST loop (soft track structure). Again, despite practical difficulties in analysis of soft track deflection data, transitions between normal lubrication, “dry” low rail and “flooded” low rail are clearly visible in both the lateral force and rail deflection data, with the data sets following a very similar trend. In this case it is worth noting the divergence of agreement between signals in the first 10 laps of measurement. This can likely be attributed to the FAST test track “settling” as a steady-state temperature is reached (note that physical movement of the track structure was observed with changing temperature).

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Figure 14. Average lateral forces and deflections (leading axles, low rail) calculated per-lap at RDG measurement site 1 (290m (6°) LH curve, soft track).
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Figure 15. Average lateral forces and deflections (leading axles, high rail) calculated per-lap at RDG measurement site 1 (290m (6°) LH curve, soft track).
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Class 1 Freight Railroad Field Testing (“Soft” track structure)

Figure 16 and Figure 17 show the time series peak lateral force and rail deflection data collected at the Class 1 field test site (soft track structure), with the TOR friction management test phases described in the Experimental Demonstration/Test Programs section (above) overlaid. As shown, higher degrees of variability in vehicle type and vertical axle load produce less “crisp” boundaries between the friction management test conditions than were seen in
FAST testing (this is true for both lateral force and rail deflection measurements). However, the response of the rail deflection measurements is very similar to that of the lateral force measurement site. As such, it can be expected that the number of rail deflection data points required to characterize TOR friction control performance will be similar to the number of lateral force data points used to characterize the same conditions.

![Graph](image1)

Figure 16. Average lateral forces and deflections (leading axles, low rail) calculated per-loaded train in the 255m radius curve at the Class 1 field test site.

![Graph](image2)

Figure 17. Average lateral forces and deflections (leading axles, high rail) calculated per-loaded train in the 255m radius curve at the Class 1 field test site.

Conclusions

A very simple, robust and portable prototype rail deflection gauge (RDG) measurement system (and associated post-processing software) has been developed to assess the suitability of rail deflection measurements in assessing top of rail friction modifier coverage and performance on a territory-wide basis.

Demonstration and testing has been carried out at both the TTCI FAST test loop and an eastern Class 1 freight railroad mainline test site. TOR friction conditions were modulated using existing lubrication / friction management capabilities at each and the RDG measurement system was installed adjacent to lateral force measurement sites for correlation purposes.

Variations in track structure can produce significantly differing deflection signals; with “stiff” track structures (i.e. direct fixation) generating deflections that closely mimic the signals seen from strain gauge based lateral force measurement sites. “Soft” track structures (i.e. wood tie / cut-spikes) tend to produce highly non-linear deflection signals with quasi-static shifts in rail position and low frequency dynamics superimposed on the linear deflection signal.

Correlations ranging from $R^2=0.48$ to 0.99 between peak lateral forces and peak deflections (compensated for non-linearities) were observed in FAST test loop and Class 1 field testing. Stiff track structures and higher lateral loads were found to produce stronger correlations. Non-zero intercepts in the correlation equations suggest that the correspondence between lateral force and rail deflection will not be purely proportional.

Per-axle peak values of rail deflection (leading axles) closely matched the trends seen in lateral forces when friction control test sequences were executed, suggesting that rail deflection can be used to assess TOR friction management coverage and performance with a similar number of samples as would be required using lateral force measurements.

Acknowledgements

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