ABSTRACT

Track modulus is an important parameter in track quality and performance. Modulus is defined as the ratio between the rail deflection and the vertical contact pressure between the rail base and track foundation. This paper describes the design of a system for on-board, real-time, non-contact measurement of track modulus.

Measuring track modulus from a moving rail car is non-trivial because there is no stable reference for the measurements. The proposed system is based on measurements of the relative displacement between the track and the wheel/rail contact point. A laser-based vision system is used to measure this relative displacement. Then a mathematical model is used to estimate track modulus.

This paper addresses new findings as a continuation of the University of Nebraska-Lincoln research presented at AREMA 2004. A description of the new system including the new loading platform and the new measurement/crew platform is presented in detail. The method of verification is discussed to provide the analytical basis for measurement. Finally, the results of recent field testing are presented for continuous measurement of 70 miles of track at moderate (≤40 mph) speeds from the moving system.
INTRODUCTION

Railroad safety is highly dependent on track quality. Track modulus is one of the accepted indicators of the quality and safety of railroad track. Modulus is defined as the coefficient of proportionality between the rail and the vertical contact pressure between the rail base and track foundation (1). More simply, it is the supporting force per unit length of rail per unit deflection (2). Track modulus is influenced by many factors such as the quality of rails, ties, rail joints, ballast, and sub-grade. The use of the word ‘track’ in this paper refers to all these components. Modern rail systems traveling at higher speeds require increasingly stiffer track to compensate for higher loads. Current methods include sending a work crew to a section of track with special equipment to apply known loads and measure the resulting deflection. This is an expensive, cumbersome, and a time consuming process. The result is knowledge of track modulus for only a short section of track.

Directly measuring track modulus is difficult. This paper presents the design of a system that will provide real-time measurements of track modulus from a moving railcar. Such a system could provide nearly continuous knowledge of track modulus for extremely long sections of track. Track modulus could be monitored over time to provide trending information to improve safety and decrease maintenance cycles.

Measurement of track modulus from a moving railcar is difficult since the moving car provides no absolute frame of reference. The proposed system estimates modulus by measuring the vertical displacement of the rail relative to the wheel/rail contact point at a fixed horizontal distance from this contact point. Deflection of the track is caused by the weight of the railcar. A heavy car on soft track will “sink” into the track. The proposed system uses analytical models of both the railcar and the track to estimate track stiffness based on these deflection measurements.
A mathematical analysis is presented to evaluate the sensitivity of the system. The analysis considers the behavior of the track and describes the function of the system. Finally, results from the field-testing are presented for a railcar at slow to moderate speeds ($\leq 40$ mph ~ 64.4 km/hr) over different sections of Class III, IV, and V track. The tests include tangent track, bridges, and grade crossings.

**BACKGROUND**

There are several theoretical methods for determining track modulus. Some of these methods include the Deflection-Area method, the Pyramid Load Distribution method, and the Beam-on-Elastic-Foundation method ($I$).

The Deflection Area method is based on the vertical equilibrium of an infinitely long rail under an applied load ($I$). In this method, the shape of the rail is measured so that the deflection curve of the rail is known. The deflection curve is then integrated along the length of the track providing the area between the curve and the unloaded rail. The track modulus is then the ratio of the applied load to the supporting area.

The Pyramid Load Distribution Method assumes the pressure beneath the rail seat is uniform at each depth across the area of an imaginary pyramid zone spreading through the ballast layer ($I$). In this theory the effective stiffness of each component is determined and then related to the overall stiffness for the entire support system. Track modulus is then the ratio of the stiffness of the entire support system to the tie spacing.

The Winkler method, or beam-on-elastic-foundation method, is a common method to describe track shape under various loading conditions. This method describes the rail as an infinitely long beam on an elastic foundation ($I, 3, 4$). From this model the track modulus is
defined as the vertical stiffness of the rail foundation (2). To determine the track modulus from this method the load applied to the rail and the resulting deflection must be measured.

Several methods have been used in the field to measure track modulus. All these methods use static loading and require deflection measurements to be made before and after the loads are applied. The methods for measuring track modulus include the Deflection Basin Test, Single Load Point Test, and the Multiple Axle Vehicle Load Test (2). Tests have been conducted showing that measuring track modulus can be used to determine track quality (5). It is also recommended that track modulus be measured continuously over the track (5, 6). Some work has been done to make these measurements at low speeds (≤ 10 mph ~ 16 km/hr).

Track inspection vehicles are becoming more capable of measuring the quality of track. These vehicles are capable of measuring track geometry, rail head profile, estimate ride quality, and wheel-rail forces at high speeds (up to 150 mph or 241.5 km/hr). Currently there is not a system to measure the track modulus at significant speeds.

A vehicle that is capable of measuring track modulus is the Track Loading Vehicle (TLV) developed by Transportation Technology Center, Inc. (TTCI). This vehicle functions at speeds up to 10 mph (7). The TLV has a center load bogie and laser reference beam, as does an accompanying tank car. During testing the center load bogie on the TLV can apply wheel loads ranging from 1 to 60 kips and the tank car center load bogie can apply wheel loads up to 3 kips. The tank car serves as an undeflected, or reference, measurement. The TLV does two runs over the track, first applying a 10 kip load and on the second pass a 40 kip load (7).

The TLV is operational however, it still has limitations. First, tests are often performed at speeds below 16.1 km/hr (10 mph) so it is difficult to test long section of track (hundreds of
miles). Second, significant expense in both equipment and personnel are required for operation. For these reasons the TLV has not yet been commonly implemented.

In this paper a simple method to determine track modulus from a moving railcar is presented. The sensor system uses a non-contact structured-lighting vision system. The proposed system is relatively inexpensive and does not require significant support equipment. It has the potential to operate at higher speeds and could potentially be automated.

**THE MEASUREMENT APPROACH**

The proposed measurement system estimates track modulus by measuring the deflection of the rail relative to the wheel/rail contact point. The modulus is estimated using the Winkler model that relates the shape of the rail to the applied loads \(^9\). It is a continuum mechanics model for a point load applied to an infinitely long elastic beam mounted on an elastic foundation. The applied load is perpendicular to the length of the beam (i.e. vertical). The vertical deflection, \( y \), for a given point load, \( P \), as a function of the distance from the load, \( x \), is:

\[
y(x) = \frac{P\beta}{2u} e^{-\beta x} \left[ \cos(\beta x) + \sin(\beta x) \right]
\]

where

\[
\beta = \left( \frac{u}{4EI_z} \right)^{\frac{1}{4}}.
\]

Here, \( E \) is the modulus of elasticity of the beam (i.e. rail) and \( I \) is the second moment of area of the beam. The variable, \( u \), is the estimate of the track modulus. This model linearly relates rail deflection to a single applied point load and shows a nonlinear relationship to track modulus. Rail deflection under a planar railcar is calculated with the Winkler model using the superposition of four point loads at each wheel contact point.
The above model gives a one to one (nonlinear) relationship between absolute deflection and track modulus. Such absolute measurements are extremely difficult from a moving railcar because of the lack of an absolute reference frame (the car bounces, rotates, and bends). For this reason the proposed approach uses relative measurements between the railcar truck and the rail. The proposed method continuously measures the relative deflection of the track and these measurements are used to estimate the relative track modulus.

![Figure 1: Winkler Model of Rail Deflection](image)

The proposed method is a non-contact measurement system that uses two line lasers and a camera mounted to each side frame of the loading platform truck, as shown in Figure 2. As seen from the camera view (Figure 2 right), each laser generates a curve across the rail head. The exact shape of the curve depends on the shape of the rail. The distance, $d$, between the curves is found using imaging software. The change in the distance $d$, as the train moves along the track represents a change in the relative displacement between the railcar truck and the track (assuming the shape of the rail and applied loads is constant) and therefore represents a change in
modulus. So as the distance between the camera and rail decreases the measured distance, \( d \), will also decrease. The opposite is also true, as the distance between the camera and rail increases the measured distance, \( d \), will increase. The position of the two lasers is used to increase the resolution of the measurement system and the overall sensitivity of the instrument.

Figure 2: Measurement System

Measuring the distance between the laser curves gives the relative displacement of the rail and the railcar truck. This relative displacement along the length of the car is shown in Figure 1. This curve is very similar to the calculated displacements shown in Figure 3 except that the curve is drawn relative to the rail/wheel contact points (zero displacement). Figure 3 is important because it shows that the location of the measurement along the length of the car \( x \) is important to the sensitivity of the sensor. For example, a measurement taken close to the rail/wheel contact point would be near zero for any value of track modulus. The maximum sensitivity to track modulus occurs at a location approximately 50 in. (1.3 m) from the rail/wheel contact point.
Figure 3: Track Deflection Relative to the Wheel/Rail Contact Point

The stated approach is based on some fundamental assumptions. First, that the Winkler model is an accurate prediction of rail shape. Or, more precisely, that the Winkler model has high resolution and can accurately predict relative changes in track modulus. A second assumption is that there are no dramatic changes in the shape of the rail head over the distances where relative measurements are taken. Also, that the applied load is constant between two measurements. Dynamic loading (bouncing of the car) can affect this assumption. However, at the low speeds (> 10 mph or 16 km/hr) dynamic loading is not a concern. The final assumption is that the wheel/side frame system is rigid. This assumption does not include the car’s suspension. The validity of the approach with respect to these assumptions is evaluated in the following sections in simulation and in field tests.

SYSTEM MODELING

The system that has been developed uses two lasers, each with optics to generate lines across the head of the rail, and a camera to create an image of these lines (Figure 2). This image is then
analyzed with computer software and the distance between the two laser lines is measured. Since the rail head is not flat the lasers appear as curves in the image. The minimum distance between the lasers is measured and a mathematical model relates this measurement to track modulus. The mathematical model is discussed in this section, along with a simulation of the system.

**System Model**

The mathematical model relates the measured distance between the lasers to the track modulus. The system that is being modeled is shown in Figure 4. The model consists of the instrumented tank car truck and a caboose truck. The rail deflection measured by the sensor is dependent on these four wheel loads.

![Figure 4: System Schematic](image)

The sensor will measure the relative rail displacement between the rail and wheel/rail contact point. This measurement can be made if it is assumed that the instrument beam, truck, and wheels are rigid. With this assumption the distance between the sensor system and wheel/rail contact point can be assumed constant. Only pitch rotation of the truck will cause this distance to change, but this rotation can be taken into account and corrected.
Figure 5: Rail Deflection/Sensor Measurement

Figure 5 illustrates that the fixed distance between the wheel/rail contact point and sensor, $H$, relates the relative rail displacement, $y_r$, to the measured height of the sensor above the rail surface, $h$. The height of the camera/lasers above the rail surface is:

$$h = H - y_r$$  \hspace{1cm} (3)

where the relative rail displacement is

$$y_r = y_{\text{wheel}} - y_{\text{camera}} \cdot$$  \hspace{1cm} (4)

Here $y_{\text{camera}}$ is the deflection of the rail at the location underneath the camera/lasers and $y_{\text{wheel}}$ is the deflection of the rail at the wheel nearest the sensor. These rail deflections are calculated using the Winkler model and superposing the deflections caused by each of the four wheel loads.

The sensor reading, which is the measured distance between the lasers, is geometrically related to the height of the sensor above the rail. The sensor in effect measures its height above the rail by measuring the distance between the lasers. As the sensor moves closer or farther from the rail surface the distance between the lasers changes. Below is a schematic of the sensor (Figure 6).
From the above figure the following equations can be written:

\[(L_1 + l_1)\tan \theta_1 = h\]  
\[(L_2 + l_2)\tan \theta_2 = h\]  
\[d = l_1 + l_2\]

where \(L_1\) and \(L_2\) are the horizontal displacement of the lasers from the camera, \(\theta_1\) and \(\theta_2\) are the angles between the lasers and the horizontal, \(l_1\) and \(l_2\) are the horizontal distance between the center of the camera and laser/rail intersection, \(h\) is the vertical distance between the camera/lasers and the surface of the rail, and \(d\) is the distance between the lasers on the rail surface. Solving these equations results in:

\[d = \frac{h}{\tan \theta_1} + \frac{h}{\tan \theta_2} - (L_1 + L_2)\]  

Using Equation 3, Equation 4, and Equation 8 a sensor reading can be calculated for any given value of track modulus. The sensor reading that will be calculated is highly dependent on the geometry of the sensor and the fixed height of the sensor above the wheel/rail contact point, \(H\). Figure 7 shows how track modulus and the sensor reading are related. Changing the height
of the sensor above the wheel/rail contact point will shift the curve along the abscissa, which is also shown in Figure 7. By curve fitting the appropriate curve in Figure 7, a mathematical model that relates track modulus to the sensor reading is determined.

![Figure 7: Track Modulus vs. Sensor Measurement](image)

**MEASUREMENT SYSTEM COMPONENTS AND CONFIGURATION**

The loading platform consists of a modified 75-foot (~23-m) tank car filled to the maximum allowable weight of 263,000 lbs (~120,000 kg) with water. The spring deflections are measured in the suspension system of the tank car to estimate the dynamic load at each axle.

The measurement instruments are laser vision devices and are divided into two independent measurement systems, one for each rail. These instruments are mounted to two structural beams, which are firmly clamped to each of the tank car’s side frames. This provided “rigid” connection between the instruments and the wheel contact point. Mounting the instruments required no significant modification or alteration to the side frames or any part of the tank car.
The laser vision devices consisted of two near-infrared line lasers and one filtered high-definition monochrome camera. The camera recorded the position of the laser lines on the top of the rail, giving track deflection through the geometry discussed earlier and an indication of the track modulus. Figures 8a and 8b show the difference between pliable and stiff track as seen by the laser vision system. The loading platform also carried two observation cameras that allow the measurement system to be monitored from the personnel platform.

The personnel platform, a converted caboose, housed all of the equipment used for electrical power generation, data storage and data processing. The information from the laser vision devices was stored as audio video interleave (AVI) formatted video via two recording devices. Global positioning system information, odometer readings and linear variable differential transformers (LVDTs) data are written over the AVI recordings to provide location and time references for each frame of video recorded. The personnel platform carried two forward looking observation cameras that provided a view of the right-of-way as the system traverses it. The video from each of the observation cameras and from the laser vision system was recorded to video tape used for locating specific trackside features.
TEST RESULTS

Several tests have been carried out using the above described system. This section will describe four recent tests. The first test was carried out to determine the repeatability of the measurement method. The second test served to determine the effect that various speeds had on the system. The third and fourth tests provided the opportunity to record data continuously over long sections of track.

Test One

Test one allowed for continuous data recording over a 25 mile (40 km) section of track at speeds up to 25 mph. Furthermore, the test included several runs over a short section of track at very low speeds that provided a very good representation of the repeatability of the testing method. This test was carried out between Cheney, NE and Bennet, NE on the Omaha Public Power
District’s private Class III track. The results are as shown in Figure 10. In Figure 10, the mean of the data collected is represented as the solid line and the range of plus and minus one standard deviation is shown by the dotted lines. Statistical analysis shows that all data falls within one standard deviation from the mean.

![Measurements Near Cheney, NE](image)

**Figure 10:** Data showing repeatability of measurement method.

**Test Two**

The second test was completed to determine the effect that speed had on the measurement system. This test was carried out near Berks, NE on Burlington Northern Santa Fe track. Five separate passes were made over the same section of track at speeds of 5, 10, 20, 32, and 40 mph (8, 16, 32, 51, and 64 km/hr). There was no significant difference in the deflection over the range of speeds that were used. Figure 11 shows the results of the second test.
Figure 11: Data showing effect of speed on measurement system.

Figure 11 shows an example of the measurements that were taken for one rail at differing speeds over the same section of track. The largest discrepancy appears at a position of roughly 710 feet. This relatively large change is a product of both the frame rate of the recording devices and the nonlinearity of the conversion to modulus from the measured parameter $d_{\text{min}}$. As the speed increases, the distance along the rail between recorded frames changes. At 5 mph or 8 km/hr the distance along the rail between frames is 3 inches or 0.07 meters, but at 40 mph or 64 km/hr this distance increases to 24 inches or 0.61 meters. This causes aliasing in the data and leads to a jerky appearance in the high speed data. This practical limitation does not change the measurements of modulus. After analysis of the data, there is no significant change in the measurements over the recorded distance for differing track speeds.
**Test Three**

The third test served to provide a long-distance, continuous-measurement test. Approximately 50 miles (80 km) of continuous track data and five sets of bridge data were attained. Both the third and fourth tests were carried out on Union Pacific Railroad’s Class V Marysville Subdivision between Level, NE and Alexandria, NE. The consist for this test was a Brandt truck, the loading platform, and the crew platform. An excerpt of data is shown in Figure 12. This figure shows the data taken on a bridge. This bridge is a 3 span concrete ballast deck bridge. There is an 8 inch thick Geoweb™ material installed for 100 feet or 30 meters on each end of the bridge. Visual inspection of the site revealed an area of pumping roughly 100 feet from the east end of the bridge, indicated by a mud hole. This feature is shown at the position of about 70 feet in the figure. In Figure 12, the outermost vertical lines represent the location of the bridge approach beginnings, and the inner vertical lines indicate the location of the bridge pilings.
Test Four

The fourth test was carried out in concert with the Transportation Technology Center Incorporated Track Loading Vehicle (TTCI TLV). The test also allowed for long-distance, continuous-measurement data collection. Figure 13 shows a one-mile (1.6 kilometer) section of track taken between MP 251 and MP 252. The data shown is the measured parameter, $d_{\text{min}}$, which is indicative of track modulus. Figure 13 shows large variations due to the existence of grade crossings (left half of figure). Figure 13 also shows an anomaly near mile post 251.45 that indicates a drop in modulus near a high speed crossover (moveable point frog) between main lines. This one mile section (one of the 50 miles measured) shows the ability to test over longer distances.
CONCLUSIONS AND FUTURE WORK

Many railroad accidents can be attributed to track failure. The measurement and analysis of track modulus information is necessary to maintain track quality and prevent accidents involving track failure. This paper describes the design of a system for on-board, real time, noncontact measurement of track modulus.

The Winkler model for track deflection that is currently used to determine track modulus was explained. A model and simulation for the sensor system were presented. Test results from a moving railcar were presented. This testing has shown that the system is capable of measuring modulus from low (5 mph or 8 km/hr) to moderate (40 mph or 64 km/hr) speeds over extremely long sections of track (up to 50 miles or 80 kilometers). This testing has also identified some of the types of track anomalies that the system is intended to find.
The testing carried out over the last year reinforces the validity of the measurement system’s design. A paradigm change is also planned for the near future, in that the primary measurements will be in terms of track deflection. This is due in part to the mathematical and interpretational difficulties associated with measuring modulus. Future work will include comparisons to other testing techniques and longer distance continuous-measurement tests.

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