UPDATE OF TTCI’S RESEARCH IN
TRACK CONDITION TESTING AND INSPECTION

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ABSTRACT

This paper presents an update of Transportation Technology Center, Inc.’s (TTCI) research in the areas of automated vertical track strength testing and performance-based track geometry inspection. In the first area, the in-motion Track Loading Vehicle (TLV) stiffness profile testing technique is now complemented by the TLV’s cone penetrating testing (CPT) capability. The continuous track stiffness profile, together with substructure layer characteristics (i.e., thickness, soil strength, and soil type) at locations probed, have been developed to identify lower track strength or abrupt transitional stiffness changes, and to determine the causes of the problems for remedies. In the second area, TTCI has developed a prototype performance-based track geometry inspection technology. It is essentially a new, “add on” technology that can be implemented on conventional track geometry inspection vehicles. It was developed to relate measured track geometry to vehicle performance on a real-time basis. It can also be used on historic geometry data to examine the effect of track geometry degradation on vehicle performance. Implementation of this technology will permit prioritized track geometry maintenance based on vehicle performance. With this technology, railroads can expect to reduce potential derailment incidents and the stress state of track structure caused by poor vehicle/track interaction.
INTRODUCTION

Railroad track acts and behaves as part of a vehicle-track interaction system. As such, assessment of track condition without regard to vehicle loads and vehicle performance is often insufficient. A performance-based track inspection system should take into account vehicle performance or actual service loads when developed for assessing track conditions. In recent years, Transportation Technology Center, Inc. (TTCI), a wholly owned subsidiary of the Association of American Railroads (AAR), has made significant progress in the areas of track condition testing and inspection. This paper presents an update in two areas. One is automated vertical track strength inspection; i.e., vertical track support assessment under service load conditions. The other is the performance-based track geometry inspection; i.e., track geometry inspection taking into account vehicle performance. The objectives of these developments are:

- Improve train operation safety by identifying and fixing track spots that produce poor vehicle performance or derailment potential.

- Optimize track maintenance activities by focusing activities where maintenance is critical and by selecting more effective maintenance or remedy methods.

- Reduce the stress state of railroads by reducing vehicle/track interaction, leading to reduced track and vehicle degradation.
VERTICAL TRACK SUPPORT

TLV and CPT Testing Techniques

In the past a few years, TTCI has developed a new method using its Track Loading Vehicle (TLV) to measure vertical track deflections under given vertical loads while in motion. The technique was developed to identify track locations of concern and to measure the load carrying capacity of existing tracks. The test-consist includes the TLV, an empty instrumented tank car, and an instrumentation coach. The TLV and the tank car are instrumented with laser displacement sensors to measure vertical deflections of the railhead relative to two reference frames mounted to the vehicle bodies (see Figure 1). Loaded and unloaded vertical deflection profiles are determined by three chordal-offset measurements from each reference frame. The loaded deflection profile is obtained under the TLV load bogie. During an in-motion test, the TLV applies a vertical force using the center load bogie. It is capable of applying a range of wheel loads anywhere from 1 to 60 kips. The standard TLV test wheel load is 40 kips. The second measurement comes from the tank car trailing the TLV. The tank car is equipped with a center load bogie much like the TLV; however, this bogie is equipped with pneumatic actuators and is only capable of applying wheel loads of up to 3 kips (2 kips normally). This load is used to assure wheel/rail contact at all times. The empty tank car is used to measure the existing vertical profile variations (unloaded profile). The empty tank car exerts only 14 kips at the end trucks, creating small basins that have little effect on the vertical profile measured from the reference frame attached under the center of the car. The data collection software overlays the loaded and unloaded profiles and subtracts them to get the actual deflection of the track caused by the TLV test load.
The difference between loaded profile and unloaded profile is “track deflection” due to the test load. This is the parameter defining the characteristics of vertical track support and represents track response under the given test load. For a given test load (40 kips), higher deflection indicates weaker track and lower defection indicates stronger track. It should be noted, however, that this is an offset-based measurement and therefore is a relative measure of track deflection under the test load.

Another parameter, “vertical strength variation index,” is calculated from the “track deflection” data. This parameter is used to show the variation of vertical track stiffness. A weaker track is generally more varied in vertical stiffness along the track; thus the values of this index will be higher for weaker track. Because this is an index showing track stiffness variation, locations such as bridge approaches and road crossings tend to have higher values, as do locations with weak subgrade supports.

The TLV stiffness profile data alone does not provide a complete picture of the exact cause of weakness in the track support. Further investigations are often needed to evaluate the track substructure conditions and provide a cost-effective remedy. This is why an effort was made to incorporate the cone penetrometer test (CPT) capability on the TLV (see Figure 2). The CPT was installed on the TLV to determine detailed track substructure conditions immediately at the locations of interest identified by the TLV in-motion testing. The CPT uses hydraulic actuators to push an instrumented cone, attached to a drill rod, down through the ballast and deep into the subgrade. The TLV data is used to pinpoint vertical support problem areas, and the CPT is then be used to further investigate the track substructure conditions.
For a CPT testing, typical measurements are taken to a depth of 15 feet. The instrumented cone was specially designed to withstand the high penetrating stresses from the ballast layer with high durability, while retaining the sensitivity necessary to measure soft subgrade conditions. During a test, the two measurements obtained are tip resistance and sleeve friction. The tip resistance is related to soil strength and stiffness (Table 1); and thus, its distribution with depth directly indicates layer strength characteristics. Using results of both tip resistance and the friction ratio, estimation of soil types can be made based on available CPT soil identification charts (Figure 3).

**Revenue Service Test Results**

In the past several years, automated vertical track strength tests have been conducted extensively on revenue service tracks to investigate the causes and remedies for problems due to subgrade and bridge approaches. One of test sites is a heavy haul coal line, which carries approximately 170 MGT of traffic annually. The line is made up of double track — the track carrying primarily the loaded trains is all concrete ties, and the track intended for the unloaded trains is wood ties. The tests were performed on the loaded track. This route has had a history of vertical track support problems. Although there has been a considerable amount of reconstructive effort to remedy the problems, this line still has vertical exceptions. During the tests conducted, a variety of track substructure conditions were measured for the problem areas as identified by the stiffness profile testing and characterized by CPT testing.

The CPT probing locations were picked based on the vertical stiffness profile data. Figure 4 shows such an example, where the peak deflection of 0.4 inch occurred at the same place as the peak in the vertical strength variation index. The results of the CPT test at this location showed a
significant depth of soft to medium subgrade support (Figure 5a) and the friction ratio showed
the soil type to be made up of clay (Figure 5b).

Another CPT test site was chosen at a TLV paint spot. This location was only about 25 feet from
a road crossing and it had visible mud pumping from underneath the ties. As can be seen from
the TLV profile test results (Figure 6a), large deflections (greater than 0.5 inch) were measured
as well as large variations in vertical strength variation index. The CPT result (Figure 6b)
showed a thin (about 1 foot deep), very soft subgrade layer. The tip resistance in this area was
only about 10-20 psi.

Figure 7 illustrates a third example. This is an area that had neither vertical deflection nor
strength index variation large enough to be of concern. The TLV data (Figure 7a) suggests this
area to be of medium track support. Examining the CPT data (Figure 7b), there are a few things
that should be noted. First, the data shows that there is almost 4 feet of granular layer thickness.
Just below the ballast, there is an area of weaker material. The large granular layer thickness
might be one of the reasons why the track showed medium support. The other contribution might
come from cross drains and shear keys installed in this area. This was a location that was worked
on in 1997 to address weak subgrade conditions.

A CPT probing test was performed at another location to illustrate the track substructure
condition for a good track support, as shown by the TLV profile results (Figure 8a). Figure 8b
shows that the tip resistance indicated medium to stiff subgrade support with an adequate
granular layer thickness.
PERFORMANCE-BASED TRACK GEOMETRY

To improve current track geometry inspection methods, TTCI has developed a performance-based track geometry (PBTG) inspection technology. It is essentially a new, “add on” technology that can be implemented on conventional inertial track geometry inspection vehicles. The technology is developed to relate measured track geometry to vehicle performance on a real-time basis. The technology can also be used on historic geometry data to examine the effect of track geometry degradation on vehicle performance in an office environment.

PBTG inspection is an improvement over the current track geometry inspection method. This is because track geometry defects, identified using the current method, do not always relate to poor vehicle performance (see Figure 9). Implementation of this technology should lead to prioritized track geometry maintenance based on vehicle performance. Thus, railroads can expect to reduce potential derailment incidents and the stress state of track structure caused by poor vehicle/track interaction.

The PBTG technology developed by TTCI allows a user to specify vehicle types sensitive to track geometry input (such as empty tank cars, loaded hoppers, and gondolas), and an array of operating speeds for vehicle performance analysis. On a real-time basis, this technology identifies track segments that may produce poor vehicle performance and generates recommended track geometry maintenance actions.

Vehicle Performance and PBTG Defects

A PBTG inspection relates measured track geometry to vehicle performance. Vehicle performance can be defined in terms of different vehicle response parameters relating to
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derailment potential, stress state of track structures, and ride quality. These vehicle responses can be defined as follows:

- “Derailment potential” is often defined by L/V ratio (lateral/vertical wheel or axle load ratio) and “vertical wheel unloading” with respect to the allowable limits. The L/V ratio criterion is intended to prevent climb derailment and the vertical unloading criterion is intended to prevent wheel lift derailment.

- The “maximum vertical and lateral wheel loads” exerted on track often quantify “Stress state.”

- “Ride quality” is often quantified by “vertical and lateral accelerations on the car body.”

The current version of the PBTG inspection system defines vehicle performance in terms of derailment potential and stress state, although it can be expanded in the future for ride quality analysis. More specifically, the current PBTG system can be used for vehicle performance analysis for the following parameters: single-wheel L/V ratio, vertical wheel load, and lateral wheel load.

The “PBTG defect” is defined as a track geometry condition within a track segment that will likely cause poor vehicle performance. Unlike a track geometry defect defined by the Federal Railroad Administration (FRA) Safety Standards or railroad maintenance standards, which is point-specific, a PBTG defect is segment-specific. It includes combined and multiple geometry deviations within a segment and takes into account the effect of track features such as curvature and spiral. Figure 10 shows an example where a combined track geometry condition led to a poor vehicle response (L/V ratio above 1.0). As shown, the combined track geometry deviations (cross level, alignment, and surface) were located between 4,500 and 4,700 feet. The presence of
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an entry spiral also contributed to the poor vehicle response. The allowable FRA limits are also shown in the figure (vertical arrows) for the measured track geometry parameters. Similar to what was illustrated in Figure 9, there were no individual defects that could be identified to relate to the poor vehicle performance. In the PBTG inspection, however, this segment would be identified as a PBTG defect.

The PBTG defect is also a *likely* defect, because an identified track segment causes poor vehicle performance (derailment potential) only under a certain vehicle operation condition. Unlike a conventionally defined track geometry defect that can be measured repeatedly, vehicle response may not be the same due to the same track geometry input if other conditions vary. Even for the same vehicle operating at the same speed, vehicle response can be different over the same track geometry when wheel/rail contact conditions change. For example, rain or snow can reduce wheel/rail friction, leading to reduced lateral loads in curves.

Having discussed the likely nature of a PBTG defect, it is important to understand that poor track geometry within a segment will always cause “undesirable” vehicle responses, although their magnitude (or sensitivity to track geometry input) can be different. In other words, the trends of vehicle responses due to the same track geometry inputs would be similar, regardless of vehicle type and operating condition.

Nevertheless, realizing possible variation of vehicle responses to the same track geometry inputs, TTCI employed a statistical approach in the development of the PBTG technology. The approach required conducting actual vehicle/track interaction tests under a wide range of track and operating conditions in revenue service. Then, based on the database created from the actual tests, many neural networks were trained to relate track geometry and operating speed to most...
likely vehicle response. In addition, the PBTG system uses the following statistical outputs to characterize vehicle performance: 1) maximum and the 98th percentile for L/V ratio, lateral, and vertical wheel loads; and 2) minimum and the 2nd percentile for vertical wheel unloading. The maximum value represents the most likely maximum responses over a given track segment, and the 98th percentile represents a magnitude greater than 98 percent of likely vehicle response occurrences over a given segment.

To identify PBTG defects, the vehicle response limits must be given. For example, the following Chapter XI criteria found in the *AAR Manual of Standards and Recommended Practices* can be used:

- Single wheel L/V ratio > 1.0
- Vertical wheel load $V < 10$ percent of static wheel load

According to the Manual, values worse than these listed are regarded as having a higher risk of unsafe behavior. Values better than these are regarded as indicating the likelihood of safe car performance.

**PBTG Inspection System**

As mentioned previously, when used on an inertial track geometry inspection vehicle, the PBTG technology is an add-on technology for real-time vehicle performance analysis. The basic functions of the PBTG system include:

- Interfacing with a conventional inertial track geometry inspection system to accept and process measured track geometry so the data can be used as inputs to the PBTG system.
Carrying out real-time vehicle performance analysis based on measured track geometry and given operating speeds.

Identifying track segments that may produce vehicle responses above the pre-determined limits (PBTG defects).

Generating recommended maintenance actions to the track segments identified with PBTG defects.

Outputting PBTG track quality index values before and after the recommended maintenance.

Figure 11 shows one of the graphical-user interfaces of the PBTG system. As illustrated, a user can enter an array of operating speeds for a given track and for a given vehicle. A user can select vehicle response parameters for real-time analysis and enter their corresponding limits. The system also allows the plotting (strip charts) of measured track geometry parameters together with vehicle response results.

Figure 12 shows an example of predicted vehicle response for single-wheel L/V ratio (maximum), based on actual track geometry measurements and vehicle operating speeds for an empty tank car. The actual test results recorded using instrumented wheelsets are also included in this figure for comparison. As shown, the predicted results were consistent with the measured results. In the example, poor vehicle responses (L/V >1.0) occurred at mileposts (MP) 229.9, 233.8, and 236.0.

Figure 13 shows another example for a longer stretch of track (50 miles). Again, as illustrated in the comparison between the test and predicted results, the PBTG system gives reasonable predictions of vehicle performance.
Exception Report and Recommended Maintenance

The PBTG system will generate a PBTG exception report from real-time vehicle response results. Table 2 shows an example report. The report lists the locations of PBTG defects identified, vehicle responses that exceed the pre-determined limits, magnitudes of likely vehicle responses, vehicle types, and operating speeds.

From this report alone, for the identified track locations, railroads can examine the actual track geometry measurement results and decide what maintenance actions need to be taken. However, the PBTG inspection developed by TTCI has also incorporated preliminary performance-based maintenance guidelines for correcting PBTG defects. To do so, track geometry conditions for an identified PBTG defect segment is categorized into four maintenance parameters: cross-level, surface, gage, and alignment. Each maintenance parameter is calculated based on maximum deviation, number of repeated deviations, and whether the segment is in a curve, spiral, or tangent. There are also weights associated with each maintenance parameter. These weights were developed based on the effect of each geometry parameter on vehicle performance. The calculated result of each geometry maintenance parameter indicates the contribution of that particular parameter to poor vehicle performance. Depending on the ranking of the results of these four maintenance parameters, track geometry maintenance actions are recommended for surfacing, lining, and/or re-gaging activity. Table 3 shows a simplified report of the recommended maintenance actions.

Note in this report that a PBTG track quality index is calculated before and after recommended maintenance action. The PBTG track quality index is a single parameter developed to sum the combined effect of all these track geometry maintenance parameters. Unlike track quality indices
developed by others, the PBTG track quality index is a performance-based quality index, and is developed based on the effect of track geometry parameters on vehicle performance. It gives an overall quantification of track geometry conditions for a given track segment in terms of how it may affect vehicle performance. Figure 14 shows the correlation between the calculated PBTG index values and actual vehicle response test results (L/V ratio) for many segments in revenue service. As shown, use of the PBTG index gives a reasonable indication of track geometry quality as it relates to actual vehicle performance directly.

TTCI has demonstrated the prototype PBTG system in revenue service and on test tracks at the FRA’s Transportation Technology Center (TTC) near Pueblo, Colorado. The demonstrations were conducted to check if the system would perform as designed in a real-time manner. To do so, the PBTG system was set up on TTCI’s track geometry measurement system (TGMS), and the interface was established between the TGMS and the PBTG system. Overall, the PBTG system performed as designed and was capable of analyzing vehicle response on-board at the same pace as the track geometry measurement vehicle ran. The PBTG system was stable and satisfactorily performed its functions. Currently, TTCI is in the process of completing the first commercial PBTG system to be implemented on BNSF’s track geometry vehicles.

**SUMMARY**

This paper provided an update of TTCI’s latest development in track condition testing and inspection. The TLV automated vertical track strength testing now has the combined capabilities of measuring continuous track stiffness profile along a track and investigating substructure conditions at the problem locations identified (cone penetrating testing). These TLV testing capabilities have been used in revenue service to quantify track vertical support such as abrupt
track stiffness changes at bridge approaches, and lower load carrying capabilities due to track substructure. It has been shown that the testing can not only identify areas of concerns, but also determine the causes of problems for effective maintenance or remedies.

In the area of the performance-based track geometry inspection, a prototype system has been developed and demonstrated at TTC and in revenue service. As a new, add-on to a conventional inertial track geometry inspection vehicle, this technology relates measured track geometry to vehicle performance for a given array of operating speeds. As such, this technology can be used to identify track segments that may generate poor vehicle performance (derailment potential), and to produce recommended maintenance actions to poor track geometry.

ACKNOWLEDGEMENTS

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<table>
<thead>
<tr>
<th>Cone Tip Resistance (psi)</th>
<th>Compressive Strength (psi)</th>
<th>Modulus (psi)</th>
<th>Subgrade Support</th>
</tr>
</thead>
<tbody>
<tr>
<td>1,000 and over</td>
<td>100 and over</td>
<td>10,000 and over</td>
<td>Hard</td>
</tr>
<tr>
<td>500 – 1,000</td>
<td>50 – 100</td>
<td>5,000 – 10,000</td>
<td>Very Stiff</td>
</tr>
<tr>
<td>300 – 500</td>
<td>30 – 50</td>
<td>3,000 – 5,000</td>
<td>Stiff</td>
</tr>
<tr>
<td>150 – 300</td>
<td>15 – 30</td>
<td>2,000 – 3,000</td>
<td>Medium</td>
</tr>
<tr>
<td>70 – 150</td>
<td>7 – 15</td>
<td>1,000 – 2,000</td>
<td>Soft</td>
</tr>
<tr>
<td>Less than 70</td>
<td>Less than 7</td>
<td>Less than 1,000</td>
<td>Very Soft</td>
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Table 2. Example of PBTG Exception Report

<table>
<thead>
<tr>
<th>MP</th>
<th>Force</th>
<th>Side</th>
<th>Car</th>
<th>Speed</th>
<th>Value</th>
<th>Limit</th>
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<tbody>
<tr>
<td>229.9</td>
<td>L/V max</td>
<td>Left</td>
<td>Empty</td>
<td>35 mph</td>
<td>1.8</td>
<td>&gt; 1.0</td>
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<tr>
<td>233.4</td>
<td>V min</td>
<td>Right</td>
<td>Covered Hopper</td>
<td>40 mph</td>
<td>3.0 kips</td>
<td>&lt; 3.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tbody>
</table>
Table 3. Example of Recommend Track Geometry Maintenance Action Report

<table>
<thead>
<tr>
<th>Geometry Parameter</th>
<th>Maintenance action</th>
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</thead>
<tbody>
<tr>
<td>Cross-level</td>
<td>YES</td>
</tr>
<tr>
<td>Surface</td>
<td>No</td>
</tr>
<tr>
<td>Gauge</td>
<td>No</td>
</tr>
<tr>
<td>Alignment</td>
<td>No</td>
</tr>
</tbody>
</table>

MP: 229.9  Curvature: 1.5 degree  PBTG Index = x.x (before)

PBTG Index = y.y (after)
Figure 1. Loaded and Unloaded Vertical Profile Measurement
Figure 2. CPT Installed on TLV
Figure 3. CPT Soil Identification Chart
Figure 4. TLV In-motion Test Results
Figure 5. CPT Test Results

a. Soft to Medium Subgrade Support

b. Showing clay soil type
Figure 6. TLV and CPT Test Results (Poor Support)
Figure 7. TLV and CPT Test Results (Medium Support)
Figure 8. TLV and CPT Test Results (Good Support)
Figure 9. Revenue Service Test Results Showing Track Geometry Defects Identified by the Current Method do not Always Relate to Vehicle Performance
Figure 10. Test result showing how poor vehicle response (L/V > 1.0) was caused by combined track geometry deviations in conjunction with an entry spiral (vertical arrows are FRA limits for individual track geometry parameters).
Figure 11. PBTG Graphical-User Interface
Figure 12. Example of PBTG Analysis Result and Comparison with Test Result
Figure 13. Example of PBTG Analysis Result and Comparison with Test Result
Figure 14. Correlation between PBTG Track Quality Index and Actual Vehicle Performance