Performance Based Track Geometry: Optimizing Transit System Maintenance

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INTRODUCTION

Poor vehicle dynamic performance and poor ride quality frequently occur at track locations that do not exceed track geometry or safety standards; e.g., curve entry or exit, special trackwork, and track misalignments that promote yaw instability or hunting.

Poor ride quality may not be an indicator of unsafe operation, but may point to an area of track or a vehicle that needs maintenance to prevent further degradation. Conversely, track geometry locations that exceed track geometry or safety standards often do not cause poor ride quality or poor vehicle performance.

To optimize transit system maintenance, methods need to be developed to identify vehicle conditions and locations in track that cause poor ride quality or vehicle performance.

Track geometry measurements alone are not always an indicator of how a vehicle behaves. Predicting the vehicle dynamic response will help address the following issues:

- Identify maintenance priorities
- Identify problem locations that do not exceed normal track geometry standards
- Identify problems as they arise rather than waiting for scheduled maintenance
- Identify car designs and car component wear issues that can contribute to poor vehicle performance and poor ride quality

To improve and advance the current track geometry inspection practice and standards, Transportation Technology Center, Inc. (TTCI) developed a track inspection method known as Performance Based Track Geometry (PBTG™). Trained neural networks in the PBTG system relate the complex dynamic relationships that exist between vehicles and track geometry to vehicle performance. They also identify track segments that may generate unwanted vehicle responses. PBTG is now used by three North American railroads and one international railroad.

A transit agency can use PBTG to optimize maintenance of the track and fleet. Onboard accelerometers on the fleet and a PBTG neural network can be used to identify track locations that need work without direct measurement of the track geometry. This allows monitoring of track condition between scheduled track geometry measurements. PBTG can also be used to identify cars whose performance is beginning to deteriorate. If all cars in the fleet are equipped with PBTG accelerometers, they can be used to build a database of information for monitoring the condition of the cars and the track over time.

Also, PBTG uses measured track geometry and the PBTG neural network to predict vehicle performance on existing track. This helps identify locations in the track likely to cause poor ride quality or other issues related to vehicle performance, which is the way PBTG is currently being applied by North American freight railroads.

An indirect benefit of implementing the PBTG system is by making validated vehicle dynamics models available to a transit agency. The models can be used for many other purposes like investigating dynamic

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performance problems, evaluating vehicle modifications, evaluating vehicle performance over proposed new track routes and alignments, and optimizing wheel and rail profile maintenance.

In support of the Transit Cooperative Research Program, TTCI conducted research to develop methods for evaluating track geometry that will account for transit system vehicle performance and passenger ride quality using a combination of PBTG and NUCARS® modeling techniques. These studies form the basis for determining improvements in track geometry and track maintenance practices to be developed in Phase II of the project. NUCARS simulations and data collected on transit systems are being used in training PBTG neural networks to evaluate the model’s ability to predict ride quality. The goal is to ascertain the ability of NUCARS and PBTG to properly predict vehicle performance and ride quality and to identify track geometry locations that require maintenance by using the initial ride quality measurements and the measured track geometry inputs.

**VEHICLE CHARACTERIZATION AND RIDE QUALITY TESTING**

TTCI partnered with Dallas Area Rapid Transit (DART) to participate in this research. DART provided support to the project by providing a test vehicle for TTCI to perform characterization and ride quality tests. All testing was performed on DART property located in Dallas, Texas. DART’s operating conditions provided a variety of track structures and a wide range of operating speeds.

A typical passenger rail vehicle operating on the DART system was selected and fully characterized. The data obtained from the characterization studies was used to develop a NUCARS model representing the vehicle. The characterized vehicle was equipped with instrumentation to collect passenger ride quality data using accelerometers and various displacement transducers. Track geometry measurements were collected within two weeks of the ride quality measurements and were used as comparisons with predictions from the NUCARS model and for future PBTG neural network training.

DART’s Super Light Rail Vehicle (SLRV) was used for testing. The SLRV is a three-section vehicle that can accommodate up to 150 seated and standing passengers. The vehicle is manufactured by Kinkisharyo (see Figure 1).

**Figure 1. DART’s Super Light Rail Vehicle**

**Vehicle Characterization Tests**

TTCI has often found that actual vehicle characteristics as assembled can vary considerably from the published design and measured individual components. To ensure an accurate NUCARS model of the SLRV, tests were conducted to measure suspension characteristics and carbody inertial and resonance characteristics. Testing included:

- Characterization of the elastic elements of the primary and secondary suspension
- Determination of the center of gravity of the railcar
- Determination of the resonant frequencies of rigid body degrees of freedom of the railcar

Results of the characterization tests were used to update and verify the preliminary NUCARS model.

**Track Inspection and Track Geometry Measurements**

A track inspection was done on the DART Red Line. Miniprof™ profiles were taken at known problem locations. Representative rail profiles were also taken in curves, curve transitions, and tangent track. Track issues and locations were documented to be compared with ride quality data.

Figure 2 shows some of the track geometry issues documented during inspection. Overall, the track was in good condition. There were several areas where rail corrugations, sun kinks, and ballast migration were evident. At the time of the inspection, the weather was extremely hot (110°F), and sun kinks were developing and being corrected on a regular basis.
Ride Quality Tests

A ride quality test was conducted on DART’s Red Line. The test conditions were similar to typical revenue service operations. Triaxial accelerometers were placed on the floor under the operator’s seat, on the floor over the truck, and on the center of the vehicle. The accelerometers measured the vehicle’s response to operating conditions and inputs from the track structure. A gyrometer was also placed on the floor under the operator’s seat. The gyrometer was used to measure carbody rotation to correlate the effect of curves and curve transitions on ride quality. This information will be used to correlate ride quality issues with track geometry. Figure 3 shows an example of the instrumentation and data acquisition system.

RIDE QUALITY AND TRACK GEOMETRY DATA ANALYSIS

The data collected during the ride quality and track geometry tests was compared to determine if a correlation between the two was possible.

Ride Quality Data Analysis

Ride quality measurements were taken on DART’s Red Line in both directions. The train was operated with typical operating conditions. Accelerations were measured on the floor at the following locations:

- A-end under operator’s seat (lateral, vertical, and longitudinal)
- B-end under operator’s seat (lateral, vertical, and longitudinal)
- A-end over truck (lateral, vertical, and longitudinal)
- A-end center of car (lateral, vertical, and longitudinal)
- Lateral accelerometer between the A and C cars
- Lateral accelerometer between the C and B cars
- Lateral accelerometers at each axle

Gyrometers were also placed under the A- and B-end operator’s seats to measure the carbody roll angle as the vehicle traveled through the curves.

Figure 4 shows an example of ride quality data. It shows Westmoreland to Pearl Street Station and the accelerations measured under the operator’s seat in the A-end of the SLRV. The data was analyzed between each station. Ride quality was determined according to ISO 2631-1997. Longitudinal, lateral, and vertical ride quality was determined between each station. The identified ride quality issues will be compared to track geometry to determine if there is a correlation.
Table 1 describes ISO 2631 ride quality index boundaries. Figures 5a and b show the crest factors calculated for each segment. There are some areas that have crest factors above nine; therefore, as required by ISO 2631, the running root-mean-square method was used to evaluate the ride quality. The vibration magnitude is defined as the maximum transient vibration value (MTVV). Figures 5 a, b, and c show the MTVV for vertical, lateral, and longitudinal accelerations in the southbound direction.

Vibration Magnitude | Comfort Level
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$a_w<0.315$ | Not uncomfortable
$0.315 \leq a_w < 0.63$ | A little uncomfortable
$0.5 \leq a_w < 1$ | Fairly uncomfortable
$0.8 \leq a_w < 1.6$ | Uncomfortable
$1.25 \leq a_w < 2.5$ | Very uncomfortable
$a_w \geq 2$ | Extremely uncomfortable

<table>
<thead>
<tr>
<th>Stations</th>
<th>Lateral Ride Quality Index</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>North Dallas Zoo to 8th &amp; Corinth</td>
<td>0.661</td>
<td>Fairly uncomfortable</td>
</tr>
<tr>
<td>North Walnut Hill to Forest Lane</td>
<td>0.763</td>
<td>Fairly uncomfortable</td>
</tr>
<tr>
<td>North LBJ/Central to Spring Valley</td>
<td>0.651</td>
<td>Fairly uncomfortable</td>
</tr>
<tr>
<td>North Galatyn Park to Bush Turnpike</td>
<td>0.681</td>
<td>Fairly uncomfortable</td>
</tr>
<tr>
<td>South Plano Center to Bush Turnpike</td>
<td>0.845</td>
<td>Uncomfortable</td>
</tr>
<tr>
<td>South Spring Valley to LBJ/Central</td>
<td>0.640</td>
<td>Fairly uncomfortable</td>
</tr>
<tr>
<td>South Cedars to 8th &amp; Corinth</td>
<td>1.056</td>
<td>Uncomfortable</td>
</tr>
</tbody>
</table>

The ride quality for the longitudinal and vertical directions did not exceed the “not uncomfortable” condition in both directions of travel. However, the lateral direction had areas with ride quality in the “little uncomfortable” to “fairly uncomfortable” range. Table 2 summarizes the areas with ride quality exceptions.

The measured track geometry in these areas was evaluated to determine if there is a correlation to the ride quality issues.
Track Geometry Data Analysis

Track geometry measurements were taken by Holland LP August 13-14, 2010, on DART’s Red Line in both directions. No measurements were taken in the tunnel because of a size restriction in the tunnel. Data from a previous track geometry run was used for the tunnel. The tunnel has direct fixation track; therefore, it was assumed that track geometry changes and the previous run were negligible.

Figure 6 shows an example of the measured track geometry. The tight gage in the embedded track is evident.

Ride Quality and Track Geometry Comparison

A major objective was to determine a correlation between ride quality and track geometry. Places on the Red Line that had ride quality issues were identified from the ride quality test. The section of track that was uncomfortable was located between Cedars and 8th & Corinth stations in the southbound direction. Figure 7 (top) shows the lateral accelerations measured under the operator’s seat in the leading end of the SLRV in this area. Figure 7 (bottom) shows the track geometry measured in the same area. The 2-second peak-to-peak value is approximately 0.35 g. In the area where this occurs, there is a deviation in the lateral alignment.

Figure 8 shows the frequency content of the acceleration data and lateral alignment of the track geometry. There are peaks at approximately 1 Hz and 1.65 Hz in the lateral vehicle response. In the lateral alignment of the track geometry in this area, there is also a 1 Hz peak corresponding to a wavelength of 88 feet. Figure 9 shows the acceleration data for the A- and B-carbodies. The two carbodies are moving approximately 90 degrees out-of-phase. Its frequency content is approximately 1.63 Hz. There is also a 1 Hz response of the vehicle that correlates to the 1 Hz frequency content of the lateral alignment of the track in this area.

It is possible to identify track geometry that can cause ride quality issues, such as the lateral deviations with the 88-foot wavelength between Cedars and 8th & Corinth stations. These track misalignments cause a response in the vehicle. It is important to note that although these track geometry deviations do not exceed any safety criteria, they can affect passenger ride quality. To identify the track geometry issues that affect ride quality, it is imperative to take track geometry measurement at the same time as ride quality measurements.

Hunting may be triggered by a combination of lateral deviation, speed, and wheel/rail interaction. The next phase of this project will investigate the potential triggers in more detail.
NUCARS MODEL

A NUCARS model was built to represent the DART SLRV, using design data updated by the measured characteristics. The model included a detailed representation of the articulation between the carodies and a full nonlinear representation of the air suspension, including the effects of damping due to air flow in the orifices between the reservoirs and air bags.\textsuperscript{2,3}

Each of the rigid body modes excited during the vehicle characterization test was analyzed and their frequencies determined. Table 3 describes all of the observable rigid body modes and the respective frequencies.

<table>
<thead>
<tr>
<th>Rigid Body Mode</th>
<th>Frequency (Hz)</th>
<th>NUCARS Model Frequency (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower Roll</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Upper Roll</td>
<td>2.0</td>
<td>2.02</td>
</tr>
<tr>
<td>Bounce</td>
<td>1.25</td>
<td>1.26</td>
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<tr>
<td>Pitch (all bodies in phase)</td>
<td>1.28</td>
<td></td>
</tr>
<tr>
<td>Pitch (u-shape)</td>
<td>1.5</td>
<td>1.50</td>
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<tr>
<td>Yaw (all bodies in phase)</td>
<td>1.42</td>
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<tr>
<td>Yaw (zigzag)</td>
<td>1.75</td>
<td>1.8</td>
</tr>
<tr>
<td>Yaw (u-shape)</td>
<td>1.57</td>
<td></td>
</tr>
</tbody>
</table>

Table 3. Rigid Body Vibration Modes and Measured Frequencies

This information was used in the eigenvalue analysis to determine the values of air suspension characteristics, carbody moments of inertia, and carbody center of gravity. The measured resonant frequencies were compared to the calculated values of the NUCARS model. Adjustments were made to the model’s suspension stiffness, center of gravity, and carbody inertias, and the resonant frequencies were recalculated. The model parameters were adjusted until the calculated values matched the measured values of the SLRV.

The measured track geometry was used as input to the model. A simulation of the same conditions as the ride quality test was done to determine if the model accurately predicted the vehicle performance.


Figure 10 shows the actual test data lateral acceleration and modeling results for the section of track between Cedars and 8th & Corinth stations. The plot shows data collected on the leading end of the vehicle. The accelerometer was placed on the floor under the operator’s seat. In the NUCARS model, representative wheel and rail profiles were used. The NUCARS model predicted the same general trend as the actual ride quality data. The model showed the yaw response subsided more quickly than it did in the test data. The model also underpredicted the lateral acceleration amplitude in this area.

Figure 11 shows the vertical accelerations of the test and the model. The model accurately predicted the trend of the acceleration, but under-predicted the amplitude.

Figure 12 shows the frequency content of the model and test data where yaw response/hunting occurred. Both the model and the test had a response at 1 Hz. This is a result of the 1 Hz frequency content in the lateral alignment. However, the model did not have the frequency response of 1.63 Hz.

The difference between the model and the test data may be due to a number of issues that will require further investigation. In the model, representative rail profiles were used in the curve and tangent. Wheel/rail interface issues may contribute to the response seen in the test. It will be necessary to use different rail profiles to determine the effect of the wheel/rail interface. In the carbody resonance test, the u-shaped yaw mode was not excited. It is evident in the ride quality test that it was excited. It will be important to review the model and update the parameters to assure the correct frequency can be simulated in the eigenvalue analysis.

CONCLUSIONS

A major objective of this research was to determine if there was a correlation between ride quality and track geometry. Places on the Red Line that had ride quality issues were identified from the ride quality test performed.

The southbound section of track between Cedars and 8th & Corinth stations was uncomfortable with a ride quality index of 1.056. This section of track contained lateral alignment deviations with a wavelength of 88 feet, which corresponds to a frequency of 1 Hz at the speed the train was running. This resulted in a vehicle yaw response of 1 Hz, clearly indicating a correlation between track geometry and vehicle response. It is important to note that although these track geometry deviations did not exceed any safety criteria, they clearly affected passenger ride quality. To identify the track geometry issues that affect ride quality, it was imperative to take track
geometry measurements at the same time as ride quality measurements.

These results indicated it should be possible to identify the effect of track geometry deviations on vehicle ride quality response during Phase II of this project. However, there is still some work required to improve the vehicle model to correctly predict this response. Identifying the influence of the following factors on vehicle response will be important to accurately model and determine track geometry triggers:

- Wheel/rail interface, including profile shapes and contact geometry
- Vehicle speed
- Understanding and identifying rigid body vibration modes of the vehicle

After these issues have been investigated, the track geometry and ride quality data collected during Phase I at DART will be used to train neural networks to predict ride quality. The validated DART vehicle NUCARS model will be used to run simulations at different speeds to generate additional neural network training data. The neural networks will then be used to predict ride quality over measured track not used in the training. The neural network output will be compared to NUCARS simulation predictions and measured ride quality to determine the accuracy of the neural network predictions.

If neural networks are determined to be a viable option for predicting ride quality, a different vehicle on a different transit system will be selected for additional investigation. Vehicle characterization and ride quality testing will be performed on the selected vehicle, and the data will be used to train and validate neural networks for the selected vehicle/system.