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Vehicle/Bridge Interaction Modeling and Validation – Part 1

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Summary

Railway bridges are critical in the transportation network and vital to the operations of the industry. Thousands of bridge spans more than 50 years of age are still in service. The current work under Association of American Railroads' Strategic Research Initiatives Program on bridge life extension focuses on the effects of increased axle loads, extending the safe service life of existing steel bridge spans, and onboard inspection of bridge structural integrity.

This *Technology Digest* presents simulation and test results of a freight car and locomotive on a NUCARS®* three-layer track model developed to analyze a railway bridge located at the Bridge Deflection Test Facility (BDTF) at the Transportation Technology Center. The BDTF was constructed to provide adjustable bridge strength and geometry conditions, for the purpose of evaluating, demonstrating, and calibrating vehicle-based bridge impairment detection systems. Various tests were conducted on the BDTF to investigate the potential for using onboard technology to detect bridge impairment or changes in bridge behavior. The results of the field tests were utilized for validation of the NUCARS model. The experimental and analytical studies will help evaluate and develop systems for onboard dynamic inspection of bridges under varying loads.

The model has potential to be used for development of an onboard measurement system. Preliminary simulations and previous test results indicated that additional measurement transducers could be added to the instrumented freight car in order to be able to detect changes in bridge condition or response. With further refinement of processing algorithms, carbody displacement from an instrumented freight car has potential to be used for indication of bridge condition. The additional accelerometers installed on the carbody and side frames of an instrumented freight car will be investigated in future tests on the BDTF.

*NUCARS® is a registered trademark of Transportation Technology Center, Inc., Pueblo, Colo.

INTRODUCTION

In an effort to provide better indication of bridges in need of maintenance or more detailed inspection, Transportation Technology Center, Inc. (TTCI) has been investigating the potential for using onboard technology to detect bridge impairment or changes in bridge behavior. The motivations for developing such a technology are twofold. First, bridges often show behavior under dynamic train loading that is difficult to observe otherwise. Second, an onboard system has the potential to provide observations for hundreds or thousands of bridges, as opposed to a structural health monitoring system that is fixed and capable of monitoring only a single bridge.

As a part of this effort, NUCARS® modeling is being used to predict performance of various vehicles. It is also being used to help determine the measurements best suited for detecting changes in bridge performance.

NUCARS® is a multi-body vehicle/track/bridge dynamic simulation program. The NUCARS track model allows simulation of flexible track/bridge structures under moving vehicles. For track on a ballast and subgrade foundation, track is usually defined as either a single-layer (flexible rails) or two-layer (flexible rails and flexible ties) flexible track model. NUCARS allows more layers and more complex track structure simulations to include features such as bridges and track slabs.

In order to determine the dynamic performance of bridges under a moving load, flexible bridge spans were added to the track model to predict the dynamic responses of the vehicle and bridge including wheel/rail interaction. The NUCARS multi-layer track model provides essential tools for evaluation of dynamic bridge performances under multiple rail vehicles.

Bridge Deflection Test Facility

The BDTF is a 42-foot, 3-span, T-rail trestle (Figure 1). The bridge can be configured to provide variable support, in terms of stringer strength as well as pier top support geometry. The bridge generally follows plans for an open deck T-rail span (sometimes called rail top) bridge, with modifications to provide the adjustments desired. The BDTF is located on a lightly used section of track, so it is not subjected to high levels of degradation as might be experienced at the Facility for Accelerated Service Testing (FAST) at the Transportation Technology Center (TTC).

Figure 1. BDTF – Adjustable Three-Span Trestle for Evaluation of Onboard Bridge Deflection System

Testing on the BDTF

In 2012, TTCI performed tests with several onboard systems at the BDTF, which was constructed to provide adjustable bridge strength and geometry conditions.[1] Three vehicles with onboard measurement systems were operated over the BDTF to determine their feasibility for use in onboard bridge condition assessment. The data was gathered using the following systems:

- Instrumented locomotive
- Instrumented freight car
- Track Loading Vehicle (TLV)
- Track geometry system (mounted on the TLV)

The instrumented locomotive and instrumented freight car measurements were primarily acceleration-based measurements, which have proven valuable in finding relatively short wavelength defects, especially related to rail surface conditions. The TLV used vertical loading to provide measurements related to track deflection and stiffness under various loads. The TLV track geometry system provided the measurements of track surface, alignment, cross level, gage, and related parameters.

In addition to onboard systems, wayside measurements were collected on the bridge. On the left and right sides of each span, vertical deflections and bending strains were measured. Figure 2 shows the three BDTF test configurations:

- Test 1: Normal condition – all bridge stringers have normal strength
- Test 2: Weak center span – both stringers in the center span are weakened by about 40 to 50 percent
- Test 3: East side of center span weak – only one stringer in the center span weakened 40 to 50 percent

The results of the tests were utilized for validation of the NUCARS simulation model.

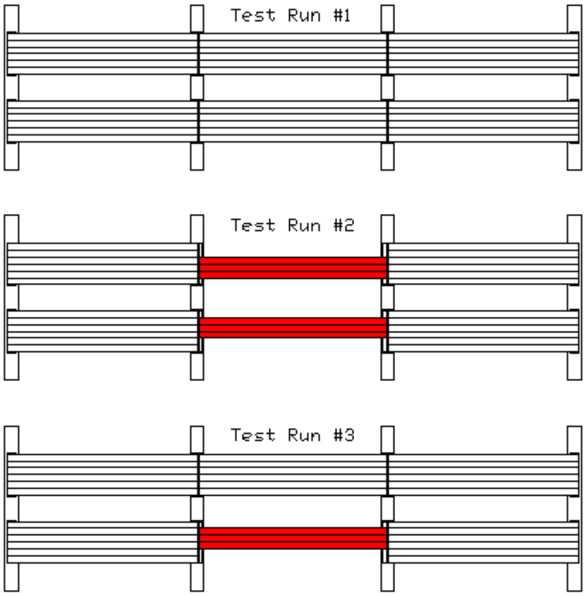

Figure 2. Illustrations of BDTF Test Conditions

NUCARS Simulations Overview

NUCARS software was used to model typical freight train equipment, a track system, and a bridge.

A model of the test train vehicles was created based on the characteristics and properties of the instrumented freight car (a loaded 110-ton hopper) and instrumented locomotive (an EMD-SD70M) used by TTCI. The track system model included the left rail, right rail, and ties.

Each span of the BDTF was modeled in NUCARS as a pair of beams: left and right. Each of the beams was modeled as a flexible element with parameters representing a real bridge. The parameters of the center span were modified to match two cases of a weakened bridge: (1) the left beam of the center span was weaker and (2) both beams of the center span were weaker.

NUCARS Three-Layer Track Model

The NUCARS track model allows simulation of flexible track/bridge structure under moving vehicles. It represents actual track structures as a multi-body system. The track is usually defined as either a single-layer (flexible rails) or two-layer flexible track model (flexible rails and flexible ties). However, more layers and more complicated track simulations to include features such as bridges and track slabs are allowed.

This study used a three-layer track model developed to analyze vehicle-bridge interaction. Figure 3 presents the connections between individual members.

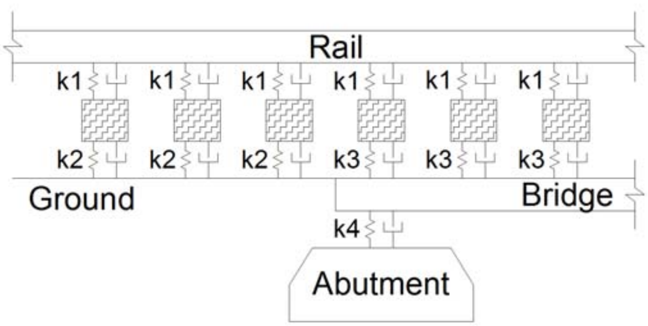

Figure 3. NUCARS Three-Layer Track Model of the BDTF

The top layer includes left and right 119 RE rails. The track is modeled to be 310 feet long. The second layer contains 7-inch by 9-inch by 8-feet 6-inch timber ties. The weight of the ties used in the model is 26.25 lb/ft (225 pounds) and the Young's Modulus of timber is 1,600 ksi. The third layer is the bridge stringers modeled as prismatic steel beams. The Young's Modulus for steel is assumed to be 30,000 ksi and the normal condition beam is built from six 136 RE rails per span. Other inertial properties used in modeling are listed in Table 1. The rails, ties, and bridge span were modeled as Euler-Bernoulli beams.

Table 2 lists the characteristic parameters for connections within the track model. The lateral stiffness of 2.0E5 and lateral damping of 100 lb-s/inch was used along with vertical parameters.

Table 1. Body Inertial Properties in NUCARS Track Model

Body Properties	Mass	Roll	Pitch	Yaw
	lb-sec^2/in	lb-sec^2-in		
Rails	31.772	40.48	0.0	0.0
Ties	0.578	503.41	6.26	504.95
Bridge Beams Normal Conditions	9.855	549.15	23,693.60	23,213.50
Bridge Beams Weak Conditions	4.928	81.62	11,655.00	11,607.90

Table 2. Characteristic of Connections used in NUCARS Track Model

Connections	Vertical Stiffness (lb/in)	Vertical Damping (lb-s/inch)
k1	1,000,000	400.0
k2	800,000	400.0
k3	1,000,000	400.0
k4	2.0×10^8	400.0

Simulation Results versus Measurements

The simulations were run with test train speeds ranging from 10 mph to 40 mph. To better simulate actual conditions, track irregularities were added to the model. The NUCARS output included vertical rail positions and deflections. The NUCARS model shows reasonable agreement with the test data, indicating that the model should be useful for predicting responses and outputs for a test train with a track deflection test car.

Figures 4–6 compare simulations of the test train over the BDTF with test data for Test 1, Test 2, and Test 3. The shape and magnitude of each of the test results and simulations are very similar. The discrepancy between measurements and modeling may be related to unknown conditions of soil properties and track geometry on the approach to the bridge and stiffness of the bridge supports. Changes to the stiffness of the bridge supports influences the overall deflection of the bridge. The parameters used in this study were adjusted based on the track modulus measurements from previous research studies on this topic.[2]

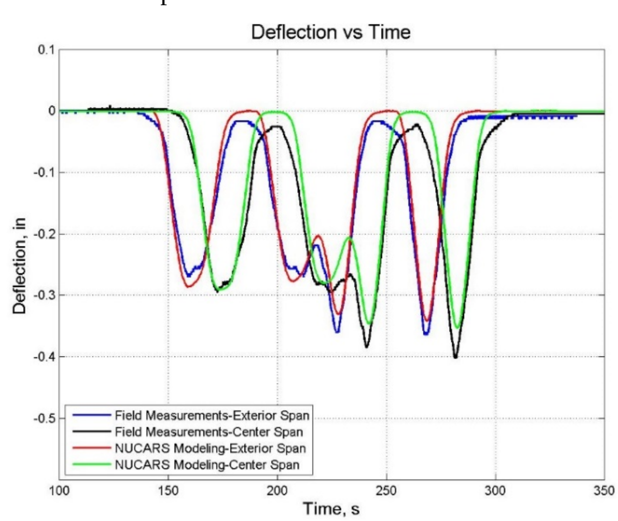

Figure 4. Deflection Histories for Center Span – Test 1

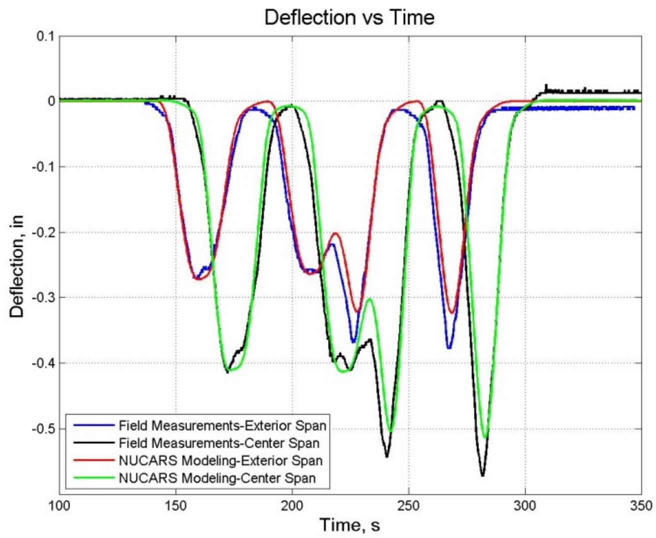

Figure 5. Deflection Histories for Center Span – Test 2

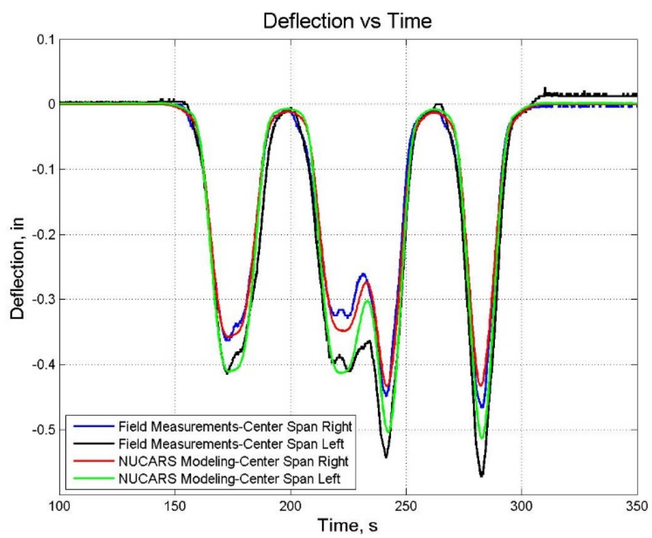

Figure 6. Deflection Histories for Center Span – Test 3

Application of the NUCARS Model

The previous sections showed that the predicted dynamic responses of bridges from NUCARS closely matched test results. The NUCARS simulations can also be used to predict the dynamic performance of the vehicle on the bridge.

The onboard measurement systems can be modeled by using transducers applied to the vehicle models in NUCARS. A second TD is a continuation of the study presented in this TD, it covers simulation results of the dynamic response of the vehicle running over the BDTF.[3] Simulations results were used to validate the NUCARS models of the vehicle. The analysis also provides information on how the onboard transducers may be used to detect changes in the bridge structure.

The simulated transducer outputs are analyzed to determine whether they can detect changes in the bridge structure and its performance. The analysis may provide information about other potential locations of transducers on the vehicle that are most likely to detect bridge conditions.

CONCLUSIONS and FUTURE RESEARCH

The NUCARS software can be used successfully to evaluate vehicle-bridge interaction. The advantages of using NUCARS over other software for analysis of railway bridges are the following:

- NUCARS can accurately model the dynamic responses of the vehicle including wheel/rail interaction.
- The track model includes multi-body flexible rail, ties, and bridge components as well as connections between them.
- Track connection parameters, such as soil properties on the bridge approach, can be estimated based on track modulus measurement data.
- NUCARS has the potential to be used for development of an onboard bridge structural integrity inspection system. Further tests and analyses were conducted in August 2014 and the findings are presented in a second TD of this study.[3]

NUCARS can only model the flexible components as simple beams; therefore, it is recommended to use the NUCARS track model for dynamic evaluation of a simple bridge structure. For detailed modeling of complex flexible structures such as truss bridges, development of an improved version of NUCARS model with finite element analysis modal inputs is recommended.

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