USDOT Tier 1 University Transportation Center Final Report

NURail Project No. # NURail2014-UKY-R08

3D Methodology for Evaluating Rail Crossing Roughness: Vehicle Dynamic Modeling

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DISCLAIMER

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TECHNICAL SUMMARY

NURail Project No. NURail2012-UKY-R08 Final Report March 2, 2015

3D Methodology for Evaluating Rail Crossing Roughness: Vehicle Dynamic Modeling

Introduction

Annually, over 2000 rail highway crossing crashes in the U.S. result in nearly 300 fatalities. Crossing roughness is a concern for the motoring public from a comfort and vehicle maintenance perspective, and to highway authorities from a maintenance perspective. Roughness may even increase the risk of crossing crashes. However, with 216,000 rail highway grade crossings in the US, maintenance management is a large undertaking. Crossings deteriorate over time, sometimes rapidly, and life cycle costs increase without preventive maintenance. However, while methods are available to quantify highway roughness, no method currently exists to quantitatively assess the condition of rail crossings. Because conventional inspection relies on qualitative judgment based on an inspector's perception of the crossing, effect on different vehicles and perception by other drivers is unknown. Further, roughness may be due to as-built geometry, crossing deterioration, or a combination of both. A quantifiable and extensible procedure is thus desired.

Approach and Methodology

In this report, vertical vehicle acceleration is proposed as a way to quantify rail highway crossing roughness. To facilitate the development of acceleration ratings for crossings, a vehicle dynamic model was developed to simulate vehicle accelerations using only a crossing terrain model and vehicle parameters as inputs. Accelerometers were used to field calibrate and validate the model.

Findings

Results indicate good agreement between modeled and measured accelerations for a test passenger vehicle at several speed ranges at two different locations. Model repeatability and data accuracy was verified, suggesting that the vehicle dynamic model can be used to quantify vehicular accelerations at various speeds and different locations.

Conclusions and Recommendations

In order for the results of the approach to be useful in decision making, one must consider that the accelerations (modeled or measured) at a rail crossing location can derive from either condition or construction of the crossing. That is to say, a crossing constructed on the level but in poor condition may induce similar accelerations or even less than a crossing in good condition, but where design limitations (hump crossing, elevated crossings, skewed crossings) or poor construction technique may be the cause of accelerations. Therefore, a logical next step in the research would be to separate the effects of condition and design/construction.

Also, if LiDAR data are already systemically available (such as for the State Highway system of Utah), the time to run the simulation model will generally be less than that required to go into the field (and would not require exposure of field personnel). However, obtaining LiDAR data for this purpose only would not be feasible or economical, and field measurements of accelerations would be the optimal approach.

Future research should investigate the effect different test vehicles would have on acceleration readings. Calibration across vehicles would be necessary to extrapolate simulations or actual field measurements of acceleration to other vehicle classes representing the roadway fleet.

Publications

Two papers addressing the objectives of the project are included as appendices to this report. These include:

Appendix A: Wang, T., R.R. Souleyrette, D. Lau, A. Aboubakr and E Randerson. “Quantifying Rail-Highway Grade Crossing Roughness: Accelerations and Dynamic Modeling.” Proceedings of the 94th Annual Meeting of TRB, Washington, DC, Jan. 2015. 11 pages

Appendix B: Wang, T., R.R. Souleyrette, A. Aboubakr and D. Lau. “A DYNAMIC MODEL FOR QUANTIFYING RAIL-HIGHWAY GRADE CROSSING ROUGHNESS.” Paper accepted for publication in the *Journal of Transportation Safety and Security.* 20 pp.

Appendix A: Wang, T., R.R. Souleyrette, D. Lau, A. Aboubakr and E Randerson. “Quantifying Rail-Highway Grade Crossing Roughness: Accelerations and Dynamic Modeling.” Proceedings of the 94th Annual Meeting of TRB, Washington, DC, Jan. 2015. 11 pages

QUANTIFYING RAIL-HIGHWAY GRADE CROSSING ROUGHNESS: ACCELERATIONS AND DYNAMIC MODELING

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Number of figures: 10
Number of tables: 1
Total equivalent word count: 2,740+10x250+250=5,490

Submssion date: 07/30/2014
A paper submitted to the TRB 94nd Annual Meeting for presentation and TRR publication

ABSTRACT

Quality of surface is an important aspect affecting both the safety and the performance of rail-highway grade crossings. Roughness may increase the risk of crashes for both trains and automobiles. Annually, there are about 2000 rail highway crossing incidents in the US resulting in nearly 300 fatalities. The problem is ubiquitous - there are over 216,000 rail highway grade crossings in the US. With so many crossings, maintenance management is a large undertaking. As with other highway assets, crossings deteriorate if not maintained, and life cycle cost increases without preventive maintenance. While there are accepted methods to quantify highway roughness (e.g., IRI), no quantitative method currently exists to assess the condition of rail crossings in order to evaluate the performance of crossings and set a quantitative trigger for their rehabilitation. As conventional inspection relies on qualitative judgment based on driving a vehicle over the crossing, it cannot assess ride experienced by different vehicles nor can it differentiate between the effects of as-built geometry and crossing deterioration. A quantifiable and extensible procedure is desired. The paper reports on the use of LiDAR to collect a 3D surface point cloud as input to a customized vehicle dynamic model. The model predicts accelerations experienced by highway vehicles using the crossing. Actual accelerations at the crossing are compared to the model estimates as a first step towards developing a simple, repeatable method for quantifying crossing roughness for policy and maintenance input.

Keywords: Rail-highway grade crossing, Roughness, Safety, LiDAR, 3D, Vehicle dynamic model, Simulation.

INTRODUCTION

The rail-highway crossing represents a unique and problematic junction of two of the most ubiquitous transportation modes. While crashes at rail-highway crossings have diminished over recent decades, the problem continues. Increasing traffic (highway and rail), distraction, and reduced patience on the part of drivers suggest that the problem could increase in the future. Driver inattention and decision making in the vicinity of the at-grade crossing are important contributors to their safety. It has long been speculated that rail highway crossing roughness may be related to safety performance. A study by Thomas Butcher (*1*) as far back as 1973 noted that drivers will change speed based on the roughness of the crossing. A more recent study by Christina Brown (*2*) suggested that poor surface conditions tend to divert drivers' attention while driving over crossings. Further, the US DOT Railroad Highway Grade Crossing Handbook (*3*) suggests that rough surfaces could distract a driver's attention from oncoming trains and that the unevenness of the crossing could result in a driver losing control of their vehicle, contributing to crash potential.

To determine the potential safety effect, it is first necessary to quantify roughness. The objective of the research is to develop a method to quickly and inexpensively quantify the roughness of a crossing, and based on correlations between roughness and safety, help prioritize crossings for rehabilitation. A first step towards this objective has already been completed. A low-cost 3D data acquisition system (DAS) based on 3D structured light imaging technology has been developed as reported in a paper given at the Joint Rail Conference in Colorado Springs, April, 2014 (*4*). As an extension of the research, a vehicle dynamic model that uses a 3D surface point cloud and vehicle wheel paths to estimate highway vehicle acceleration has been developed by the authors. By combining measurement and simulation technologies, this research represents a next step towards development of a methodology to quantify crossing roughness condition as a function of acceleration caused by crossing surface variation. To calibrate and validate a vehicle dynamic model, actual acceleration data are required.

This paper focuses on the collection and analysis of acceleration data and use of a vehicle dynamic simulation model to quantify rail-highway grade crossing roughness. The methods presented in this research are tested for repeatability and data accuracy.

LITERATURE REVIEW

While track roughness may be evaluated by a railroad geometry car, highway crossings are usually qualitatively evaluated. Previous work by the University of Kentucky (*5*) investigated a laser based inertial profiler and rolling dipstick for applicability in evaluating rail crossing roughness. Results were of limited practicality. In that research, investigation of alternative technology was recommended. A study from Purdue University (*6*) of railroad crossing roughness classification in Indiana and documents from Illinois DOT (*7*) showed how railroad crossing roughness could be classified into different groups such as smooth, medium, and rough based on qualitative rideability evaluations (good, fair, poor) at different driving speeds. However, subjective ratings for the crossing could be different for different vehicles. Further, the effect of crossing condition cannot be differentiated from effects of original geometric design using the current method. Additionally, the effect of surface quality cannot be distinguished from that of subsidence or movement of the crossing over time (or during crossing).

Roughness of highway pavements has long been studied. Various quantitative methods such as international roughness index (IRI) (*8*), and profile index (PI) (*9*) have been developed in the last 30 to 40 years. However, none of these technologies are applicable to measuring rail-highway crossing roughness due to the short distance and unique structure of the crossing.

Due to the various geometries that need to be accommodated at a highway rail crossing (grade of rail, elevation of rail, grade of highway, cross section of highway, drainage, …), it is difficult or impossible to field rate a crossing (by driving over it) and establish its performance for many combinations of crossing vehicle types, speeds and lateral placement of highway vehicle. To model its performance, an accurate 3D terrain model is required. Today, technology exists to map crossing surfaces at different levels of precision and at various costs. For example, LiDAR (Light Detection Ranging) is a remote sensing technology that measures distance and other properties such as shapes and dimensions by illuminating a target with a laser and analyzing the reflected light (*10*). LiDAR and 3D sensing in general find many applications in civil, construction and transportation engineering. For example LiDAR has been used to verify highway bridge clearance (*11*) and modern pavement management systems use laser scanners to quantify highway surface condition ratings. In this paper, the authors us a LiDAR-derived surface point cloud as an input to a vehicle dynamic model to quantify rail-highway grade crossing roughness.

TEST LOCATION AND 3D SURFACE POINT CLOUD

A field test was conducted at the Norfolk Southern Brannon Road Crossing in Jessamine County, KY, just south of Lexington (USDOT Crossing number 841647U). Current highway traffic on Brannon Road is 5,900 vehicles per day and about 70 trains per day pass the crossing (as shown in Figure 1). The FRA Web Accident Prediction System (WBAPS) predicted number of crashes per year at this crossing is 0.042 (*12*). Highway traffic at the crossing is expected to increase to 14,000 vehicles per day by 2040. To improve the safety of the road, the Brannon Road Improvement and Safety Project is being conducted by the Kentucky Transportation Cabinet. The project's construction phase is set to start in 2019 (*13*).

FIGURE 1. Brannon road crossing

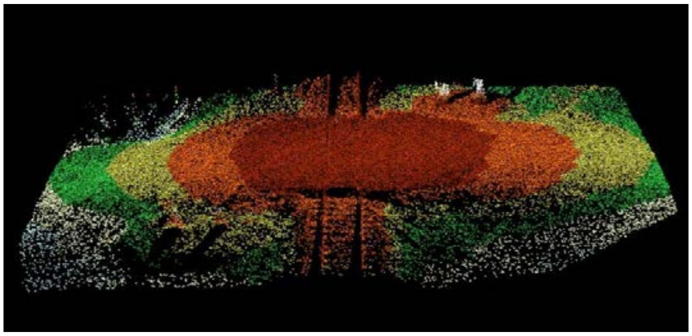

FIGURE 2. Brannon road crossing 3D point cloud (green to red indicates increasing elevation).

A Brannon Rd Crossing 3D surface point cloud was collected using LiDAR, as shown in Figure 2. The crossing is generally rough as can be seen in elevation changes on the highway approaches as depicted in Figures 1 and 2.

ACCELERATION FIELD DATA COLLECTION

The test vehicle chosen was a 2009 Chevrolet Impala sedan. Other equipment and devices used in field tests included 1) a real time acceleration sensor which records and stores 3 axis (XYZ) acceleration data at 100 hertz with the range of +/- 10 g, accuracy +/- 1% and resolution at 0.010 g, 2) a laptop PC preloaded with real time recording software, 3) a smart phone with built-in A-GPS that records and stores the GPS coordinates and vehicle speed at 1 hertz (see Figure 3), and, 4) a stop watch. Both the acceleration sensor and smart phone were mounted on the center of the dashboard of the vehicle during the test.

FIGURE 3. Smart phone GPS user face.

Two students performed the test, a driver who tried to drive at a constant speed over the crossing and a passenger recording the time before and after passing the crossing, referencing a fixed objective such as a tree or light pole. The acceleration sensor and GPS were kept running during the entire test. See Figure 4.

FIGURE 4. Field acceleration data collection.

The driver tried to drive as close to 35 mph as possible – the speed limit of the main road in the vicinity of the crossing on Brannon Rd. Several runs were made at this speed. Other tests were run at speeds as low as 15 mph and as high as 45 mph. Note that while the advisory speed of the crossing is 15 mph, accelerations at that speed were negligible.

Only the acceleration on the Z axis (vertical direction) was used for the analysis as it is a better indicator of the roughness of the crossing. Results are plotted as Z Acceleration vs Time for a period approximately 0.5 second before to 0.5 second after the vehicle passed the crossing surface. The average speed of the vehicle passing the crossing was obtained from the smart phone GPS associated with each test (using a time stamp). The results are shown in Figure 5.

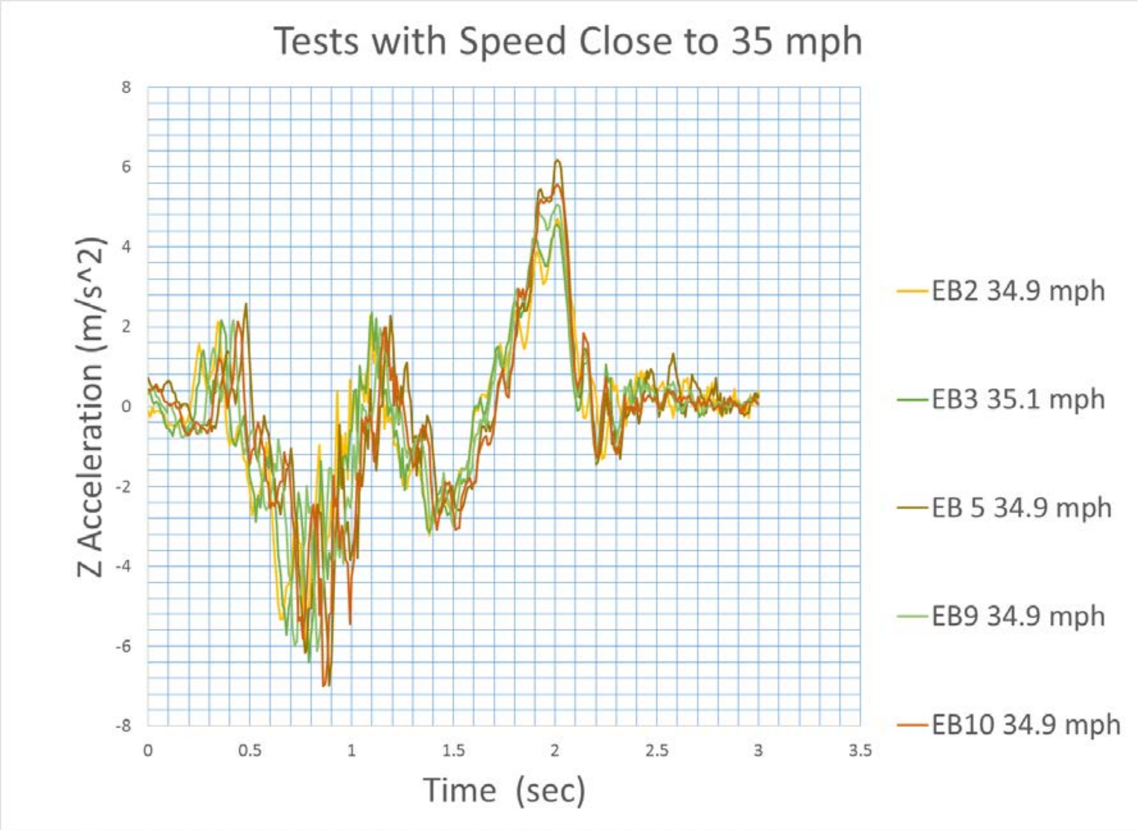

FIGURE 5. Tests with speed close to 35 mph.

Figures 5 shows that when the test speed is held constant (35 mph), both the frequency and amplitude of acceleration from repeated test are very close. This indicates that the test is highly repeatable and method is reliable for future work.

To test the effect of speed variation on accelerations, several tests were performed at various speeds. Results of these tests are shown in Figures 6. It can be seen that as expected, acceleration amplitudes and frequencies increase with increasing speeds.

FIGURE 6.Tests with various speeds.

VEHICLE DYNAMIC MODEL SIMULATION

In order to simulate the highway vehicle driving over a crossing and estimate accelerations, a highway vehicle dynamic model was developed based on the computer code ATTIF (Analysis of Train/Track Interaction Forces). The model was developed at the Dynamic Simulation Laboratory (DSL) of the University of Illinois at Chicago (UIC). Its original purpose was to simulate train and track interaction. ATTIF included a detailed wheel/rail contact model based on surface geometry (see Figure 7).

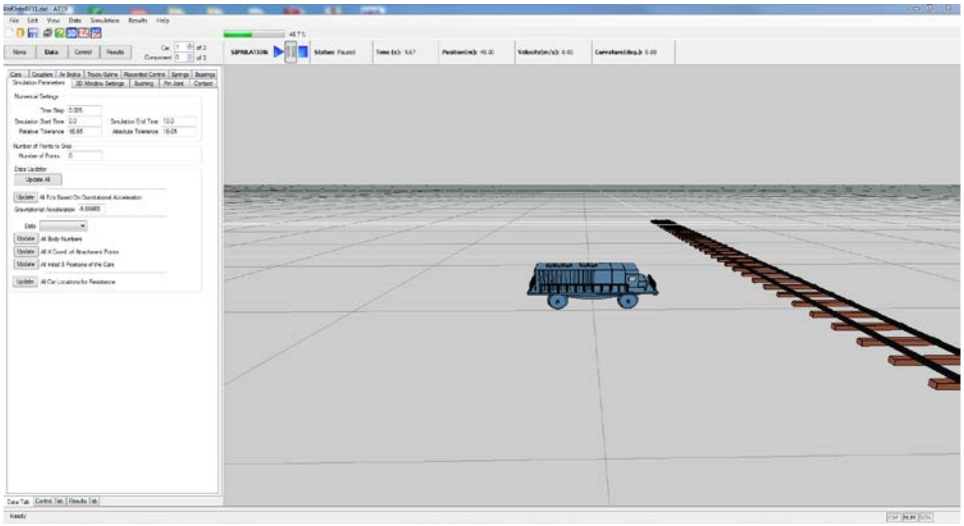

FIGURE 7. ATTIF based vehicle dynamic simulation model

The authors modified the ATTIF vehicle dynamic model which uses the 3D surface point cloud coordinate data together with realistic vehicle parameters such for weight, velocity, wheel radius, wheel-base and suspension characteristics to simulate a vehicle driving over the rail crossing. During the validation and calibration process, the initial simulation acceleration result was about 3 times larger than the field observation. It also had a lot high frequency noise in the wave as shown in Figure 8.

FIGURE 8. Initial simulation result vs field collection data @ 34.9 mph

The amplitude and frequency differences between the simulation and field observation were caused by the stiffness and damping of the vehicle tires which were significantly different to rail steel wheels. After reducing the tire stiffness and increasing its damping, the model was calibrated. Simulated accelerations were then compared to field observations as discussed in the following section.

SIMULATION RESULT COMPARING TO FIELD COLLECTION DATA

Simulation results vs. field collection data for two different speeds are shown in Figure 9 and 10 below.

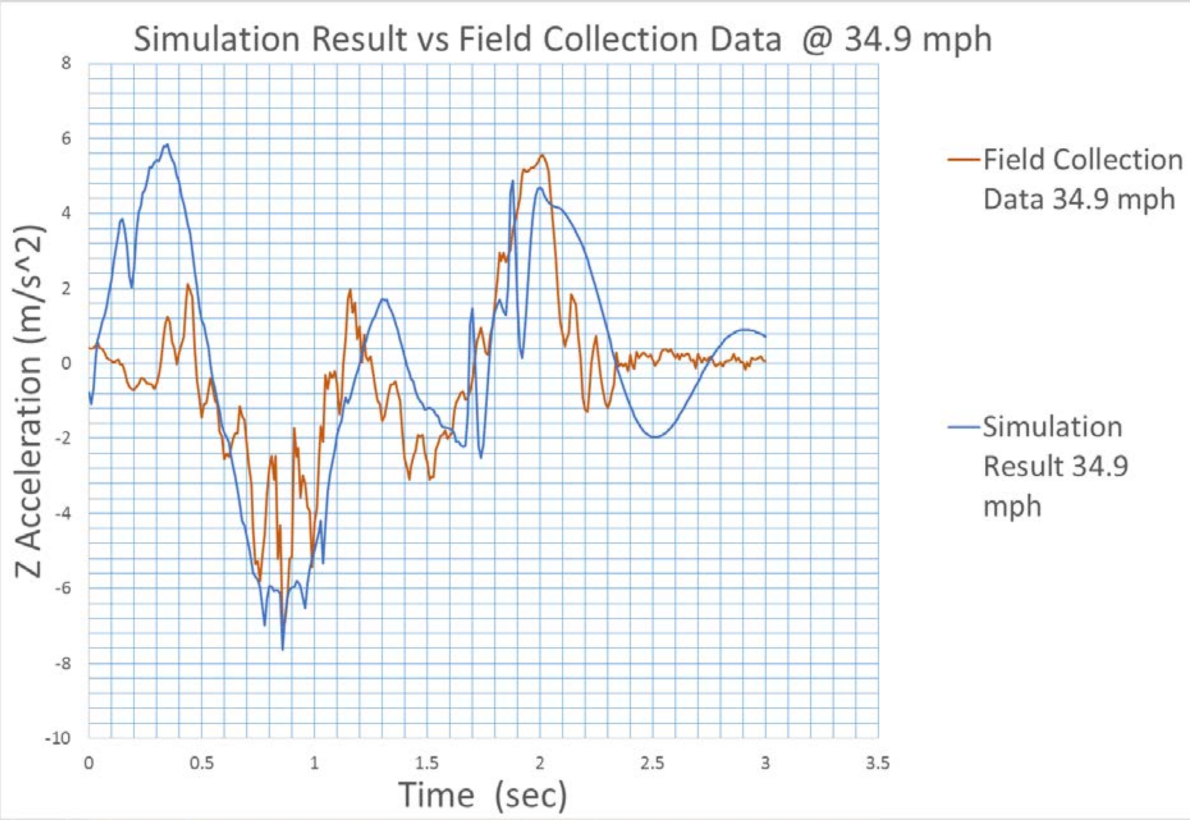

FIGURE 9. Simulation result vs field collection data @ 34.9 mph

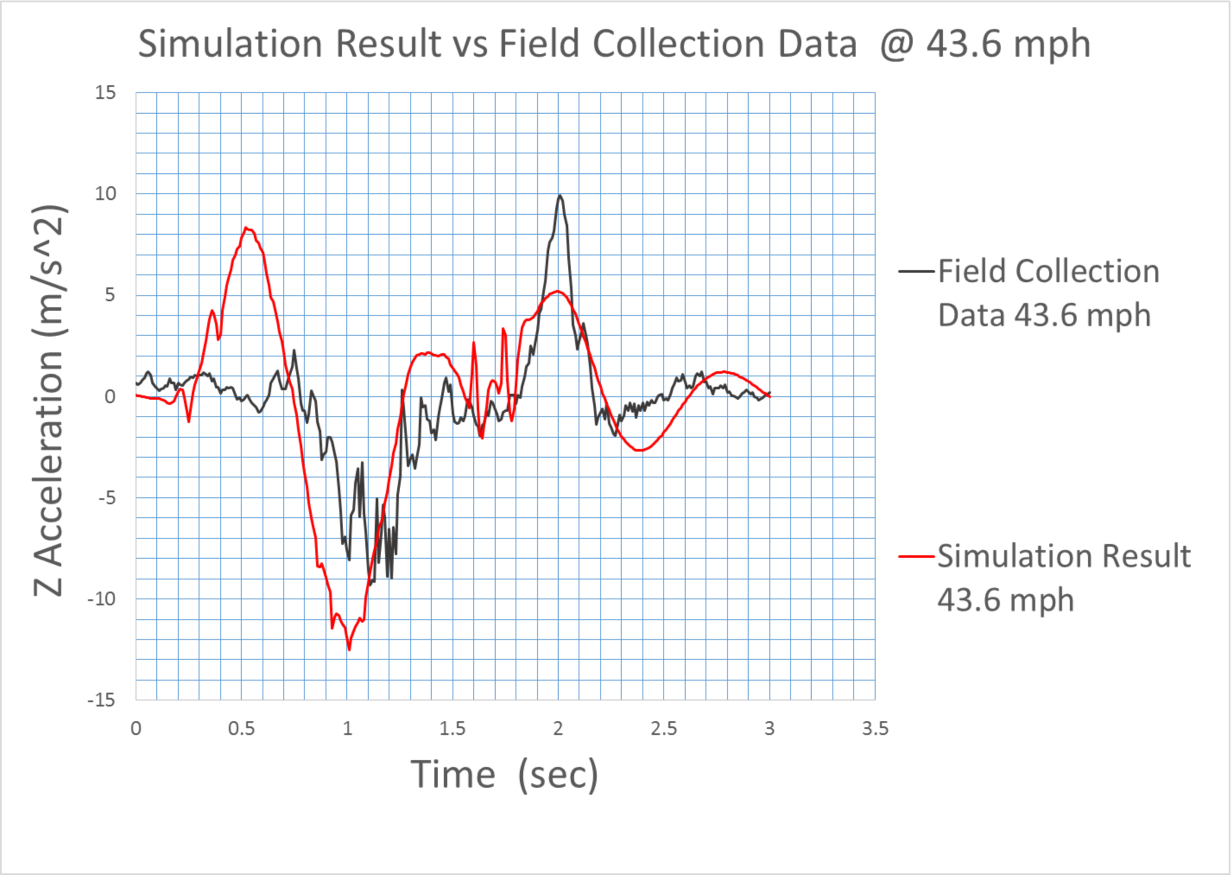

FIGURE 10. Simulation result vs field collection data @ 43.6 mph

As can be seen in Figures 9 and 10, simulation results are similar to field observations. General trends of the acceleration waves are similar, and maximum and minimum values of accelerations are quite close. In Figure 9 (comparison at 34.9 mph), the first 0.5 second and last 0.5 second data have higher error. These boundary effects are artifacts of the virtual transition of simulated profile to the assumed approaches, and can be ignored.

To quantify the goodness-of-fit and similarity of the two waves in the plot, a MATLAB script was developed by using a cross correlation index (P in equation 1) and mean squared error (MSE). Results are shown in Table 1.

TABLE 1. Simulation Results Compared to Field Collection Data

Speed	P(A:B) A=field B=simulated	MSE (normalized to maximum acceleration)	MAX(A):MAX(B) in m/s^2	MIN(A):MIN(B) in m/s^2
23.9 mph	0.4443	0.3352	1.96:4.27	-3.29:-3.51
26.2 mph	0.6522	0.1957	2.58:4.72	-3.74:-3.68
34.9 mph	0.9338	0.1553	5.56:5.84	-7.00:-7.64
43.6 mph	0.9346	0.1587	9.92:8.36	-9.32:-12.51

$$\text{cross correlation index } \mathrm{P(A:B)} = \frac{\text{cross correlation (A:B)}}{\text{cross correlation (A:A)}} \qquad (1)$$

where A, B are time series waves with the same number of data.
And P(A:B) = 1, when wave A and B are the same shape.

SUMMARY AND NEXT STEPS

To model rail-highway crossing roughness, a 3D surface is needed. Previously, a low cost 3D data acquisition system was developed. In this paper, a vehicle dynamic simulation model was developed and calibrated using 3D data and field accelerometer readings. Test repeatability and data accuracy was verified. In future, the vehicle dynamic model will facilitate estimation of vehicular accelerations at various speeds for different vehicles and lateral positioning. A method could be developed to extrapolate acceleration readings to those experienced by a design vehicle. These tasks, listed below, are all a part of making it quicker and easier for highway agencies to quantitatively evaluate the condition of a crossing as part of an objective, measurable performance program.

1) Low cost 3D sensor (previous)
2) Accelerometer validation (this paper)
3) Dynamic model calibration (this paper)
4) Calibration of dynamic model for different speeds (future)
5) Test/calibration of dynamic model for different vehicles and crossings (future)
6) Test of effect of lateral placement (future)
7) Development of method to extrapolate acceleration readings to design vehicle (future)
8) Use of 3D sensor to quantify hump crossings (future)

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Appendix B: Wang, T., R.R. Souleyrette, A. Aboubakr and D. Lau. “A DYNAMIC MODEL FOR QUANTIFYING RAIL-HIGHWAY GRADE CROSSING ROUGHNESS.” Paper accepted for publication in the *Journal of Transportation Safety and Security*. 37 pp.

A DYNAMIC MODEL FOR QUANTIFYING RAIL-HIGHWAY GRADE CROSSING ROUGHNESS

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ABSTRACT

Annually, over 2000 rail highway crossing crashes in the U.S. result in nearly 300 fatalities. crossing roughness is a concern for the motoring public from a comfort and vehicle maintance perspective, and to highway authorities from a maintenance perspective. Roughness may even increase the risk of crossing crashes. However, with 216,000 rail highway grade crossings in the US, maintenance management is a large undertaking. Crossings deteriorate over time, sometimes rapidly, and life cycle costs increase without preventive maintenance. However, while methods are available to quantify highway roughness, no method currently exists to quantitatively assess the condition of rail crossings. Because conventional inspection relies on qualitative judgment based on an inspector's perception of the crossing, effect on different vehicles and perception by other drivers is unknown. Further, roughness may be due to as-built geometry, crossing deterioration, or a combination of both. A quantifiable and extensible procedure is thus desired. The paper details the use of 3D surface models and a customized vehicle dynamic model to predict accelerations experienced by highway vehicles using the crossing. The model is validated with field measured accelerations. Results indicate good agreement between modeled and measured accelerations for a test passenger vehicle at several speed ranges at two different locations.

Keywords: Railway, Simulation, Field research, Highway, Infrastructure Design

1. INTRODUCTION

The rail-highway crossing represents a unique and problematic junction of two of the most ubiquitous transportation modes. While crashes at rail-highway crossings have diminished over recent decades, the problem continues. Increasing traffic (highway and rail), distraction, and reduced patience on the part of drivers suggest that the problem could increase in the future. Driver inattention and decision making in the vicinity of the at-grade crossing are important contributors to their safety. It has long been speculated that rail highway crossing roughness may be related to safety performance. A study as far back as 1973 (Butcher, 1973) noted that drivers will change speed based on the roughness of the crossing. A more recent study (Rudin-Brown et al. 2014) suggested that poor surface conditions tend to divert drivers' attention while driving over crossings. Further, the US DOT Railroad Highway Grade Crossing Handbook (Ogden, 2007) suggests that rough surfaces could distract a driver's attention from oncoming trains and that the unevenness of the crossing could result in a driver losing control of their vehicle, contributing to crash potential.

To determine the potential safety effect, it is first necessary to quantify roughness. The overall objective of our research is to develop a method to quickly and inexpensively quantify the roughness of a crossing, and, based on correlations between roughness and safety, prioritize crossings for rehabilitation. A first step towards that objective is reported in Wang et al (2014). In that paper, the development of a low-cost 3D data acquisition system (DAS) based on 3D structured light imaging technology was reported. As an extension of that research, a vehicle dynamic model was developed to use a 3D surface point cloud and vehicle wheel path to estimate accelerations. An initial attempt to calibrate that vehicle dynamic model is reported Wang, et al (2015).

The present paper describes the continued development, calibration and validation of the dynamic simulation model for a single test vehicle, as applied to two different crossings for a number of vehicle speeds. Hence, the model is tested for both accuracy and repeatability across speeds and locations.

2. LITERATURE REVIEW

While track roughness may be evaluated by a railroad geometry car, highway crossings are usually qualitatively evaluated. However, previous work (Rose et al. 2009) investigated the use of a laser based inertial profiler and rolling dipstick to quantify rail crossing roughness. Results were of limited practicality, and investigation of alternative technology was recommended. A study of railroad crossing roughness classification in Indiana (Williams, 2003) and a report from Illinois (Illinois DOT, 2001) showed how railroad crossing roughness could be classified into different groups such as smooth, medium, and rough based on qualitative rideability evaluations (good, fair, poor) at different driving speeds. However, subjective ratings for crossings were found to be different for different vehicles. Further, the effect of crossing condition cannot be differentiated from effects of original geometric design using qualitative methods.

Roughness of highway pavements has long been studied. Various quantitative methods such as international roughness index (IRI) (Sayers, 1995), and profile index (PI) (Sayers and Karamihas, 1998) have been developed in the last 30 to 40 years. However, none of these technologies are applicable to measuring rail-highway crossing roughness due to the short distance and unique structure of the crossing.

Due to the various geometries that need to be accommodated at a highway rail crossing (grade of rail, elevation of rail, grade of highway, cross section of highway, drainage, …), it is difficult or impossible to field rate a crossing (by driving over it) and establish its performance for many combinations of crossing vehicle types, speeds and lateral placement of highway vehicle. A modeling approach is therefore desired. To model acceleration, an accurate 3D terrain model is required. Technology exists to map crossing surfaces at different levels of precision and at various costs. For example, LiDAR (Light Detection Ranging) is a remote sensing technology that measures distance and other properties such as shapes and dimensions by illuminating a target with a laser and analyzing the reflected light (Olsen et al. 2013). LiDAR and 3D sensing in general find many applications in civil, construction and transportation engineering. For example LiDAR has been used to verify highway bridge clearance (Rister et al. 2013) and modern pavement management systems use laser scanners to quantify highway surface condition ratings.

3. APPROACH AND OUTLINE

To quantify crossing roughness in the field, we measure accelerations from inside the passenger compartment of a passenger vehicle using a commercially available digital accelerometer. To estimate these accelerations without directly measuring with an accelerometer, we customize a vehicle dynamic simulation model. To run the model, a crossing terrain model is required.

This paper is organized as follows: Following a section on development of terrain models used in this research, we present a section on field measurement of acceleration. Next, the development of the dynamic simulation model is described. Following that section, we present calibration and validation documentation. We conclude with a summary of our work, discuss limitations and suggest future research.

4. TERRAIN MODEL

A test location for this research was selected as the Norfolk Southern Brannon Road Crossing in Jessamine County, KY, just south of Lexington (USDOT Crossing number 841647U). Current highway traffic on Brannon Road is 5,900 vehicles per day and about 70 trains per day pass the crossing (as shown in Figure 1). The FRA Web Accident Prediction System (WBAPS) predicted number of crashes per year at this crossing is 0.042 (FRA, 2014). Highway traffic at the crossing is expected to increase to 14,000 vehicles per day by 2040. To improve the safety of the road, the Brannon Road Improvement and Safety Project is being conducted by the Kentucky Transportation Cabinet. The project's construction phase is set to start in 2019 (Essig, 2014).

FIGURE 1. Brannon road crossing

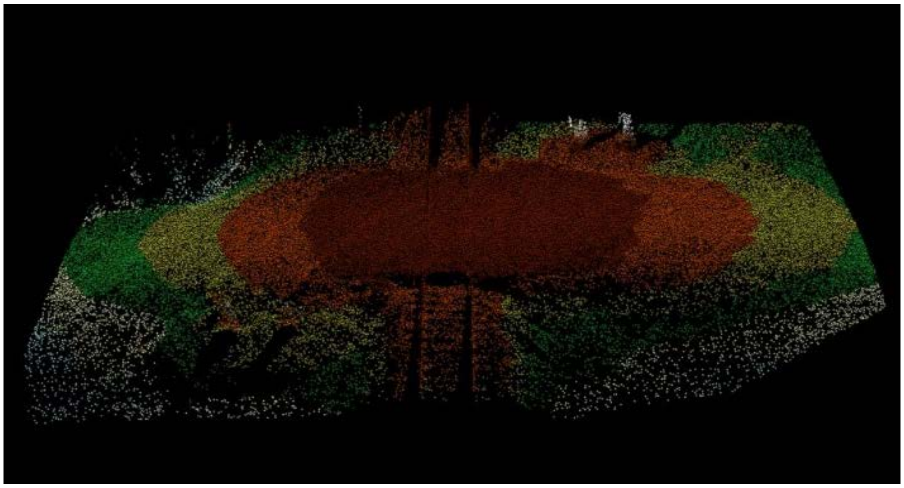


FIGURE 2. Brannon road crossing 3D point cloud

At the Brannon Rd Crossing test site, a 3D surface point cloud was collected using LiDAR (see Figure 2). The LiDAR data were collected using an Optech Lynx SG1 mobile LiDAR system. This 2-sensor system has a range precision of 5mm, 1σ (see: http://www.optech.com/wp-content/uploads/specification_lynx-sg1.pdf). is The crossing is generally rough as can be seen in elevation changes on the highway approaches as depicted in Figures 1 and 2.

For validation purposed (discussed later in this paper), a terrain model was also developed for a second location along the RJ Corman Railroad at Bryan Station Road in Fayette County, KY, just north of Lexington (USDOT Crossing number 346839X). Current highway traffic at the Bryan Station crossing is 2541 vehicles per day and on average less than one train per day pass the crossing.

5. FIELD ACCELERATION DATA COLLECTION

The test vehicle chosen was a 2009 Chevrolet Impala sedan. Other equipment and devices used in field tests included 1) a real time acceleration sensor which records and stores 3 axis (XYZ) acceleration data at 100 hertz with the range of +/- 10 g, accuracy +/- 1% and resolution at 0.010 g, 2) a laptop PC preloaded with real time recording software, 3) a smart phone with built-in A-GPS that records and stores the GPS coordinates and vehicle speed at 1 hertz (see Figure 3), and, 4) a stop watch. Both the acceleration sensor and smart phone were mounted on the center of the dashboard of the vehicle during the test.

GPS Position
Latitude
38:1:11.85673
Longitude
-84:29:16.61258
Other GPS information
GPS Bearing: 116.5°
Satellites: 18 locked, 19 visible
Precision: 3m

FIGURE 3. Smart phone GPS user face.

Two students performed the test, a driver who tried to drive at a constant speed over the crossing and a passenger recording the time before and after passing the crossing, referencing a fixed objective such as a tree or light pole. The acceleration sensor and GPS were kept running during the entire test. See Figure 4.

FIGURE 4. Field acceleration data collection.

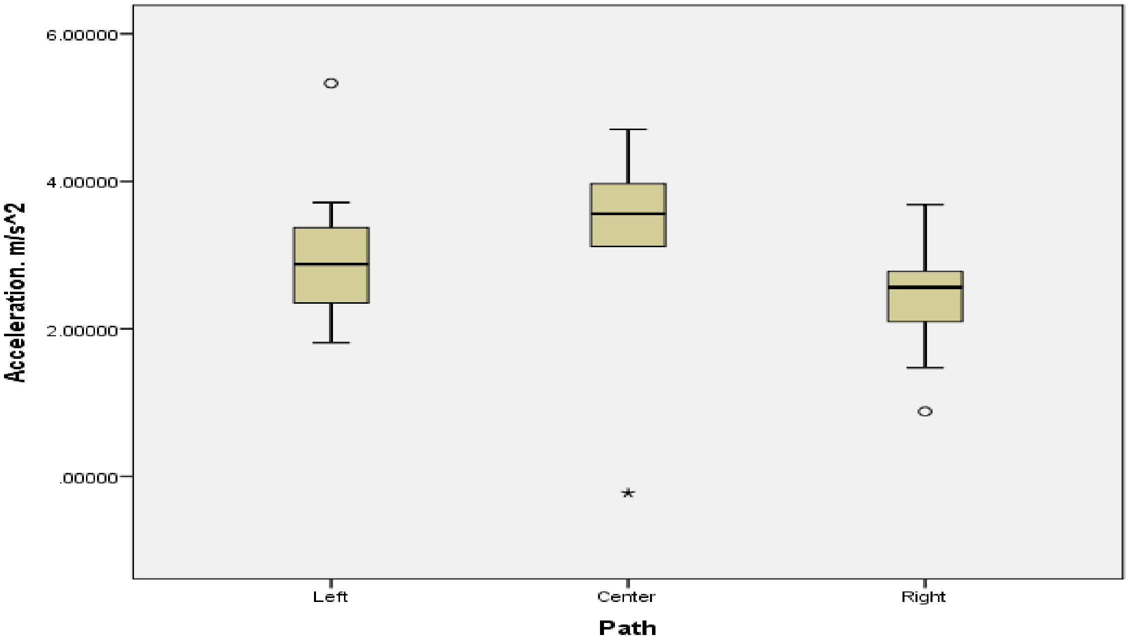
The driver tried to drive as close to 35 mph as possible – the speed limit of the main road in the vicinity of the crossing on Brannon Rd. Several runs were made at this speed. Other tests were run at speeds as low as 15 mph and as high as 45 mph. Note that while the advisory speed of the crossing is 15 mph, accelerations at that speed were negligible.

Only the acceleration on the Z axis (vertical direction) was used for the analysis as it is a better indicator of the roughness of the crossing. Results are plotted as Z Acceleration vs Time for a period approximately 0.5 second before to 0.5 second after the vehicle passed the crossing surface. The average speed of the vehicle passing the crossing was obtained from the smart phone GPS associated with each test (using a time stamp). The results are shown in Figure 5.

FIGURE 5. Accelerations Measured at Speeds Close to 35 mph.

Figures 5 shows that when the test speed is held constant (35 mph), both the frequency and amplitude of acceleration from repeated test are very close. This indicates that the test is highly repeatable and method is reliable for future work.

It should be noted that in our field data collection, we use the Z axis (vertical direction) as an indicator of the roughness and show that repeated test results represented similar patterns in terms of the frequency and amplitude of vertical acceleration. However, different drivers may choose different paths where roughness may be different. That is, ground roughness varies horizontally and therefore, the roughness experiences is a function of the chosen path. For example, we present the varying accelerations resulting from driving a sample crossing in different lateral positions in figure 6. To minimize the effects of lateral placement, all tests performed in this research were done with similar wheel paths over crossings with minimal lateral surface variation.



. **FIGURE 6. Effect of Lateral Wheel Path Position on Measured Accelerations.**

To test the effect of speed variation on accelerations, several tests were performed at various speeds. Results of these tests are shown in Figures 7. It can be seen that as expected, acceleration amplitudes and frequencies increase with increasing speeds.

FIGURE 7. Accelerations Measured at Various Speeds.

6. SIMULATION OF ACCELERATION

In order to simulate the highway vehicle driving over a crossing and estimate accelerations, a highway vehicle dynamic model was developed based on the computer code ATTIF (Analysis of Train/Track Interaction Forces). The model was developed at the Dynamic Simulation Laboratory (DSL) of the University of Illinois at Chicago (UIC). Its original purpose was to simulate train and track interaction. ATTIF included a detailed wheel/rail contact model based on surface geometry (see Figure 8).

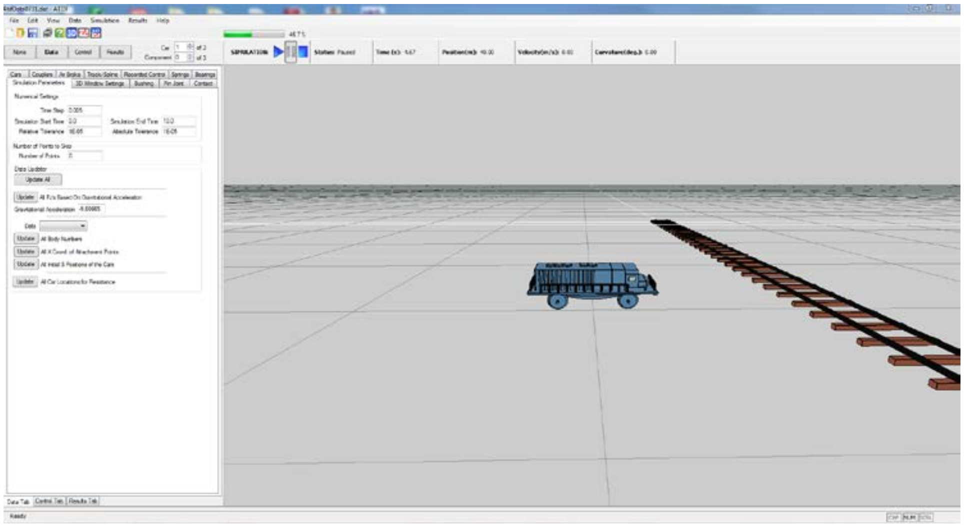


FIGURE 8. ATTIF based vehicle dynamic simulation model GUI

The authors modified the ATTIF vehicle dynamic model which uses the 3D surface point cloud coordinate data together with realistic vehicle parameters such for weight, velocity, wheel radius, wheel-base and suspension characteristics to simulate a vehicle driving over the rail crossing. During the validation and calibration process, the initial simulation acceleration result was about 3 times larger than the field observation. It also had a lot high frequency noise in the wave as shown in Figure 9.

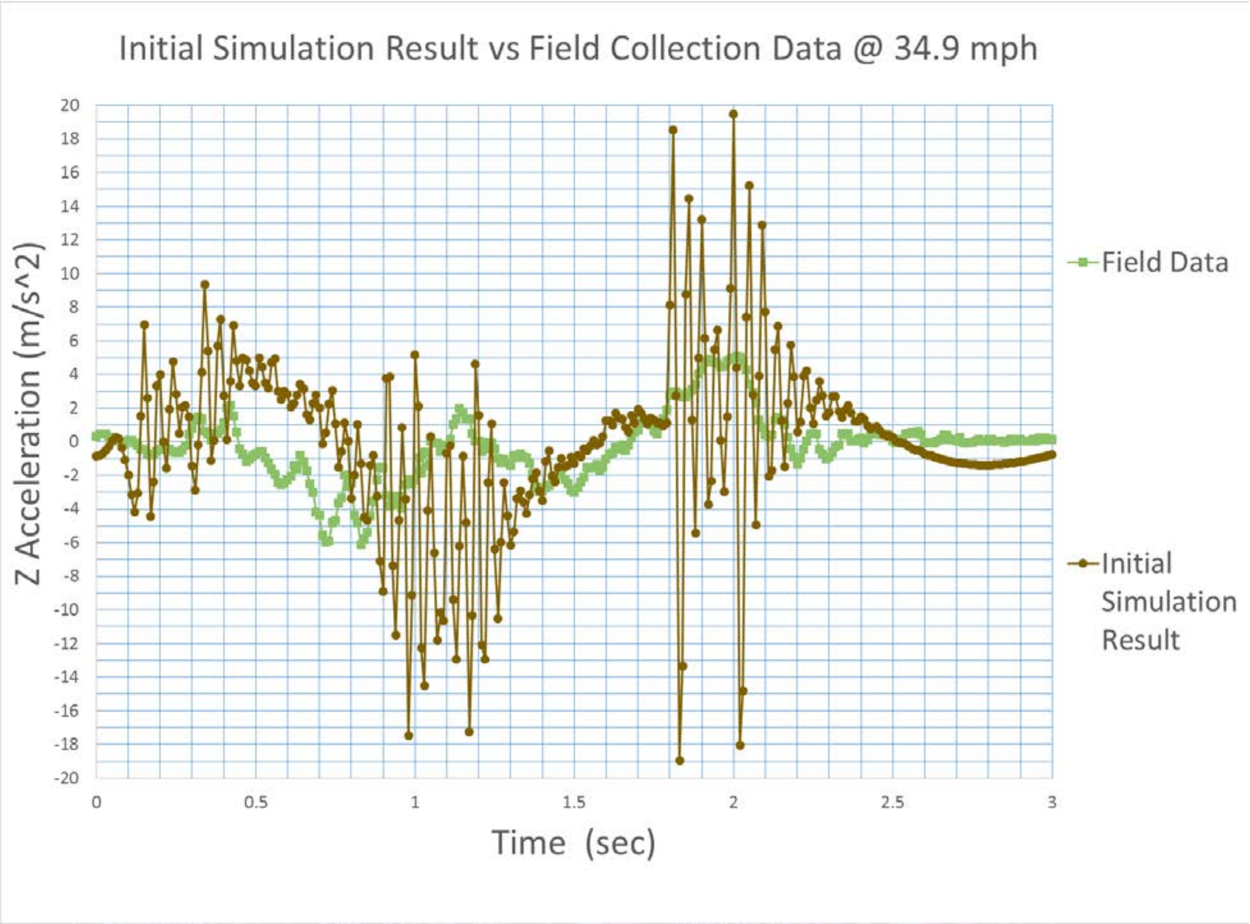


FIGURE 9. Initial simulation result vs field measured accelerations @ 34.9 mph

The amplitude and frequency differences between the simulation and field observation were caused by the stiffness and damping of the vehicle tires which were significantly different to rail steel wheels. As the basic model is initial design for steel on steel, wheel to track model, although we added 4 springs to represent tires/wheels and another 4 springs to represent the suspension between the frame and car body, with rigid parameters, steel wheel still pick up any tiny little change on the profile spline comparing to a rubber vehicle tire.

7. MODEL CALIBRATION AND VALIDATION

To calibrate the model, a trial and error process was used to modify vehicle component parameters to best match the mid-range speed, 34.9mph. Tire stiffness was decreased by a factor of 12.5 and its damping factor was increased by a factor of 3.5. Suspension stiffness was increased by a factor of 4 and its damping factor was increased by a factor of about 2. Simulated accelerations were then compared to field observations for various speeds. These comparisons can be seen in Figures 10 and 11.

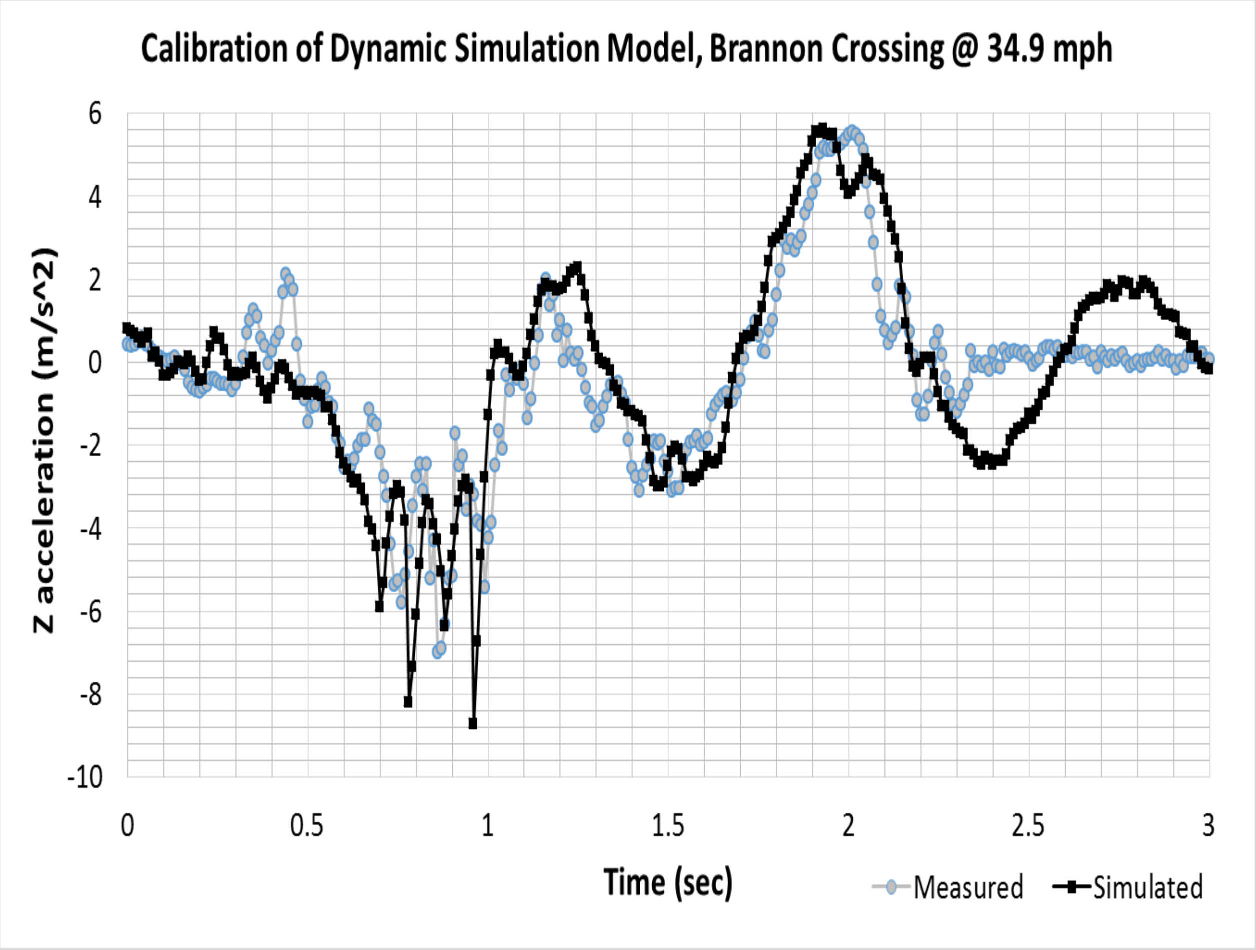


FIGURE 10. Calibration of Dynamic Simulation Model, Brannon Crossing @ 34.9 mph

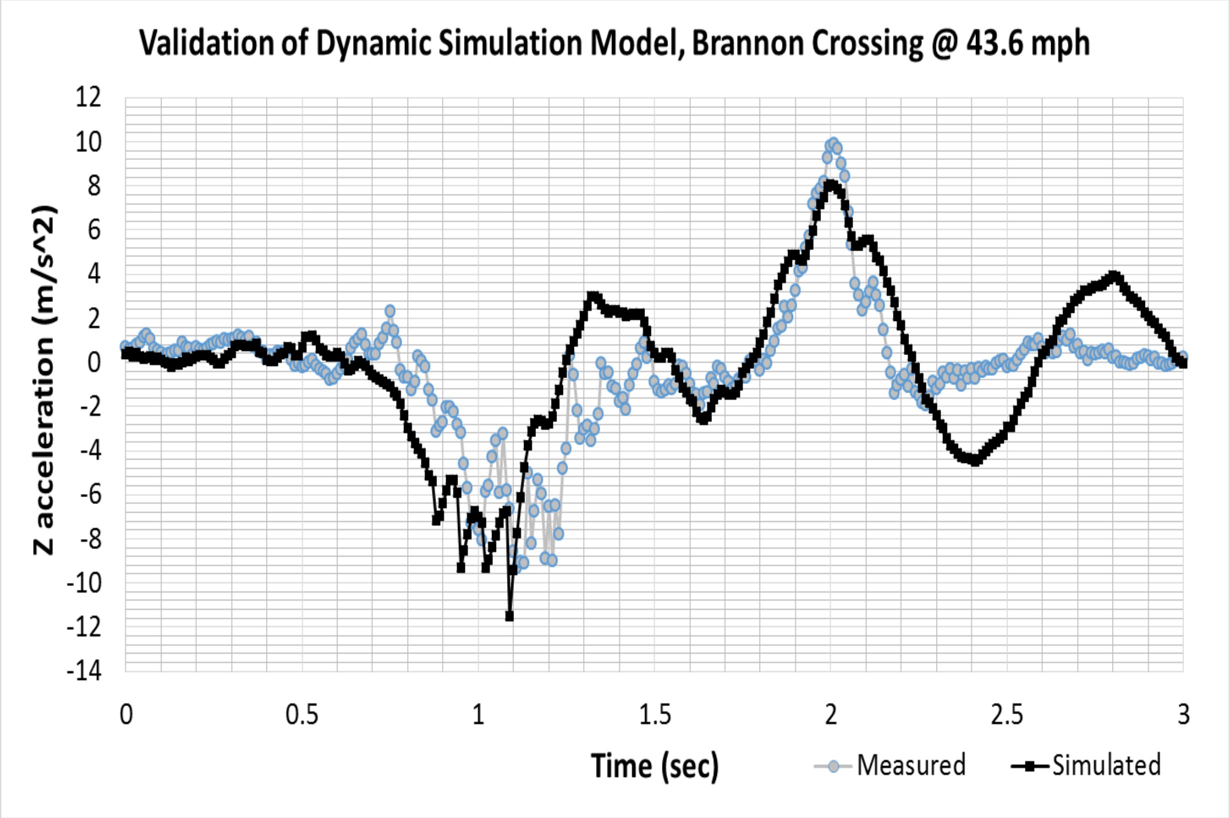


FIGURE 11. Validation (different speed) of Dynamic Simulation Model, Brannon Crossing @ 43.6 mph

The relationship between estimated and field observed accelerations are generally similar (peaks align, overall magnitudes of accelerations are similar – often very close). Table 1 presents a numerical comparison of simulated and field-observed results. Maximum accelerations at all speeds are quite similar. For the higher speeds (at or above 34 mph) minimum accelerations are also quite similar. Peak differences vary from a low 0.09 m/s^2 to a high of 4.98 m/s^2. Estimation errors are higher at lower speeds and are likely due to nonlinear behaviors of vehicle suspensions. For example, when a car “bottoms out” (springs fully compress or shocks reach their maximum compression or extension), calibration of the model across all speeds will be impossible.

To quantify the goodness-of-fit and similarity of the two waves in the plot, a MATLAB script was developed to compute a *cross correlation index* (P in equation 1) and mean squared error (MSE).

TABLE 1. Calibration of Dynamic Simulation Model (Brannon Crossing)

Speed	P(A:B) A=field B=simulated	MSE (normalized to maximum acceleration)	MAX(A):MAX(B) in m/s^2	MIN(A):MIN(B) in m/s^2
23.9 mph	0.645	0.352	1.96 : 2.55	-3.29 : -8.27
26.2 mph	0.468	0.278	2.58 : 2.38	-3.74 : -7.01
34.9 mph	0.786	0.063	5.56 : 5.65	-7.00 : -8.70
43.6 mph	0.801	0.086	9.92 : 8.02	-9.32 : -11.57

$$\text{cross correlation index } P(A:B) = \frac{\text{cross correlation (A:B)}}{\text{cross correlation (A:A)}} \qquad (1)$$

A and B are time series waves with the same number of points, and P(A:B) = 1, when wave A and B are the same shape.

The simulation model, calibrated for the Brannon Road crossing, was then used, without further calibration, to estimate the accelerations at a second crossing (Bryan Station). These “location validation” results are similar to those obtained during calibration (see Figure 12 and Table 2).

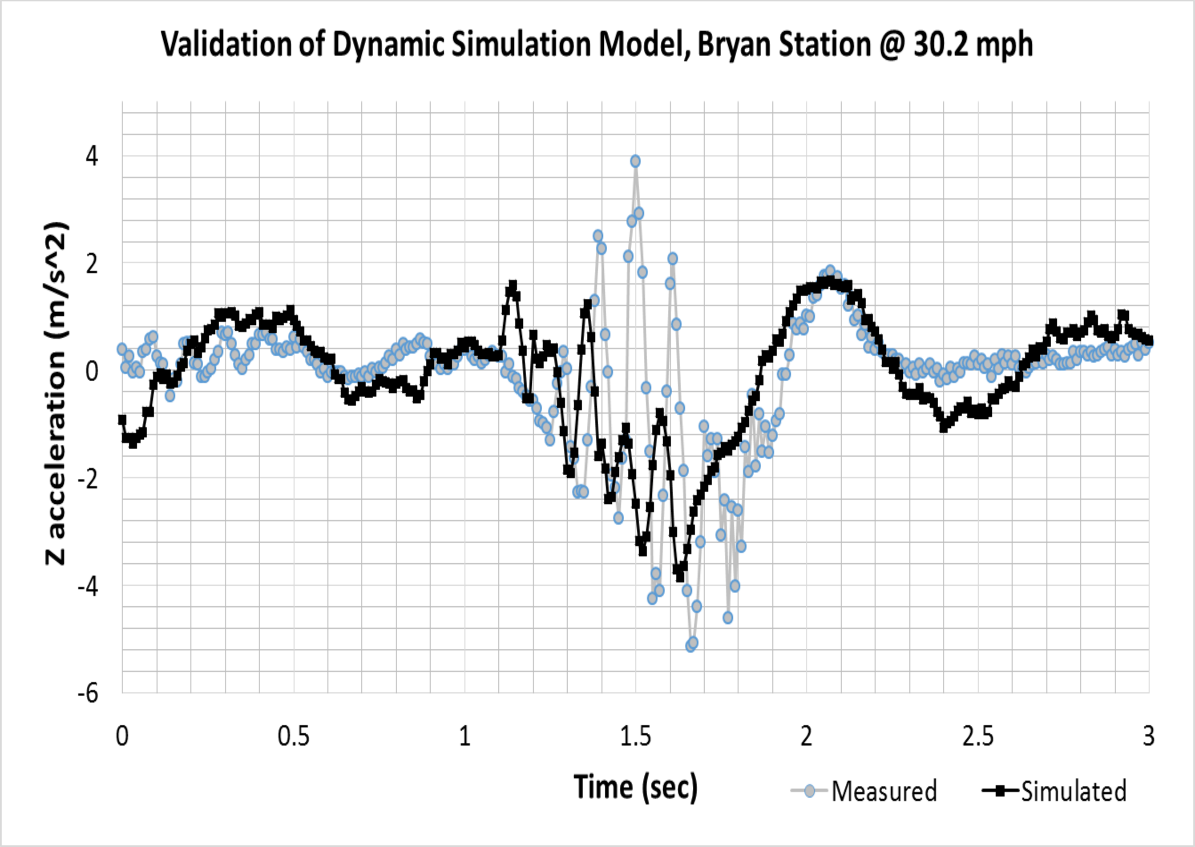


FIGURE 12. Validation of Dynamic Simulation Model, Different Location, Bryan Station @ 30.2 mph

TABLE 2. Validation of Dynamic Simulation Model (Bryan Station)

Speed	P(A:B) A=field B=simulated	MSE (normalized to maximum acceleration)	MAX(A):MAX(B) in m/s^2	MIN(A):MIN(B) in m/s^2
30.2 mph	0.842	0.363	3.88 : 1.68	-5.13 : -3.86
36.0 mph	1.189	0.187	5.22 : 2.53	-7.54 : -4.17
40.3 mph	1.155	0.159	3.91 : 3.67	-6.09 : -5.35

8. CONCLUSIONS AND RECOMMENDATIONS

In this paper, vertical vehicle acceleration is proposed as a way to quantify rail highway crossing roughness. To facilitate the development of acceleration ratings for crossings, a vehicle dynamic model was developed to simulate vehicle accelerations using only a crossing terrain model and vehicle parameters as inputs. Accelerometers were used to field calibrate and validate the model. Model repeatability and data accuracy was verified, suggesting that the vehicle dynamic model can be used to quantify vehicular accelerations at various speeds and different locations.

In order for the results of the approach to be useful in decision making, one must consider that the accelerations (modeled or measured) at a rail crossing location can derive from either condition or construction of the crossing. That is to say, a crossing constructed on the level but in poor condition may induce similar accelerations or even less than a crossing in good condition, but where design limitations (hump crossing, elevated crossings, skewed crossings) or poor construction technique may be the cause of accelerations. Therefore, a logical next step in the research would be to separate the effects of condition and design/construction.

Also, if LiDAR data are already systemically available (such as for the State Highway system of Utah), the time to run the simulation model will generally be less than that required to go into the field (and would not require exposure of field personnel). However, obtaining LiDAR data for this purpose only would not be feasible or economical, and field measurements of accelerations would be the optimal approach.

In future research, we intend to investigate the effect different test vehicles would have on acceleration readings. This calibration across vehicles would be necessary to extrapolate simulations or even actual field measurements of acceleration to other vehicle classes representing the roadway fleet.

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