USDOT Tier 1 University Transportation Center Final Report

NURail Project No. # NURail2012-UKY-R03 and NURail2013-UKY-R06

3D Methodology for Evaluating Rail Crossing Roughness

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02 March 2015

Grant Number: DTRT12-G-UTC18

DISCLAIMER

Funding for this research was provided by the NURail Center, University of Illinois at Urbana - Champaign under Grant No. DTRT12-G-UTC18 of the U.S. Department of Transportation, Office of the Assistant Secretary for Research & Technology (OST-R), University Transportation Centers Program. The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the information presented herein. This document is disseminated under the sponsorship of the U.S. Department of Transportation's University Transportation Centers Program, in the interest of information exchange. The U.S. Government assumes no liability for the contents or use thereof.

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TECHNICAL SUMMARY

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Final Report March 2, 2015

3D Methodology for Evaluating Rail Crossing Roughness

Summary

The following report covers work done to develop and test a 3D methodology to assess the ride-ability of rail highway grade crossings. It is comprised of introductory and background material that motivates the need for such a methodology and previous work related to the same. Two conference papers are attached as appendices. These papers cover the development of a low-cost 3D sensor and the potential use of accelerometers to evaluate crossing roughness.

Problem Statement

Quality of surface is an important aspect affecting both the safety and the performance of at-grade rail-highway crossings. Roughness may increase the risk of crashes for both trains and automobiles. Varying grades in crossing profiles increase the likelihood of high-centered crossing collisions between train and truck [1]. The US DOT Railroad Highway Grade Crossing Handbook [2] 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 resulting in a crash.

While crashes at rail-highway crossings have diminished over recent decades, the problem continues. For example, there were 1,963 rail highway crossing incidents in the US in 2012 and over 1,300 incidents in the first eight months of 2013 [3]. The problem is ubiquitous - there are over 216,000 rail highway grade crossings in the US and over 9000 in the state of Kentucky alone [4]. With so many crossings, maintenance management is a large undertaking. Even simple inventory requires significant time and effort. As with other highway assets, crossings deteriorate if not maintained, and life cycle cost increases without preventive maintenance. No quantitative method currently exists to quickly and economically assess the condition of rail crossings in order to evaluate the long term performance of crossings and set a quantitative trigger for their rehabilitation. The conventional method to measure the surface of quality of crossings is based on expert judgment, whereby crossing surfaces are classified as poor, fair or good after an inspector visits and drives over the crossing. However, actual condition of the crossing could be different from the subjective rating. Poor condition rating crossings may not always offer the most cost-effective locations for preventive maintenance to lower overall life-cycle costs. As the conventional method only use ratings from the inspector by driving a test vehicle over the crossing for several times, which ignored the roughness ratings of grade crossings could be influenced by different vehicle types and crossing construction methods. A quantifiable and extensible procedure is desired.

With rapid advances in computer science, 3D sensing and imaging technologies, it seems logical that a cost-effective quantitative method could be developed to determine the need to rehabilitate rail crossings and assess long term performance.

The scope of the research includes investigation of sensor capabilities, development of a measurement methodology and proof of technology concept. The research is seen as a first step towards automating the crossing inspection process, ultimately leading to the quantification and estimation of future performance of rail crossing. Methods may be applicable to other transportation infrastructures such as highways, specifically for pavements, asset management and safety assessment.

Research Goal and Objectives

The goal of the proposed research is to test and develop low-cost sensors and methods for measuring rail crossing surfaces and a method for evaluating the crossings to support both safety and maintenance programs.

Specific objectives include

1. develop and test a sensor platform based on different 3D sensing, imaging and measurement technologies;
2. test and validate a method and platform to include the quantitative crossing roughness threshold for crossing maintenance;
3. develop a vehicle dynamics model based on vehicle and surface conditions to discover the relationship between vehicle response and crossing roughness;

A flow chart depicting the steps to be followed in this research is shown in figure 1. Note that not all of the flowchart steps are addressed in the current report.

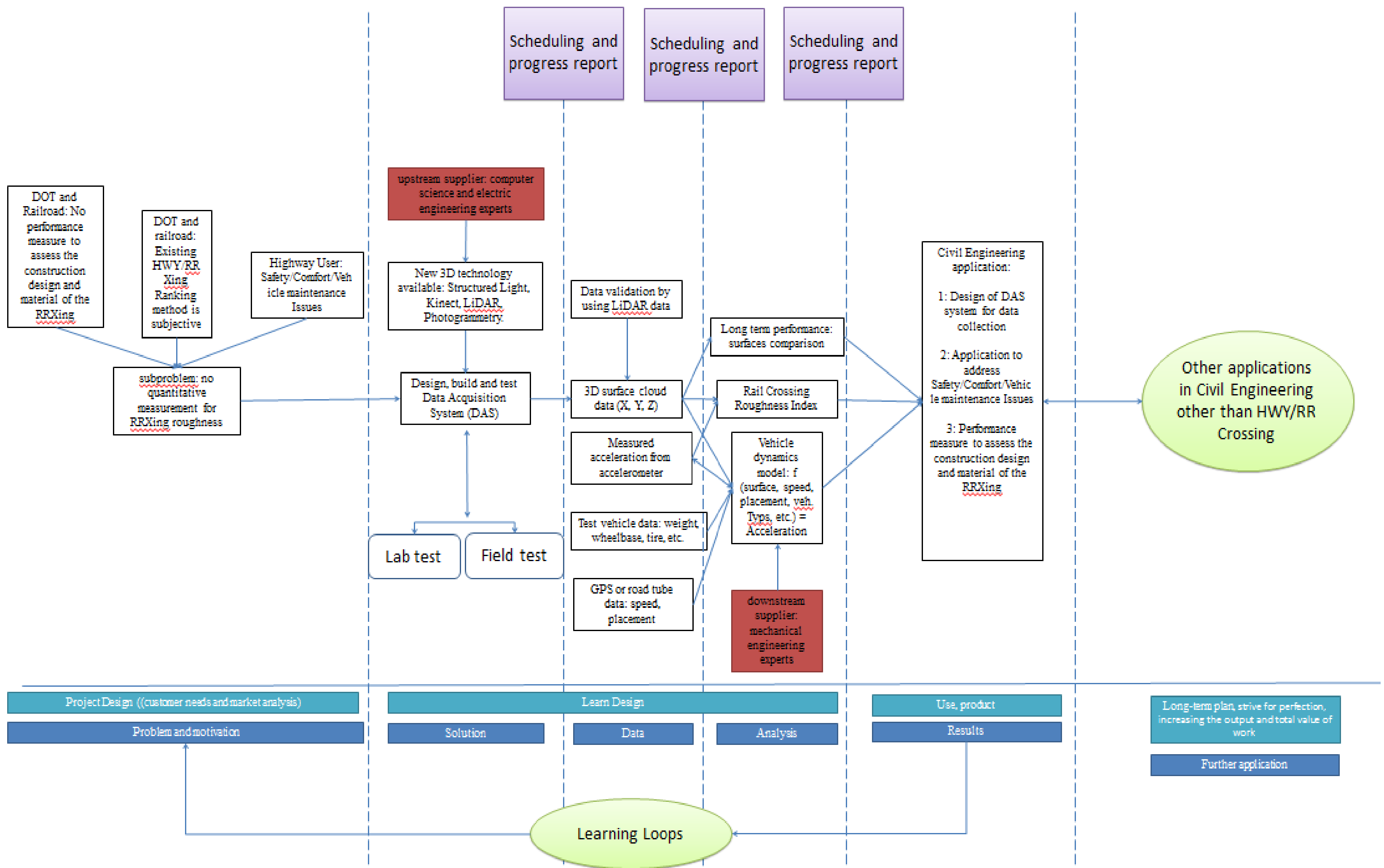
Scheduling and progress report
Scheduling and progress report
Scheduling and progress report
DOT and Railroad: No performance measure to assess the construction design and material of the RRXing
DOT and railroad: Existing HWY/RR Xing Ranking method is subjective
Highway User: Safety/Comfort/Vehicle maintenance Issues
subproblem: no quantitative measurement for RRXing roughness
upstream supplier: computer science and electric engineering experts
New 3D technology available: Structured Light, Kinect, LiDAR, Photogrammetry.
Design, build and test Data Acquisition System (DAS)
Lab test
Field test
Data validation by using LiDAR data
3D surface cloud data (X, Y, Z)
Measured acceleration from accelerometer
Test vehicle data: weight, wheelbase, tire, etc.
GPS or road tube data: speed, placement
Long term performance: surfaces comparison
Rail Crossing Roughness Index
Vehicle dynamics model: f (surface, speed, placement, veh. Typs, etc.) = Acceleration
downstream supplier: mechanical engineering experts
Civil Engineering application:
1: Design of DAS system for data collection
2: Application to address Safety/Comfort/Vehicle maintenance Issues
3: Performance measure to assess the construction design and material of the RRXing
Other applications in Civil Engineering other than HWY/RR Crossing
Project Design ((customer needs and market analysis)
Problem and motivation
Learn Design
Solution
Data
Analysis
Use, product
Results
Long-term plan, strive for perfection, increasing the output and total value of work
Further application
Learning Loops

Figure1. Research Flow Chart

Railroad Crossing Roughness

While track roughness may be evaluated by the 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. Future research with 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 of good, fair and poor at different driving speeds.

Highway pavement roughness has been studied and various quantitative methods such as international roughness index (IRI) [8], and profile index (PI) [9] have been developed in the last 30 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.

3D Technology

Technology already exists to map crossing surfaces at different levels of precision and at various costs. LiDAR (Light Detection Ranging), for example, 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]. There are many applications of LiDAR in civil, construction and transportation engineering. One local example [11] uses LiDAR to verify bridge clearance heights on a western Kentucky parkway. Mobile LiDAR data can achieve an average accuracy of +/- 3cm or better, but comes with a high equipment cost (about 1 million USD). A lower cost option is desired in this project. See figure 2 for an example LiDAR image where colors depict elevation.

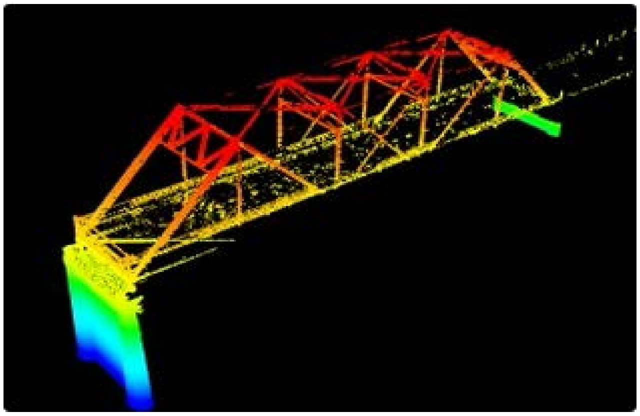

Figure 2. LiDAR image [11]

Another method, aerial photogrammetry as shown in figure 3, uses photographic images to determine the geometric location and elevation of terrain. Close-range photogrammetry can be used to create 3D models (image-based modeling). Precision on the order of a few inches is attainable.

Figure 3. Aerial photogrammetry

With the advent of new sensing and imaging technologies, much more capability has become available at very low cost. For example, the Microsoft Kinect sensor (around $150) features an RGB camera, laser depth sensor and multi-array microphone. While originally designed to support video gaming, the sensor platform is beginning to find alternative practical and scientific applications. For example, the Kinect has been applied to road pavement management by Becerik-Gerber at the University of Southern California [12].

Figure 4. Kinect sensor

Another 3D imaging technology known as structured light 3D scanning uses projected light patterns and a high resolution digital camera system to measure the shape, depth and surface information of an object. A known pattern of pixels (light strip) is distorted when projected on a non-flat surface. From recording of this information, depth and shape of the object may be calculated [13] [14]. A structured light 3D scanner can provide scan data at very high accuracy (sub-centimeter) with a relatively low investment of about $5,000 in equipment.

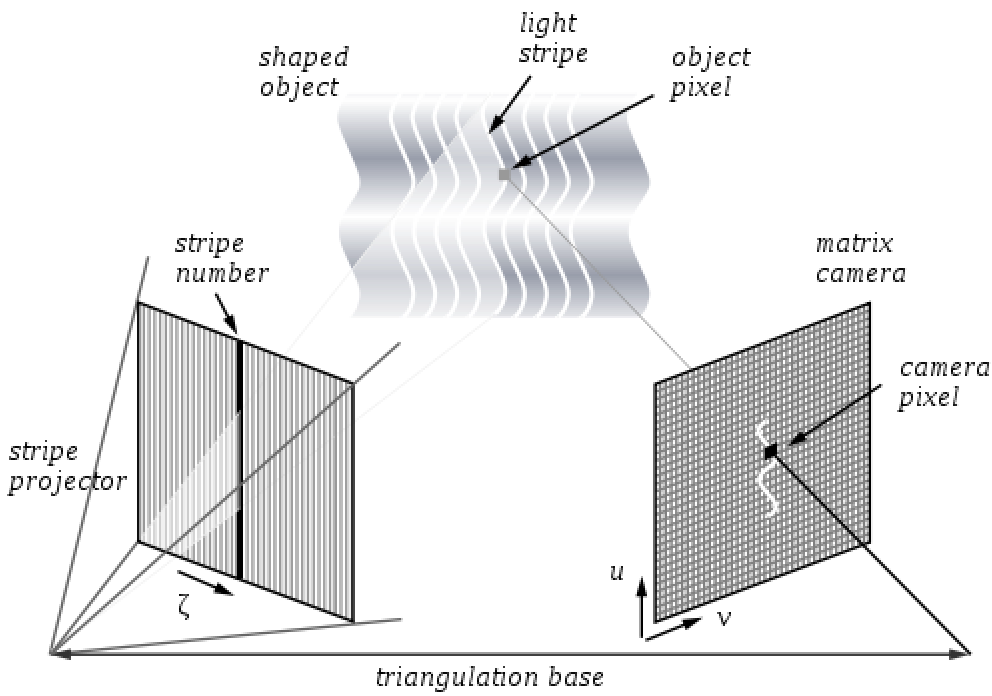

Figure 5. Structured light

While several studies conducted by Carnegie Mellon University [15], Budapest University of Technology and Economics [16],[17] and University of Texas [18], use projected structured light or laser to monitor and measure pavement quality on highway, no application of structured light on highway railroad crossing has been found.

Methodology and Results

A low-cost 3D data acquisition system (DAS) based on 3D structured light imaging technology was developed. Several field tests were conducted at crossings around Lexington, KY and at the site of the Bluegrass Railroad Museum in Versailles, KY. A field test for measuring vehicular accelerations was next developed and tested. The test validated the repeatability, sensor reliability, and accuracy.

The project developed a method to quantify condition as a function of accelerations caused by crossing roughness for various vehicle types.

Appendices

Several papers and presentations addressing the objectives of the project are included as attachments to this report. These include:

Appendix A: Wang, T., R. Souleyrette, D. Lau and P. Xu, "Rail Highway Grade Crossing Roughness Quantitative Measurement Using 3D Technology," Proceedings of the 2014 Joint Rail Conference, Colorado Springs, CO, April 2-4, 2014.

Appendix B: Wang, T, R. Souleyrette, A. Aboubakr* and E. Randerson, "Quantifying Grade Crossing Condition as an Input to Modeling Safety," Proceedings of the 2014 Global Level Crossing Safety & Trespass Prevention Symposium, Urbana, IL, August 3 - 8, 2014.

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Appendix A:

Wang, T., R. Souleyrette, D. Lau and P. Xu, "Rail Highway Grade Crossing Roughness Quantitative Measurement Using 3D Technology," Proceedings of the 2014 Joint Rail Conference, Colorado Springs, CO, April 2-4, 2014.

Proceedings of the 2014 Joint Rail Conference
JRC2014
April 2-4, 2014, Colorado Springs, CO, USA

JRC2014-3778

RAIL HIGHWAY GRADE CROSSING ROUGHNESS QUANTITATIVE MEASUREMENT USING 3D TECHNOLOGY

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ABSTRACT

Quality of surface is an important aspect affecting both the safety and the performance of at-grade rail-highway crossings. Roughness may increase the risk of crashes for both trains and automobiles. Varying grades in crossing profiles increase the likelihood of high-centered crossing collisions between train and truck [1]. The US DOT Railroad Highway Grade Crossing Handbook [2] 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 resulting in a crash.

No quantitative method currently exists to quickly and economically assess the condition of rail crossings in order to evaluate the long term performance of crossings and set a quantitative trigger for their rehabilitation. The conventional method to measure the surface of quality of crossings is based on expert judgment, whereby crossing surfaces are classified as poor, fair or good after an inspector visits and drives over the crossing. However, actual condition of the crossing could be different from the subjective rating. Poor condition rating crossings may not always present the most cost-effective locations for preventive maintenance to lower overall life-cycle costs. Conventional ratings may derive from driving a passenger car of pickup once over the crossing. Effects of various speed, on various vehicles (suspension), and at various places (laterally) cannot be determined or even estimated except at the smoothest of crossings. A quantifiable and extensible procedure is desired.

With rapid advances in computer science, 3D sensing and imaging technologies, it seems logical that a cost-effective quantitative method could be developed to determine the need to rehabilitate rail crossings and assess long term performance. Fundamental to the quantification of crossing condition is the acquisition of an accurate 3D surface model of the crossing in its present state. This paper reports on the development of an accurate, low cost and readily deployable sensor capable of rapid collection of this 3D surface. The research is seen as a first step towards automating the crossing inspection process, ultimately leading to the quantification and estimation of future performance of rail crossing.

1 INTRODUCTION

While track roughness may be evaluated by the railroad geometry car, highway crossings are usually qualitatively evaluated. Previous work by the University of Kentucky [3] 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 [4] of railroad crossing roughness classification in Indiana and documents from Illinois DOT [5] showed how railroad crossing roughness could be classified into different groups such as smooth, medium, and rough based on qualitative rideability evaluations of good, fair and poor at different driving speeds.

Roughness of highway pavements has long been studied. Various quantitative methods such as international roughness index (IRI) [6], and profile index (PI) [7] have been developed in the last 30 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 heterogeneous nature of a highway rail crossing (longitudinal and lateral slopes), 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. 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. LiDAR (Light Detection Ranging), for example, 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 [8]. There are many applications of LiDAR in civil, construction and transportation engineering. An example application is the use of LiDAR to verify highway bridge clearance [9]. LiDAR may be collected from stationary or moving platforms. For highway applications, mobile LiDAR data can achieve an average accuracy of +/- 3cm or better, but is typically expensive and complicated to operate and process its data. A lower cost option that may be deployed by regular inspectors would be desirable.

The goal of the research is to develop and test a low-cost sensor for measuring rail crossing surfaces and to develop a method for evaluating crossings to support both safety and maintenance programs. The rest of the content is organized as follows. Section 2 briefly introduces 3D structured light as the technology investigated and deployed for this study. The processes of design and construction of a prototype data acquisition system (DAS) follows in section 3. Field collection of 3D point-cloud data is described in section 4. Data analysis comprises section 5. Conclusions and suggestions for next steps are then summarized.

2 3D STRUCTURED LIGHT

A low-cost 3D imaging technology (structured light 3D scanning) uses projected light patterns and a high resolution digital camera system to measure the shape, depth and surface information of an object as shown in figure 1. A known pattern of pixels (light strip) is distorted when projected on a non-flat surface. From recording of this information, depth and shape of the object may be calculated [10] [11]. A structured light 3D scanner can provide scan data at very high accuracy (sub-centimeter) with a relatively low investment of about $5,000 in equipment.

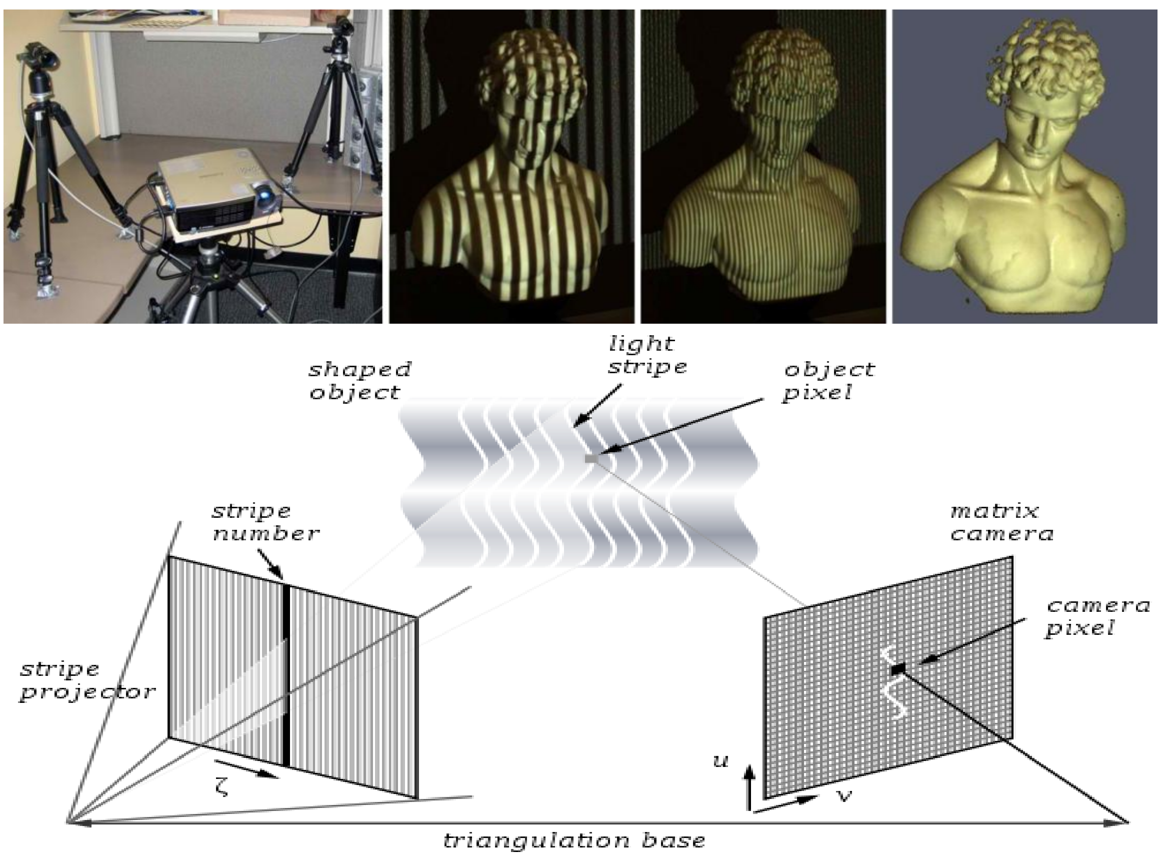

Figure 1. 3D Structured light scanner [12],[13]

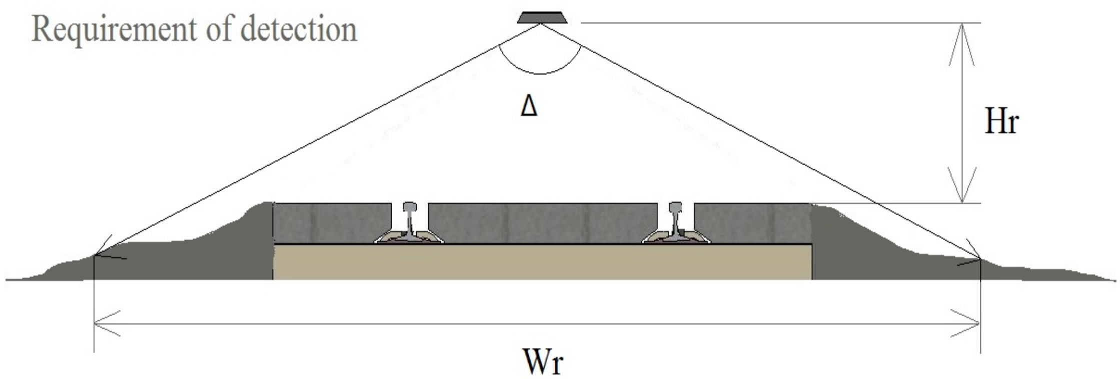

Figure 2. Requirement of detection. Wr: width requirement, Hr: high requirement

3 DESIGN AND BUILD DATA ACQUISITION SYSTEM (DAS)

We have designed, built and tested a 3D structured light-based data acquisition system (DAS) that creates an accurate surface points cloud of a crossing. The scanner has a minimum scan area of 3'x5.1' when the projector's lens is 42" above ground and a maximum scan area of 6'x10.2' when projector's lens is 80" above the ground. The DAS camera has 1280*800 pixel resolution. Therefore, pixels are about 0.25 centimeters average in size when the lens is at its highest point above the ground as shown in figure 2. It is possible to scan at a rate of about one scan per 30 seconds in the field.

As a scanner platform, a rail cart was built to include a frame with wheels, a laptop computer with structured light data capturing software, an 1100 watt AC/DC converter, power cables and power provided by the battery of a test vehicle as shown in figure 3.

Figure 3. DAS prototype

A series of lab tests have been performed as shown in figure 4 to test the camera, lens, projector and software. During these tests, the DAS prototype was incrementally improved. For example, lenses were changed to the wide angle variety in order to capture larger scanning areas. The center supporting beam has been replaced by a taller one (also to provide a larger scanning area). Scanning software was also updated after debugging.

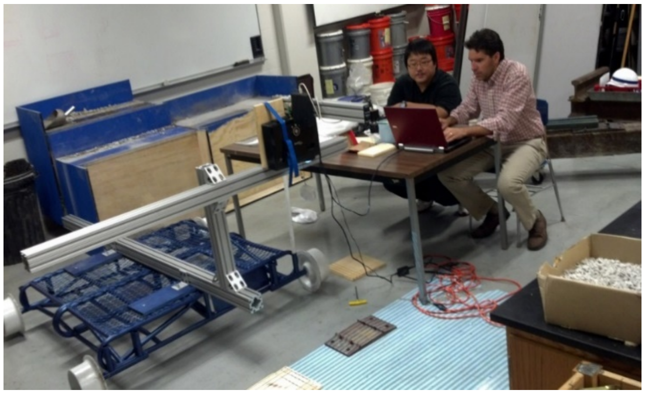

Figure 4. Lab test.

4 FIELD TESTS

Several field tests have been conducted at crossings around Lexington, KY and at the site of the Bluegrass Railroad Museum in Versailles, KY. Figure 5 pictured one field test at crossing (USDOT 719862A) on Beasley Rd. Versailles, KY. There was one scanner mounted at each end of the beam of the DAS. Each scanner took one scan of one side of the crossing alternatively to avoid light pattern across each other. In the end, there were total 52 scans collected for this crossing. The test took about 2 hours. During the scanning process, each scan had 6'x10.2' in size and one foot overlapped area in the longitudinal direction with the other scans before and after it. Two scanned 3D points clouds were shown in figure 6.

Figure 5. Field Test at crossing (USDOT 719862A) on Beasley Rd. Versailles, KY

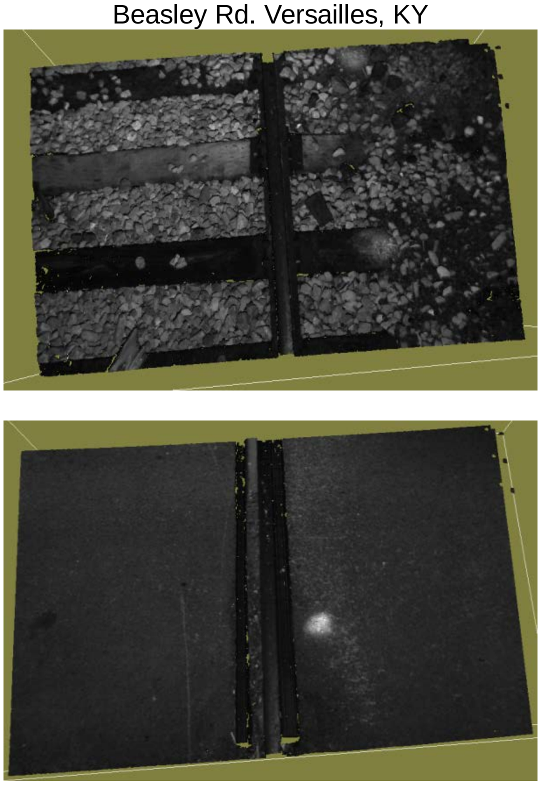

Figure 6. . Sample of data collected in the field

5 DATA ANALYSIS

Each 3D point cloud "tile" is measured as 10' x 6' in area with 1280 x 800 resolutions at the size of about 30 Megabytes. Every two adjacent scans can be stitched and merged by using data comparison (using our scanning software) within the overlapped area. For example, in the field test, there were total of 52 scanned 3D point clouds collected for that crossing. By using the overlapped area of every two contiguous scans, all scans were stitched and merged into one whole crossing surface 3D cloud as shown in figure 7.

After the all 3D points cloud tiles were merged into one crossing surface, each point had X, Y, Z coordinates recorded (to the nearest millimeter). A color coded rendering of the crossing surface elevations can be seen in figure 8. Blue indicates lower elevation, while red shows the higher elevations. With the 3D point cloud, the distance between any two points of the crossing can be measured. Locations where a vehicle (truck, trailer, etc.) may get high-centered or hang-up on the crossing may be directly computed given vehicle dimensions of wheel base and clearance height.

Using the 3D point cloud, crossing roughness may be quantified as depth and area of cracks, area and volume of bumps or pot-holes, or other formulations. An example displaying surface curvature gradient is illustrated in figure 9. Blue areas are relatively flat as compared to red areas in this visualization.

6 NEXT STEPS

This paper presents only the first step in a larger effort to develop a quantitative method to assess the condition and performance of highway rail grade crossings. Next steps include:

1) Validation of the accuracy of the resulting point clouds using established precision measurement (e.g., total station surveying) for:
    a. Roughness and vehicle accelerations (low fidelity)
    b. Materials performance (high fidelity)
2) Development of a roughness index based on crossing geometry
3) Development and validation of a highway vehicle dynamics model that uses the 3D point cloud and vehicle characteristics to facilitate modeling of vehicular accelerations at various speeds and lateral positioning
4) Development of a crossing condition index based on vehicular accelerations for a design vehicle(s).

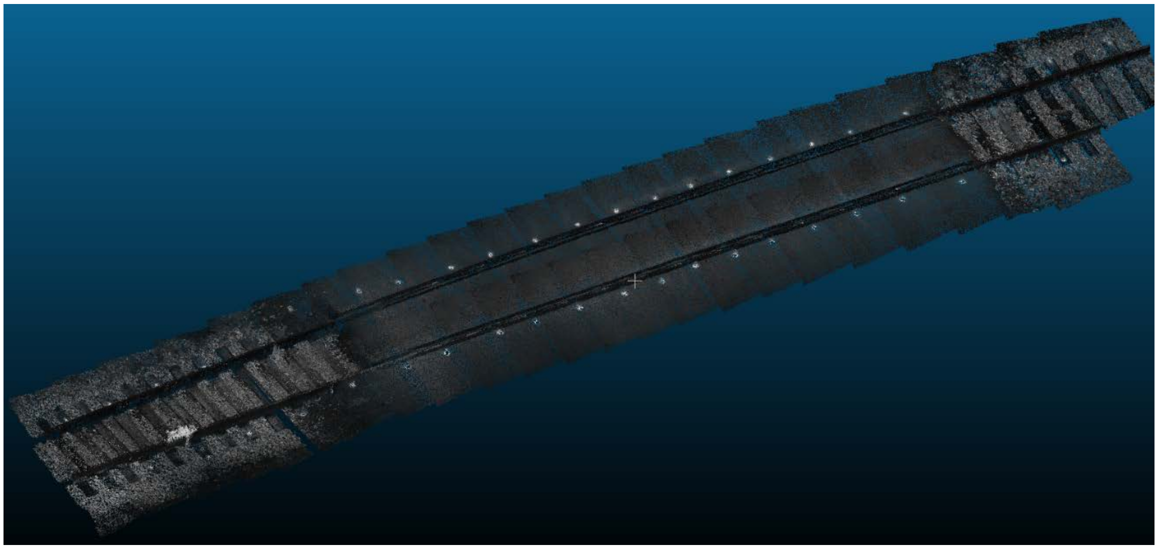
Figure 7. A highway rail crossing surface 3D points cloud.
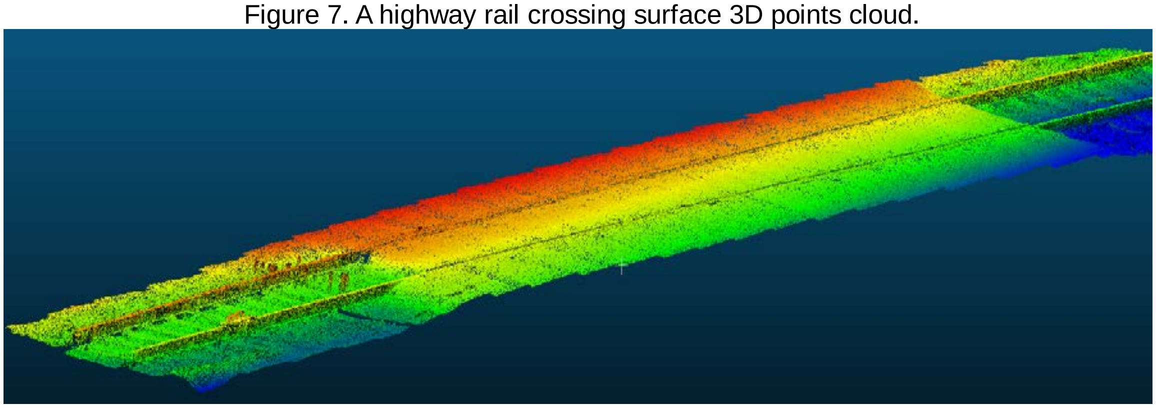
Figure 8 Elevation distribution of the crossing.
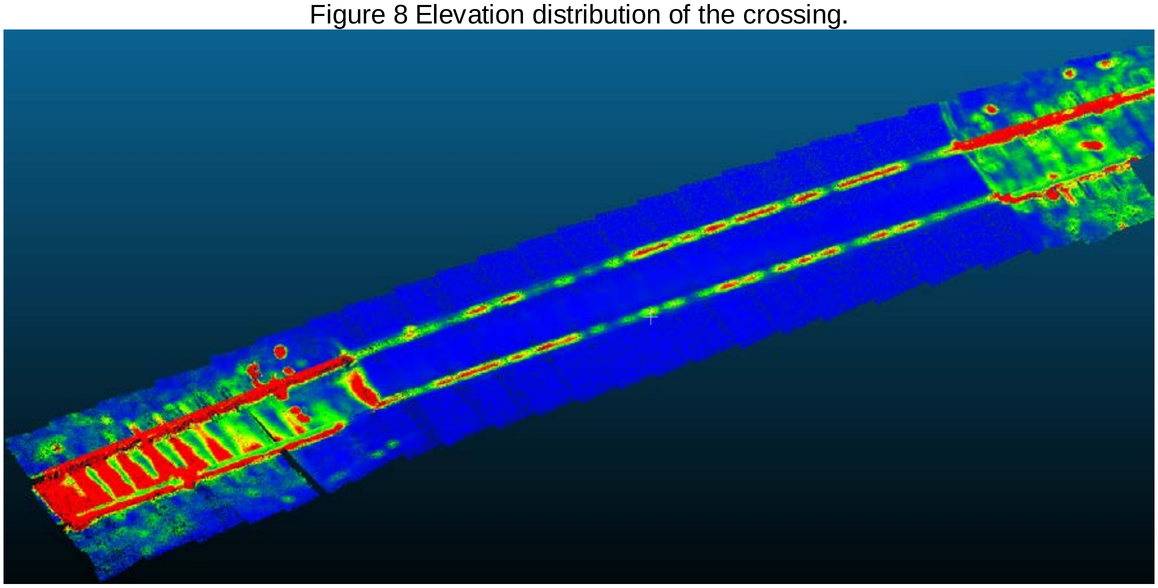
Figure 9. Surface condition (roughness) of the crossing.

ACKNOWLEDGEMENTS

This research is supported by the National University Rail Center (NURail). We would like to thank the following individuals for their contributions: Sam Carter of CSX Transportation, and Professor Jerry Rose, William Staats, Brett Malloy, and Shushu Liu from University of Kentucky.

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Appendix B:

Wang, T, R. Souleyrette, A. Aboubakr* and E. Randerson, "Quantifying Grade Crossing Condition as an Input to Modeling Safety," Proceedings of the 2014 Global Level Crossing Safety & Trespass Prevention Symposium, Urbana, IL, August 3 - 8, 2014.

GLXS2014-1088

QUANTIFYING GRADE CROSSING CONDITION AS AN INPUT TO MODELING SAFETY

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ABSTRACT

While improved as compared to 30 years ago, at-grade or level crossings continue to present a public safety hazard. Annually, there are about 2000 rail highway crossing incidents in the US resulting in nearly 300 fatalities. Inattention of motor vehicle operators is likely a principal contributing factor in these collisions. Some have speculated that condition of a rail highway grade crossing may relate to driver human factors that could either increase or decrease the probability of collision with a train. For example, if a motorist is aware or can perceive that a crossing is in poor condition, they may slow their vehicle thereby giving them more time to react to any oncoming train. On the other hand, a motorist may be distracted from looking for an approaching train if they are more concerned about controlling their vehicle (by positioning or speed) to minimize accelerations due to running over the rough surface. However, no study to date has attempted to correlate condition of crossing surface to safety performance. To determine the potential safety effect of roughness, it is first necessary to quantify roughness. While there are accepted methods to quantify highway roughness (e.g., IRI), no such measure is available for the highway grade crossing. This paper presents research addressing this need. In this paper, a crossing on a two lane suburban road is investigated. LiDAR is used to develop a 3D point cloud model. A vehicle dynamic model is developed and used to predict accelerations experienced by highway vehicles using the crossing. Actual accelerations at the crossing for a test vehicle are collected and then compared to the model estimates.

INTRODUCTION

Safety continues to be the primary consideration at rail highway grade crossings. For example, there were 1,963 rail highway crossing incidents in the US in 2012 and over 1,300 incidents in the first eight months of 2013 [1]. While crashes at rail-highway crossings have diminished over recent decades, the problem continues. Driver inattention and decision making in the vicinity of the at-grade crossing can be important contributors to the safety of these crossings. It has long been speculated that rail highway crossing roughness may be related to highway safety. A study by Thomas Butcher [2] 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 [3] suggested that poor surface conditions tend to divert drivers' attention while driving over crossings. The US DOT Railroad Highway Grade Crossing Handbook [4] also 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, potentially contributing to the cause of a crash.

To determine if surface roughness plays a role in crossing safety, one must first be able to quantify the quality of the surface. The long term objective of the current project 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 renewal. 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 [5]. As an extension of the research, a vehicle dynamic model that uses a 3D surface cloud model and vehicle wheel paths to estimate highway vehicle acceleration has also been developed by the authors. By combining these technologies, the project is expected to result in a method to quantify condition as a function of accelerations caused by crossing roughness for various vehicle types. In turn, the technologies should contribute to the determination of safety as a function of rail crossing condition.

For purposes of validation and calibration of the vehicle dynamic model, actual acceleration data are required. The method must be tested for repeatability, sensor reliability and data accuracy. This paper focuses on acceleration data collection testing and results which are key to the refinement of the vehicle dynamic model.

TEST CROSSING BACKGROUND AND 3D 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). The current highway traffic on the Brannon Road is 5,900 vehicles per day and about 70 trains per day pass the crossing. The FRA Web Accident Prediction System (WBAPS) predicted number of crashes per year at this crossing is 0.042 [6]. Along the three mile section of Brannon Road, there have been 263 highway crashes in the past ten years. Typically, the crashes are due to narrow lanes, insufficient shoulders, poor visibility due to numerous hills and curves and other factors. The projected highway traffic is 14,000 vehicles per day in 2040 [7]. To improve the safety of the road, the Brannon Road Improvement and Safety Project is being planned and scheduled by the Kentucky Transportation Cabinet. The project construction phase is set to start in 2019 [7].

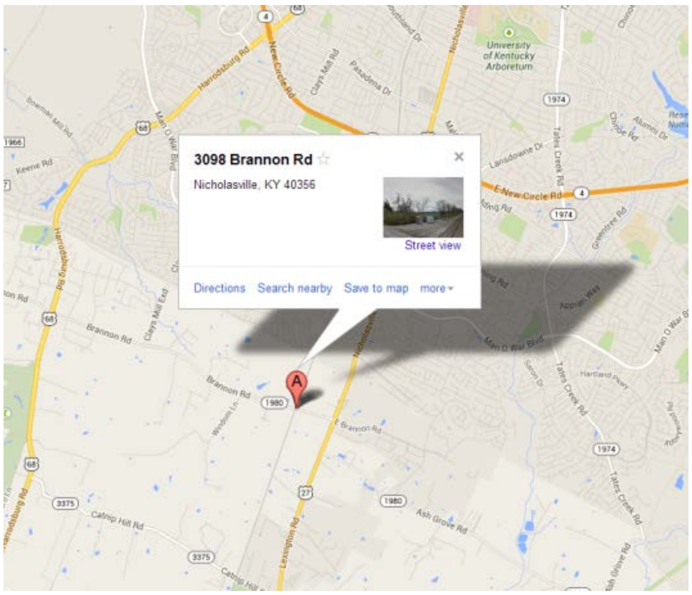

Figure 1. Location of the Brannon Rd Crossing [8].

Figure 2. Brannon Rd Crossing

A Brannon Rd Crossing 3D point cloud was collected using Lidar, as shown in Figure 3.

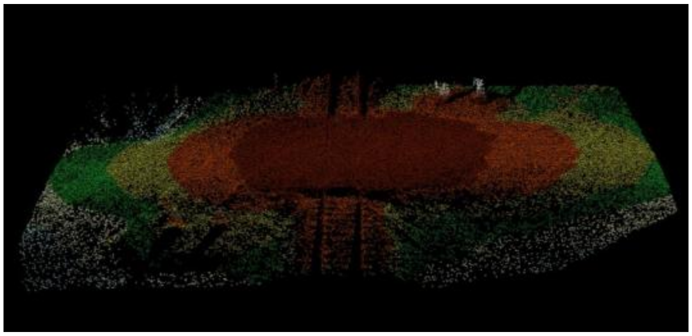

Figure 3. Brannon Rd Crossing 3D point cloud. Green to red indicates increasing elevation.

The crossing is generally rough as can be seen in elevation changes on the highway approaches as depicted in Figures 2 and 3.

FIELD TESTS

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 from PASCO model number PS-2119 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 PASCO 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 4), 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 4. 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 5.


Figure 5. Field acceleration data collection.

The acceleration data were divided into eastbound and westbound groups for the crossing. 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. Other tests were run at speeds as low as 15 mph and as high as 45 mph. Note that the posted advisory speed of the crossing is 15 mph. However, accelerations at 15 mph were nominal.

DATA ANALYSIS AND TEST RESULTS

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 10 seconds before to 10 seconds 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).

After the primary data analysis, 16 tests were performed on the eastbound and 18 on the westbound directions. The results are shown in Figure 6 and 7. All individual test plots can be found in Appendix A.

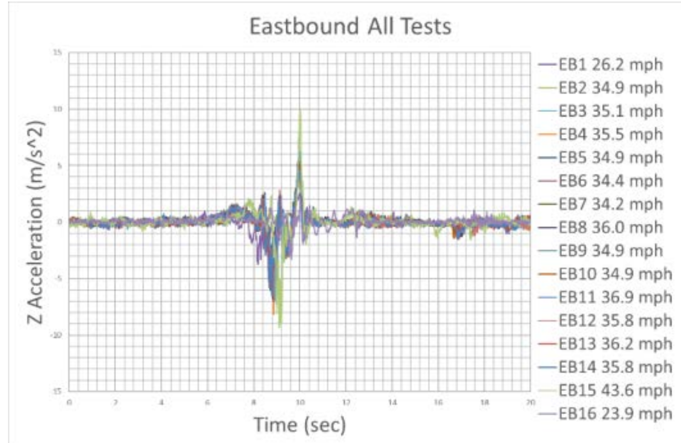

Figure 6. Eastbound acceleration tests.

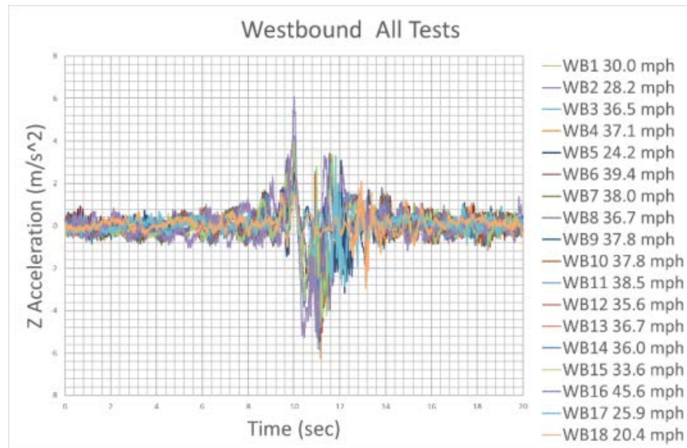

Figure 7. Westbound acceleration tests

For each of the eastbound and westbound groups, 10 tests with speeds close to 35 mph were selected. Results are shown in Figures 8 and 9.

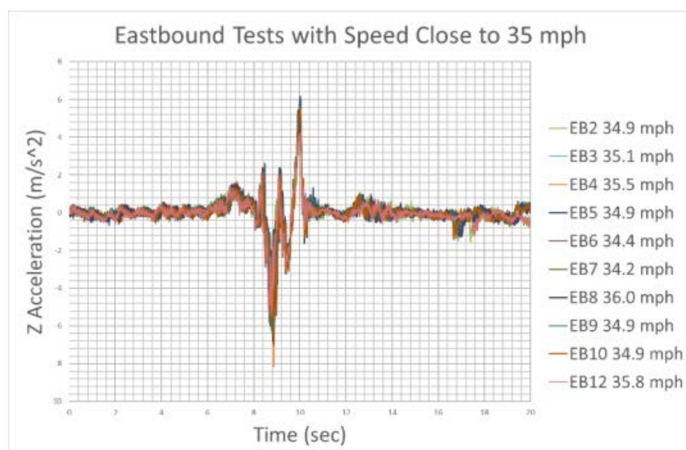

Figure 8. Eastbound tests with speed close to 35 mph.

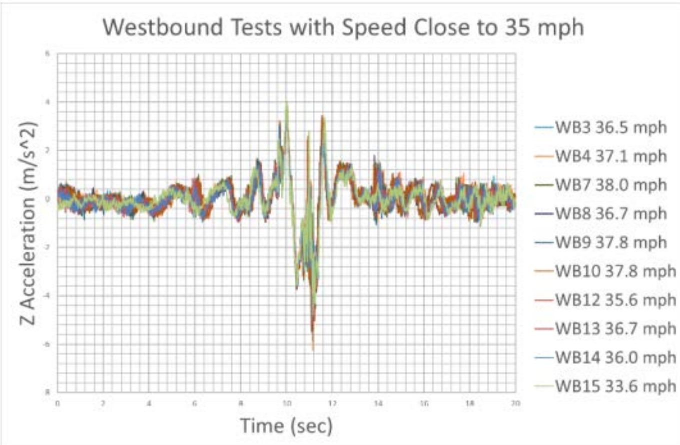

Figure 9. Westbound tests with speed close to 35 mph.

Figures 8 and 9 both show that when the test speed is held constant (35 mph), both the frequency and amplitude of acceleration from one 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 in both directions. Results of these tests are shown in Figures 10 and 11. Note that in the plots, darker shades indicate higher speeds.

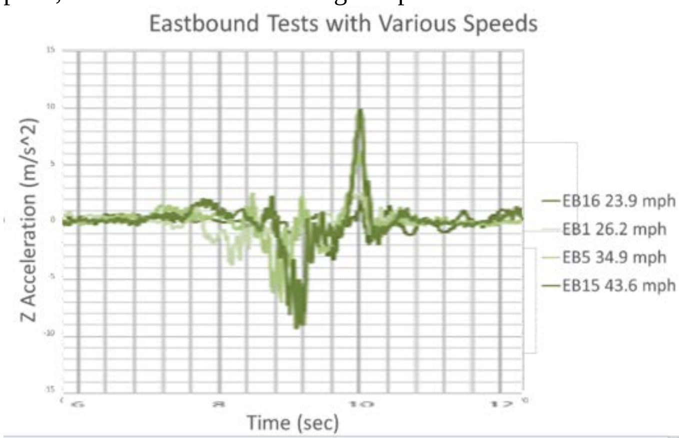

Figure 10. Eastbound tests with various speeds.

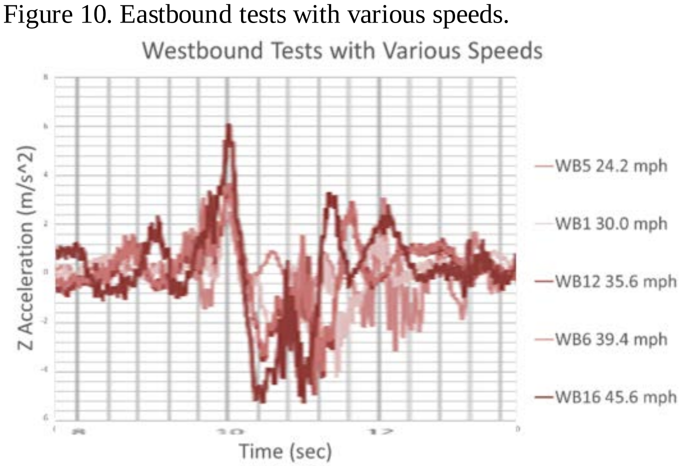

Figure 11. Westbound tests with various speeds.

From Figures 10 and 11, it can be seen that as expected, acceleration amplitudes and frequencies increase with increasing speeds.

CONCLUSION AND NEXT STEPS

This paper presents a necessary step in the development of a technique to quantify the relationship of rail crossing roughness and safety. In it, a field acceleration data method is developed and tested. The test is shown to be repeatable and that sensor reliability and accuracy behave as expected and will support future calibration of a vehicle dynamic model (see Figure 12.) Combining crossing 3D point clouds and vehicle dynamic model will facilitate the development of a rail-highway grade crossing roughness index that may be used to evaluate performance and safety of a crossing.

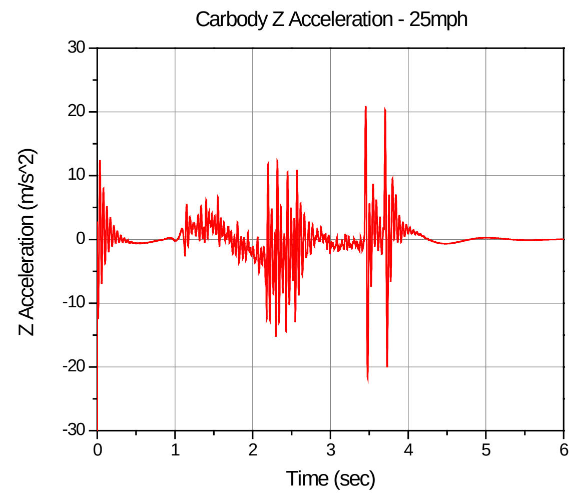

Figure 12. Initial results of a vehicle dynamic model for Brannon Crossing, 25mph (uncalibrated)

ACKNOWLEDGMENTS

This research is supported by the National University Rail Center (NURail). We would like to thank the following individuals for their contributions: Mr. Brad Rister of the Kentucky Transportation Center, and Professor Daniel Lau, Professor Jerry Rose and Mr. William Staats from University of Kentucky Department of Civil Engineering.

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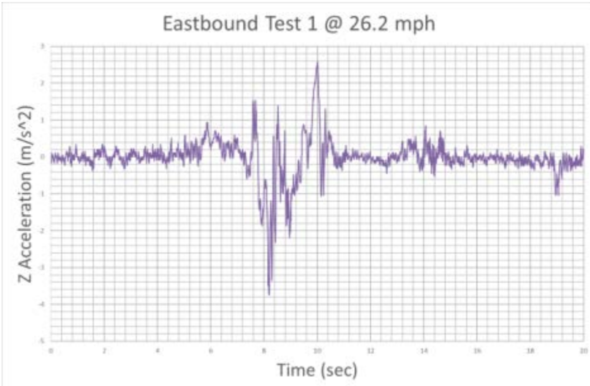
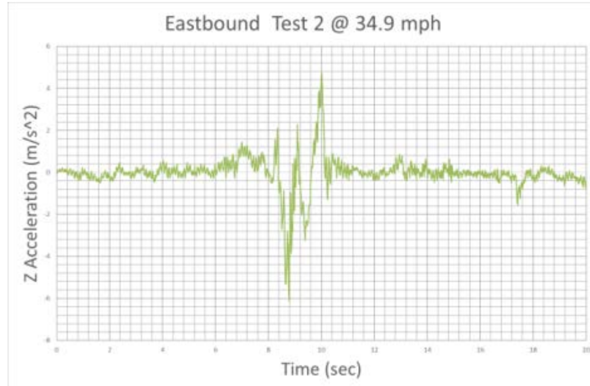
7. Kentucky Transportation Cabinet, Brannon Road: Improvement and Safety Project Public Meeting-South Christian Church, Nicholasville, KY, June 3, 2014. Available from: http://www.centralkynews.com/jessaminejournal/news/local/community-residents-discuss-proposals-for-brannon-road-at-public-meeting/article_af18eafa-ebfe-11e3-b801-0017a43b2370.html

8. Location of the Brannon Rd Crossing. Available from: http://goo.gl/maps/CcJpb


Eastbound Test 1 @ 26.2 mph
Z Acceleration (m/s^2)
Time (sec)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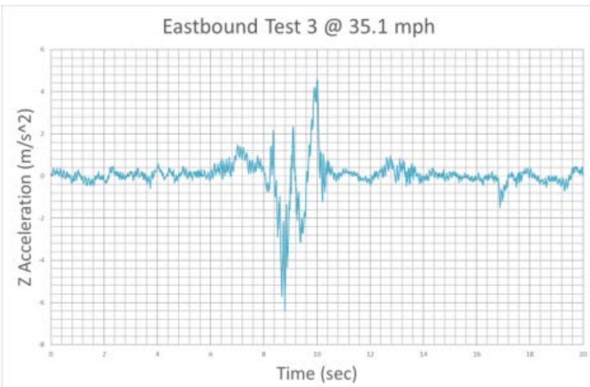
Z Acceleration (m/s^2)
Time (sec)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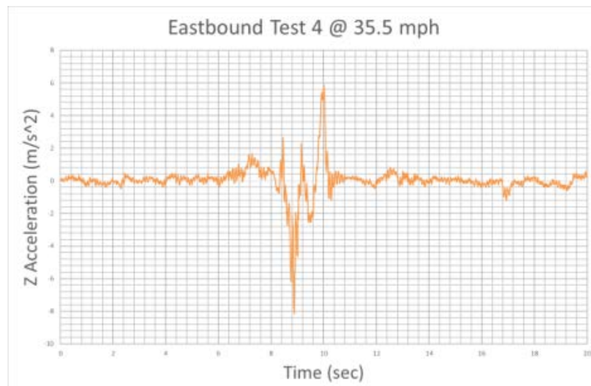
Z Acceleration (m/s^2)
Time (sec)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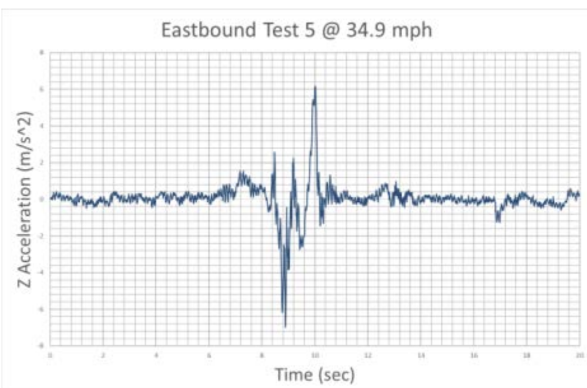
Z Acceleration (m/s^2)
Time (sec)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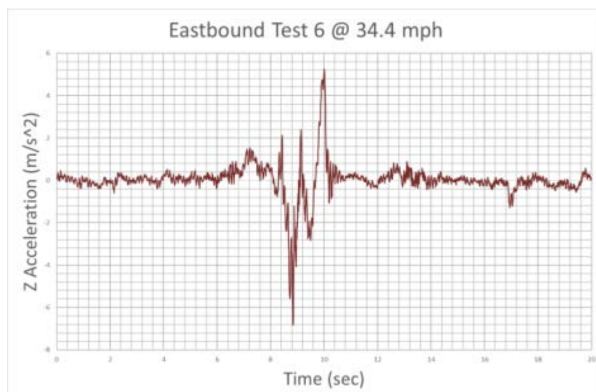
Z Acceleration (m/s^2)
Time (sec)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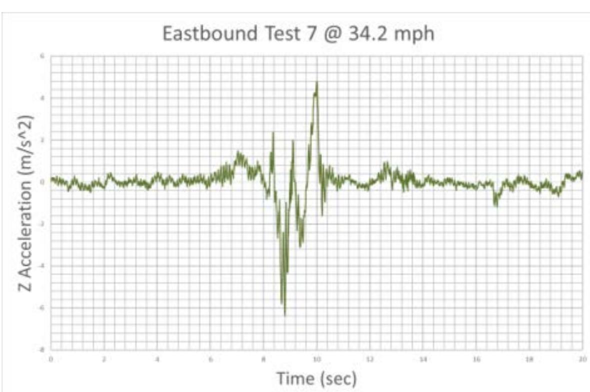
Z Acceleration (m/s^2)
Time (sec)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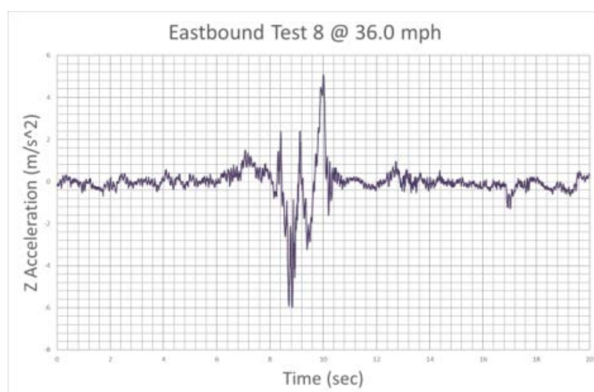
Z Acceleration (m/s^2)
Time (sec)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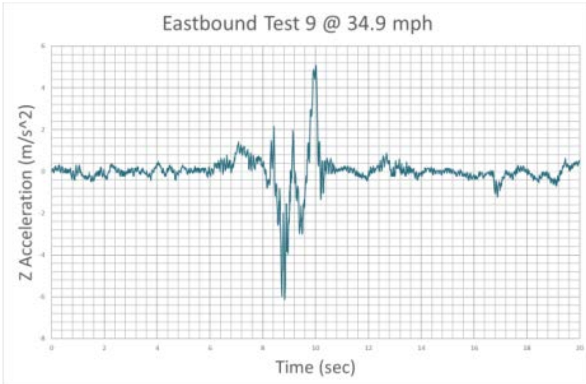
Z Acceleration (m/s^2)
Time (sec)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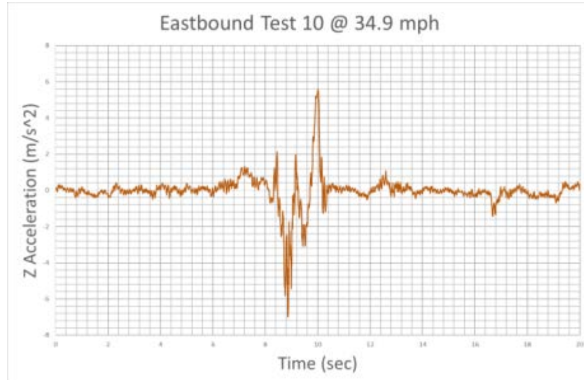
Z Acceleration (m/s^2)
Time (sec)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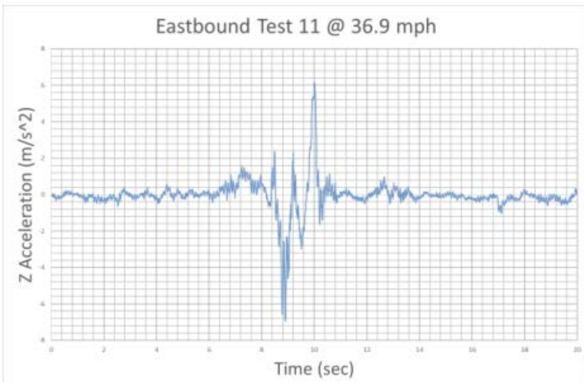
Z Acceleration (m/s^2)
Time (sec)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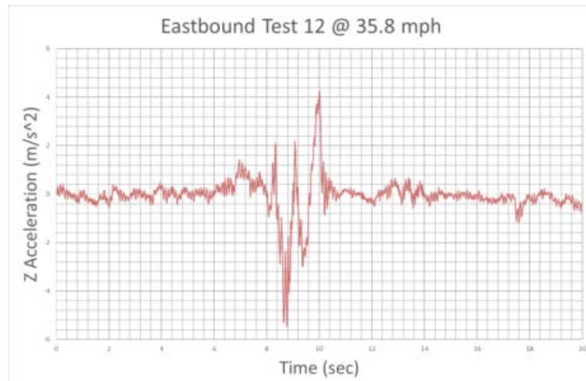
Z Acceleration (m/s^2)
Time (sec)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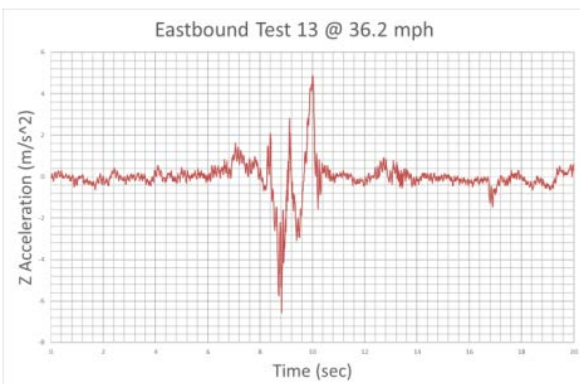
Z Acceleration (m/s^2)
Time (sec)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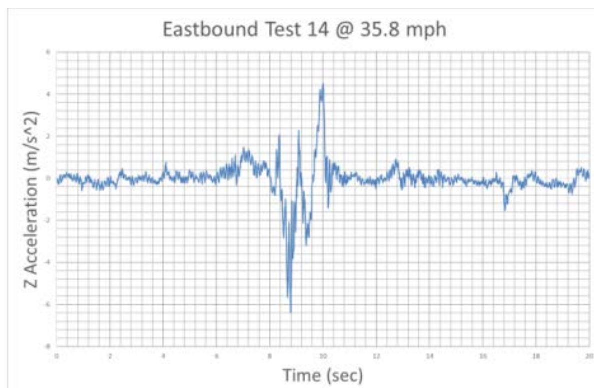
Time (sec)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Z Acceleration (m/s^2)
Time (sec)


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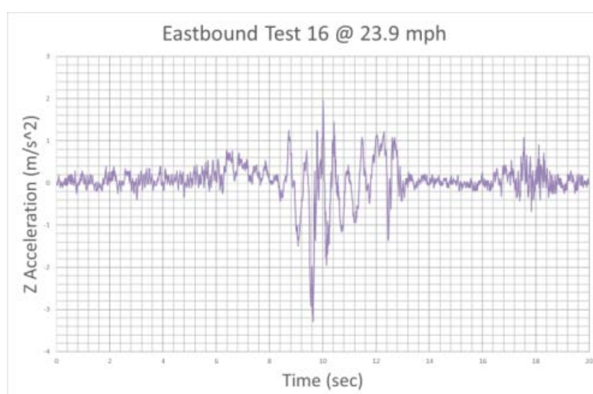
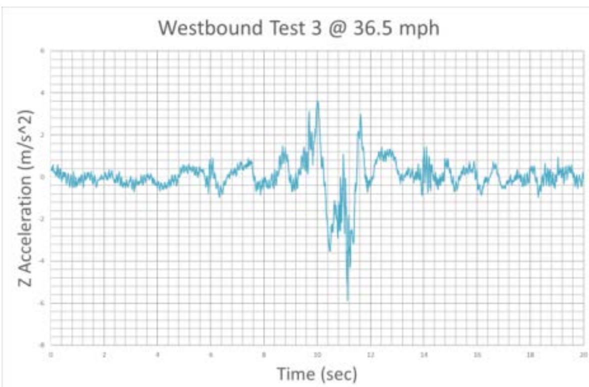
Z Acceleration (m/s^2)
Time (sec)


Eastbound Test 16 @ 23.9 mph
Z Acceleration (m/s^2)
Time (sec)


Westbound Test 1 @ 30.0 mph
Z Acceleration (m/s^2)
Time (sec)


Westbound Test 2 @ 28.2 mph
Z Acceleration (m/s^2)
Time (sec)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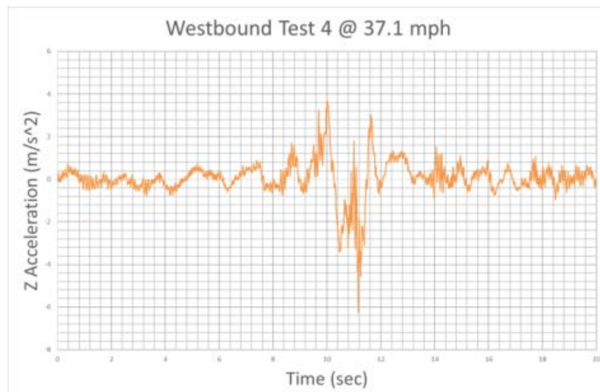
Z Acceleration (m/s^2)
Time (sec)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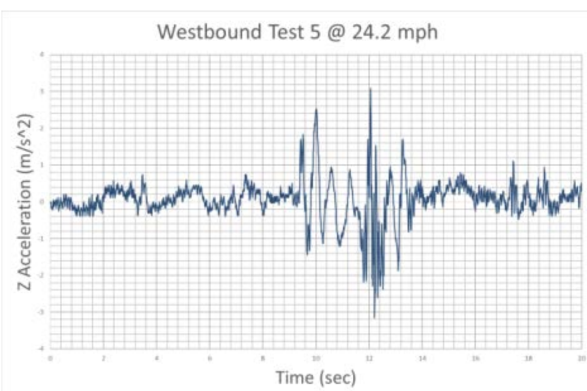
Z Acceleration (m/s^2)
Time (sec)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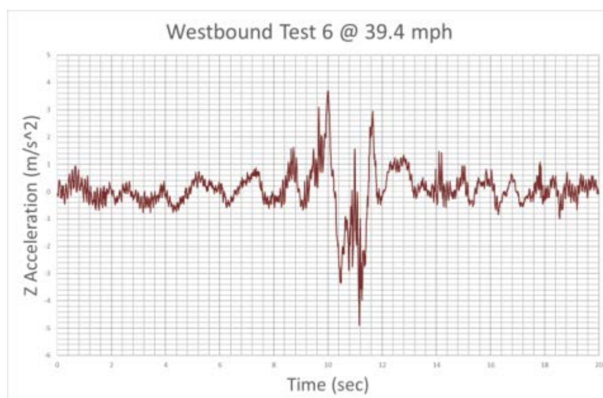
Time (sec)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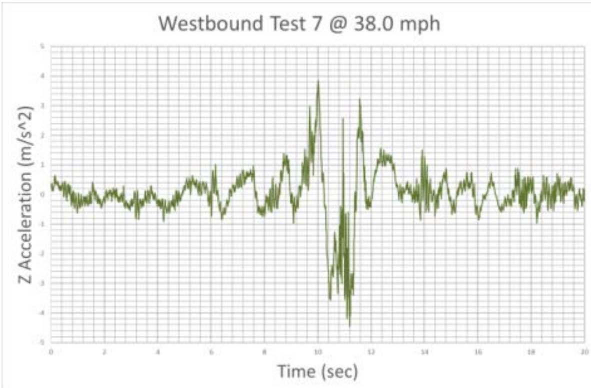
Z Acceleration (m/s^2)
Time (sec)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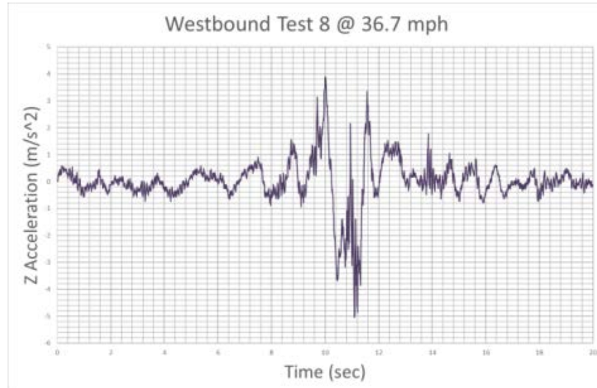
Z Acceleration (m/s^2)
Time (sec)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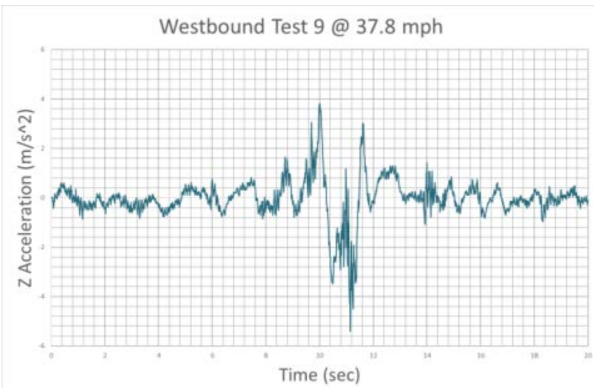
Time (sec)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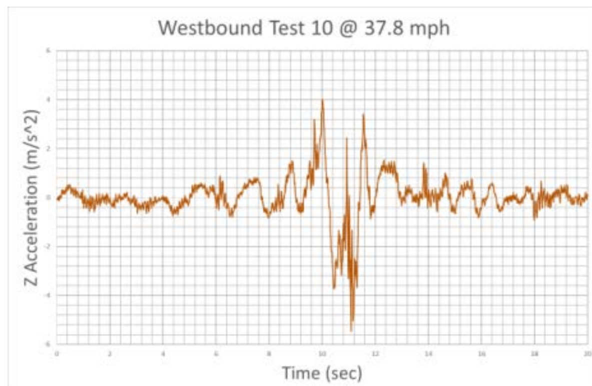
Z Acceleration (m/s^2)
Time (sec)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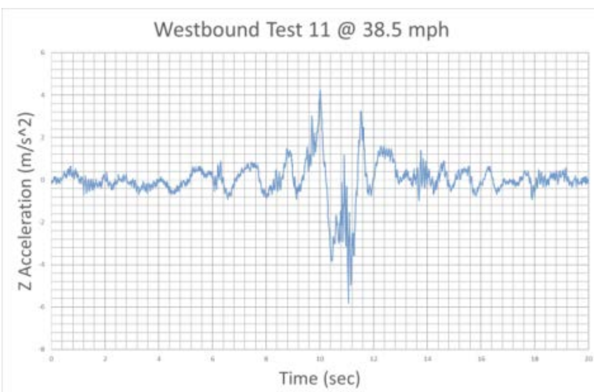
Time (sec)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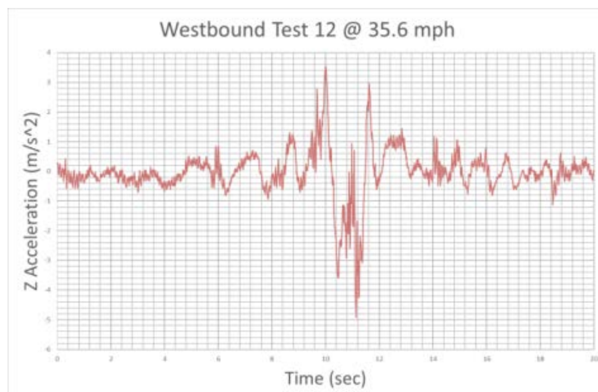
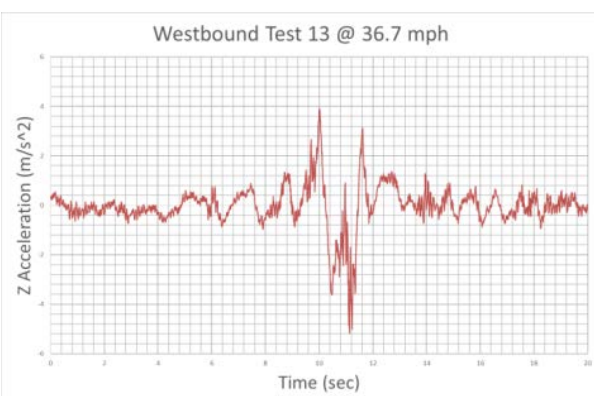
Z Acceleration (m/s^2)
Time (sec)


Westbound Test 12 @ 35.6 mph
Z Acceleration (m/s^2)
Time (sec)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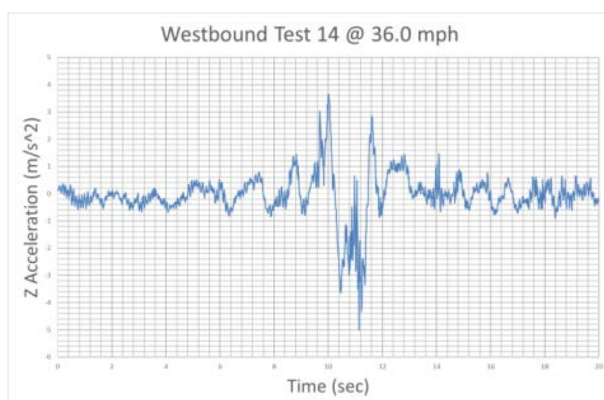
Z Acceleration (m/s^2)
Time (sec)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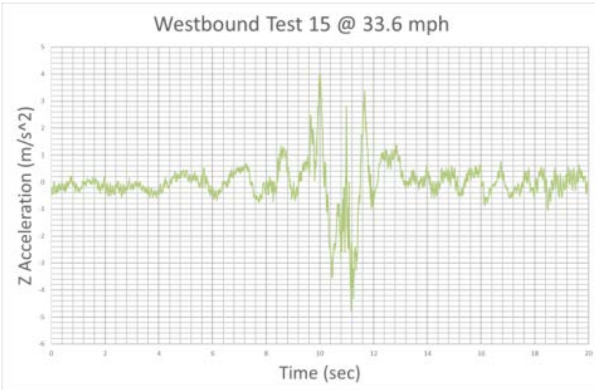
Z Acceleration (m/s^2)
Time (sec)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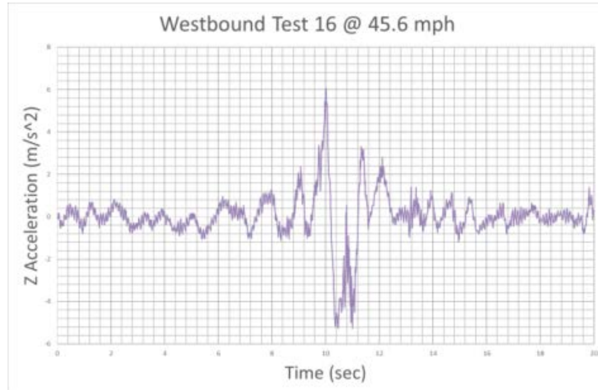
Z Acceleration (m/s^2)
Time (sec)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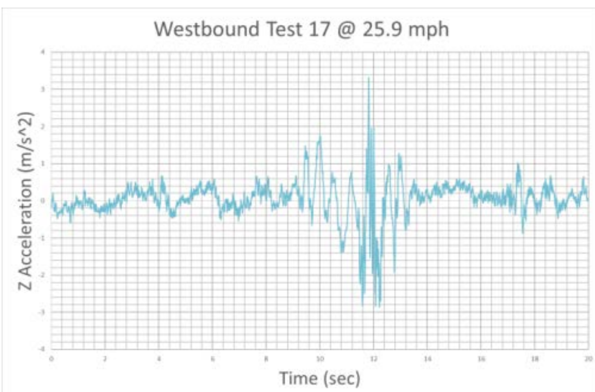
Time (sec)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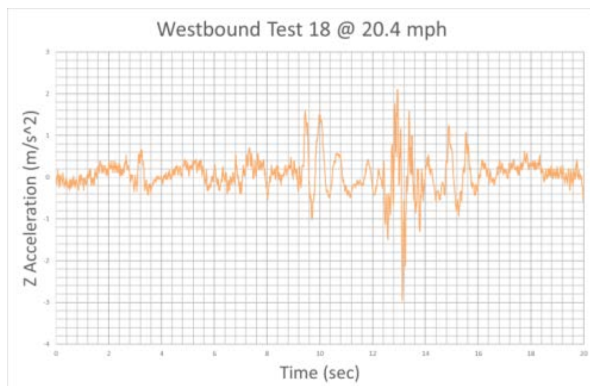
Z Acceleration (m/s^2)
Time (sec)


Westbound Test 18 @ 20.4 mph
Z Acceleration (m/s^2)
Time (sec)