THE EFFECT OF JOINTS IN PORTLAND CEMENT CONCRETE PAVEMENT

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SQDH 2008-1 ; HL 2008-7

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November 2008

Purdue University's Institute for Safe, Quiet, and Durable Highways and the American Concrete Paving Association

The Effect of Joints in Portland Cement Concrete Pavement

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3/1/2008

EXECUTIVE SUMMARY

An experimental investigation was conducted to determine the effects of Portland cement concrete (PCC) pavement joint width, fill condition and faulting on tire-pavement noise generation. This investigation was conducted by Purdue University's Institute for Safe, Quiet, and Durable Highways (SQDH) using the Tire-Pavement Test Apparatus (TPTA) for the American Concrete Paving Association (ACPA).

Tire-pavement noise generation was found to increase with joint width and faulting height. Step-down faulting was found to be louder than the equivalent step-up faulting. Increased filler recess was found to lead to increased noise generation for a given joint width. However, for narrow joints, and particularly real-world joint widths, this effect was found to be negligible.

The noise data was curve-fitted in order to predict the noise contribution from the joint as a function of speed, joint width and filler height. These empirical models were used to predict noise generation at 60 mph for various joints. The influence of the joints relative to concrete without joints was estimated.

TABLE OF CONTENTS

List of Tables

LIST OF FIGURES

1 INTRODUCTION

Joints are put into concrete pavements to alleviate stresses that occur during the curing and setting process of the concrete and those due to drastic temperature changes. These stresses, whether due to temperature or to setting, can cause cracks to form in the pavement. By placing joints in the pavement, the number and width of these cracks are controlled by reducing the stresses occurring with these processes. The physical characteristics of these joints vary so the acoustic properties of these variances were studied.

An investigation was conducted to document the effect of pavement joint width, fill condition, and faulting on tire-pavement noise generation in Portland cement concrete (PCC) pavement. This investigation was conducted by the Institute for Safe, Quiet and Durable Highways (SQDH) at Purdue University using the Tire-Pavement Test Apparatus (TPTA). To ensure a comprehensive study, several joint widths and fill conditions were evaluated.

Joint widths ranging from 1/8" to 1" were tested in 1/8" increments. A 0.0787" (2 mm) wide joint and a 1/2" wide joint that was beveled with 1/4", 45 degree bevels were also tested. In total ten joint widths were tested. These joints were tested in the unfilled state, the 1/2" recessed fill state, and the 1/8" recessed fill state.

In addition to the width and fill evaluation, joint faulting cases were tested with step-up and step-down faulting of 1/16", 1/8", and 1/4". All cases were tested using both a Goodyear Aquatred III tire and a Uniroyal Tiger Paw tire at speeds of 10, 15, 20, 25, and 30 mph.

2 Background

2.1 Tire-Pavement Test Apparatus

A picture of Purdue University's TPTA is shown in Figure 1. In Figure 2, a schematic drawing of the TPTA is shown to more fully depict the interior of the apparatus.

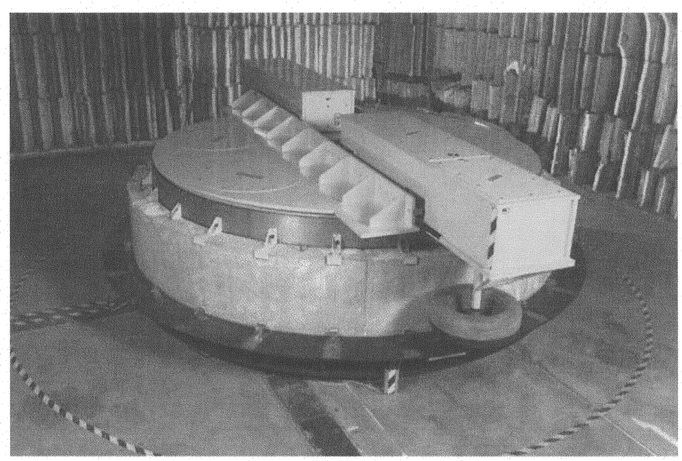

Figure 1: Purdue University's Tire-Pavement Test Apparatus (TPTA)

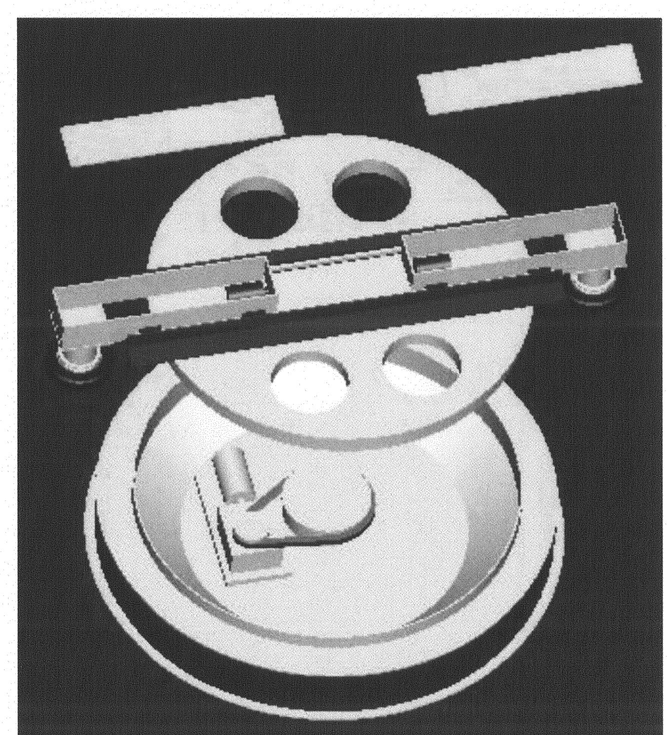

Figure 2: Schematic showing interior assembly of TPTA

The TPTA is a 12.14 ft (3.7 m) diameter drum containing a motor, gear box and pulley that drive a steel plate above the drum. Attached to the plate are two arms, with a wheel attached to each. Six curved, concrete samples are mounted around the drum. As the steel plate rotates, the two testing tires roll along the outside of the samples. Normal loads of up to 1 600 lbf (7 040 N) can be applied to each tire, simulating a 4 000 lb (1 800 kg) vehicle. Speed can be controlled from 0–30 mph (0–48 kph). Both the tires and the samples can be exchanged to study other tire-pavement combinations.

2.2 Data Collection System

Intensity probes were mounted near one of the test tires on the TPTA according to the draft AASHTO standard for On-Board Sound Intensity (OBSI)[3]. Phase-matched microphone pairs were mounted near the leading and trailing edges of the contact patch, with the center of the probes 2.76 in (70 mm) from the pavement and 4.02 in (102 mm) above the edge of the tire as depicted in Figures 3 and 4. The microphones were Brüel & Kjær Type 4197 Sound Intensity Microphone Pairs and the separation between the two microphones for each probe was 0.67 in (17 mm). The probes were connected to a Brüel & Kjær portable PULSE data acquisition system. Data were transferred to a laptop computer via a wireless router. Magnetic triggers, mounted as shown in Figure 5, were also connected to the data acquisition system and were used to start each measurement to ensure the joint occurred at the same time with each pass.

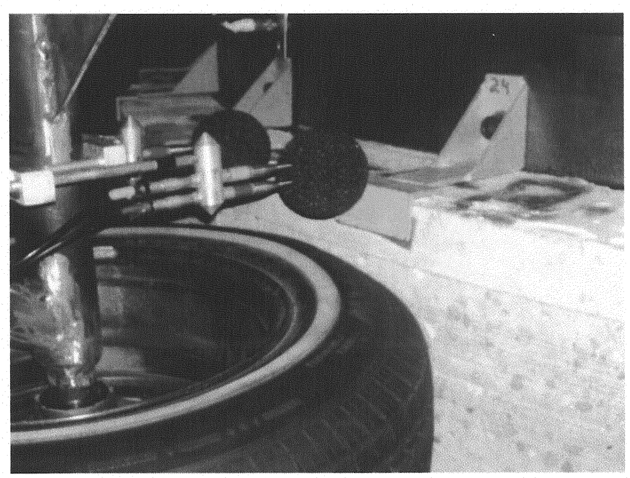

Figure 3: On-board sound intensity probes

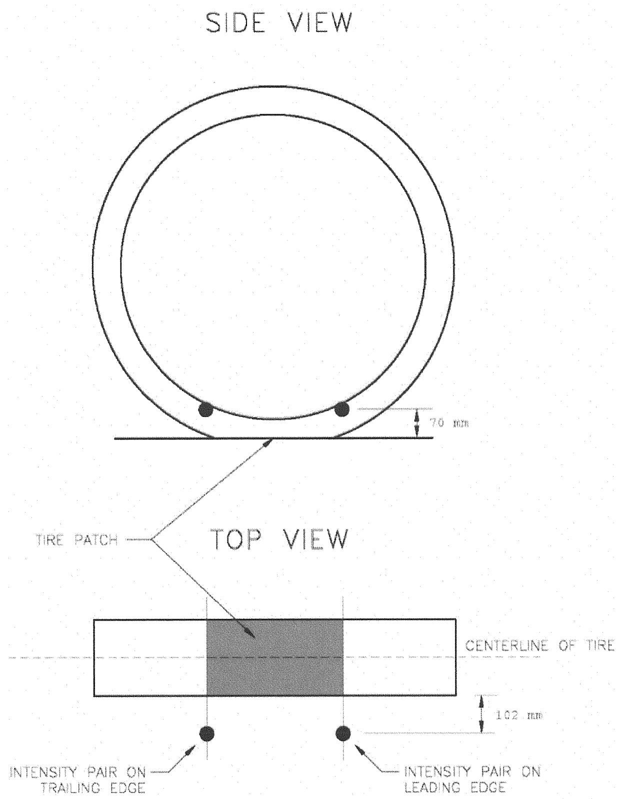

Figure 4: Intensity probe placement[3]

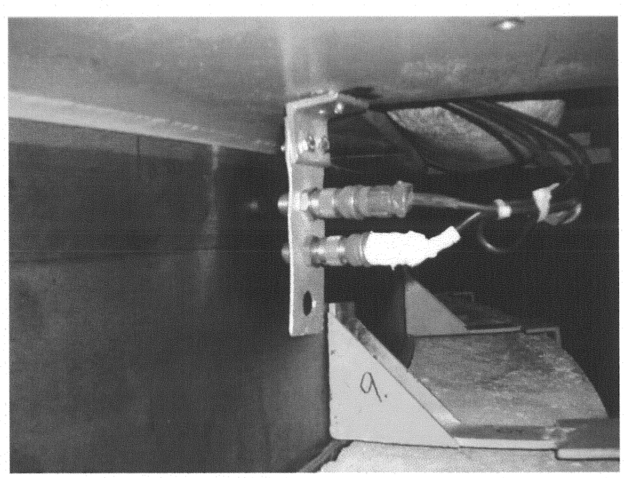

Figure 5: Magnetic triggers attached near test tire on TPTA

2.3 Data Processing

For each measurement, A-weighted, narrow-band intensity spectra were collected and averaged over 100 passes of the test tire over the joint sample with a sampling rate of 12 800 Hz. The narrow-band intensity data resolution was 12.5 Hz over the frequency range from 12.5 to 5 000 Hz. The intensities from the leading and trailing probes were averaged at each frequency. One-third octave band intensity spectra from 630 to 4 000 Hz were calculated by summing the narrow-band intensities in each one-third octave band. Overall intensity levels were calculated by adding all of the narrow-band intensities from 500 to 5 000 Hz. Both one-third octave band and overall intensity data were averaged over two different tires to average the tire effect.

3 Test Method

3.1 Sample Preparation

The concrete was specified as 4000 lb non-air stone PCC with an average slump of 6". Concrete was poured into steel forms and allowed to set for one week. While the samples were in the forms, the tops of them were covered in burlap and plastic sheeting for wet curing. The samples were then removed from the forms and wrapped in burlap and plastic sheeting to continue the wet curing process. The samples were allowed to cure for one month. During curing the samples were uncovered and moistened with a hose every three to four days. After the samples had cured, they were loaded onto the TPTA to have the joints cut. A jig was constructed to allow precise placement and cutting of the various joints. The various joints were saw-cut into the concrete samples. The saw cut joints had a nominal depth of 1". A typical saw-cut joint is shown in Figure 6. The various widths were accomplished by stacking multiple diamond-tipped concrete saw blades. Two joints were sawed into each of the concrete samples.

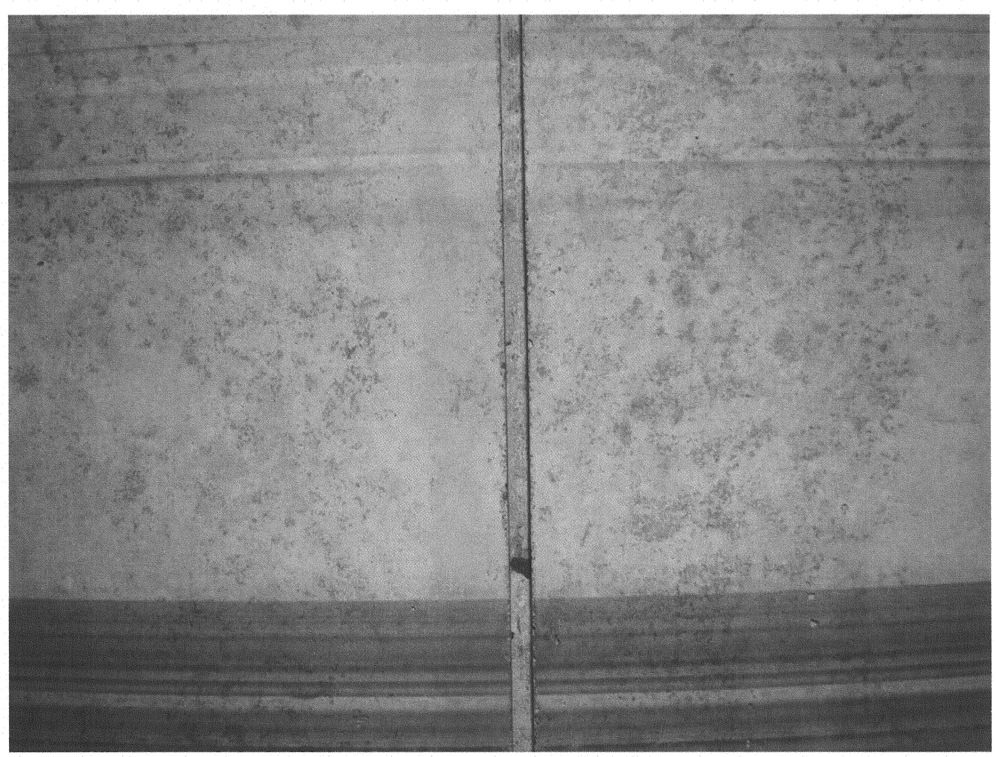

Figure 6: TPTA sample with 3/8" joint

Following the initial testing of the eight joints, the 1/2" joint was modified to include 1/4", 45 degree bevels as shown in Figures 7 and 8. This modified 1/2" joint had an effective opening width at the surface of 1”. An additional 2 mm width joint was cut using a single diamond saw blade.

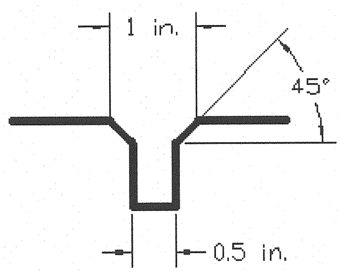

Figure 7: Diagram of TPTA sample with 1/2” beveled joint (effective width 1”).

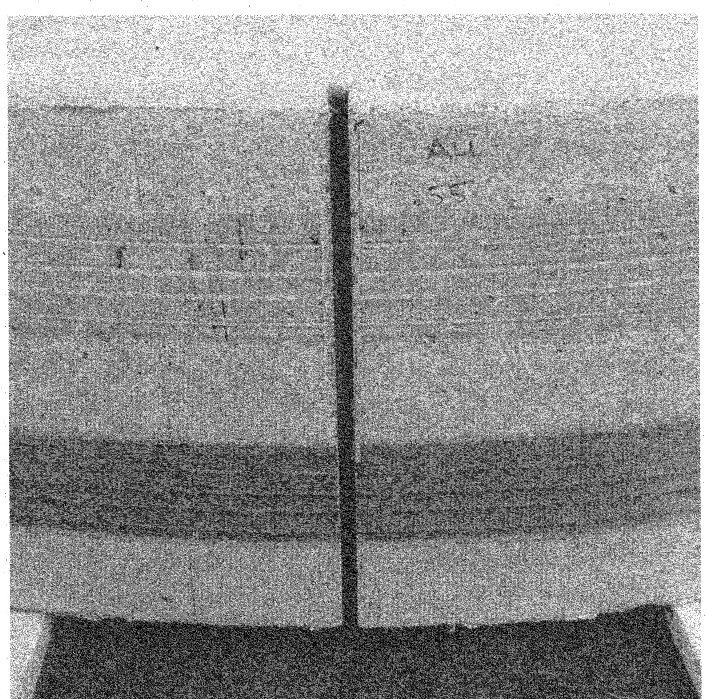

Figure 8: Picture of TPTA sample with 1/2” beveled joint (effective width 1”).

3.2 Testing and Data Acquisition

The four concrete samples containing the eight joints were placed on the TPTA along with two filler samples to complete the test surface. Two tires were then mounted and loaded to 600 pounds normal force and run at 30 mph for 30 minutes to confirm the durability of the saw cut joints. No visible erosion or spalling was observed during this break-in procedure. The mounted samples ready for testing are shown in Figure 9.

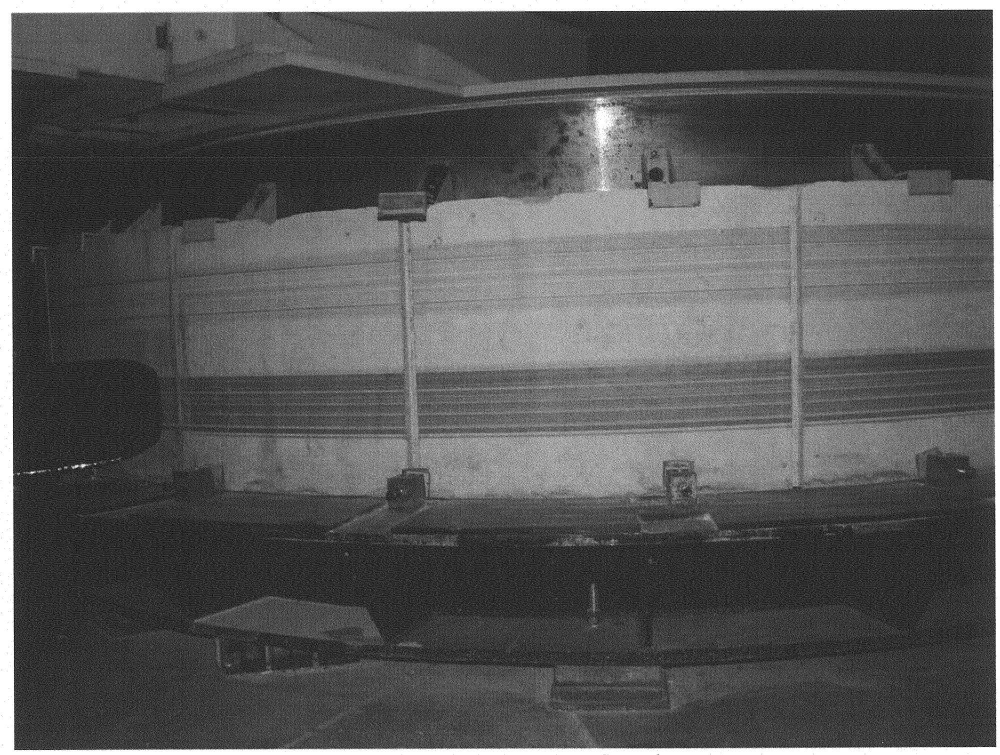

Figure 9: Joint samples mounted on the TPTA

For the purposes of this testing only the inboard OBSI microphones locations were used as only sound pressure level measurements would be conducted. These microphones are shown in Figure 10.

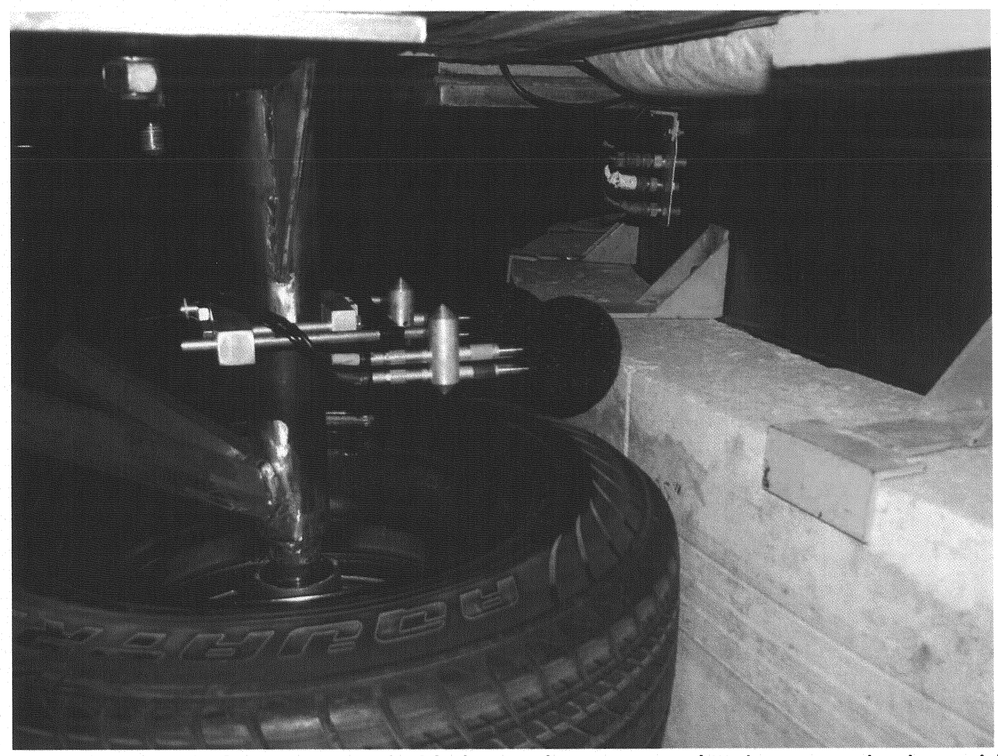

Figure 10: TPTA microphone fixture mounted with the Goodyear Aquatred III tire, magnetic trigger pickups are visible in the background.

Each of the various joints was tested with two tires, a Goodyear Aquatred III and a Uniroyal Tiger Paw at speeds of 10, 15, 20, 25 and 30 mph. In all cases, including the joint faulting tests, the normal load between the tire and pavement was set such that as the joint entered the contact patch the normal load was 600 pounds. Particularly in the case of the faulting tests this arrangement was the most representative of real-world normal loading. For each of the various joint widths, noise testing was performed for three filler conditions: unfilled, 1/2 in. filler recess, and 1/8 in. filler recess. In the case of the joint faulting testing, it was found that filler condition did not make a difference in tire-pavement noise generation. Thus these cases were tested only in the unfilled state.

All testing was performed according to the following routine:

1. Mount test tire
2. Set normal load to 600 pounds
3. Run tire pavement test apparatus for approximately 30 minutes to warm up tire
4. Set tire air pressure to 32 psi
5. Reset the normal load to 600 pounds with joint in the center of the contact patch
6. Place a magnetic trigger to indicate when the joint is entering contact patch
7. Acquire tire-pavement noise data (100 passes of the tire)
8. Repeat from step four for the next joint

9. Repeat from step one for second tire
10. Repeat from step one for next filler condition

Each of the individual joints was tested independently according to this procedure to ensure that the normal load was set correctly for that particular joint.

Noise data was initially collected for the eight unfilled joint cases. These joints were then filled to the half-inch recess filler case and retested. Finally joints were filled to the 1/8" recess case and retested.

Joint faulting noise testing was performed on the butt joints between adjacent concrete samples. The faulting height was set by placing shims behind the appropriate concrete sample. The joint width was a nominal 3/8 in. for all faulting tests.

For each of the joint cases, a short duration, A-weighted equivalent sound pressure level was computed. Based upon previous research, it was determined that tire-pavement noise generation due to discontinuities such as joints is largely a function of tire dynamic behavior. Thus the equivalent sound pressure level was computed over a constant 30 ms period rather than for a fixed distance of travel for all speed cases. A typical time history is shown in Figure 11, where sound pressure in Pascals (Pa) is plotted versus time for the Goodyear Aquatread III tire traveling over a 3/8" joint. This time history represents a time averaging over 100 passes of the tire over the joint.

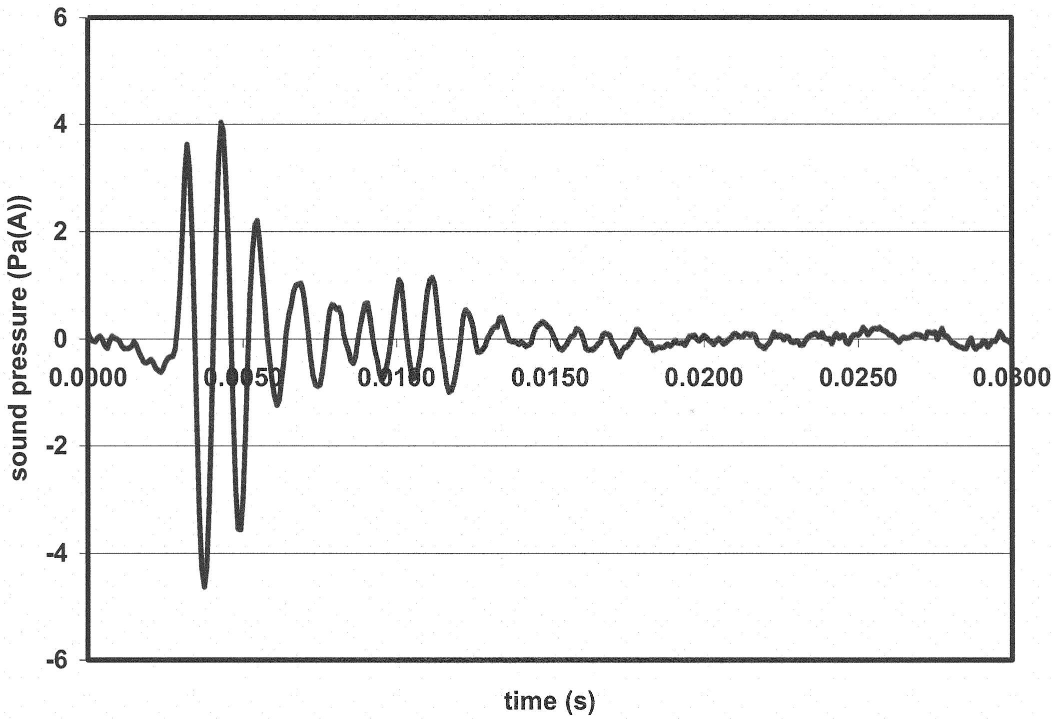

Figure 11: Unfilled 3/8" joint event time history, time averaged over 100 passes of the Goodyear Aquatread III tire over the joint.

4 Results

The collected data were analyzed in order to determine the effects of joint width, speed, filler condition, and faulting on tire-pavement noise generation.

4.1 Joint Width

Sound pressure level was found to increase linearly with increasing joint width. This was found to be true for all speeds and filler cases. A plot of sound pressure level versus joint width for the unfilled joint using the Goodyear tire at all speeds is shown in Figure 12. For an unfilled joint, it was found that sound pressure level increases by approximately 10 dB per inch of joint width. This was found to be consistent for both tires.

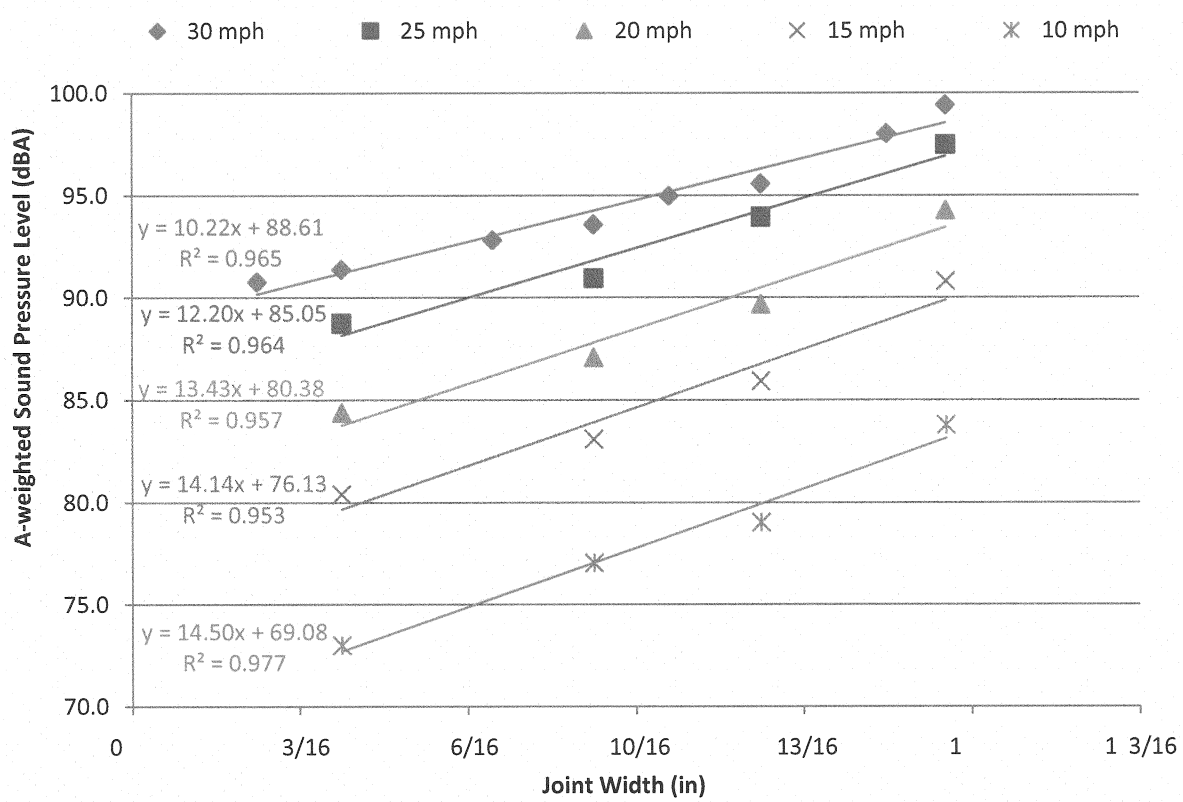

Figure 12: A-weighted sound pressure level versus joint width for the Goodyear tire traveling at 10, 15, 20, 25 and 30 miles per hour.

The noise generated for a 2 mm joint width case could not be measured. The noise of the tire running over the smooth as-cast pavement represents an effective measurement noise floor and the sound pressure level of the 2 mm joint did not exceed this measurement noise floor.

The beveled 1/2" joint which had a 1" effective opening width was found to behave identically to the 1" saw cut joint. The opening width at the pavement surface is the dominant noise parameter for a pavement joint. Comparisons between the nominal half-inch joint, pre- and post-beveling, and the nominal 1" joint are shown in Figures 13 and 14 for the Goodyear and Uniroyal tires respectively.

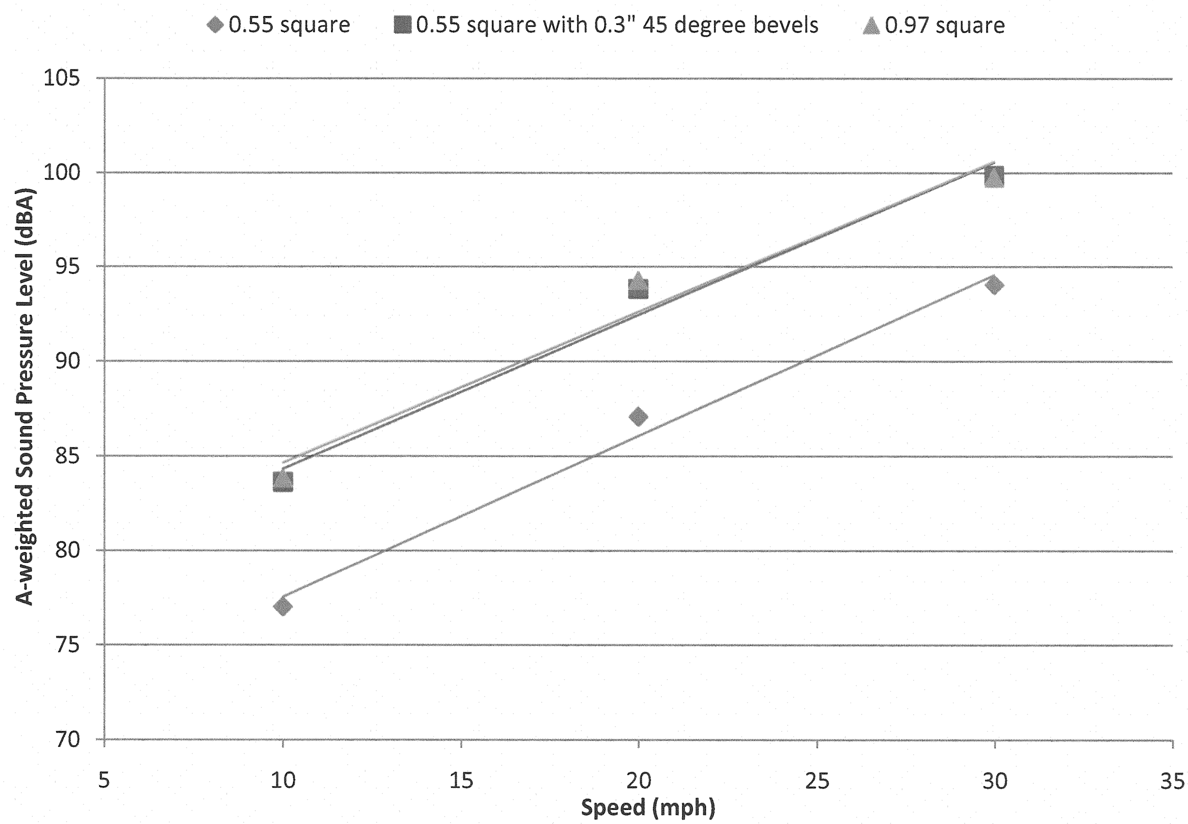

Figure 13: A-weighted sound pressure level versus speed for the Goodyear tire over the nominal ½" joint (pre/post beveling) and the beveled ½" joint (effective 1" joint).

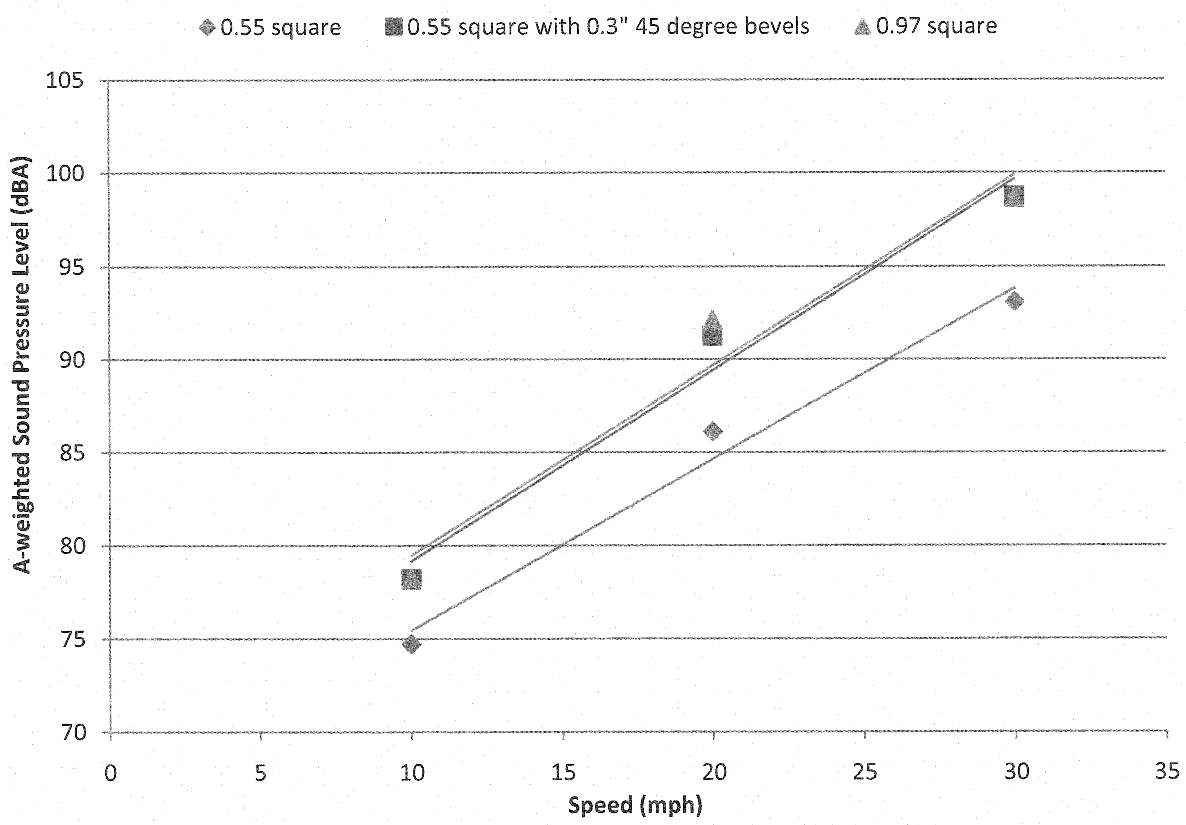

Figure 14: A-weighted sound pressure level versus speed for the Uniroyal tire over the nominal ½" joint (pre/post beveling) and the nominal 1" joint.

Sound pressure level was found to increase as a logarithmic function of speed for a given joint. A plot of sound pressure level versus speed for four unfilled joint widths for the Goodyear tire is shown in Figure 15. This behavior was consistent for both tires.

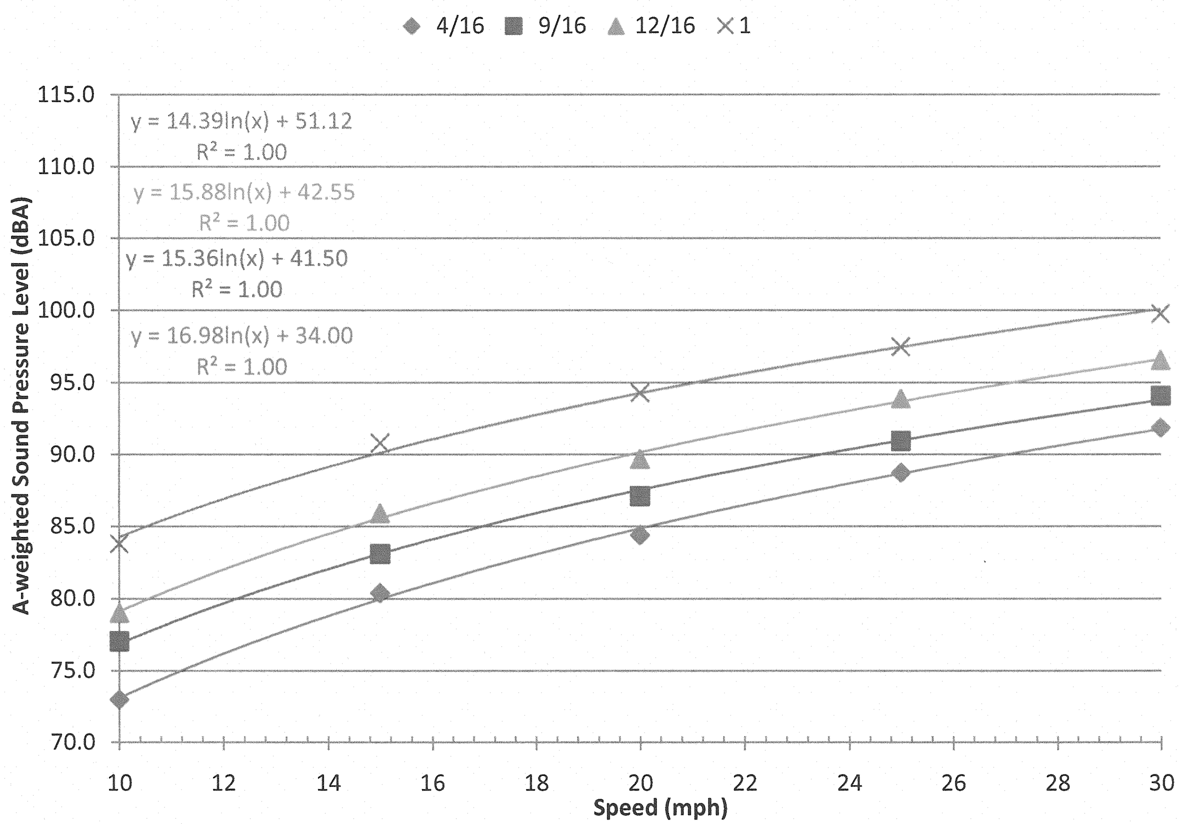

Figure 15: A-weighted sound pressure level versus speed for the Goodyear tire traveling over four unfilled joints.

4.2 Joint Fill Condition

Sound pressure level was found to increase with increasing filler recess depth for a given joint and speed. This effect was found to be a strong function of joint width; narrow joints became slightly louder with increased filler recess while wide joints became significantly louder with increased filler recess. A plot of sound pressure level versus filler recess for various joint widths for the Goodyear tire at 30 miles an hour is shown in Figure 16. This effect was found to be consistent for both tires.

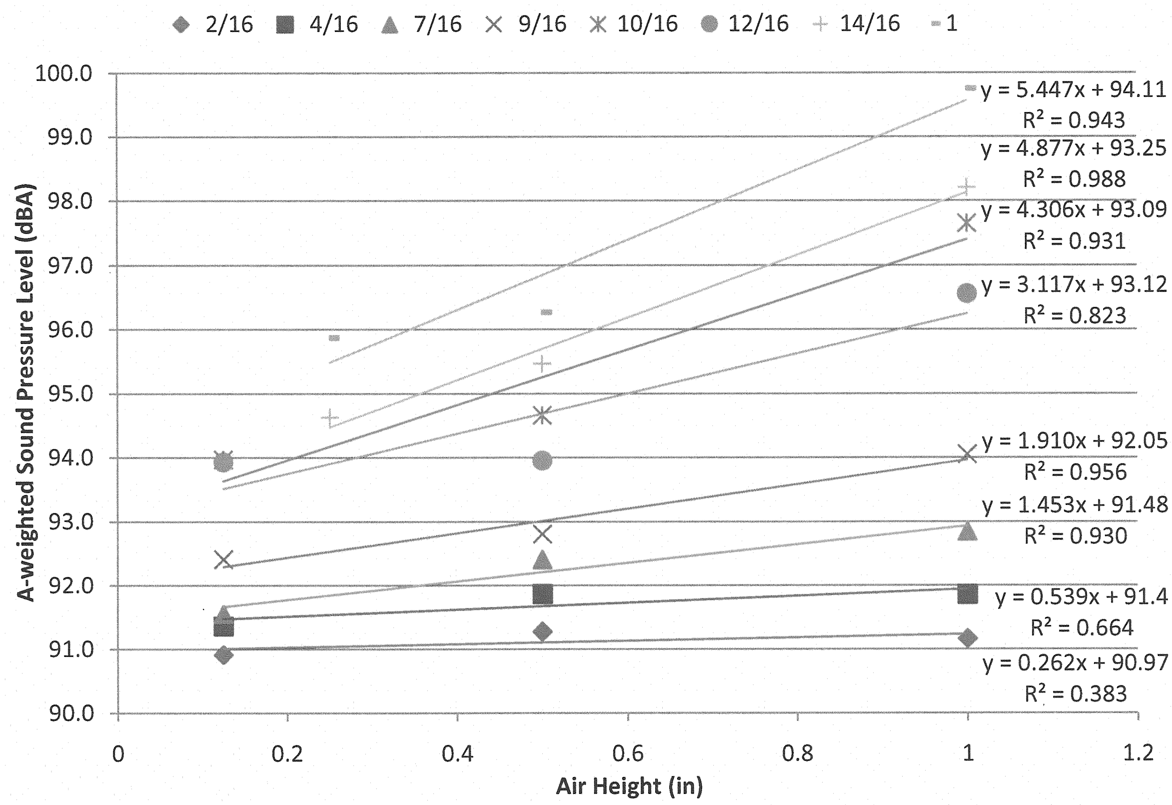

Figure 16: A-weighted sound pressure level versus filler recess depth for various joints for the Goodyear tire at 30 mph.

4.3 Joint Faulting

Sound pressure level was found to increase with increasing faulting height. For a given fault height, step down faulting was found to be louder. A plot of sound pressure level versus fault height for both tires at 10, 20 and 30 miles an hour is shown in Figure 17, where negative fault heights denote step-down faulting and positive values denote step-up faulting.

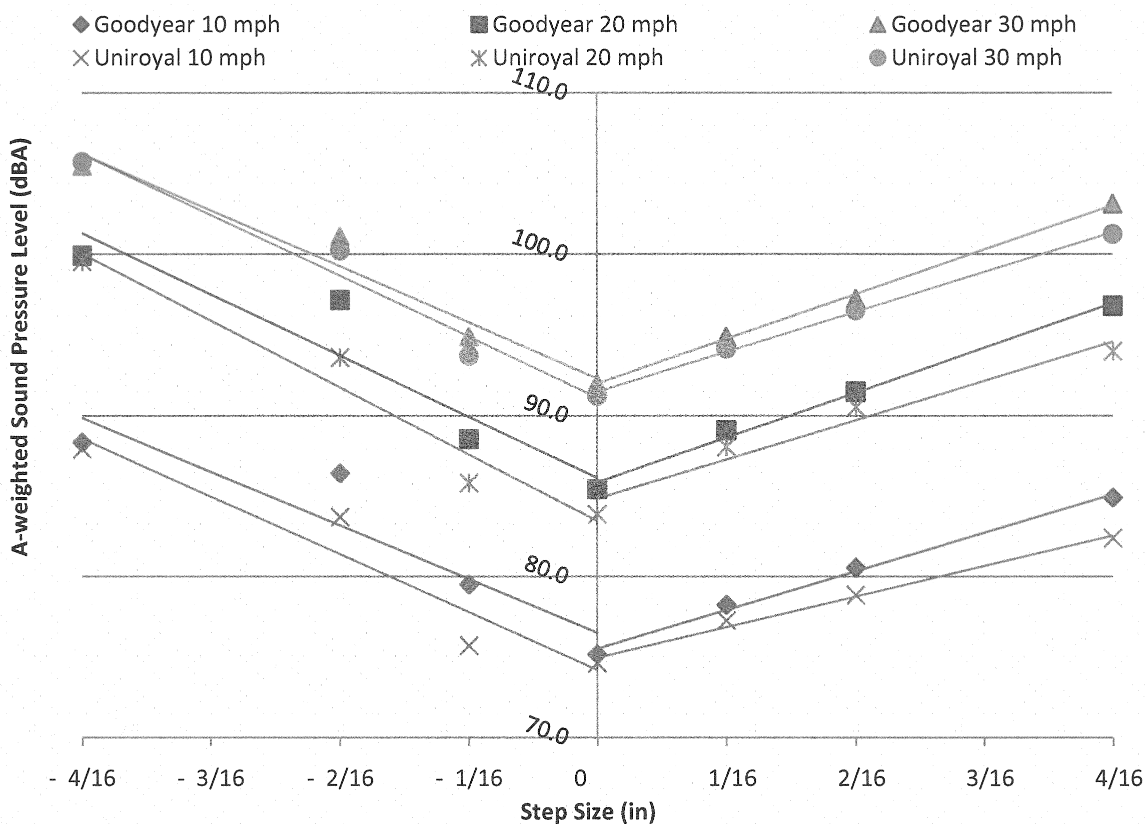

Figure 17: A-weighted sound pressure level versus fault height for both tires at 10, 20 and 30 mph.

4.4 Linear Regression Analysis

A three-dimensional linear regression analysis was performed using MATLAB. The three parameters used were the logarithm of speed, the joint width, and the filler recess depth. The goal of the analysis was to obtain a formula for the sound pressure level produced by a joint as a function of the three parameters. From the initial analysis, it was determined that the equivalent sound pressure level increased linearly with the log of speed, joint width, and filler recess depth. It was further determined from the fill recess experiment (Figure 17) that there likely existed cross terms (e.g., width*speed) in the desired formula.

Several iterations of linear regression analysis were conducted. The formulas for these iterations and their results can be found in Table 1. The goal of the iterations was to minimize the number of terms in the formula while maintaining a high correlation. The formula chosen involves three terms: log(speed), joint width, and joint width times filler recess depth related as shown in Equation 1.

$$L_{eq} = c_1 + c_2 w + c_3 \log(s) + c_4 wd = 32.0 + 5.2 \times w + 38.7 \times \log(s) + 4.8 \times wd \qquad \textbf{Equation 1}$$

This formula has an R-squared value of 0.9756 and an adjusted R-squared value of 0.9749. This formula was chosen because it uses a minimal number of terms while maintaining a high R-squared value. Other formulas have higher R-squared values, but the terms involving filler recess depth usually had very small coefficients compared to the other terms. The formula is also useful because it can be written in the form given in Equation 2.

$$L_{eq} = c_1 + c_2 \log(s) + c_3 w(c_4 + d) \qquad \textbf{Equation 2}$$

where the filler recess depth appears as a "correction factor" to the joint width.
This representation implies that the filler recess depth is a secondary factor to the joint width and vehicle speed, contributing at most 5 dB per inch of filler recess depth versus at least 10 dB per inch of joint width. Alternatively, the acoustic pressure can be written as given in Equation 3.

$$\frac{p}{p_{ref}} = b_1 s \times 10^{b_2 + b_3 w(b_4 + d)} \qquad \textbf{Equation 3}$$

Table 1: Formulas and R^2 values for linear regression analysis

Formula	R^2	Adjusted R^2
$L = c_1 + c_2 w + c_3 d + c_4 \log(s) + c_5 wd + c_6 \log(s) \times d + c_7 \log(s) \times w + c_8 d^2 \ldots$ $\ldots c_9 w^2 + c_{10} w^2 d + c_{11} wd^2 + c_{12} \log(s) \times w^2 + c_{13} \log(s) \times d^2 + c_{14} w^2 d^2$	0.9814	0.9808
$L = c_1 + c_2 \log(s) + c_3 d^2 + c_4 w^2 + c_5 \log(s) \times w^2 + c_6 \log(s) \times d^2 + c_7 w^2 d^2$	0.9807	0.9802
$L = c_1 + c_2 w + c_3 d + c_4 \log(s) + c_5 wd + c_6 \log(s) \times d + c_7 \log(s) \times w + c_8 d^2 + c_9 w^2$	0.9798	0.9792
$L = c_1 + c_2 w + c_3 d + c_4 \log(s) + c_5 wd + c_6 \log(s) \times d + c_7 \log(s) \times w$	0.9772	0.9765
$L = c_1 + c_2 w + c_3 d + c_4 \log(s) + c_5 wd + c_6 \log(s) \times w$	0.9771	0.9765
$L = c_1 + c_2 w + c_3 d + c_4 \log(s) + c_5 wd$	0.9765	0.9758
$L = c_1 + c_2 w + c_3 d + c_4 \log(s) + c_5 wd + c_6 \log(s) \times d$	0.9765	0.9758
$L = c_1 + c_2 w + c_3 \log(s) + c_4 wd$	0.9756	0.9749

$L = c_1 + c_2 w + c_3 d + c_4 \log(s) + c_5 d^2 + c_6 w^2$	0.9724	0.9716
$L = c_1 + c_2 \log(s) + c_3 d^2 + c_4 w^2$	0.9720	0.9712
$L = c_1 + c_2 d + c_3 \log(s) + c_4 wd$	0.9698	0.9689
$L = c_1 + c_2 w + c_3 d + c_4 \log(s) + c_5 \log(s) \times w$	0.9692	0.9682
$L = c_1 + c_2 w + c_3 d + c_4 \log(s) + c_5 \log(s) \times d + c_6 \log(s) \times w$	0.9692	0.9682
$L = c_1 + c_2 w + c_3 d + c_4 \log(s)$	0.9682	0.9672
$L = c_1 + c_2 w + c_3 d + c_4 \log(s) + c_5 \log(s) \times d$	0.9682	0.9672

The sound pressure levels predicted using this empirical model were compared to the all of the data collected on the TPTA as provided in Figure 18. The data points are closely clustered around the 1:1 line, indicating a good fit of the prediction. Furthermore, the data points within a given speed and fill condition are also evenly spaced above and below the 1:1 line.

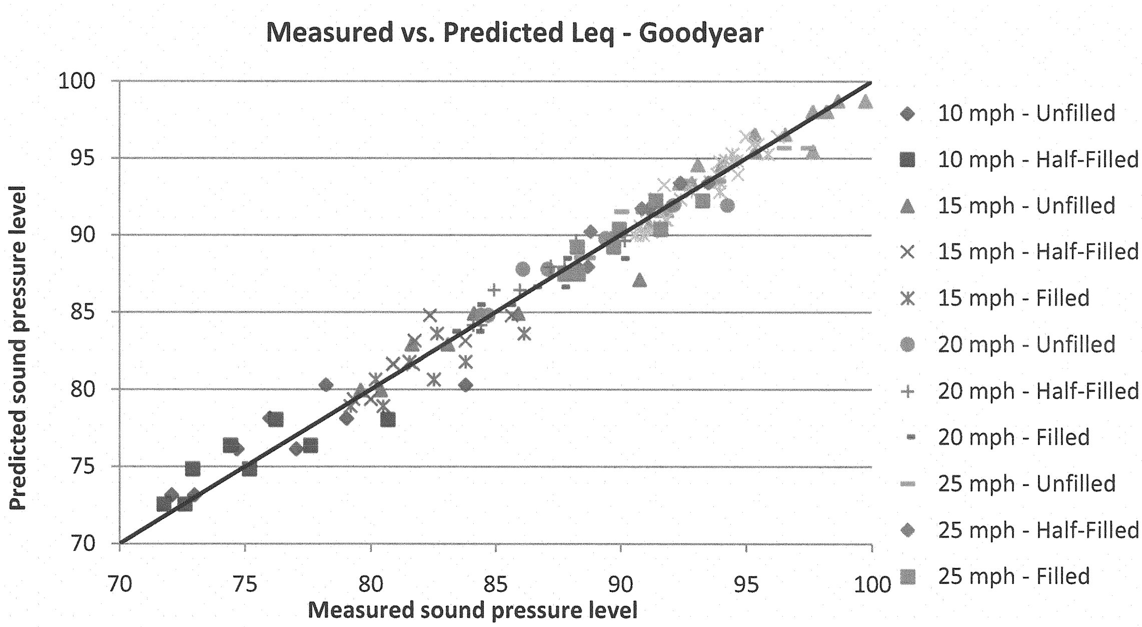

Figure 18: Predicted and measured sound pressure levles for varying speeds and fill conditions

4.5 Effect on Overall Pavement Noise

An analysis was done to determine the effects of joints on overall pavement noise. The analysis was based on the assumption that the joints would be spaced 15 ft. apart on a roadway and that all joint noise attenuates within 30 ms. The average noise levels from different joint widths and filler conditions was combined with the average noise levels of some pavements to determine the levels of the pavement and joints together. At 60 mph, joints spaced at 15 ft. intervals cause the joint noise to occur every 0.170 seconds. The average level of the pavement with joints is given in Equation 4.

$$L_O = 10 \times \log\left(\frac{0.030 \times 10^{(L_J/10)} + 0.140 \times 10^{(L_P/10)}}{0.170} \right)$$ **Equation 4**

where L_O is the overall level of the pavement with joints

L_J is the level of the joints measured on the TPTA

L_P is the level of the pavement without joints

Table 2 shows the increase in level for given joint filler combinations for joints spaced at 15 ft. intervals on 100, 105, and 110 dB(A) pavements. The same method was used to predict the effects of faulting on overall pavement levels. Table 3 shows the increase in level for a given faulting height with a 3/8" joint width.

Table 2: Effects of joint width and fill condition on overall roadway sound pressure levels

Filled joint (1/8" filler recess)

Joint width	SPL extrapolated to 60 mph	Increase with 100 dB(A) pavement	Increase with 105 dB(A) pavement	Increase with 110 dB(A) pavement
1/8"	101.5	0.3	None	None
1/4"	102.2	0.5	None	None
1/2"	103.6	0.9	None	None
1"	106.5	2.1	0.3	None

Half-filled joint (1/2" filler recess)

Joint width	SPL extrapolated to 60 mph	Increase with 100 dB(A) pavement	Increase with 105 dB(A) pavement	Increase with 110 dB(A) pavement
1/8"	101.7	0.3	None	None
1/4"	102.6	0.6	None	None
1/2"	104.5	1.2	None	None
1"	108.3	3.0	0.8	None

Unfilled joint (1" filler recess)

Joint width	SPL extrapolated to 60 mph	Increase with 100 dB(A) pavement	Increase with 105 dB(A) pavement	Increase with 110 dB(A) pavement
1/8"	102.0	0.4	None	None

1/4"	103.2	0.8	None	None
1/2"	105.7	1.7	0.1	None
1"	110.7	4.6	1.7	0.1

Table 3: Effects of faulting of 3/8" joint on overall roadway sound pressure levels

Step Up - Goodyear

Step Size	SPL extrapolated to 60 mph	Increase with 100 dB(A) pavement	Increase with 105 dB(A) pavement	Increase with 110 dB(A) pavement
0"	102.5	0.5	None	None
1/16"	105.6	1.6	0.1	None
1/8"	108.0	2.9	0.7	None
1/4"	114.8	7.9	4.0	1.3

Step Down - Goodyear

Step Size	SPL extrapolated to 60 mph	Increase with 100 dB(A) pavement	Increase with 105 dB(A) pavement	Increase with 110 dB(A) pavement
0"	102.5	0.5	None	None
1/16"	104.3	1.1	None	None
1/8"	111.1	4.9	1.9	0.2
1/4"	116.7	9.6	5.3	2.2

Step Up - Uniroyal

Step Size	SPL extrapolated to 60 mph	Increase with 100 dB(A) pavement	Increase with 105 dB(A) pavement	Increase with 110 dB(A) pavement
0"	101.2	0.2	None	None
1/16"	104.9	1.4	None	None
1/8"	107.9	2.8	0.7	None
1/4"	113.0	6.4	2.9	0.7

Step Down - Uniroyal

Step Size	SPL extrapolated to 60 mph	Increase with 100 dB(A) pavement	Increase with 105 dB(A) pavement	Increase with 110 dB(A) pavement
0"	101.2	0.2	None	None
1/16"	104.4	1.2	None	None

1/8"	110.3	4.4	1.5	0.1
1/4"	117.1	9.9	5.7	2.4

5 Conclusions

Tire pavement noise generation due to pavement joints was found to be a strong function of joint width suggesting that in order to decrease noise levels it is necessary to construct pavements with the narrowest joint width practical. In addition, increased filler recess depth was found to produce increased noise generation for a given joint width. However, for a realistic joint width such as 3/8”, this effect is minimal.

Acknowledgements

The authors wish to thank Jerry Voigt and Larry Scofield of the American Concrete Pavement Association for financial and logistical support for this project and Ron Evans and Tanya Wulf for assistance with experimentation and report preparation. In addition, we wish to thank Terry Kraemer of Diamond Surface, Inc. and the International Grinding and Grooving Association for providing the equipment, the blades and support to assist in the testing.

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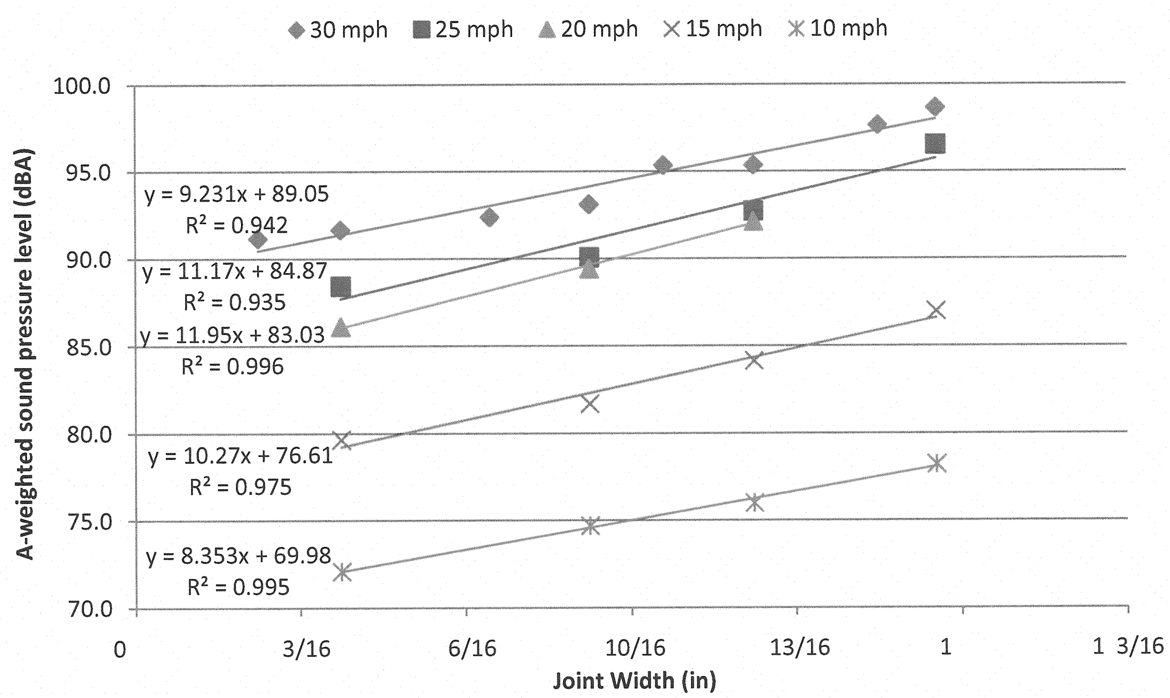
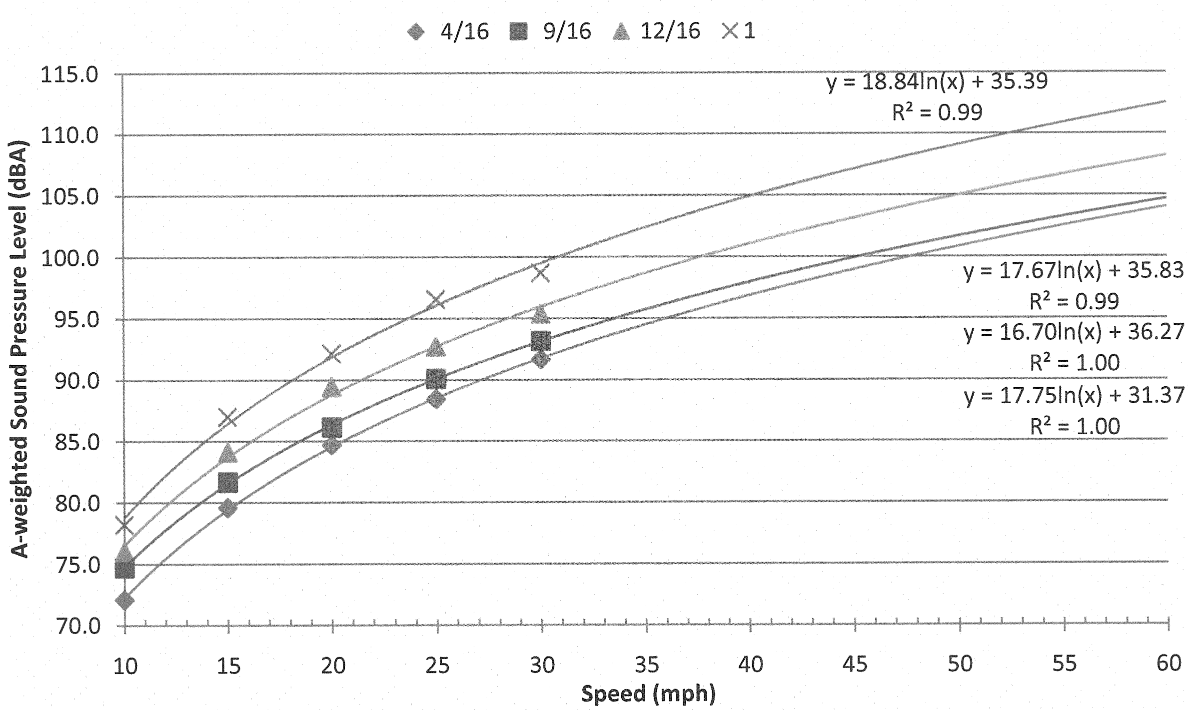
[2] Mark B. Snyder, *Pavement Surface Characteristics – A Synthesis and Guide*, American Concrete Pavement Association, Skokie, Illinois, 2006.

[3] AASHTO Draft: “Standard Practice for Measurement of On-Board Tire-Pavement Noise”, personal communication, FHWA Expert Task Group, 2007.

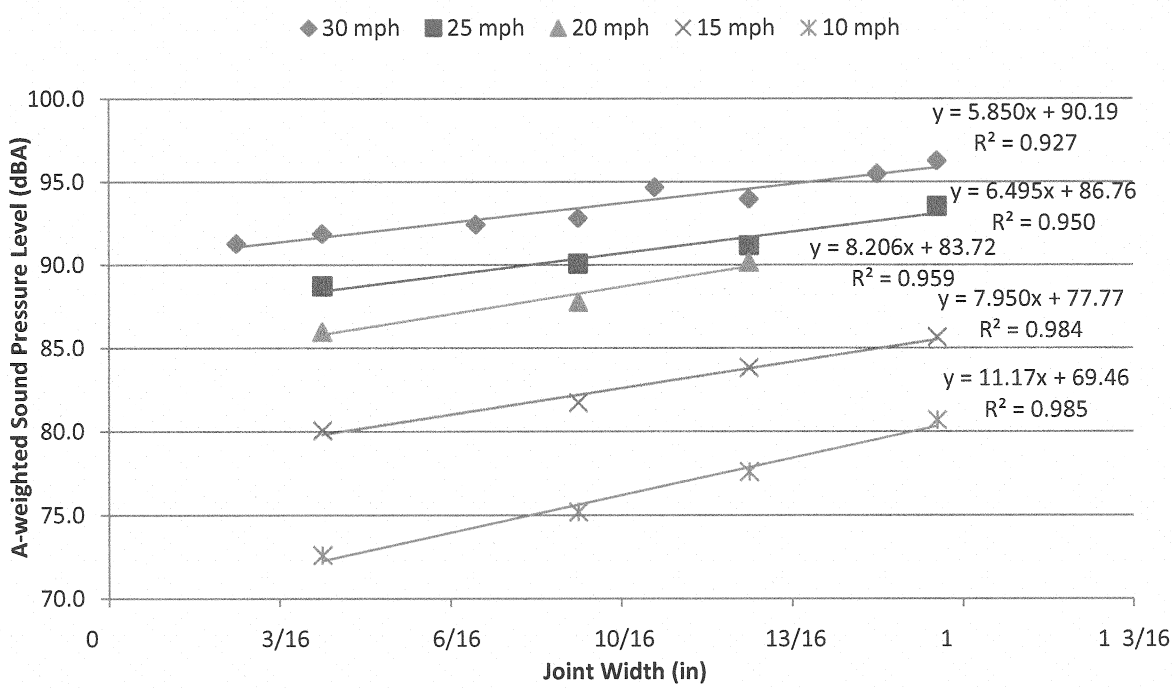
Appendix A: Joint Width Data



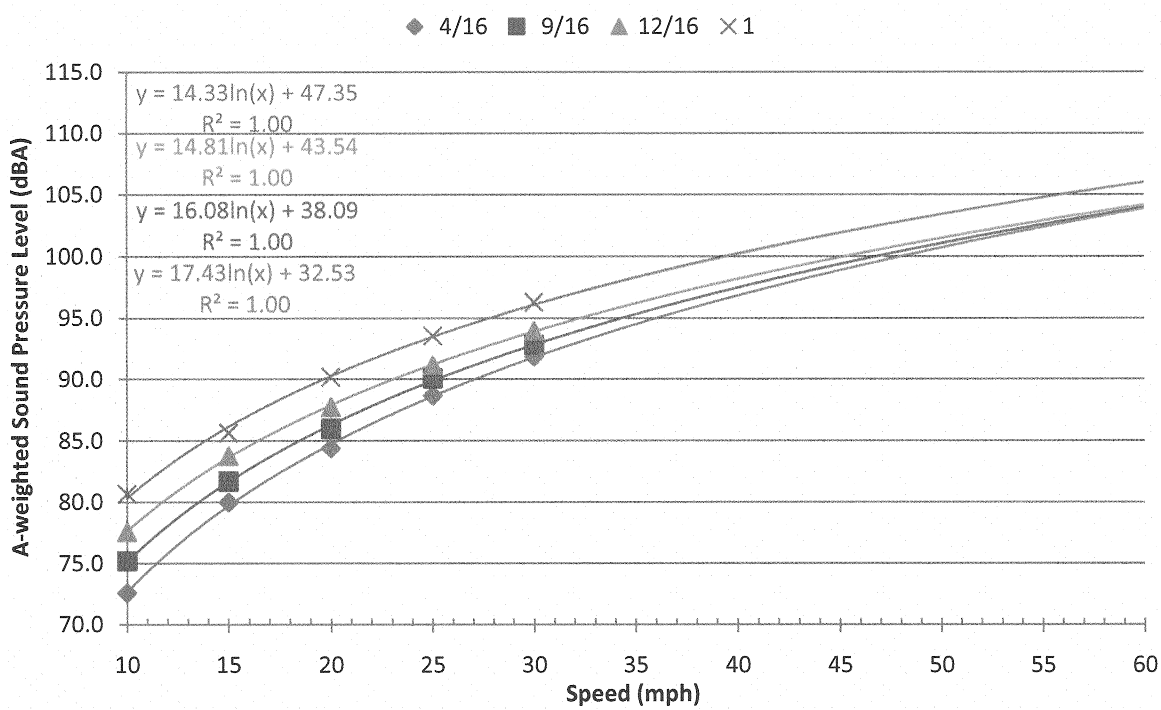
Appendix Figure A.1: A-weighted sound pressure level versus joint width for the Uniroyal tire with unfilled joints.



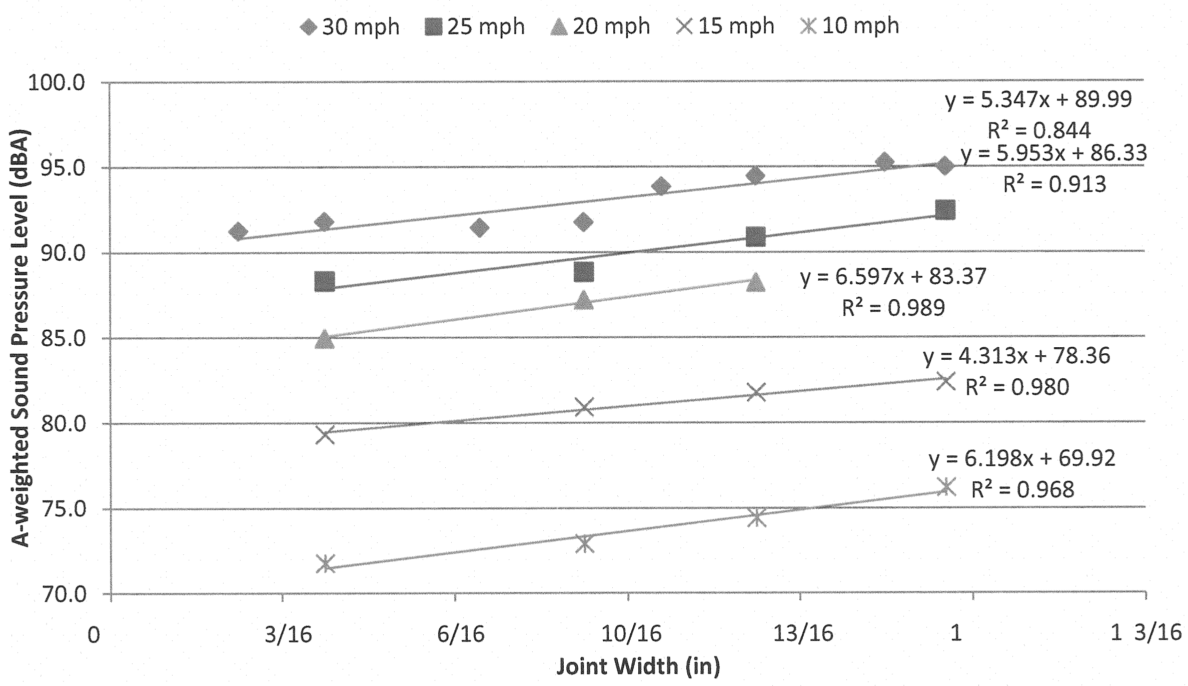
Appendix Figure A.2: A-weighted sound pressure level versus speed for the Uniroyal tire for unfilled joints.



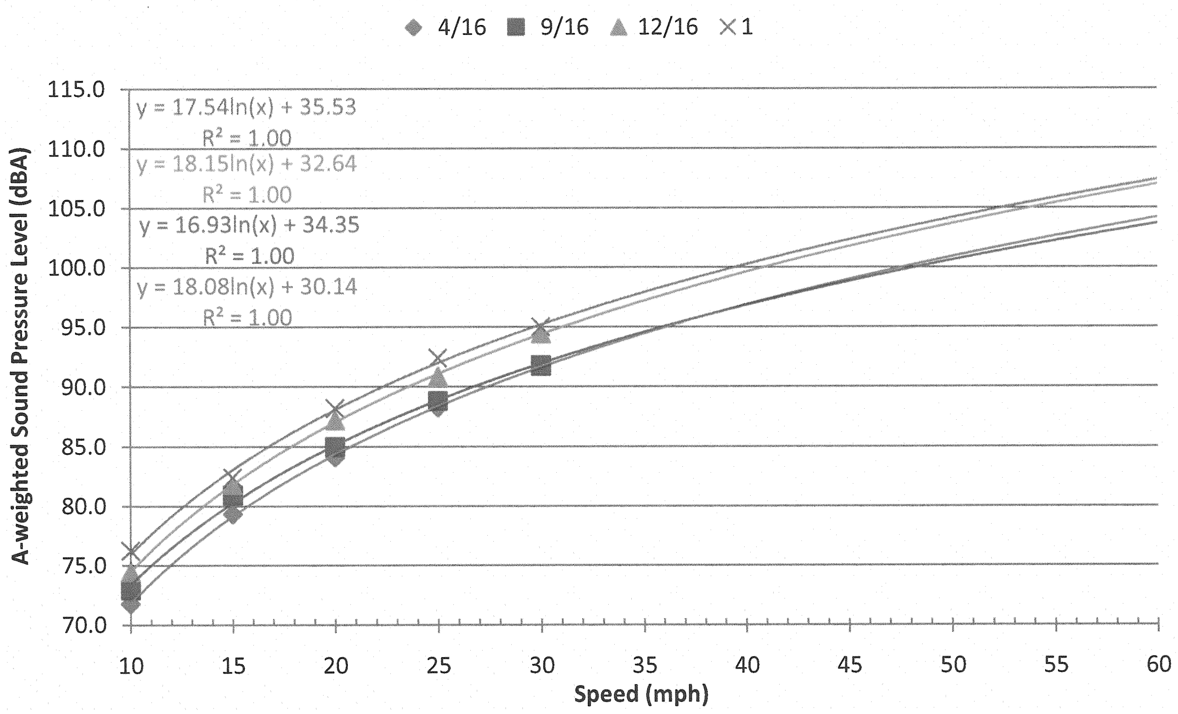
Appendix Figure A.3: A-weighted sound pressure level versus joint width for the Goodyear tire for ½" filler recess joints.



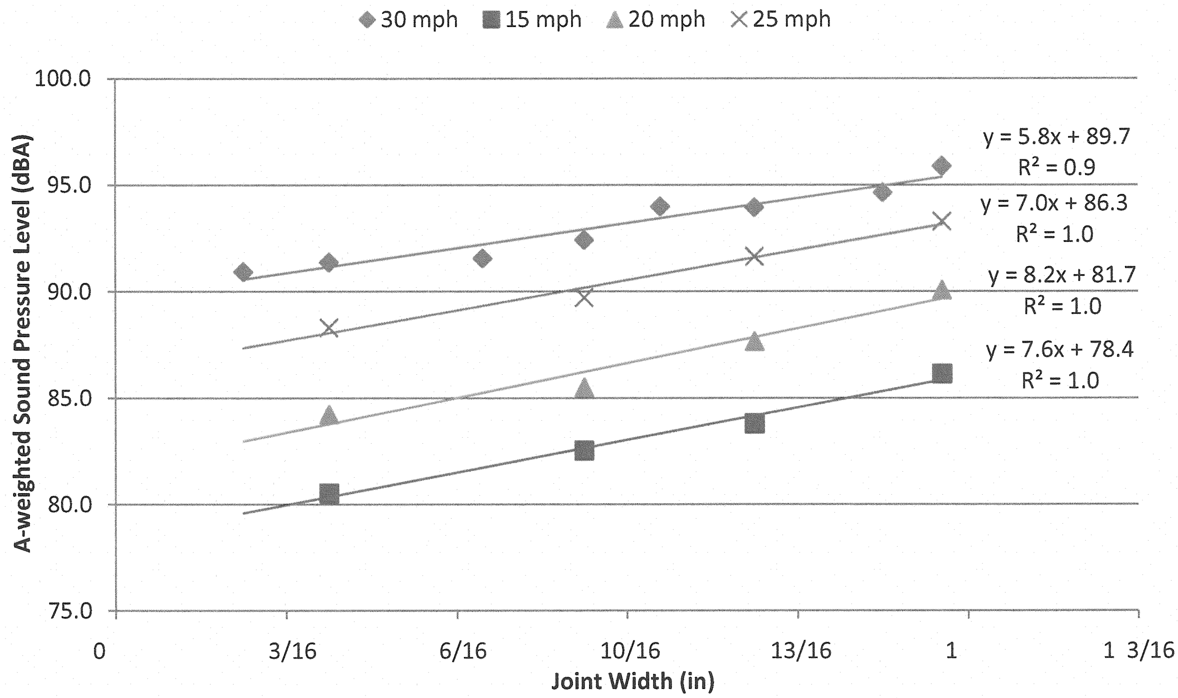
Appendix Figure A.4: A-weighted sound pressure level versus speed for the Goodyear tire for ½" filler recess joints.



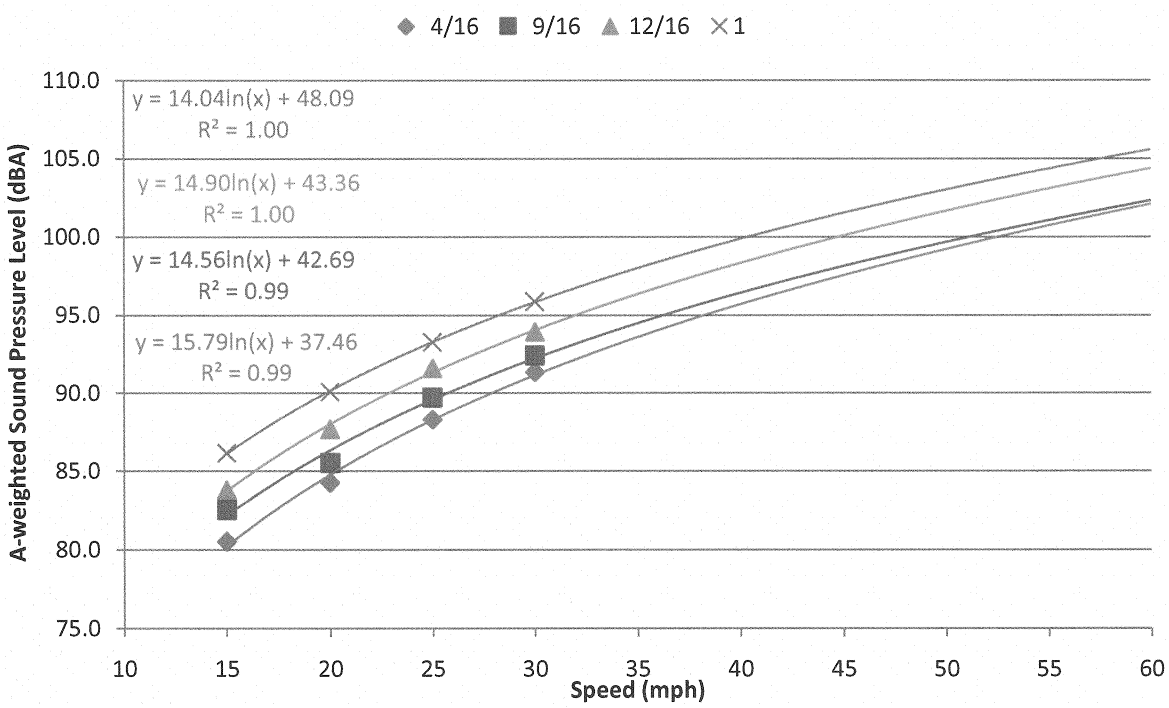
Appendix Figure A.5: A-weighted sound pressure level versus joint width for the Uniroyal tire for ½" filler recess joints.



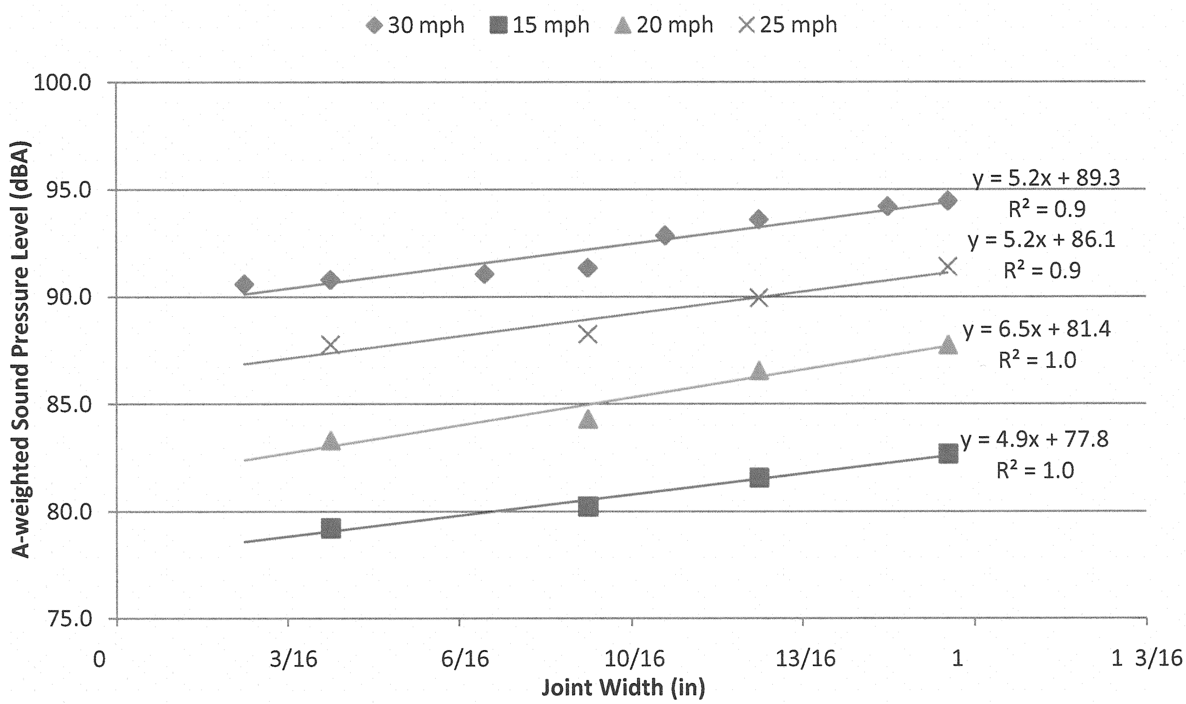
Appendix Figure A.6: A-weighted sound pressure level versus speed for the Uniroyal tire for ½" filler recess joints.



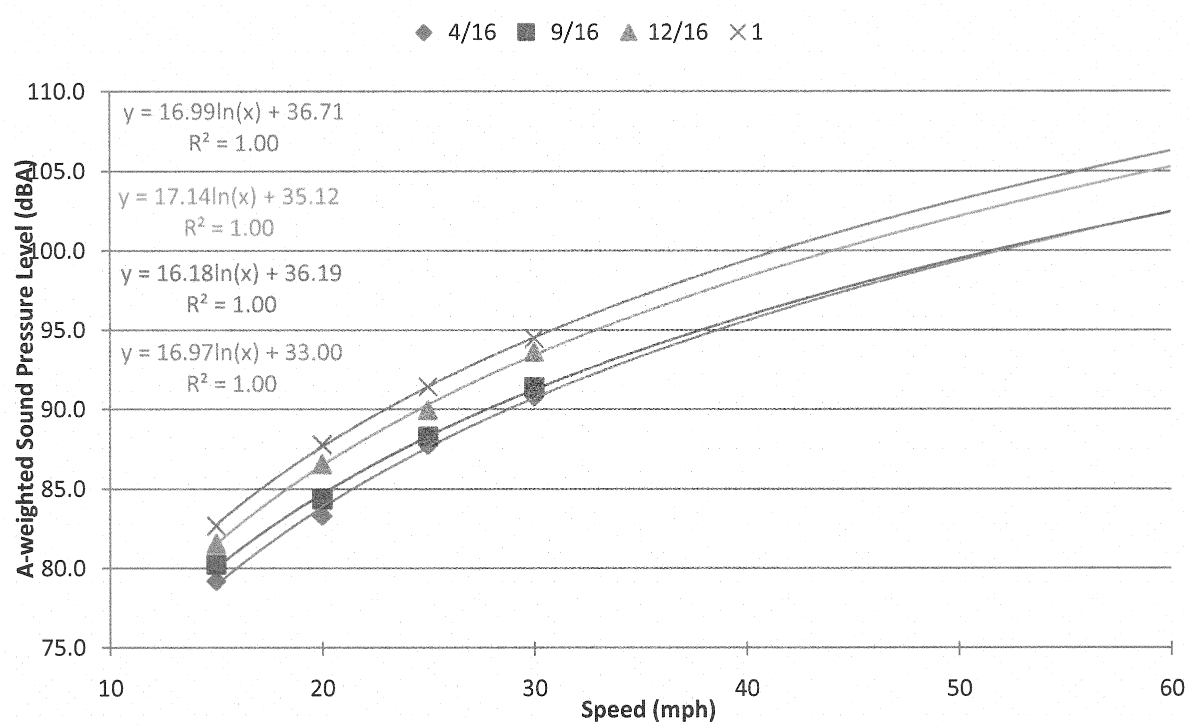
Appendix Figure A.7: A-weighted sound pressure level versus joint width for the Goodyear tire for 1/8" filler recess joints.



Appendix Figure A.8: A-weighted sound pressure level versus speed for the Goodyear tire for 1/8" filler recess joints.

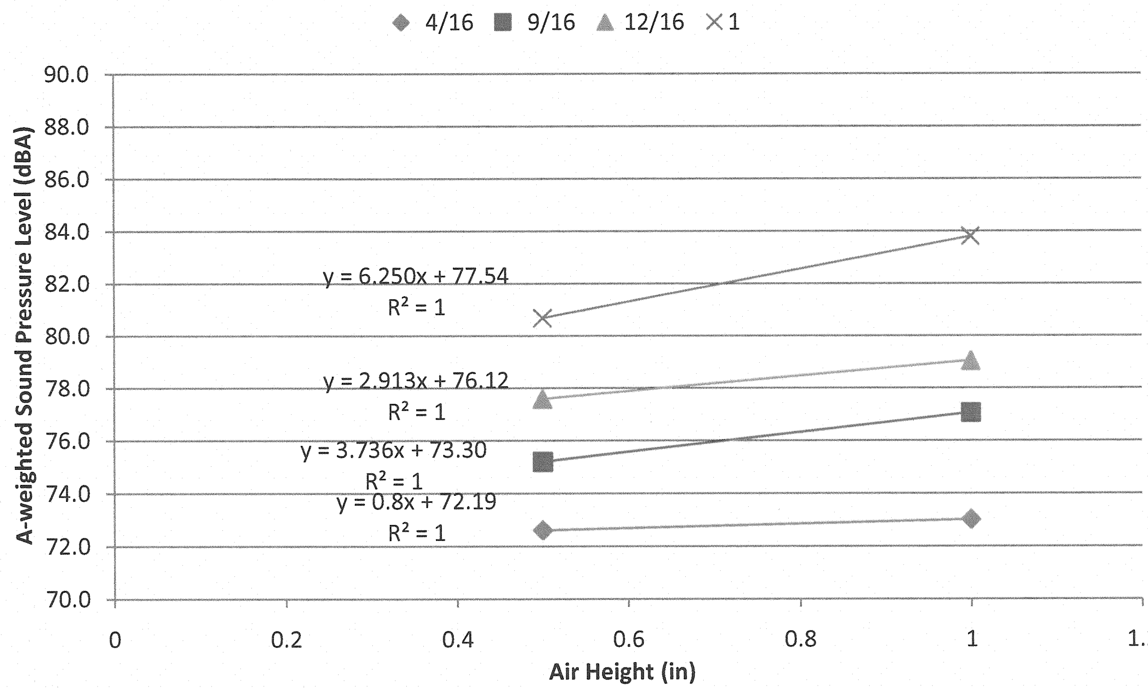


Appendix Figure A.9: A-weighted sound pressure level versus joint width for the Uniroyal tire for 1/8" filler recess joints.

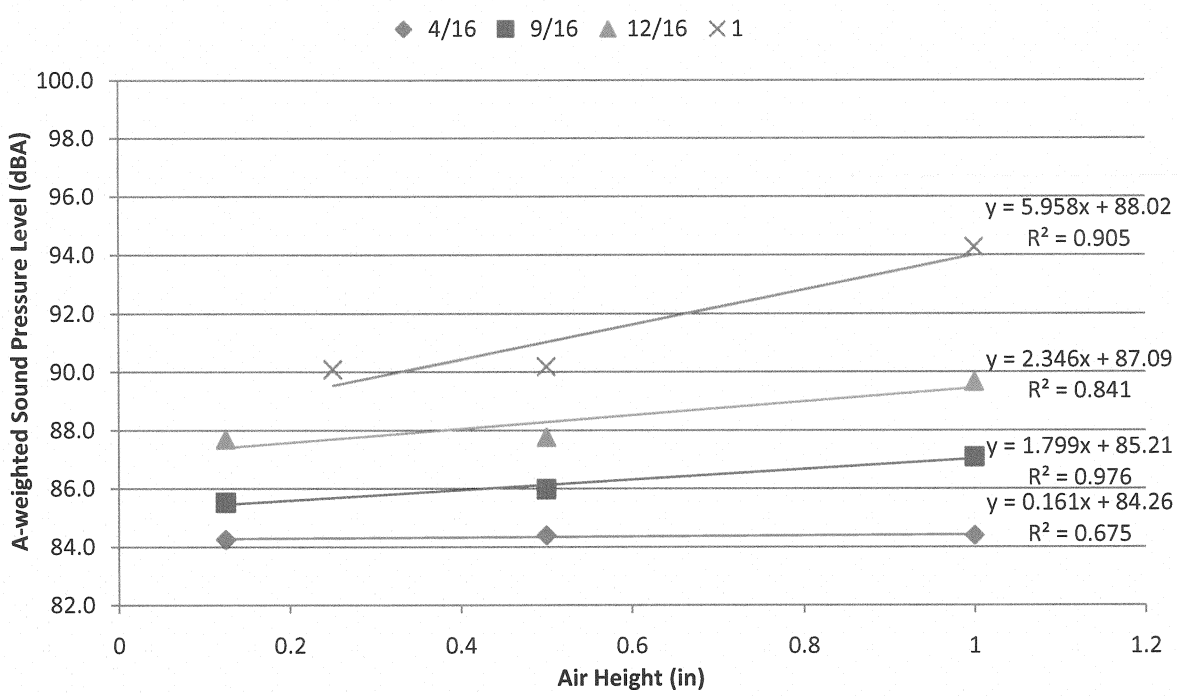


Appendix Figure A.10: A-weighted sound pressure level versus speed for the Uniroyal tire over 1/8" filler recess joints.

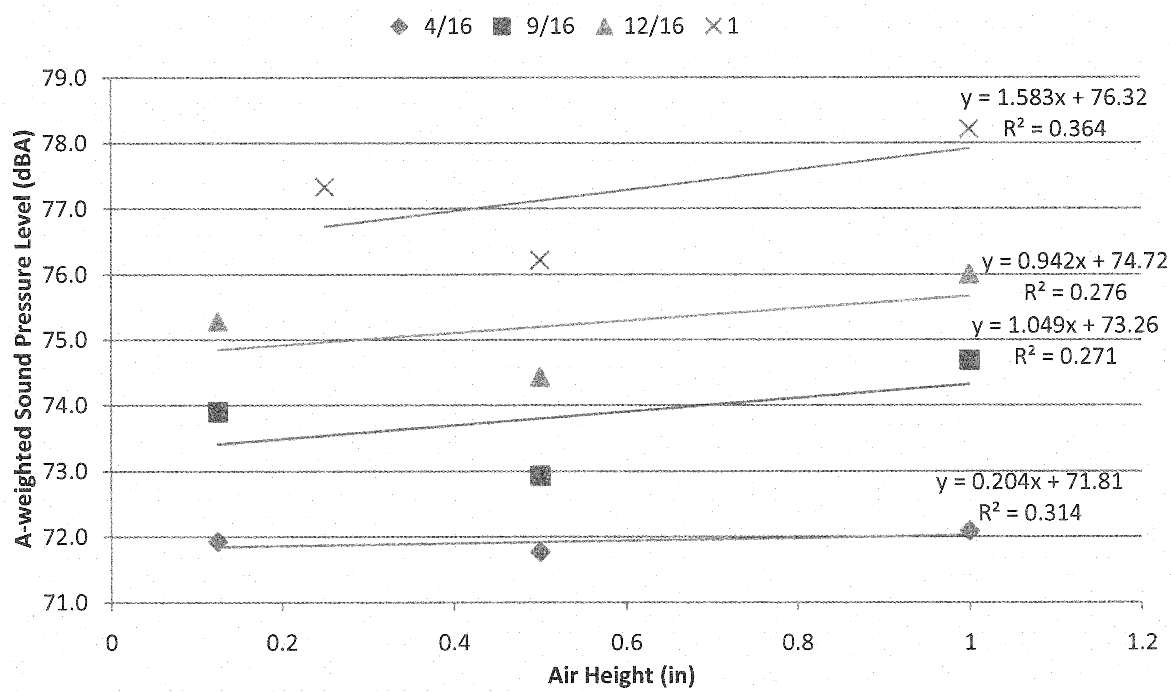
Appendix B: Joint Fill Condition Data



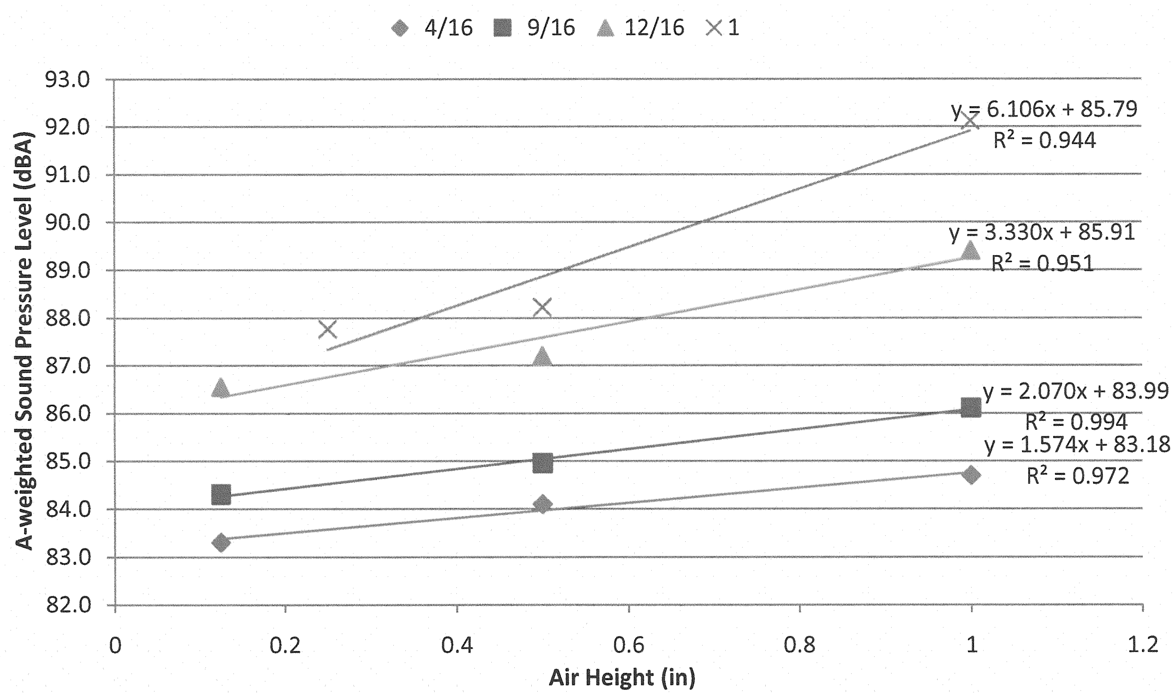
Appendix Figure B.1: A-weighted sound pressure level versus filler recess depth for various joints for the 10 mph Goodyear



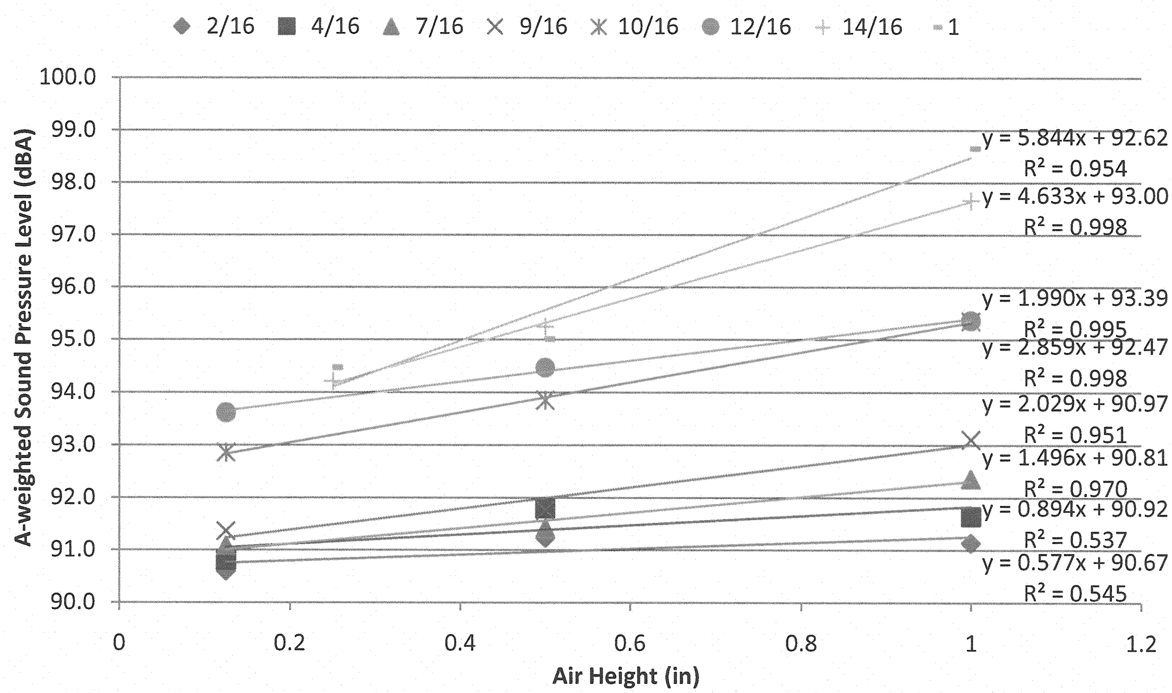
Appendix Figure B.2: A-weighted sound pressure level versus filler recess depth for various joints for the 20 mph Goodyear



Appendix Figure B.3: A-weighted sound pressure level versus filler recess depth for various joints for the 10 mph Uniroyal



Appendix Figure B.4: A-weighted sound pressure level versus filler recess depth for various joints for the 20 mph Uniroyal



Appendix Figure B.5: A-weighted sound pressure level versus filler recess depth for various joints for the 30 mph Uniroyal