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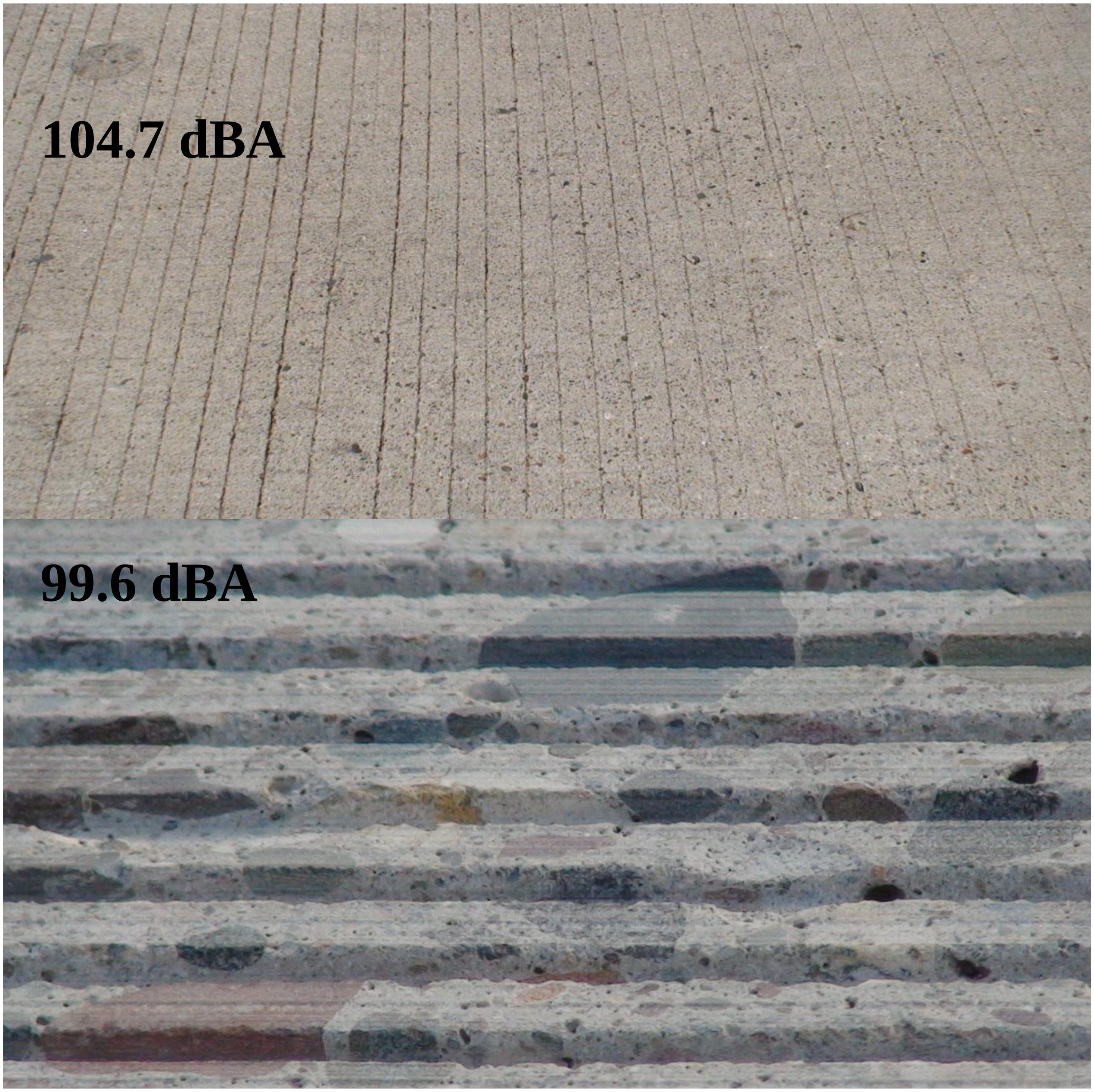
Field Evaluation of the Effect of Joint Sealant on Transverse Joint Slap Noise



Draft August 6, 2008

Count on Concrete
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Introduction

Transverse joints in concrete pavements have been a noise source since the very beginning. In the early days, wagon wheels would strike the joints making loud and damaging impacts. Today, even with modern tires, transverse joints can be a source of both interior and exterior noise if not properly constructed and managed. To better understand this phenomenon and to identify means by which to minimize or eliminate this effect, the ACPA contracted with Purdue University to study the joint slap event.

Purdue evaluated three joint related noise effects: faulting induced noise, the effect of joint opening width on noise, and the effect of sealant level recess or existence on noise.

Purdue University's Herrick Laboratory has a Tire Pavement Test Apparatus (e.g. TPTA). This device consists of a 38,000-pound, 12-foot-diameter drum that makes it possible to test numerous types of pavement textures and compositions in combination with various tire designs. Six, curved test-pavement sections fit together to form a circle. Two tires are then rolled over the test samples at varying speeds while microphones and other sensors record noise and data. Figure 1 indicates a view of the device and Figure 2 the OnBoard Sound Intensity (OBSI) equipment used to measure noise at the tire pavement interface. Testing can be conducted at speeds varying between 0-30 mph and at different environmental conditions.

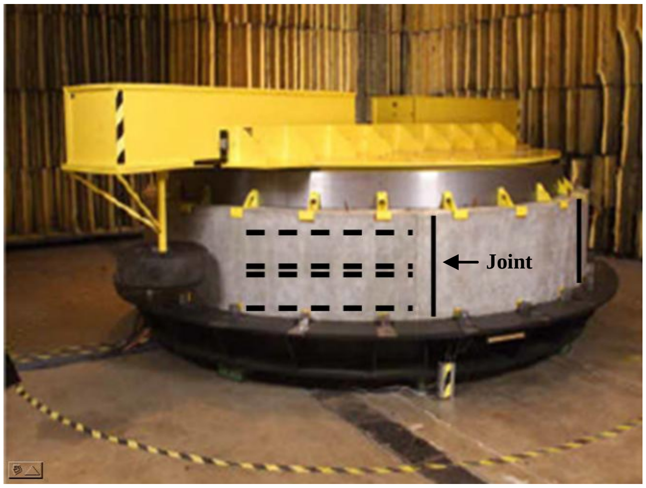


Figure 1 Photo of Purdue Tire Pavement Test Apparatus (TPTA)

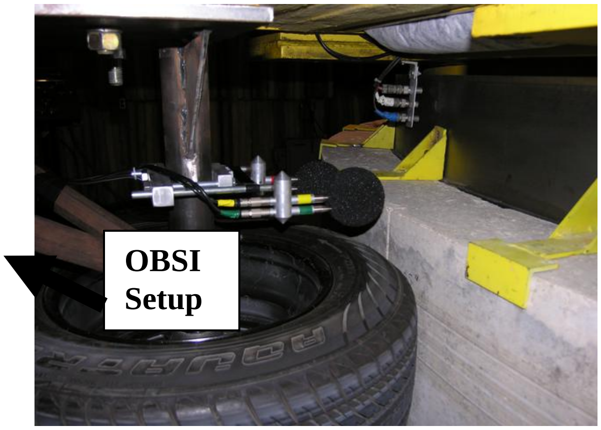


Figure 2 Photo of On Board Sound Intensity Equipment

Purdue TPTA Laboratory Results

Transverse Joint Slap Phenomenon

As a tire passes over a transverse joint in a pavement, a transient noise is generated as indicated in Figure 3. The noise generation is due to the vibration in the tire tread and carcass created by the impact with the joint. The first and largest response is the leading edge impact as indicated. The vibrations attain their maximum impulse shortly after leading edge contact and then begin “ringing out” until the trailing edge of the tire contact patch impacts the joint again, when a second impulse occurs with attendant “ringing out” as indicated. The total event happens over a period of approximately 0.02 seconds at 30 mph.

A joint slap condition creates a transient noise event which can be 4-6 dBA louder than noise produced by the pavement texture alone. However, when the joint event is included into the overall pavement noise level, its affect is often overshadowed by the time averaging process since the “slap” occurs over a very short time interval. The annoyance from this slap is detectable by humans, particularly within the vehicle itself.

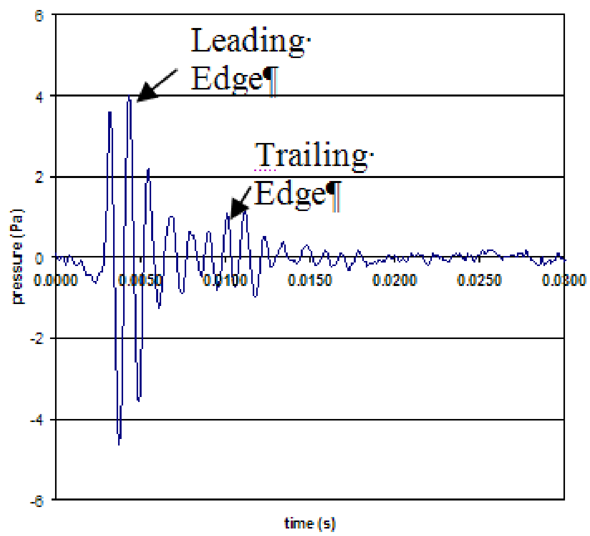


Figure 3 Sound Pressure (e.g. noise) Resulting from Contact of Tire with Transverse Joint @30 MPH

From the Purdue work, it is apparent that joint slap has three factors contributing to this effect; the amount of faulting, the width of the joint opening, and the amount the sealant is recessed below the surface in the joint. Since the overall effect of joint slap is also a function of the texture of the existing pavement surface, this makes it difficult to separate the joint slap from the overall noise level and adds complexity to determining its real world contribution.

Effect of Transverse Joint Opening Width

The Purdue research indicated that the resulting transient joint slap effect increased with increasing joint opening width. It is detectable at an opening width of approximately 1/8 inch and increases linearly until at one inch opening width it produces a 10 dBA transient noise increase. This indicates that the narrower the joint, the less joint slap noise produced. This same 10 dBA spread also exists at 60 mph. The 1/8 inch opening width proved to be the cellar for this effect in the Purdue testing. That is, joint opening widths narrower than this did not change the results.

However, this "cellar" value is also a function of the existing pavement texture. As indicated in Figure 4, the noisier the existing texture the wider the joint opening width before overall noise level is affected. Had the existing texture been noisier, the "cellar" value (e.g. the joint opening width at which joint slap contributes to overall level) would have been wider. Figure 4 indicates the joint opening effect in relationship to the existing texture noise level for three pavement conditions; quiet (100 dBA), noisy (105 dBA), and very noisy (110 dBA).

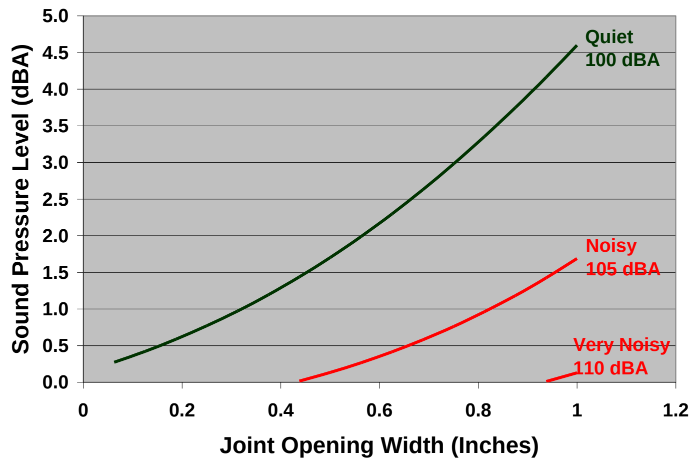


Figure 4 Transverse Joint Opening Width Effect in Relationship to Existing Pavement Texture Noise Levels @ 60 MPH

For a common joint opening width of 3/8 inch, the impact on overall noise level would be insignificant for both the noisy and very noisy textures. It would add approximately 1 dBA to the overall level for the quiet texture. As indicated, as the existing pavement texture noise level (e.g. background noise) increases, the contribution of the joint opening effect becomes less and less. For the quiet pavement surface shown in Figure 4, the joint opening effect begins around 1/8 inch opening size and adds about 4-5 dBA to the overall tire-pavement noise level at a one inch opening width. For the very noisy pavement, the joint opening size needs to be approximately one inch to contribute to the overall noise level at the tire-pavement interface, and even then it is negligible. This suggests that the joint opening width needs to be considered in the design process when quiet pavements are a concern.

Effect of Joint Faulting

The Purdue work indicated that step-off faulting (e.g. the departure slab is lower than the approach slab) condition creates more joint slap than the step-up fault condition. This is unfortunate since the typical fault condition is the step-off condition.

Figure 5 indicates the affect of different fault levels on joint slap (e.g. step-off case) for the three surface noise levels previously described. A joint opening width of 3/8 inch was used for all testing and a sealed condition with a 3/8" recess. As indicated in Figure 5, a ¼ inch fault level can add approximately nine dBA to a quiet pavement surface while only adding approximately two dBA to the very noisy surface.

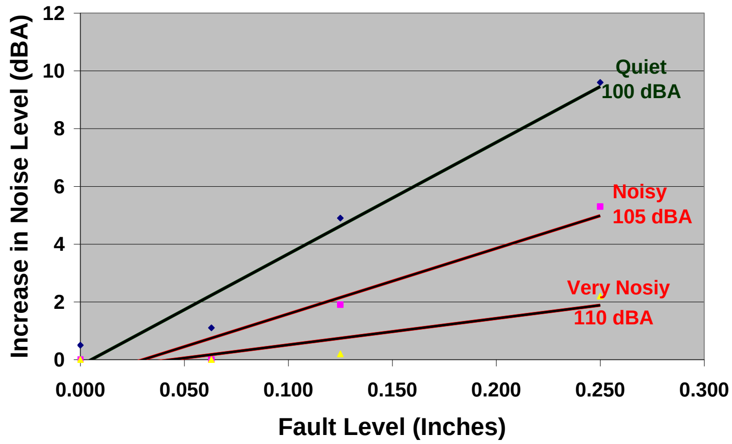


Figure 5 Effect of Fault Level on Overall Tire-Pavement Noise Level as a Function of Surface Noise Level @ 60 MPH

The Effect of Joint Sealing

One of the effects discovered by Purdue was the pronounced influence that sealant recess or existence has on overall tire-pavement noise level. This effect is indicated in Figure 6. For this example, the filled condition represents a 1/8 inch recess, the half filled condition, a ½ inch recess condition, and the unfilled a 1 inch recess condition (e.g. no sealant used). In Figure 6, both the sealant recess depth and the joint opening are varied so that the combined effect of these features can be observed. Due to sealant sag, the 1 inch joint filled condition has approximately a ¼ inch recess instead of the targeted 1/8 inch. Only silicone sealant, with a backer rod, was used in this comparison.

As indicated, the sealed condition provides a quieter pavement than the unsealed or the half sealed conditions. The filled condition (e.g. sealed) reduced the overall noise level approximately 2.5 dBA for the quiet pavement and 1.5 dBA for the noisy pavement for the one inch joint opening. For the very noisy pavement the effect was on the order of 0.1 dBA and should be considered negligible. For a typical transverse joint width of 3/8", the sealant effect results in slightly over ½ dBA difference. For a narrow joint of ¼ inch or less, this effect is negligible.

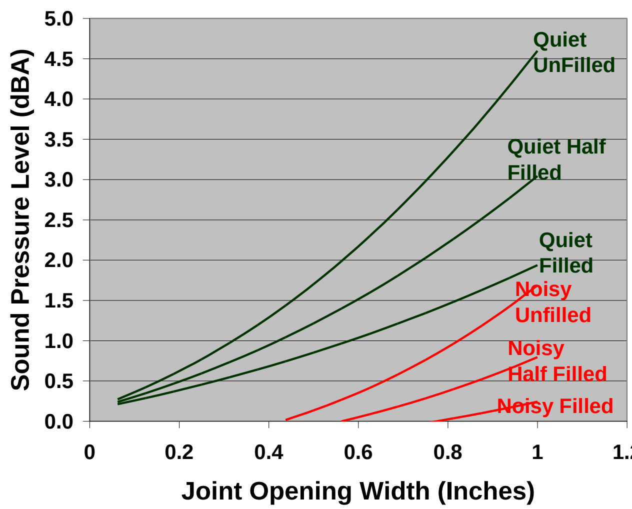


Figure 6 Effect of Joint Sealant Recess on Overall Tire-Pavement Noise @60 MPH

Method of Extrapolation

The Purdue TPTA testing was conducted at speeds ranging from 0 to 30 mph using both a Goodyear Aqua Tread and Michelin Tiger Paw tire. Linear regressions were developed from this data to extrapolate to the 60 mph condition. The results from the Aqua Tread and Tiger Paw tires were averaged. As an example, 142 data points were used to develop the regressions to extrapolate to 60 mph in Figure 6.

Once the results had been extrapolated to 60 mph, the joint effect was mathematically time averaged into a theoretical 15 ft long slab. Three theoretical slab conditions were evaluated, representing each of the pavement texture noise levels: quiet, noisy, and very noisy (e.g. 100, 105, 110 dBA).

Field Validation Testing

Three attempts have been conducted to field validate the Purdue TPTA Laboratory results at Cell 37 of the MnROADs Low Volume Roads facility. Cell 37 is located as indicated in Figure 7. Since there is no faulting at this site, and all the joints are approximately 0.41 inches in width, this validation can only be accomplished for a single joint opening width with no faulting.

On June 19, 2007 cell 37 had three, five hundred foot-long sections diamond ground into the WB (e.g. outside) lane by Diamond Surfaces, Inc.. These three sections were constructed to field validate the Purdue texture research conducted for the ACPA. These sections were also used for the joint effects validation study. The location of the diamond ground test sections (e.g. wheel tracks) within cell 37 is indicated in Figure 8.

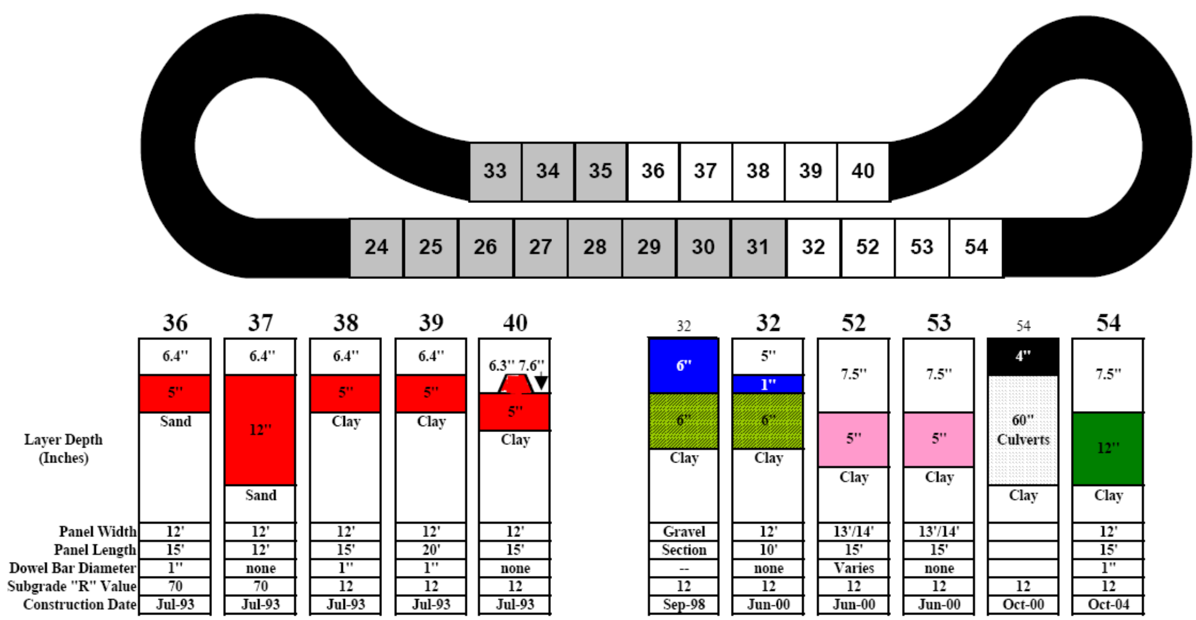


Figure 7 Layout of Mn ROAD Low Volume Road Sections

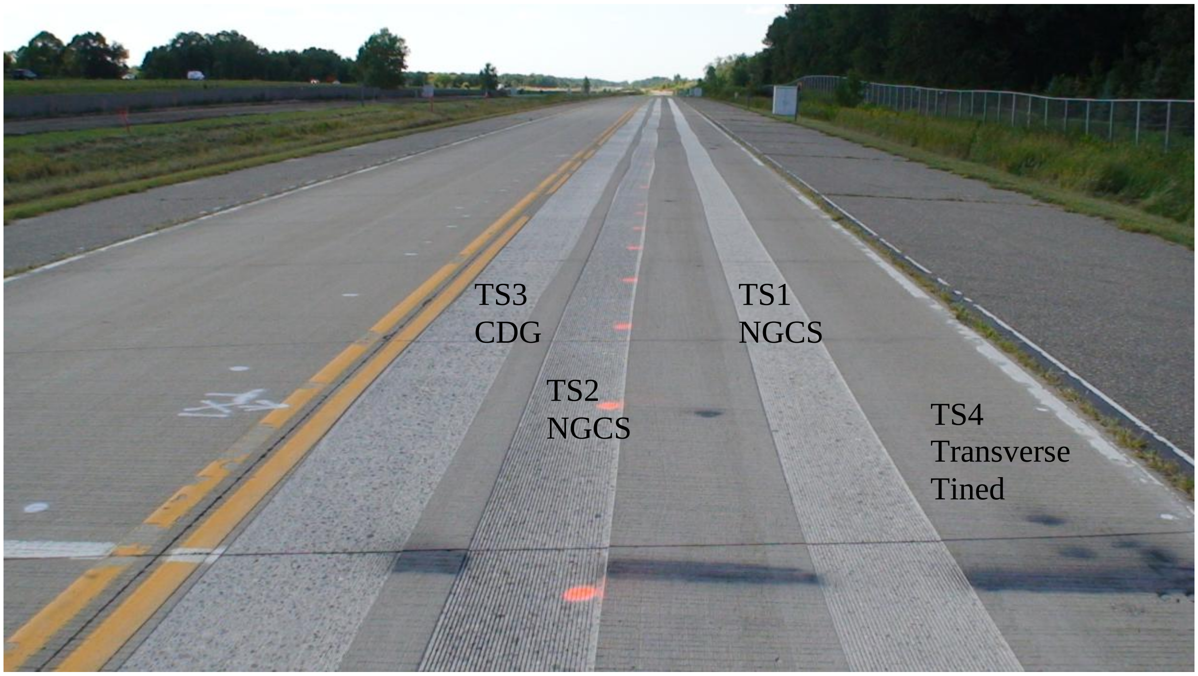


Figure 8 Layout of Wheel Track Test Surfaces in Cell 37

Prior to discussing each of the three validation attempts, it should be noted that the field conditions differ to a large extent from the TPTA conditions. For example, the TPTA testing was conducted upon a smooth cast texture in order to provide a low noise surface for the comparison. Figure 9 is a photo of that surface and one of the installed joints. As evident, the existing laboratory surface is very smooth. In contrast, the NGCS surface, indicated in Figure 10, is not a single edge but instead a serrated edge consisting of step ups and downs across the length of the joint. This provides additional/different escape passages for air trapped by the passing tire.


Figure 9 Photo of Purdue TPTA Surface and Joint Sealant

Figure 10 Photo of Existing (Left side) and NGCS (Right Side) Textures

Figure 11 indicates one additional difference that may have affected the field validation of the laboratory testing. As indicated in Figure 11, the Purdue TPTA joint was sawn one inch in depth with only a reservoir cut. There was no contraction joint sawn prior to the reservoir cut.

The Purdue testing used the Goodyear Aqua Tread 3 and Uniroyal Tiger Paw tires for TPTA testing. The field validation work used the ASTM SRTT Tire. The effect resulting from using different tires was not evaluated in this experiment.

Upon examination of Figure 10, it is also evident that the recess differs between the random transverse tined (e.g. RTT) surface (left side) and the NGCS (right side). This is the result of approximately two tenths of an inch of removal during the grinding process. Once the sealant is removed the RTT wheeltrack would have a larger unsealed depth by this same amount. In addition, the field unsealed joint could be affected by the initial contraction joint that extends beyond the bottom of the reservoir. The effect of these differences cannot be accounted for in the current evaluation.

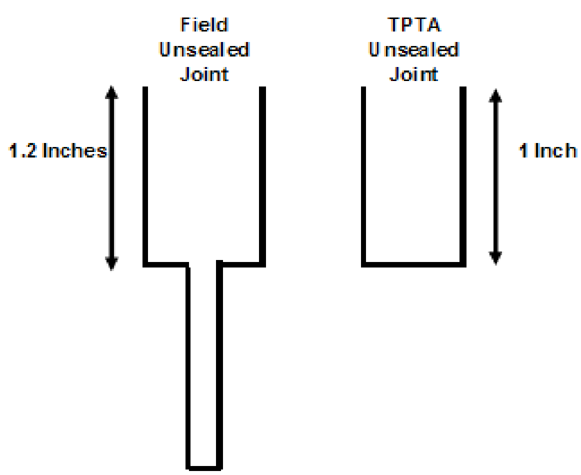


Figure 11 Drawing of Field and Laboratory Transverse Joints

Figure 12 indicates another difference between the field and laboratory sealed condition. For the NGCS texture, the removal of the concrete reduced the recess depth and, in some instances, exposed the sealant. Whether this had any influence is not known.

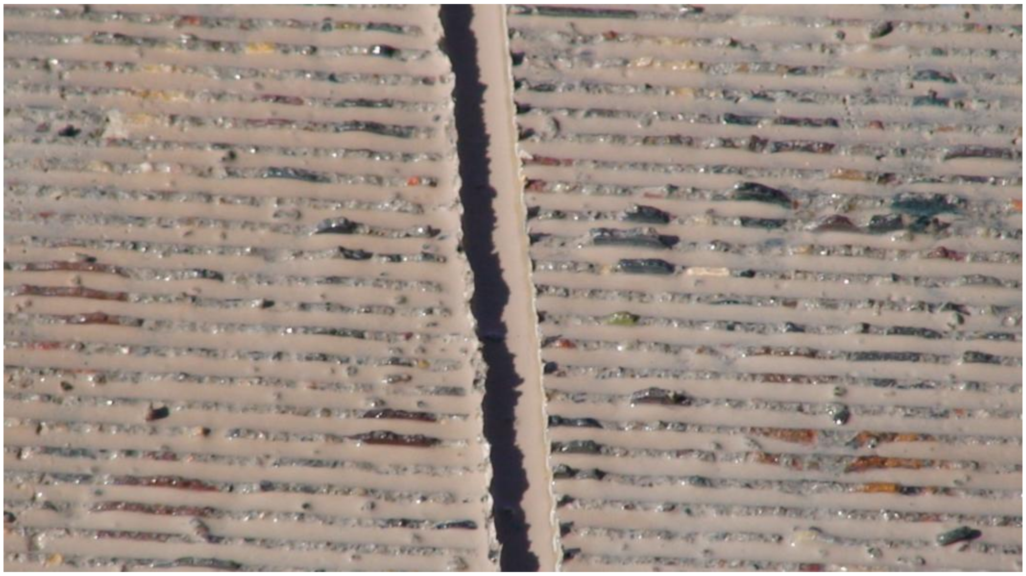


Figure 12 Silicone Sealant Extending Above Surface after Grinding

The final difference between the field and the TPTA conditions/predictions is that MnROADs used skewed joints at a 12 ft spacing, where as the Purdue work used non-skewed joints and the predictions were based upon a 15 ft spacing.

First Attempt at Field Validation (6/20-21/07)

Upon completion of the diamond grinding and subsequent cleaning of the three test tracks, shown in Figure 8, OBSI testing was conducted. Five repeat runs were conducted for the sealed condition and four repeat runs were conducted for the "unsealed condition". A "spotter" was used to verify the proper alignment within each wheel track during testing.

Wheel tracks T1, T2 and T4 were used for the comparison. Wheel tracks T1 and T2 (see Figure 8) represented quiet pavement textures (e.g. 99.4 dBA NGCS) and wheel track T4 represented a noisy texture (e.g. 104.5 dBA random transverse tining). The sealed condition for this experiment was based upon the condition of the original 14 year old silicone sealant that was recessed approximately 5/16 inch before grinding. The sealant was generally in good condition for its age.

The MnROAD validation results indicated that there was a 0.3 - 0.4 dBA and 0.9 dBA difference in overall noise level between the sealed and unsealed conditions for the quiet and noisy textures, respectively. Although the validation work did confirm the beneficial effect of sealing the joints on overall noise level, the results regarding the effect of existing texture were opposite those of the Purdue model. That is, there should have been a greater effect on the quieter pavement.

Using the Purdue prediction curves, there should have been approximately an undetectable joint slap effect for the noisy condition (e.g. random transverse tined) and approximately a 1.5 dBA difference for the quiet texture (e.g. Purdue Grind/Groove) between the sealed and unsealed conditions for a 7/16 inch joint opening size. This was not the case for the field validation.

Second Attempt at Field Validation (8/15/07)

A second attempt at field validation was attempted on 8/15/07 by a collaborative effort between ACPA and Purdue. For this attempt it was decided to use a laser to trigger the exact location of each joint in relationship to the OBSI recording. This would then be similar to what was done at Purdue on the TPTA. The plan was to measure 10 joints, ten times each providing one hundred measurements to evaluate the joint effect. A laser was mounted to the OBSI test vehicle and linked to the audio recordings through the use of the fifth channel in the B&K frame as indicated in Figure 13. (Appendix 2 has a photo of the laser dot on the roadway).

Reflective tape was placed in advance of each of the ten joints so that it would trigger the laser at an offset to the exact instant the tire was passing over the joint as indicated in Figures 13 & 14. In this manner, the joint location could be included in the audio recording as indicated in Figure 15. The blue lines represent the audio recording and the red line the joint location indicated by the laser trigger. The black lines indicate the window of the joint noise impulse.

Testing was conducted on the TS1 and TS4 wheel tracks indicated in Figure 8. TS1, as before, represents the quiet pavement, and TS4 represents the noisy pavement. The laser encountered considerable difficulties during initial testing until it was determined that sunlight affected laser performance. Testing was then conducted during nighttime to provide better triggering events. This created an issue in knowing whether the test vehicle was tracking properly so a second vehicle traveled behind the test vehicle to validate the correct alignment within the wheeltrack.

Figure 13 Side View of OBSI Equipment and Laser Trigger Suspended from Vehicle

Figure 14 View of Tape and Laser Trigger on OBSI Vehicle

Since the sealant was removed during the first validation attempt, the unsealed condition was tested first. Upon completion of that testing the ten joints had new backer rod installed and silicone sealant hand placed into the joint. The sealant and backer rod were only installed for the width of the wheel tracks (See Appendix 3). No cleaning of the joints took place so any debris that entered the unsealed joints after the sealant removal on 6-21-08, almost two months earlier, could have affected results. Since the work was conducted at night, under headlights, the cleanliness of the joints is unknown.

<u>As before, the results indicated the benefit of using sealant to reduce the noise level</u>**.** However, the results again were not consistent with the original predictions. For TSI (e.g. NGCS quiet pavement) the overall noise was reduced approximately 0.2 dBA by sealing, whereas TS4 (e.g. RTT Noisy pavement) was reduced approximately 0.7 dBA. The reason for the larger reduction was attributed to inaccurate joint opening width measurements which was not the case (see Appendix 1). The Purdue report is provided in Appendix 3.

For the TS1 wheel track (e.g. NGCS quiet) Purdue developed a modified prediction curve based on a 12 ft joint spacing. The results are shown in Figure 16. It should be noted that the actual joint opening widths are approximately 0.41 inches. With this adjustment, the sealed condition is very close to the predicted value. For the unsealed condition it moves it further away from the predicted values. No plot was attempted for the TS4 surface as the results were very inconsistent with the predictions.

Third and Final Attempt at Field Validation (7/30/08)

The final attempt to field validate the Purdue joint effects testing was conducted on 7/30/08 on MnROADs cell 37. This attempt used the entire length of wheel tracks for TS1 and TS4 as was done for the first validation attempt. Four repeat runs in the unsealed and sealed condition were conducted and the results averaged. No "spotter" was used for this testing as was done in validation attempts one and two.

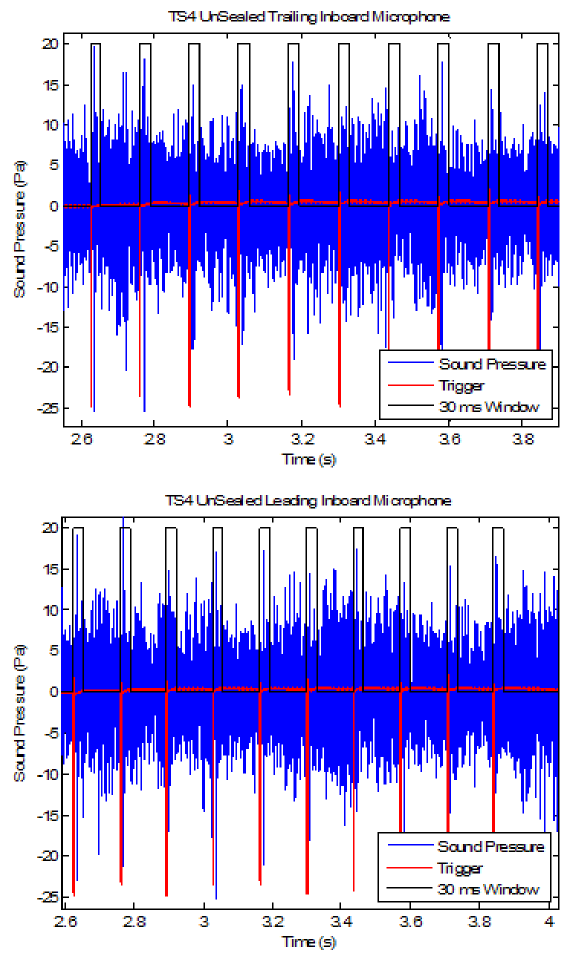


Figure 15 Joint Location Event Superimposed onto the Audio Recordings

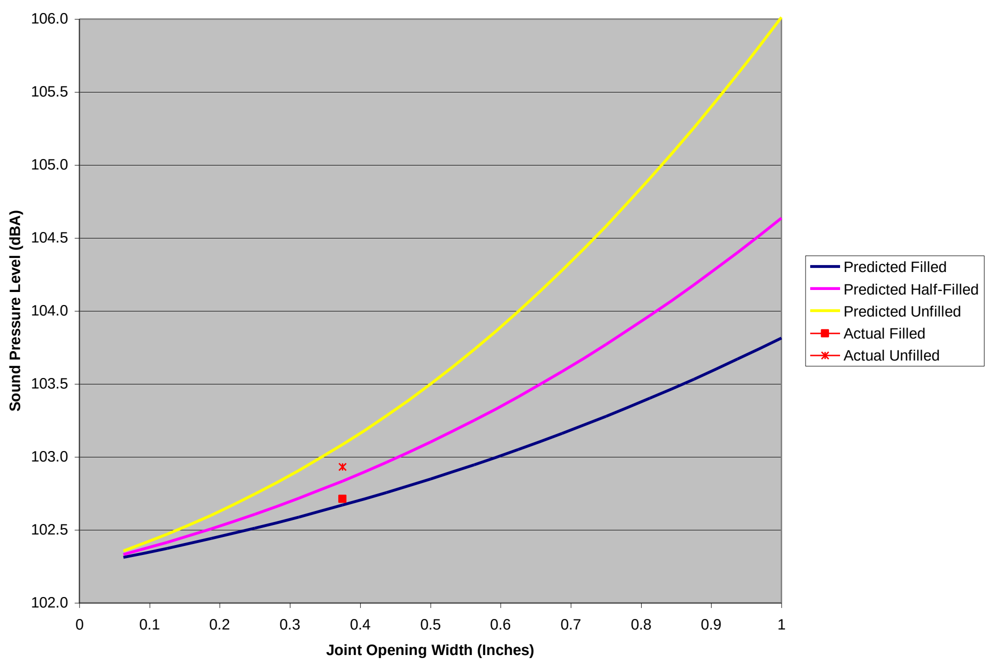


Figure 16 Comparison of Actual Versus Predicted Noise Levels for TS1

Since all but the ten joints resealed during attempt number two were still unsealed, the testing began with the unsealed condition. It was observed upon inspection of the joints that considerable debris had entered the joints. Therefore, it was decided to use a wire wheel attached to an up-cut saw to remove all the debris from the joints within the wheel track area. This was the first time that the joints had been cleaned to the bottom of the reservoir cut. In the two previous attempts it had been assumed that this was not necessary.

Experience in testing in Chicago on I-355 indicated that joints filled with debris prior to placing the reservoir cut tested quieter than the sealed sections. This suggested that perhaps the debris was affecting the joint slap measurements. To eliminate this variable it was decided to clean the joint to the bottom of the reservoir cut. However, the initial saw cut still remained a variable as some areas included debris and others did not.

The results of that testing are indicated in Figure 17. For TS1 (NGCS-Quiet pavement) a 1 dBA decrease resulted from the sealant installation. For TS4 (TT-Noisy pavement) there was a 0.7 dBA reduction. <u>As in both of the first two attempts at validation, the sealant reduced the noise level</u>. However, as before, there was a significant improvement for the noisy pavement which was not predicted by the Purdue work. In this third validation attempt the quieter surface achieved a slightly higher reduction than predicted while the noisy pavement achieved a significantly higher reduction. In all three validation attempts the TS4 section has attained a 0.7 dBA to 0.9 dBA reduction due to sealing. The prediction for this section is that almost no improvement should be possible.

Figure 18 indicates the frequency spectrums for the two tracks and two conditions tested. As indicated in Figure 18, there is no distinct shift in the unsealed spectrum that occurs in relationship to the speed-spacing relationship of the joint slap event. Instead an overall level is noted for the unsealed condition for most all frequencies.

Discussion

<u>Although the three attempts at field validation could not successfully validate the Purdue sealant effects, they confirmed that sealing of the joints reduced overall noise levels.</u> It is further believed that the Purdue predictions can be used as guidance but not as absolute values. The joint slap event appears more complex than can be analyzed by a single surface type. Additionally, the field variables existing at this site make direct validation an unlikely possibility. As discussed previously, a number of the differences between the TPTA testing and the actual field conditions are indicated in the bullets below.

- Smooth texture versus coarse texture
- Irregular edge versus a sharp edge
- Skewed versus right angel joints
- Reservoir cut versus Reservoir plus a contraction cut

In addition to the previously described differences, some additional factors probably come into play on attempting this validation. First, since there is an approximate 3 dBA increase in noise level for each additional ten miles per hour in speed, a one mile per hour speed difference could affect the results by approximately 0.3 dBA. Since no independent speed measurement system was used during this evaluation, it is easy to see how the effects that were to be measured could be influenced dramatically by the ability to attain the desired speed. It was assumed for this experiment that by using four repeat runs, with vehicle speed established by cruise control, adequate results could be obtained.

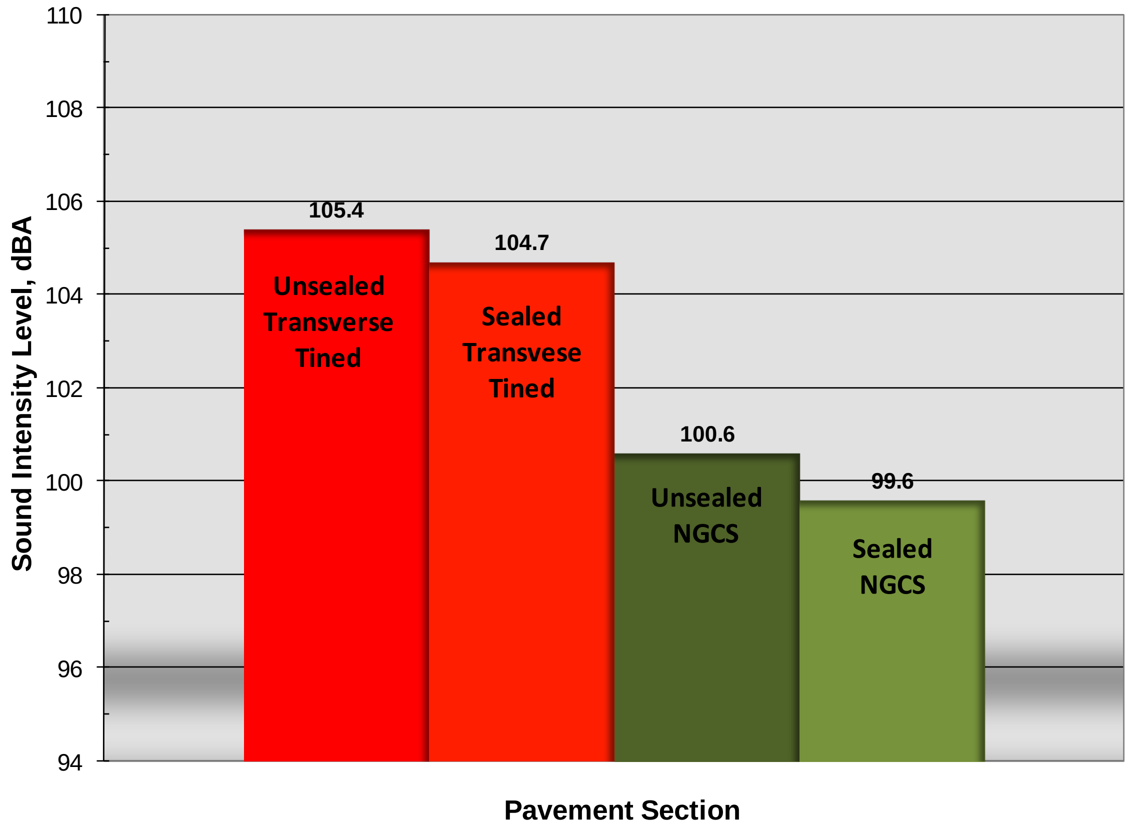


Figure 17 MnROADs Low Volume Road Seal – No Seal OBSI Results

Another factor that could be very significant in regards to the validation is the actual geometric pattern of the joint face. The Purdue work used a very rectangular joint configuration with no rounding of the edges from traffic wear. The NGCS is a serrated edge which provides considerable opportunity for the air to escape from beneath the tire footprint and could alter the manner in which the contact patch envelopes the surface. That is, it may alter the actual tire impact. Figure 19 indicates this problem. It should also be noted in Figure 19 that the concrete itself, as a result of the grinding operation, is more subtle than a sharp rectangular edge in new concrete.

The use of the existing roadways involved cutting out the silicone sealant with a knife and simply pulling out the major portion of the sealant. It did not include sawing the joint faces to remove the silicone bonded to the concrete. It is possible that the silicone on the face of the NGCS surface provided some cushioning to the tire impact reducing the effect of the unsealed condition. This cushioning would not be possible with the transverse tined section since the sealant was recessed too far below the surface.

In this section it has been noted why differences may exist between the Purdue predications and the field validation attempts. Although these factors may explain the differences for the NGCS results, it is difficult to explain how the measured improvement on the noisy surface (e.g. transverse tined) can be explained by these factors. At this time it is not well understood why the noisy texture improved as much or more than the quiet texture in these field tests. Even if a slight faulting existed, and was not observed, it would seem that this still would not be an explanation unless there is a secondary interaction between the faulting and the sealant recess. <u>If so, this would further suggest the benefits of sealing, particularly on faulted pavements.</u>

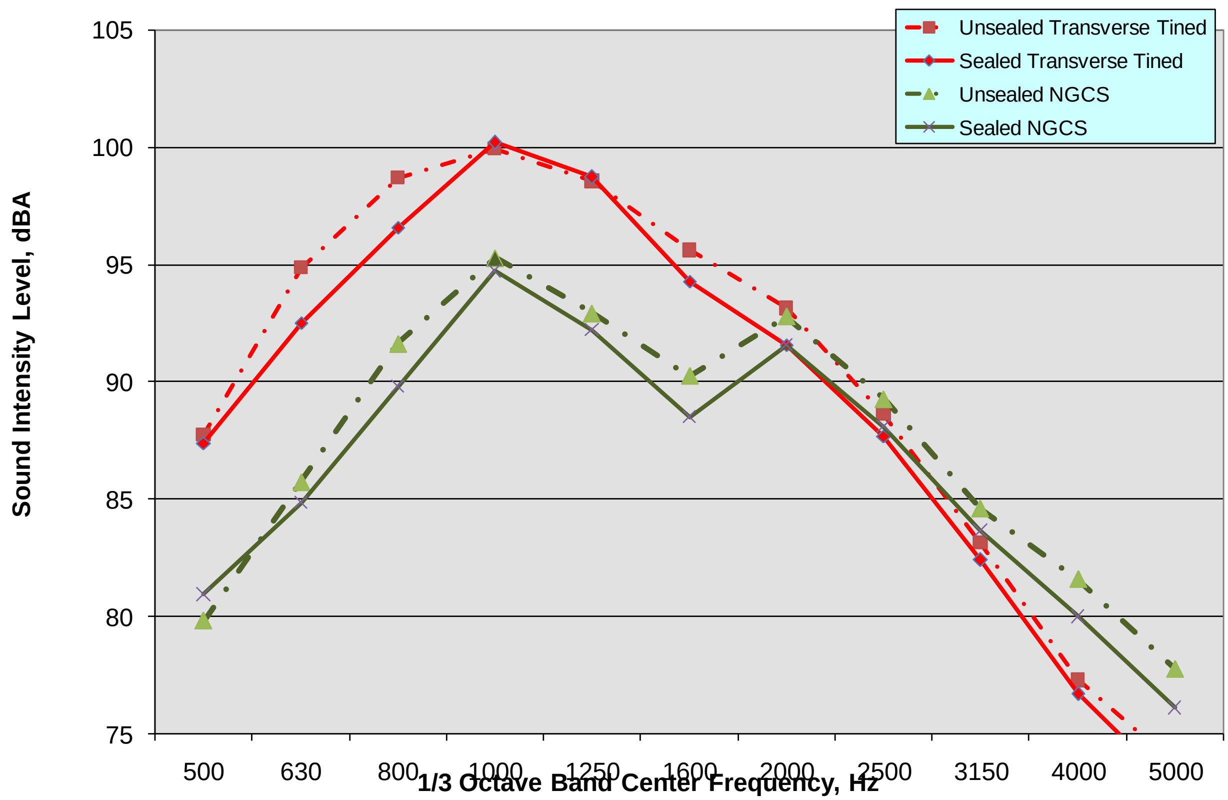


Figure 18 Third-Octave Spectral Plot For the Sealed and Unsealed Conditions for the NGCS and the Transverse Tined Wheel Tracks

Conclusions

The MnROADs testing verified the Purdue finding that sealing joints reduces tire-pavement noise. The effect appears to be similar to that predicted for the quieter pavement but is more significant than expected for the noisier surface, primarily because the joints appear to make more noise for the noisier surface than expected. Although only a single width of joint opening was evaluated, it is believed that the trend predicted by Purdue in regards to joint opening width is real. That is, as joint opening widths become larger they will generate greater and greater impacts on the overall noise level.

The field testing at the MnROAD facility indicated that sealing of the transverse joints resulted in approximately a ½ to one dBA reduction in noise level for the approximately 0.4 inch wide joint. This improvement was seemingly independent of the surface texture noise.

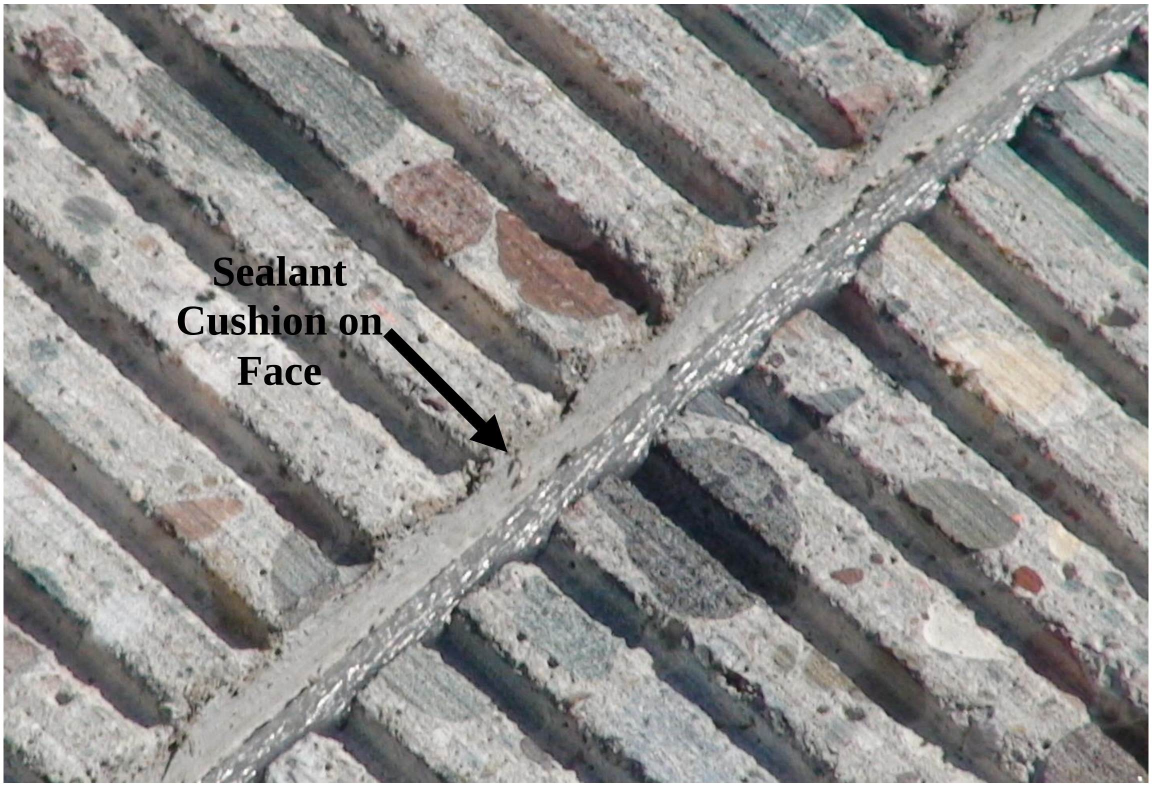


Figure 19 Photo of Sealant Reservoir in NGCS Section with Silicone still on Sidewalls

The results reported herein pertain to noise levels at the tire-pavement interface. As this noise propagates to the wayside these effects may be less discernible and measurable. The joint slap effect presumably is most important to interior noise conditions which relate more to consumer satisfaction than noise mitigation measures. The OBSI measurements may under estimate the interior noise annoyance of the joint slap event.

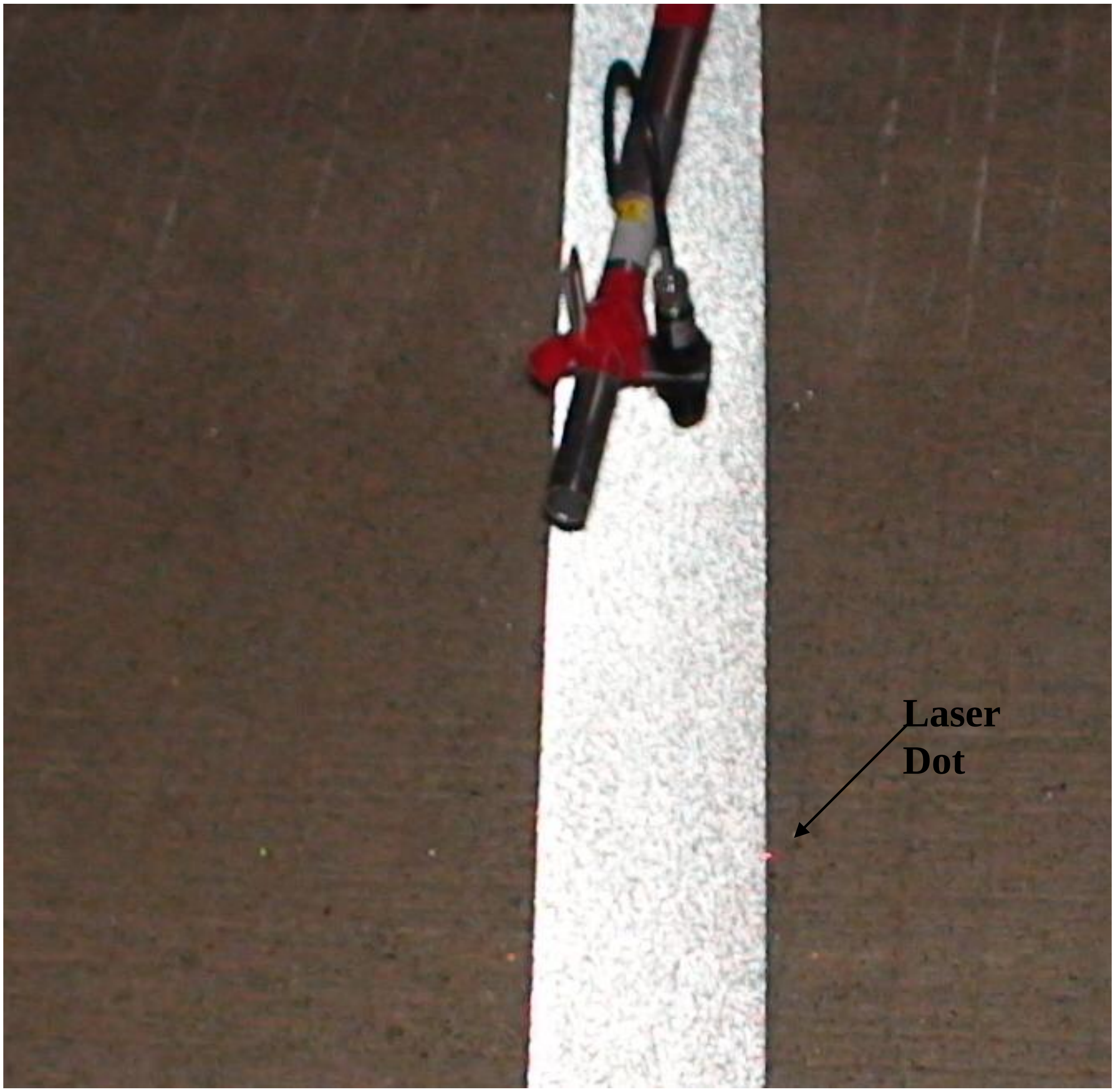
Appendix 1
MnROAD Cell 37 Joint Dimensions

Joint		Transverse Tined					NGCS		
Number	Width	Depth			Ave	Width	Depth		Ave
1	0.39	1.23	1.09	1.18	1.17	0.4	1.25		1.25
2	0.4	1.26	1.28		1.27	0.4	1.2		1.20
3	0.41	1.2			1.20	0.41	1.3		1.30
4	0.41	1.18	1.2		1.19	0.4	1.24	1.35	1.30
5	0.38	1.19	1.25		1.22	0.38	1.28	1.4	1.34
6	0.42	1.35	1.45		1.40	0.42	1.2	1.05	1.13
7	0.41	1.4			1.40	0.42	1.25	1.31	1.28
8	0.41	1.44			1.44	0.42	1.25		1.25
9	0.41	1.52	1.54		1.53	0.41	1.32	1.25	1.29
10	0.4	1.43			1.43	0.41	1.29		1.29
11	0.42	1.48			1.48	0.42	1.25		1.25
12	0.42	1.49	1.43		1.46	0.42	1.26	1.31	1.29
13	0.42	1.4			1.40	0.42	1.31	1.35	1.33
14	0.42	1.44			1.44	0.42	1.34	1.36	1.35
15	0.42	1.44	1.48		1.46	0.42		1.29	1.29
16	0.38	1.48			1.48	0.4	1.34	1.37	1.36
17	0.42	1.45	1.38		1.42	0.43		1.22	1.22
18	0.42	1.46	1.54		1.50	0.42		1.29	1.29
22	0.38	1.55			1.55	0.41	1.38	1.35	1.37
23	0.42	1.54			1.54	0.42		1.42	1.42
24	0.42	1.54			1.54	0.44	1.35	1.43	1.39
25	0.42	1.55	1.58		1.57	0.42	1.4	1.35	1.38
26	0.42	1.55			1.55	0.42	1.4	1.33	1.37
27	0.4	1.65	1.55		1.60	0.4		1.45	1.45
28	0.4	1.61	1.55		1.58	0.43		1.39	1.39
29	0.42	1.66	1.64		1.65	0.42	1.4	1.32	1.36
30	0.41	1.59			1.59	0.4	1.44	1.48	1.46
31	0.42	1.58			1.58	0.43	1.35	1.38	1.37
32	0.44	1.57	1.62		1.60	0.43		1.37	1.37
33	0.4	1.54			1.54	0.43		1.39	1.39
34	0.41	1.64			1.64	0.43		1.39	1.39
35	0.42	1.62			1.62	0.42		1.49	1.49
36	0.41	1.54			1.54	0.42		1.43	1.43
37	0.41	1.55			1.55	0.41		1.38	1.38
38	**0.41**				**1.47**	**0.42**			**1.33**
39									
40									
41									
42									
43									
44									

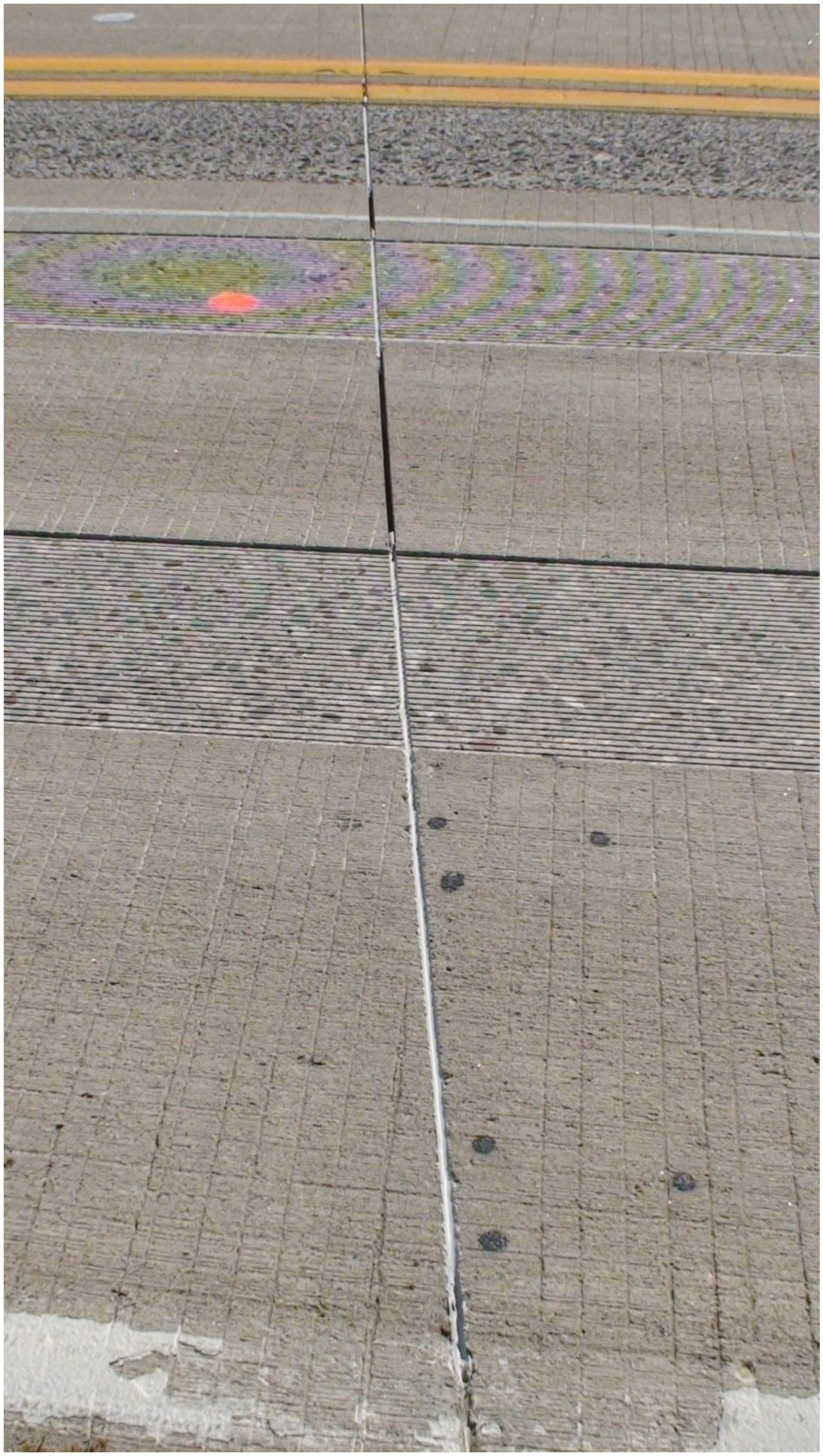
Difference in Joint Depth is 0.14 inches

Note that Joint Numbering began on the east end of the cell 37.

Appendix 2
Photo of Laser Dot



Appendix 3
Sealant in Wheeltracks of Validation Attempt 2



Appendix 4
Purdue Memo on Field Validation Attempt 2

Data Collection

Data collected from MnRoads were processed to obtain the effects of joints and joint sealer on noise levels. Both loud (TS4) and quiet (TS1) pavements were analyzed. Joints were nominally 3/8” wide and spaced at 12’ intervals. For each pavement, ten passes were done over ten joints. For each pass, pressure measurements were taken using the inside microphones from both the leading and trailing probes of an OBSI testing rig. Reflective tape placed before each joint triggered a LaserTach. The output of the LaserTach was recorded with the pressure measurements to identify the locations of the joints in the raw data.

The data were processed by first isolating each of the ten joints in each pass. For each pass, the data were separated into three parts:

1. Joints
2. Panels
3. Data to disregard

The joint portion of the data was taken to start at the time of the LaserTach trigger and last for 30 ms. The panel portion was taken to start after the previous joint portion (i.e., 30 ms after a trigger) and last until the next trigger. Data before the first joint and data after the last joint were disregarded, as the data acquisition system was not started at a specified point before the first trigger, so different amounts of the road surface were measured. The LaserTach system failed to trigger on a few of the joints in several of the passes. These joints, as well as the panels before and after, were also disregarded because there was no way to determine where the joints were in the time history. After each joint and panel was isolated, an overall rms sound pressure level was obtained for each joint and panel. For example, tables 1 and 2 show the rms sound pressure levels for each joint and each panel on TS1 without joint sealant. The missing data from failed triggers are shown as blanks. The panels before and after each missing joint are also considered missing data, because it is not clear where the panels begin and end.

Table 1: rms sound pressure levels for each joint for unsealed TS1

		Joint Number									
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
	1	103.8	103.4		103.7	103.6	104.5	102.8	104.0	103.3	103.8
	2	101.7	103.9	103.9	103.4	102.8	103.9	102.8	103.2	104.5	105.4
	3	104.1	104.5	104.8	103.2	103.0	103.7	104.9	102.8	104.5	103.4
	4	103.7	103.6	104.4	103.5		103.8	102.8	103.6	103.6	103.5
Run Number	**5**	104.2	103.8	103.0	103.4	104.7	103.9	104.1	105.5		104.2
	6	103.3	103.5	104.6	103.7	103.0	103.5	104.5	103.2	104.3	103.0
	7	103.7	103.6	103.3	103.5	103.2	103.5		102.8		103.4
	8	103.8	104.2	104.2	104.0	103.7			103.2	103.6	
	9	104.3	104.6	103.9	103.1	103.3	104.0	104.2	102.6	103.8	104.0
	10	104.3	103.7	103.6	104.0	103.1	104.3	104.0	104.6	102.9	103.8
	11	104.0	103.9	104.0	104.0	102.7	103.2	103.7	104.0	104.2	103.2

Table 2: rms sound pressure levels for each panel for unsealed TS1

		Panel Number (before joint number)								
		2	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
	1	102.6			103.0	102.7	103.0	102.6	103.1	102.5
	2	101.1	102.4	103.0	103.0	102.2	102.8	103.0	102.4	103.1
	3	103.2	102.7	102.1	102.3	102.3	102.7	102.5	102.9	102.5
	4	102.9	102.6	102.7			102.4	102.3	102.1	102.7
Run Number	**5**	102.9	103.0	102.8	102.8	103.2	102.6	102.3		
	6	102.8	103.0	102.5	102.9	102.8	102.8	102.5	102.6	102.7
	7	102.8	102.6	102.3	102.4	102.8				
	8	102.8	102.7	102.8	102.6				101.9	
	9	103.3	102.5	102.5	102.9	102.1	102.8	102.3	102.2	102.2
	10	103.2	103.2	102.7	103.0	102.9	102.6	102.5	103.2	102.7
	11	102.8	102.5	102.9	102.4	102.3	102.6	102.5	102.8	102.6

An rms sound pressure level was calculated for each “joint-panel pair”, defined as a valid panel and the joint after it. These data represent how loud a road would be with the same construction. If there were no joints missed due to triggering, the overall level of the road would simply be the average of these joint-panel pairs.

Speed Normalization

The large effect of vehicle speed on tire-pavement noise was established in previous research using the TPTA. Therefore, an effort was made to correct the MnRoads data for variations in vehicle speed. It was determined that in order to normalize the data so that each joint was contacted at the same speed, a correction factor would need to be added to each rms SPL. Through research on the TPTA, this correction factor was determined to be

$$\Delta L_{rms} = 38.65*\log_{10}(60/S)$$

where S is vehicle speed in miles per hour. The correction ranged from -0.5 to +0.1 dB. The speed was calculated by counting the number of sample points and using the sample rate and nominal joint spacing. Unfortunately, the exact joint spacing was not measured at the test site. Assuming a 12’ joint spacing, however, the vehicle speed was between 61 and 62 mph. It was assumed that this large of a difference in speed would have been noticed by those conducting the experiment, so likely the joint spacing was not reliable. Because of the inaccuracy in the joint spacing measurements, the normalized values of the sound pressure levels were not used in any of the following conclusions.

Variation in Joint Noise

The noise for a given joint in each pass on varied by 2 to 3 dB on TS1 and 3 to 5 dB on TS4. For a given pass, the noise for each joint varied by similar amounts. The average noise for each joint was calculated. On TS1, the average SPL for each joint varies by about 0.7 dB and there are no joints that are consistently louder. On TS4, the average SPL varies by up to 2.5 dB and there are obvious louder and quieter joints.

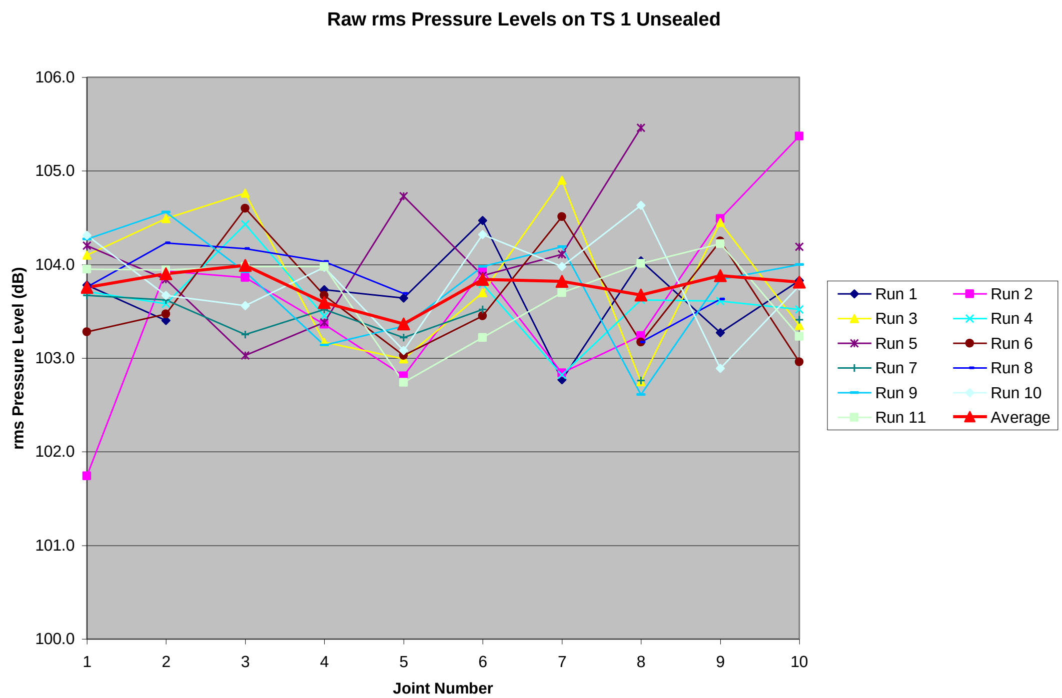


Figure 1: Joint noise levels on unsealed TS1. The average SPL varies by a small amount and no joints are consistently louder or quieter.

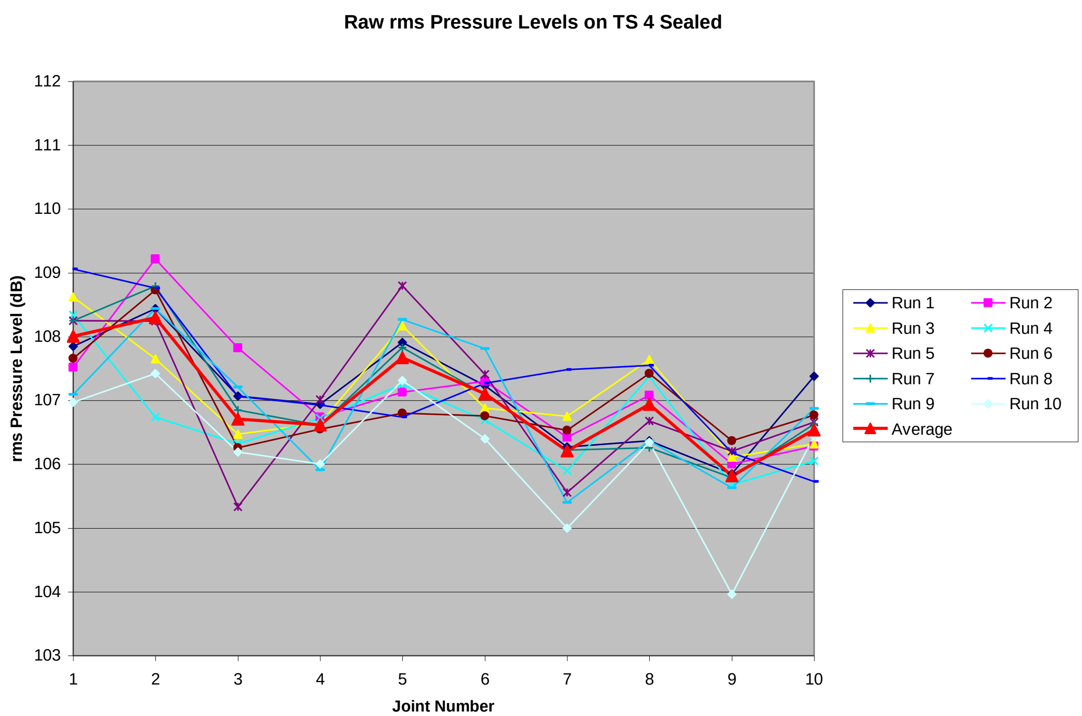


Figure 2: Joint noise levels on sealed TS4. The average SPL varies by a larger amount and some joints are consistently louder than others.

Since the average joint noise levels on TS1 were similar, it was concluded that the joints were close to the intended 3/8” width and had not been altered significantly from the grinding process. On TS4, however, there are louder and quieter joints, indicating that some of the joints were altered due to the grinding process. It was concluded that the nominal 3/8” joint width was not reliable for TS4.

Sealer Effect

The effect of the sealer was measured by its reduction of noise levels on the joints and the total road, as represented by the joint-panel pairs.

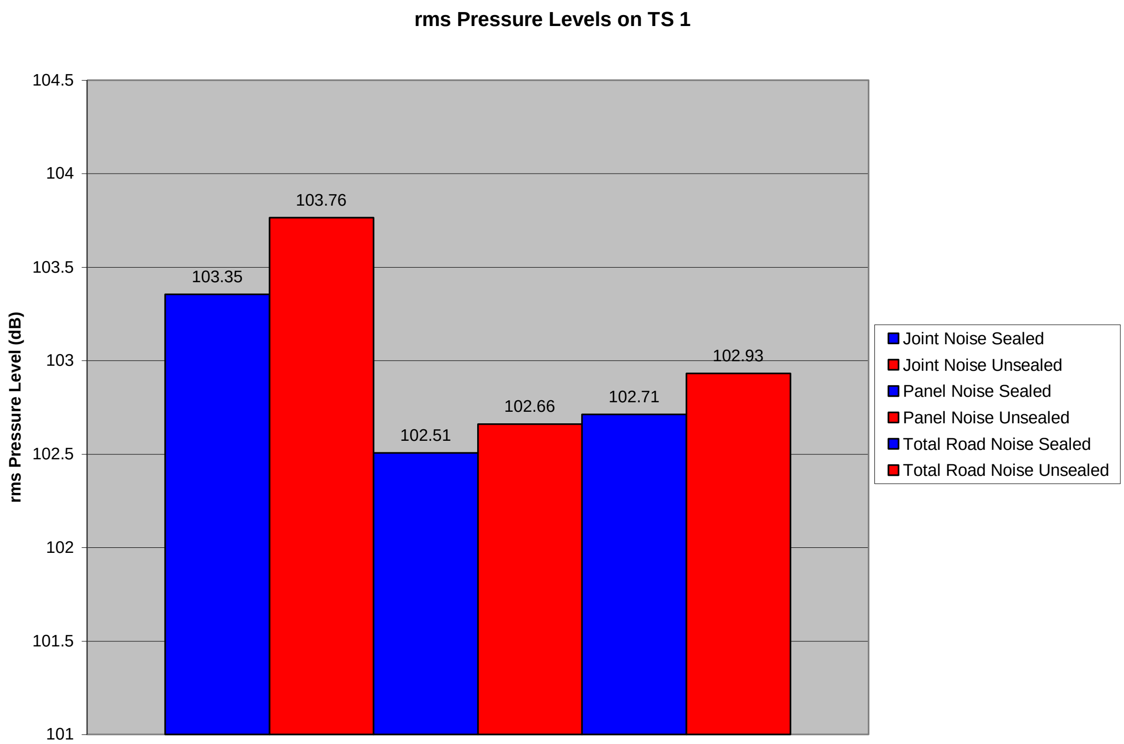


Figure 3: rms Pressure Levels on sealed and unsealed TS1.

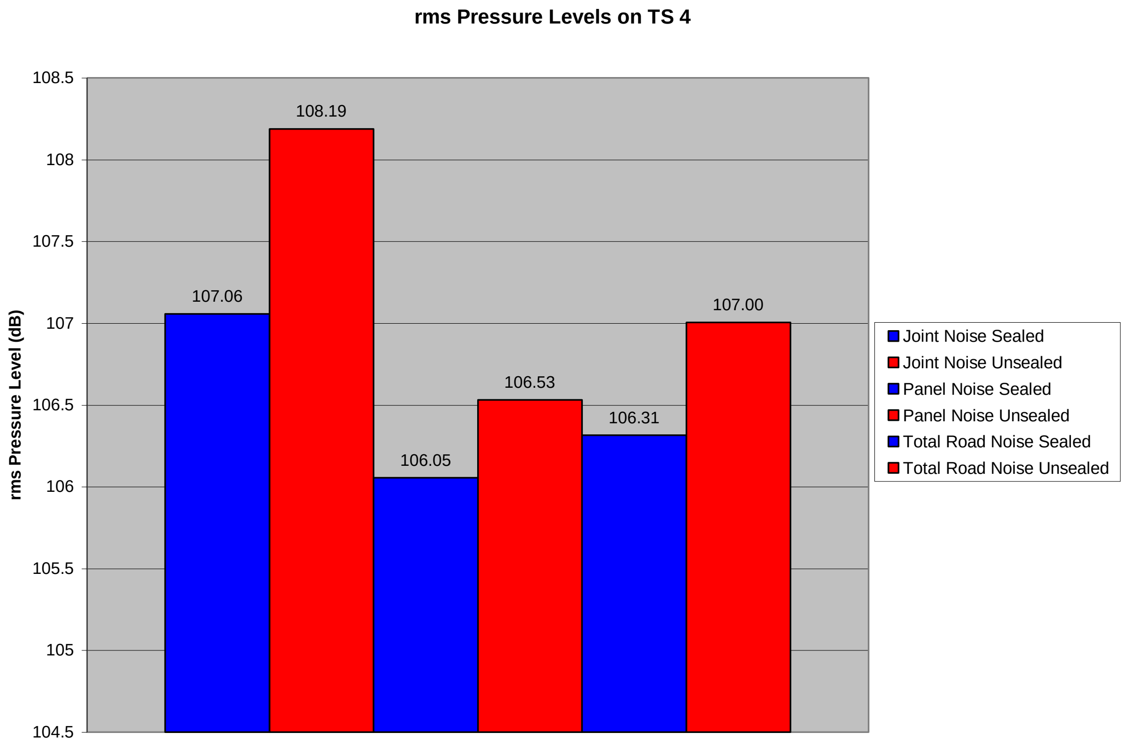


Figure 4: rms pressure levels on sealed and unsealed TS4.

On both surfaces, the addition of sealer reduced the both the joint noise and overall road noise. On TS1, the joint noise was reduced by 0.4 dB, and the overall road noise was reduced by 0.2 dB. On TS4, the joint noise was reduced by 1.1 dB, and the overall road noise was reduced by 0.7 dB. It was predicted that the panel noise would be the same for the sealed and unsealed cases on both roads. In reality, the panels after the unsealed joints were 0.2 dB louder on TS1 and 0.5 dB louder on TS4. No explanation is readily available for this discrepancy, but one explanation could be that the joint noise lasts longer than 30 ms, which would mean that some joint noise included in the panel measurements.

Comparison to TPTA Predictions

Since it was determined that the nominal joint widths on TS4 were likely incorrect, comparison to TPTA predictions was only possible on TS1. Predictions of the joint noise level were made using the nominal joint dimensions on TS1: 3/8" width with 1" filler recess on the unsealed joints and 1/8" filler recess on the sealed joints. The predictions were made assuming a vehicle speed of 60 mph. Predictions of the overall road noise were also made, assuming a joint spacing of 12'. The average panel noise of 102.6 dB was used to predict the average total road noise. The predictions closely match the results obtained.

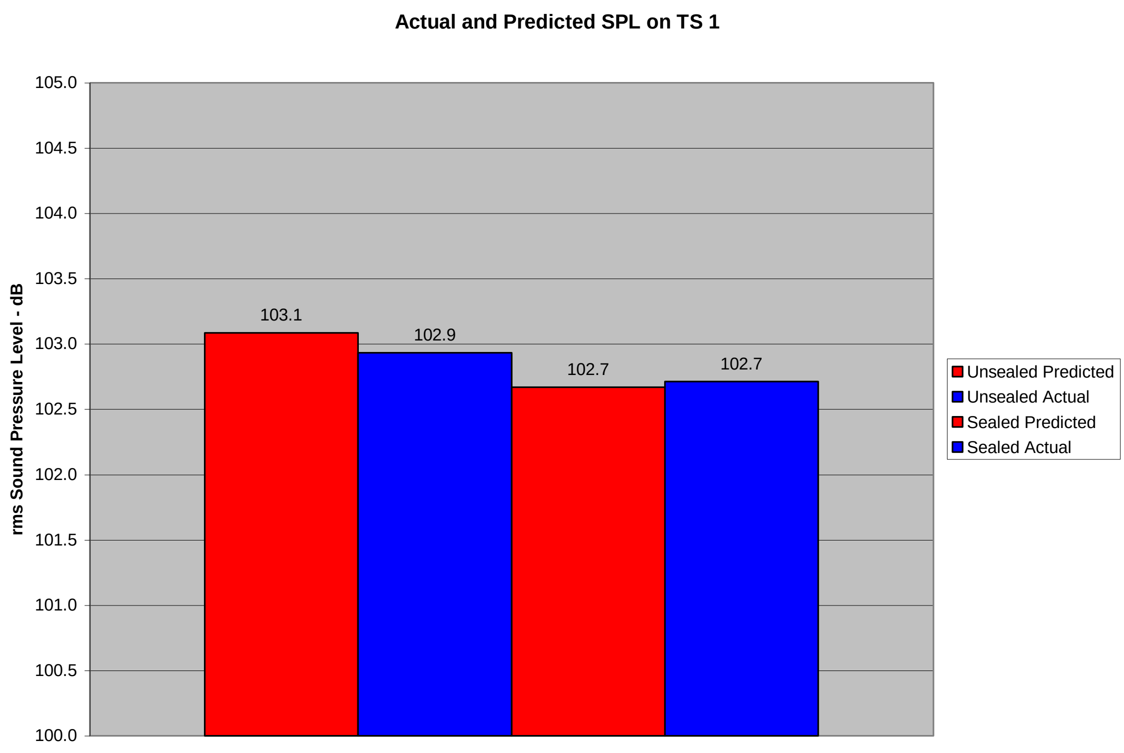


Figure 5: Actual and predicted rms SPL for sealed and unsealed TS1

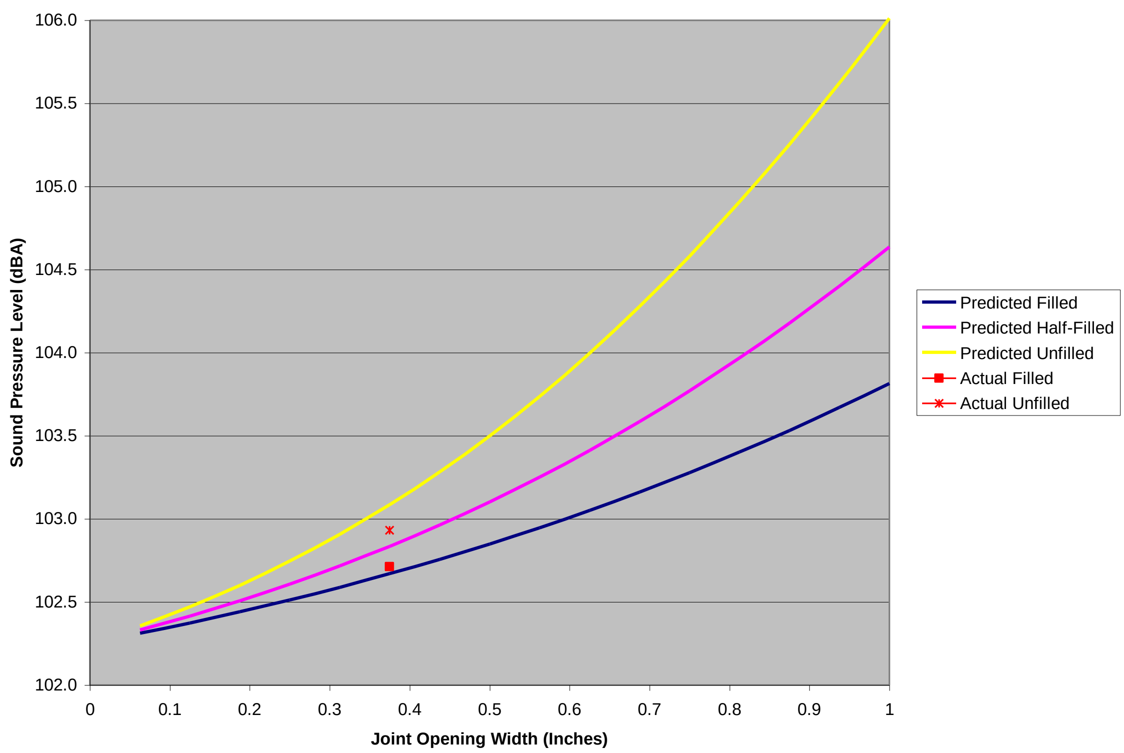


Figure 6: Actual and predicted noise level for joints on 102.6 dB(A) pavement