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20th Anniversary 1999-2019

November 12, 2019

Mr. Chris Cote
MDT Environmental Services
PO Box 201001
Helena MT 59620-1001

Re: Rumble Strip Wayside Noise Study
Experimental Project MT-18-02, UPN 9370000
BSA Project #19134

Dear Chris:

Big Sky Acoustics (BSA) has completed MDT's Rumble Strip Wayside Noise Study project. The attached report summarizes the field methodology, measurement results and recommendations, and incorporates MDT's comments received on the draft report.

Thank you for the opportunity to work with MDT on this experimental project. If you have any questions concerning this report, please do not hesitate to call me at (406) 457-0407, or email me at sean@bigskyacoustics.com.

Sincerely,

Sean Connolly

Sean Connolly, INCE Bd. Cert.
BIG SKY ACOUSTICS

Attachment

cc: Joe Radonich/MDT
Craig Abernathy/MDT

RUMBLE STRIP WAYSIDE NOISE STUDY
EXPERIMENTAL PROJECT MT-18-02, UPN 9370000

Prepared for:

MONTANA MDT DEPARTMENT OF TRANSPORTATION

PO Box 201001
Helena, MT 59620-1001

Completed by:

Big Sky Acoustics

November 12, 2019

TABLE OF CONTENTS

ACRONYM LIST

BSA	Big Sky Acoustics
dB	decibels
dBA	A-weighted decibels
Caltrans	California Department of Transportation
CLRS	centerline rumble strip
FHWA	Federal Highway Administration
Hz	hertz
L_{max}	maximum instantaneous sound level
MDT	Montana Department of Transportation
MNDOT	Minnesota Department of Transportation
mph	miles per hour
MWHC	Mountain West Holding Company
NCHRP	National Cooperative Highway Research Program
RP	reference post
SCLRS	sinusoidal centerline rumble strip
TRB	Transportation Research Board
WSDOT	Washington State Department of Transportation

1.0 BACKGROUND, PURPOSE & STUDY DESIGN

The Montana Department of Transportation (MDT) initiated the Rumble Strip Wayside Noise Study to determine if sinusoidal rumble strips result in lower exterior noise levels at noise sensitive locations, such as residences, located adjacent to Montana roadways. Rumble strips are an effective traffic safety feature, but have caused increased citizen complaints in the last decade due to noise when vehicle tires strike MDT's standard rumble strip.

Big Sky Acoustics (BSA) teamed with Mountain West Holding Company (MWHC) to complete this project. This wayside noise study helped determine whether or not a particular design of sinusoidal centerline rumble strips (SCLRS) reduced exterior noise compared to MDT's standard centerline rumble strip (CLRS).

In 2018, a contractor installed four test sections of milled (i.e., in-ground) SCLRS on MT-39 (P-39N) between Reference Post (RP) 31 and RP 32.4, approximately 8 miles north of Colstrip, Montana. MDT's standard CLRS is located at both ends of the sinusoidal rumble strips. The sections tested for this wayside noise study included the following, and are documented in the photolog in **Appendix A**:

1. Standard 12" wide CLRS, ½" to 5/8" depth, milled in pairs, 36" on center
2. SCLRS Design S1: 14" longitudinal frequency, 12" wide, 1/8" to ½" depth
3. SCLRS Design S2: 24" longitudinal frequency, 12" wide, 1/8" to ½" depth
4. SCLRS Design S3: 14" longitudinal frequency, 14" wide tapered, 1/8" to ½" depth
5. SCLRS Design S3A: 24" longitudinal frequency, 14" wide tapered, 1/8" to ½" depth
6. Chipseal Pavement (Type 1, 3/8" aggregate) without striking the rumble strip (i.e., baseline).

The SCLRS installation and details are provided in MDT's *Sinusoidal Centerline Rumble Strip Evaluation* report (MDT 2019). The rumble strip sections are shown on **Figure 1** (attached).

2.0 NOISE TERMINOLOGY

Noise levels are quantified using units of decibels (dB). The L_{max} metric denotes the maximum instantaneous sound level recorded during a measurement period. Humans typically have reduced hearing sensitivity at low frequencies compared with their response at high frequencies. The "A-weighting" of noise levels, or A-weighted decibels (dBA), closely correlates to the frequency response of normal human hearing (250 to 4,000 hertz [Hz]).

Noise levels typically decrease by approximately 6 dBA every time the distance between the source and receptor is doubled, depending on the characteristics of the source and the conditions over the path that the noise travels. The reduction in noise levels can be increased if a solid barrier or natural topography blocks the line of sight between the source and receptor.

Since a person's response to noise is subjective, the perception of noise can vary from person to person. **Table 2-1**, on the following page, indicates the relationship between changes in noise levels and a person's typical perception of the change.

Table 2-1: Changes in Noise Levels vs. Apparent Change in Loudness

Change in Sound Level (dBA)	Apparent Change in Loudness to a Person
±1	Imperceptible
±3	Barely audible (i.e., barely noticeable reduction)
±5	Clearly audible (i.e., clearly noticeable reduction)
±10	Half as loud or twice as loud as the original noise (significant change)
±20	One quarter as loud or four times as loud as the original noise (very significant change)

Source: Egan 1988

3.0 FIELD METHODOLOGY

Fieldwork was completed on July 29-30, 2019. On July 29, the Team met in Billings and discussed traffic control, communication, equipment, and measurement specifics. Using information in MDT's SCLRS report and field observations, BSA also identified, measured and flagged the noise measurement and vehicle strike locations along MT-39, and ensured the ground conditions and topography at each of centerline rumble strip measurement locations were similar (**Appendix A**).

Early morning on July 30, MWHC set up the traffic control signage and cones for the 2-lane, short-term flagging operation on MT-39, which included all residential approaches and private roads. The Team conducted a safety and coordination meeting prior to the testing, and was in continuous radio-communication during the fieldwork. The team consisted of a noise specialist (BSA), passenger vehicle driver (BSA), medium truck driver (MWHC), heavy truck driver (MWHC), traffic control supervisor (MWHC), and two flaggers (MWHC). MDT provided oversight of the field operations.

The standard CLRS, the four SCLRS designs, and the existing chipseal pavement were tested separately. For each measurement location, the strike zones were marked by cones on both shoulders and a clear view of the road was visible over relatively flat ground for several hundred feet in each direction (**Appendix A**). The vehicles drove over the rumble strips with the tires closest to the sound level meter (SLM) so that the vehicles did not shield the equipment. Depending on traffic control, some tests were conducted in both north/south directions and some tests were conducted one-way. Traffic was not held or delayed more than 10 minutes at a time during the fieldwork. Testing proceeded from south to north, and the measurement locations and rumble strip sections are shown on **Figure 1**.

The three test vehicles (passenger vehicle, medium truck and heavy truck) passed by the SLM while striking the rumble strip for a minimum of 100 feet on each side of the measurement location (200 feet total). Three measurements were completed for each vehicle passing by the SLM measurement location at each of the test speeds (30, 50 and 70 mph), three times each, at the six sections (**Section 1.0**).

3.1 Equipment

As shown in the photolog in **Appendix A**, the vehicles used for the tests included the following:

1. Passenger vehicle (2-axle, 4-tire): 2018 Toyota 4Runner, P265/70R17 (10.4-inch tire width)
2. Medium truck (2-axle, 6-tire): 2007 Dodge Ram 3500 Dually, P230/80R17 (9-inch tire width)
3. Heavy truck: (3-axle, 10-tire): 2000 Volvo Truck Tractor, P275/11R22.5 (10.8-inch tire width)

BSA conducted the measurements with a Larson Davis Model 831 Type I SLM set to fast response, with a preamplifier and 0.5-inch diameter microphone. The meter was field-calibrated using a Larson Davis Model CAL200 prior to each measurement location, and verified at the conclusion of the measurements.

The SLM was located 50 feet from the centerline rumble strip at each test section, with a clear view of the roadway. For each measurement, the microphone was 5 feet above the road surface, which was between 8- and 9.5-feet above the ground surface at the measurement locations as shown in **Appendix A**. A wind screen as used over the microphone.

3.2 Wayside Noise Level Measurements

BSA conducted the wayside noise level measurements in general accordance with AASHTO TP 98-18, *Standard Method of Test for Determining the Influence of Road Surfaces on Vehicle Noise Using the Statistical Isolated Pass-by Method*, and FHWA's *Measurement of Highway-Related Noise*. For each vehicle pass-by, the overall L_{max} noise levels and the 1/3 octave band frequency L_{max} spectra (50 to 10,000 Hz) were recorded, and the SLM recorded an audio clip for reference. The measurements were conducted between approximately 0725 and 1410 hours, and the field notes are included in **Appendix B**.

Temperature, relative humidity, wind speed/direction were measured using Kestrel 3000 meter. The data is shown in **Table 3-1**. The data indicates atmospheric conditions did not affect the measured sound levels, primarily because the wind speed throughout the measurements was calm to 3 mph.

Table 3-1: Weather Data Recorded during Measurements

Time (hours)	Temperature	Relative Humidity	Wind speed
0750	67°F	66%	Calm
0840	79°F	68%	Calm
0915	84°F	50%	Calm to 3 mph from S
0945	82°F	55%	Calm
1100	87°F	51%	Calm
1215	92°F	41%	Calm to 3 mph from S
1305	92°F	39%	Calm to 3 mph from S
1330	90°F	40%	Calm to 3 mph from S

4.0 RESULTS

For comparison, the L_{max} of the measured sound level data from the three tests for each vehicle and speed combination were calculated and averaged. The 1/3-octave band frequency L_{max} measurement data for each vehicle tested are included in **Section 4.2**.

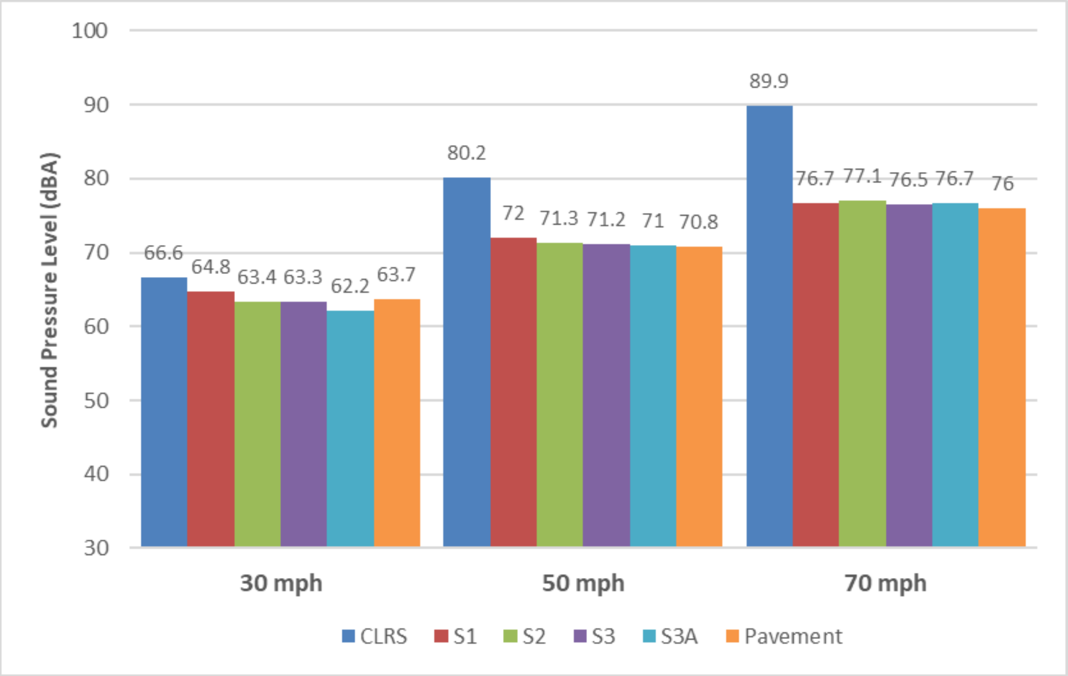
Although the goal of this project was to compare the wayside noise levels of the SCLRS designs, the wayside noise levels due to vehicles traveling on the chipseal pavement, without striking the rumble strips, were also field-measured. This baseline measured pavement data is included in the results shown in the following subsections for comparison to the SCLRS designs and standard CLRS.

4.1 Wayside Noise Level Results

4.1.1 Passenger Vehicle

The measured average overall L_{max} sound levels for the passenger vehicle are summarized on **Figure 4-1**. As shown, the wayside noise levels of the standard CLRS are the highest at each speed, but more notably at 50 and 70 mph. The wayside noise levels of the four SCLRS are similar to each other, and one design is not significantly quieter than another. Compared to the CLRS, the wayside SCLRS noise levels of the passenger vehicle are 1.8 to 4.4 dBA quieter at 30 mph (i.e., a barely to clearly noticeable reduction), 8.2 to 9.2 dBA quieter at 50 mph (i.e., a clearly noticeable reduction to half as loud), and 12.8 to 13.4 dBA quieter at 70 mph, which is typically perceived as half as loud (**Table 2-1**) (Egan 1988). The wayside noise levels of the four SCLRS designs are also similar to the chipsealed pavement (baseline) at each of the three test speeds (**Figure 4-1**).

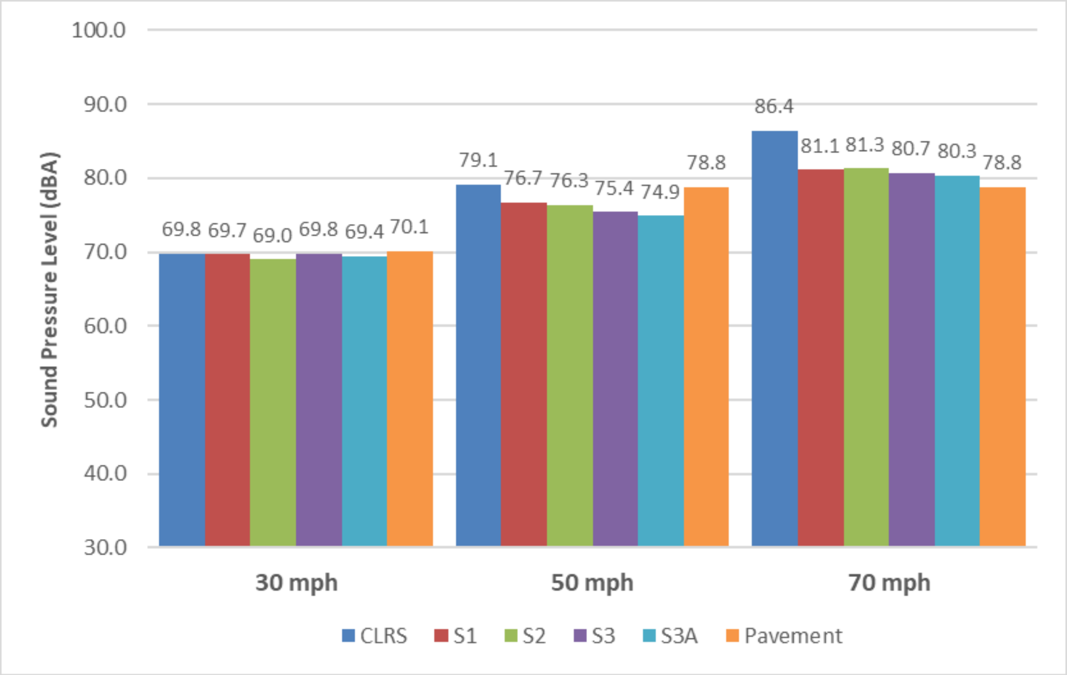
Figure 4-1: Measured Average Overall L_{max} Noise Levels—Passenger Vehicle



4.1.2 Medium Truck

The measured average overall L_{max} sound levels for the medium truck are summarized on **Figure 4-2**. As shown, the wayside noise levels of the standard CLRS are the highest at 50 and 70 mph. The wayside noise levels of the four SCLRS are similar to each other, and one design is not significantly quieter than another. Compared to the CLRS, the wayside SCLRS noise levels of the medium truck are within -0.8 to 0 dBA of the CLRS at 30 mph (i.e., imperceptible), 2.4 to 4.2 dBA quieter at 50 mph (i.e., a barely noticeable reduction), and 5.1 to 6.1 dBA quieter at 70 mph, (i.e., a clearly noticeable reduction) (**Table 2-1**) (Egan 1988). The medium truck wayside noise levels of the four SCLRS designs are also similar to the chipsealed pavement (baseline) at 30 and 70 mph (**Figure 4-2**). However, at 50 mph, the SCLRS designs had lower noise levels than the pavement. This difference appears to be due to the engine sounds of the truck, which produced a tone at 100 Hz during the pavement noise level measurements (**Section 4.2**).

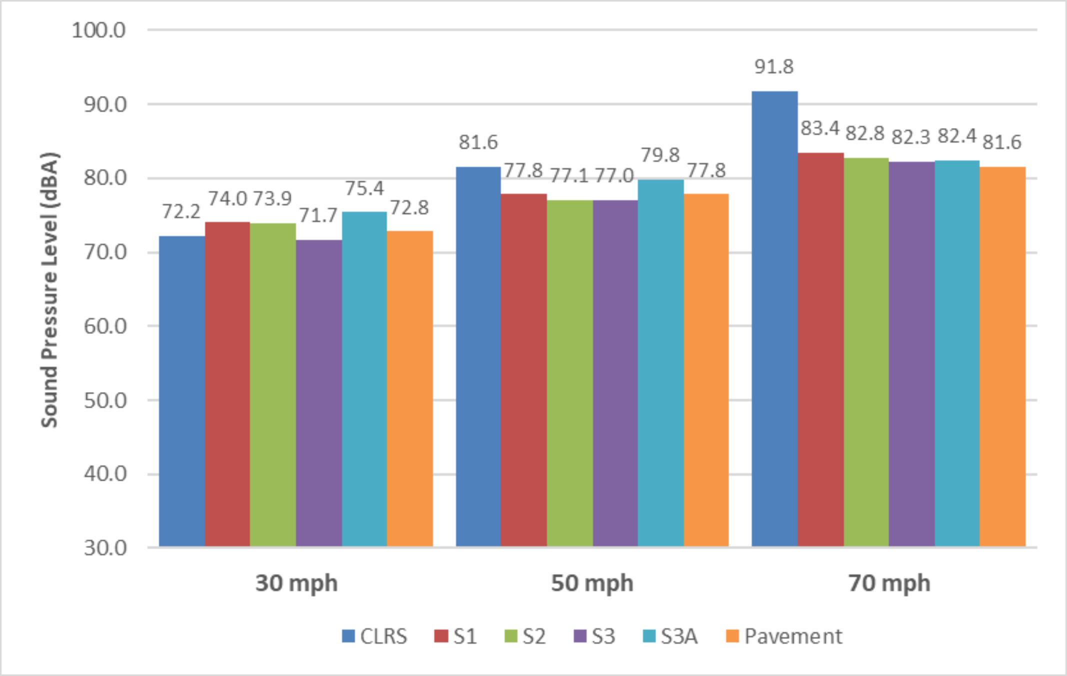
Figure 4-2: Measured Average Overall L_{max} Noise Levels—Medium Truck



4.1.3 Heavy Truck

The measured average overall L_{max} sound levels for the heavy truck are summarized on **Figure 4-3**. As shown, the wayside noise levels of the standard CLRS are the highest at 50 and 70 mph. The wayside noise levels of the four SCLRS are similar to each other and one design is not significantly quieter than another. Compared to the CLRS, the wayside SCLRS noise levels of the heavy truck are within -0.5 to 3.2 dBA of the CLRS at 30 mph (i.e., imperceptible), 1.8 to 4.6 dBA quieter at 50 mph (i.e., a barely noticeable reduction), and 8.4 to 9.5 dBA quieter at 70 mph, (i.e., a clearly noticeable reduction to half as loud) (**Table 2-1**) (Egan 1988). The heavy truck wayside noise levels of the four SCLRS designs are also similar to the chipsealed pavement (baseline) at each of the three test speeds (**Figure 4-3**).

Figure 4-3: Measured Average Overall L_{max} Noise Levels—Heavy Truck



4.2 Analysis

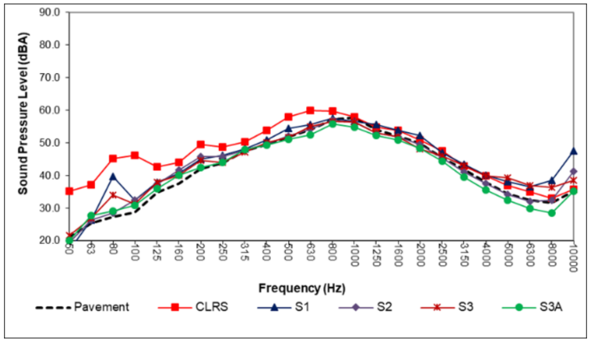
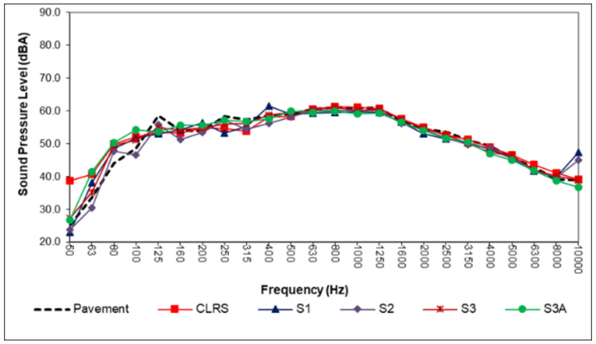
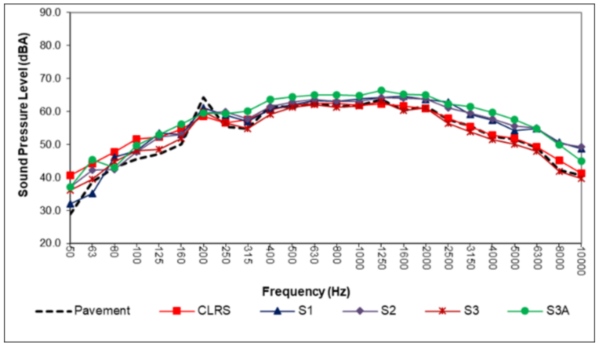
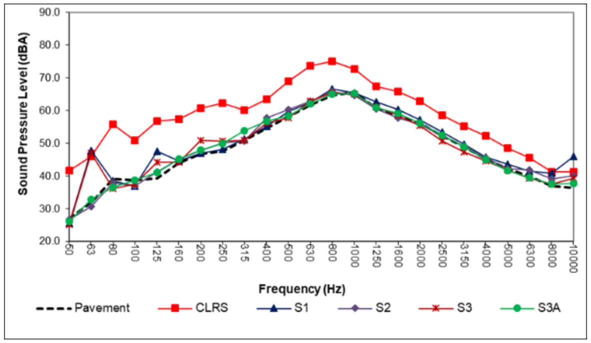
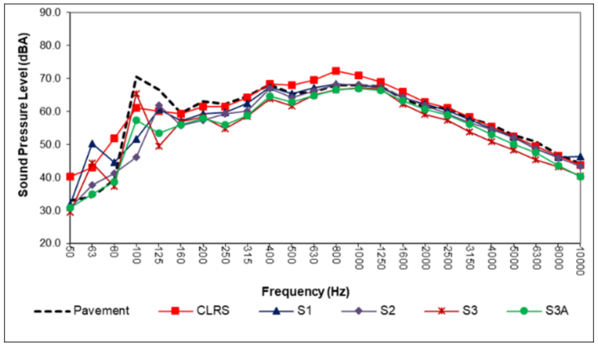
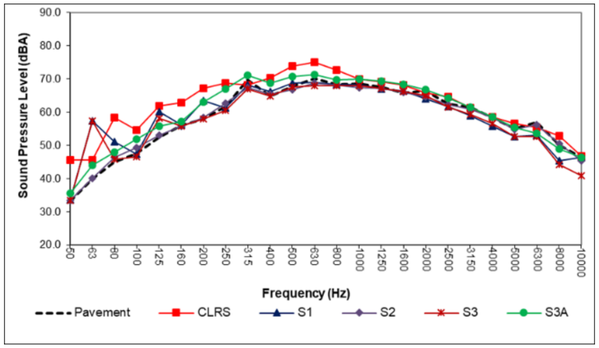
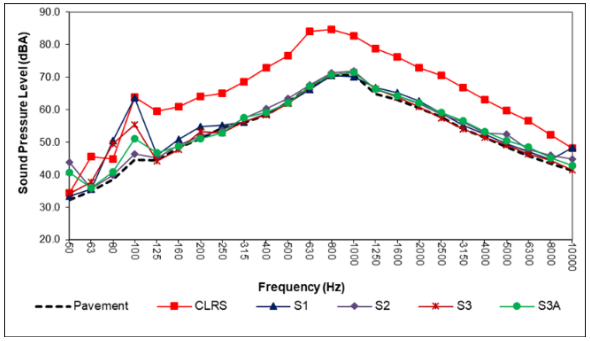
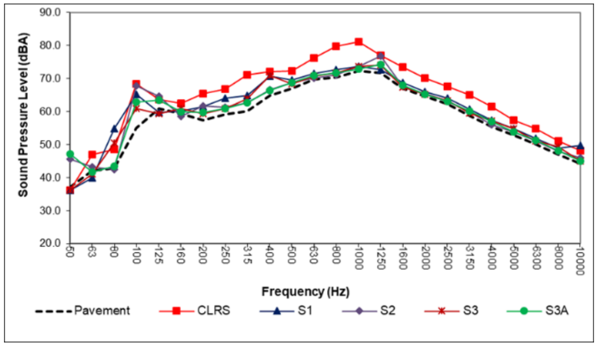
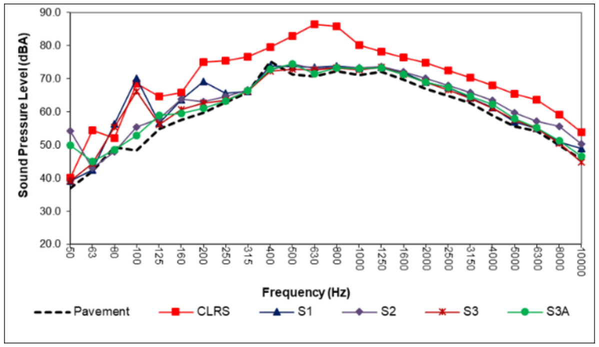
Although the results shown on the graphs on **Figures 4-1, 4-2** and **4-3** do indicate differing overall wayside noise levels between the four SCLRS designs, the variances were hard to distinguish audibly roadside. However, an external vibratory response (shaking) of the heavy truck was observed when testing SCLRS S3A, and loud wayside roadside rumble was heard roadside when all vehicles stuck MDT's standard CLRS (**Appendix B**).

As discussed in **Section 4.1**, for each vehicle and test speed the wayside noise levels of the four SCLRS designs are similar to each other, and one design is not significantly quieter than another. In general, the wayside noise level difference between MDT's standard CLRS and the four SCLRS designs increased with increasing speed for each vehicle type, with the largest difference occurring at 70 mph.

The largest difference between the CLRS and the SCLRS designs occurred for the passenger vehicle, and the smallest difference occurred for the medium truck. The difference appears to be due to how much contact the vehicle's front and rear tires have with the rumble strips. For the passenger vehicle, both the front and rear tires were in contact with the strips. For the medium truck, the front tire was aligned with the space between the two dually rear tires. Therefore, although the medium truck front tire was in contact with the rumble strips during the tests, the rear tires were only partially in contact with the strips. For the heavy truck, the front tire and the outer rear tires were approximately in alignment (**Appendix A**), and in contact with the strips. Therefore, the inner rear tires on the heavy truck did not contact the strips.

Figure 4-4 on the next page, indicates the measured 1/3-octave band L_{max} spectra for the SCLRS designs are similar for each vehicle type and speed combination, and the SCLRS spectra are similar to the pavement spectra. The comparison of frequency spectra confirms that the noise generated by the four SCLRS designs and the pavement all sound very similar. The prominent peaks for all vehicles in the spectra between 50 Hz and 125 Hz are due to the forcing and second harmonic frequencies of the tires rolling over the 14-inch longitudinal frequency of SCLRS S1 and S3, and the 24-inch longitudinal frequency SCLRS S2 and S3A, which varies by speed (TRB 2017). Although these peaks are pronounced in the spectra, they are lower than the general “hump” in the SCLRS spectra around 800 to 1,000 Hz, which is typical for tire-pavement noise.

Figure 4-4: Measured Average L_{max} 1/3-Octave Band Frequency Spectra

Speed	Passenger Vehicle	Medium Truck	Heavy Truck
30 mph			
50 mph			
70 mph			

4.3 Interior Observations

The purpose of the project was to measure the exterior wayside noise of the standard CLRS and four SCLRS rumble strip designs (**Section 1.0**). Therefore, interior noise levels inside the vehicles or steering column vibration were not measured. However, in order to help determine the noise and vibratory effectiveness of the differing SCLRS designs, the drivers made qualitative assessments, took notes, and made dash videos of the interior conditions inside the vehicles during the field testing, as listed in **Table 4-3** and **Appendix B**.

Table 4-3: Driver Interior Observations Noted during Testing

Rumble Strip Design	Speed	Passenger Vehicle	Medium Truck	Heavy Truck	Driver Opinions of Rumble Strip
MDT Std CLRS	30 mph	Low rumble	Loud vibrations	Loud vibrations	Loud interior noise and vibration levels
	50 mph	Louder and shaking interior	Loud vibrations	Loud vibrations	
	70 mph	Loud noise and vibrations	Loud vibrations	Loud vibrations	
SCLRS S1 14” LF, 12” wide	30 mph	Steering wheel vibrations, hard to stay on rumble strip	Very hard to stay on rumble strip	Quiet and very smooth (i.e., little vibration)	Concerned that S1 may cause some drivers to overcorrect when coming into contact with strip, since vehicles were “pushed” off strip.
	50 mph	Quieter than 30 mph, steering wheel vibrations, pushed car off rumble strip	Smoother (i.e., less vibration) than 30 mph	Smooth, but more vibration than 30 mph	
	70 mph	Quieter than 30 mph, louder than 50 mph	Very rough and pushed truck off rumble strip	Louder than 30 and 50 mph, but pushed and pulled truck off rumble strip	
SCLRS S2 24” LF, 12” wide	30 mph	Quietest interior noise and vibration levels	Smooth and quiet	Little vibration and noise	Concerned that S2 would not alert or rouse a driver of all vehicle types effectively at all speeds.
	50 mph	Very quiet	Very little vibration	Little vibration and noise	
	70 mph	Same as 50 mph, lower frequency than S1	Very little vibration	Little vibration and noise	
SCLRS S3 14” LF, 14” wide-tapered	30 mph	Noise and vibration in front end of vehicle, and louder when on tapered edge	Smooth and quiet, but a little more vibration than S2	Very quiet	Design S3 appeared ineffective for a heavy truck, and may not alert or rouse a driver effectively.
	50 mph	Same as 30 mph	Same as 30 mph	Hardly noticeable noise or vibration	
	70 mph	Same as 30 mph	Same as 30 mph	Hardly noticeable noise or vibration	
SCLRS S3A 24” LF, 14” wide-tapered	30 mph	Lots of noise and vibration	Good sound and vibrations	Better than S1, S2 and S3, i.e., more noticeable noise and vibration inside truck	Favorite SCLRS tested by drivers. Effective noise and vibration for all vehicle types and at all speeds.
	50 mph	Quieter and less vibration than 30 mph	Quieter than 30 mph	Same as 30 mph	
	70 mph	Good noise and vibration, louder than 50 mph, less than 30 mph.	Louder sound and vibrations than 30 & 50 mph	Same as 30 mph	

4.4 Sources of Error and Variables

There were several potential sources of error and variables that could have affected the measurement results, as listed below.

- Diesel engine noise from the medium dually truck may have influenced some of the measurement results.
- Condition and age of the tires on the vehicles at the time of the measurements. Different tread patterns and depth of tread patterns may produce different results for the same types of vehicles.
- Different tire sizes. Both 12-inch wide and 14-inch wide-tapered SCLRS designs were tested, with depths ranging from 1/8 to ½-inches deep (**Section 1.0**). Therefore, width of the tires tested (9 to 10.8 inches) and positioning on the vehicle (**Section 4.2**) determines the amount of tire in contact with the rumble strip, versus the pavement, concurrently.
- Different pavement types will produce varying noise level results based on wear, age, size of chipseal aggregate, or smoother pavement. Type 1 chipseal, 3/8-inch aggregate, overlayed in 2011, was tested for this project, and the SCLRS were milled in 2018 (MDT 2019).

5.0 LITERATURE REVIEW

Many States have different standard rumble strip configurations, and are evaluating the effectiveness of varying designs of sinusoidal rumble strips. Numerous longitudinal frequencies (12 to 24 inches), widths (8 to 16 inches) and depths (1/8 to 1/2 inches) have been tested on varying pavements, speeds, and using different vehicle types. In general, shorter longitudinal frequency designs (12 to 16 inches) have been more effective at shallower depths (5/16 inches or less), and tapered width patterns have been more effective than straight edge patterns (Caltrans 2018a). Because of the many sinusoidal patterns tested, it is challenging to correlate the data results and conclusions among the studies, and to date, the optimal design for all vehicle types has not been determined. However, similar to the findings of this project, the studies reported lower wayside noise levels in all vehicle types for sinusoidal designs, and a greater interior noise and vibration response in passenger vehicles than heavy trucks (Caltrans 2018a, Mathew 2018, MNDOT 2016, WSDOT 2018).

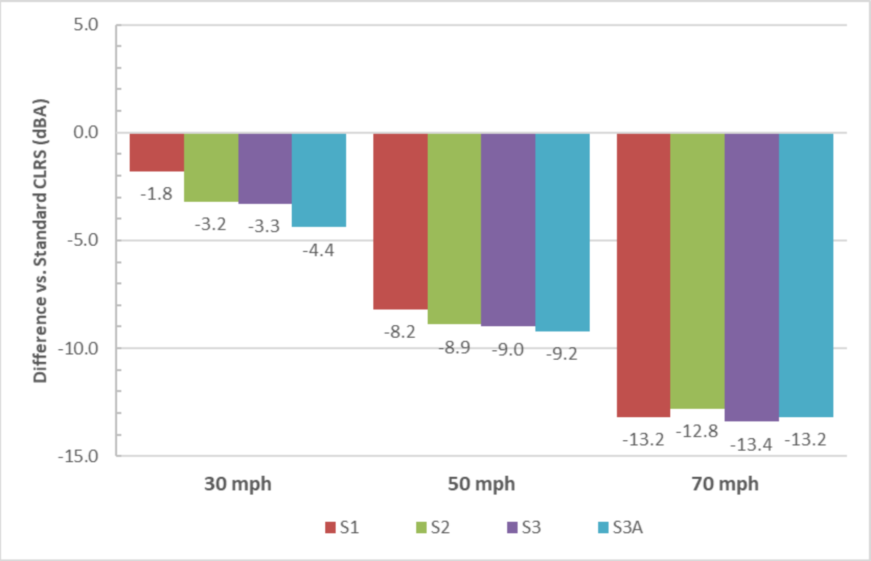
The National Cooperative Highway Research Program (NCHRP) recommends that centerline rumble strips should be designed to produce interior sound level differences (above background) of 10 to 15 dBA inside the passenger compartment in rural areas, and 6 to 12 dBA near residential or urban areas (NCHRP 2009). Chipsealed pavements produce higher background noise levels, and therefore, effective rumble strip designs in Montana need to produce higher absolute interior sound levels, which were not measured for this project.

6.0 CONCLUSIONS

This wayside noise study helped determine whether or not the four SCLRS designs installed on MT-39 reduced exterior noise compared to MDT's standard CLRS. For the passenger vehicle, medium truck and heavy truck tested at 30, 50 and 70 mph, the wayside noise levels of the four SCLRS designs are similar to each other, and one design is not significantly quieter than another. The wayside noise levels of the four SCLRS designs are also similar to the chipsealed pavement (baseline) at each speed, for each vehicle type (**Figures 4-1, 4-2 and 4-3**).

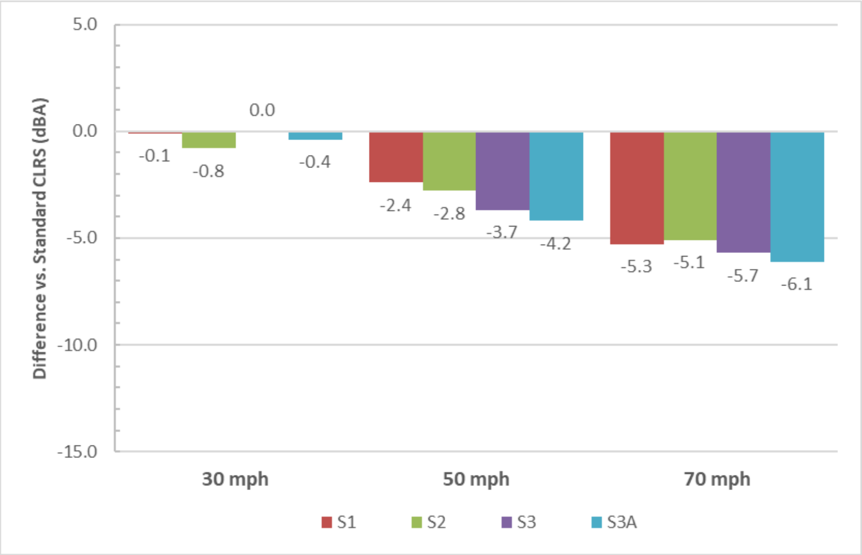
The wayside noise level difference between MDT's standard CLRS and the four SCLRS designs increase with increasing speed for each vehicle type, with the largest difference occurring at 70 mph. The wayside noise difference between MDT's standard CLRS and the four SCLRS designs are shown graphically in **Figures 6-1, 6-2** and **6-3**.

Figure 6-1: Difference between CLRS and SCLRS Noise Levels—Passenger Vehicle



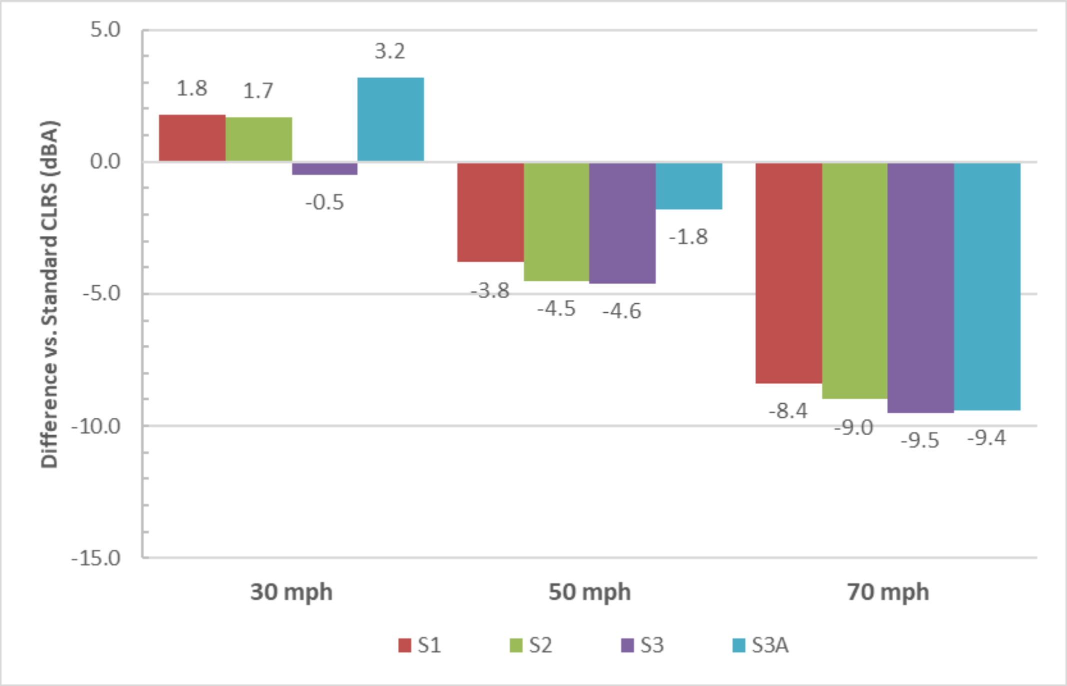
1.8 to 4.4 dBA quieter at 30 mph (i.e., a barely to clearly noticeable reduction)
8.2 to 9.2 dBA quieter at 50 mph (i.e., a clearly noticeable reduction to half as loud)
12.8 to 13.4 dBA quieter at 70 mph, which is typically perceived as half as loud (Egan 1988)

Figure 6-2: Difference between CLRS and SCLRS Noise Levels—Medium Truck



Within -0.8 to 0 dBA at 30 mph (i.e., imperceptible)
2.4 to 4.2 dBA quieter at 50 mph (i.e., a barely noticeable reduction)
5.1 to 6.1 dBA quieter at 70 mph, (i.e., a clearly noticeable reduction) (Egan 1988)

Figure 6-2: Difference between CLRS and SCLRS Noise Levels—Heavy Truck



Within -0.5 to 3.2 dBA at 30 mph (i.e., imperceptible)
1.8 to 4.6 dBA quieter at 50 mph (i.e., a barely noticeable reduction)
8.4 to 9.5 dBA quieter at 70 mph (i.e., a clearly noticeable reduction to half as loud) (Egan 1988)

The interior noise levels inside the vehicles or steering column vibration were not measured for this project. However, as listed in **Table 4-3**, for design SCLRS S3A (i.e., 24-inch longitudinal frequency, 14-inch wide tapered) the drivers noticed the most interior noise and vibration in all vehicle types at all speeds of the SCLRS designs. MDT's standard CLRS also provided considerable interior noise and vibration in all vehicle types, but significantly louder wayside noise levels at faster speeds than all the SCLRS designs.

7.0 RECOMMENDATIONS

Some interior response from all the SCLRS designs was noted in the passenger vehicle, but the CLRS and SCLRS S3A provided the most interior response in all the tested vehicles (**Table 4-3**). Before MDT standardizes a SCLRS design for use on Montana's roadways, interior noise and vibration (i.e., seat track and steering column) should be tested to comply with NCHRP guidelines (NCHRP 2009). BSA also recommends testing a small passenger vehicle with narrower tires (less than 9 inches), to determine the internal noise, vibration and variability responses of a small car on the MT-39 SCLRS designs.

The Federal Highway Administration (FHWA 2015) published guidance for rumble strip setback distances for two-lane roadways. Studies cited determined that when standard rumble strips end approximately 650 feet (direct distance) prior to a noise-sensitive receptor (i.e., residence) or urban area the noise impacts are "tolerable", and within 1,640 feet the noise generated from standard strips is "negligible". MDT should monitor current guidance and consider appropriate setback distances when terminating standard rumble strips in residential or urban areas and/or replacing with sinusoidal strips.

MDT should monitor/observe the four SCLRS designs during the winter months to determine if water pooling/ice collects in the SCLRS troughs, which may be a safety issue. MDT should also continue to monitor the durability of the SCLRS and striping over the years for degradation due to snow removal and/or normal wearing.

The California Department of Transportation (Caltrans 2018b) has extensively studied "mumble" strips (aka sinusoidal rumble strips), and recommends the following key design parameters of SCLRS for MDT's consideration if installed in Montana:

- Provide lower roadside noise levels.
- Maintain or increase interior sound and vibration levels.
- Cause minimal disturbance to vehicle dynamics.
- Be bicycle friendly – design considerations for safe bicycle navigation on shoulder sinusoidal rumble strips (e.g., adequate riding space—4 feet from edge of pavement, and gaps for exiting and entering bicyclists) (TRB 2017).
- Fit within the roadway cross-section, limit depth of material removal, be cost effective, and provide ease of construction (Caltrans 2018b).

8.0 REFERENCES

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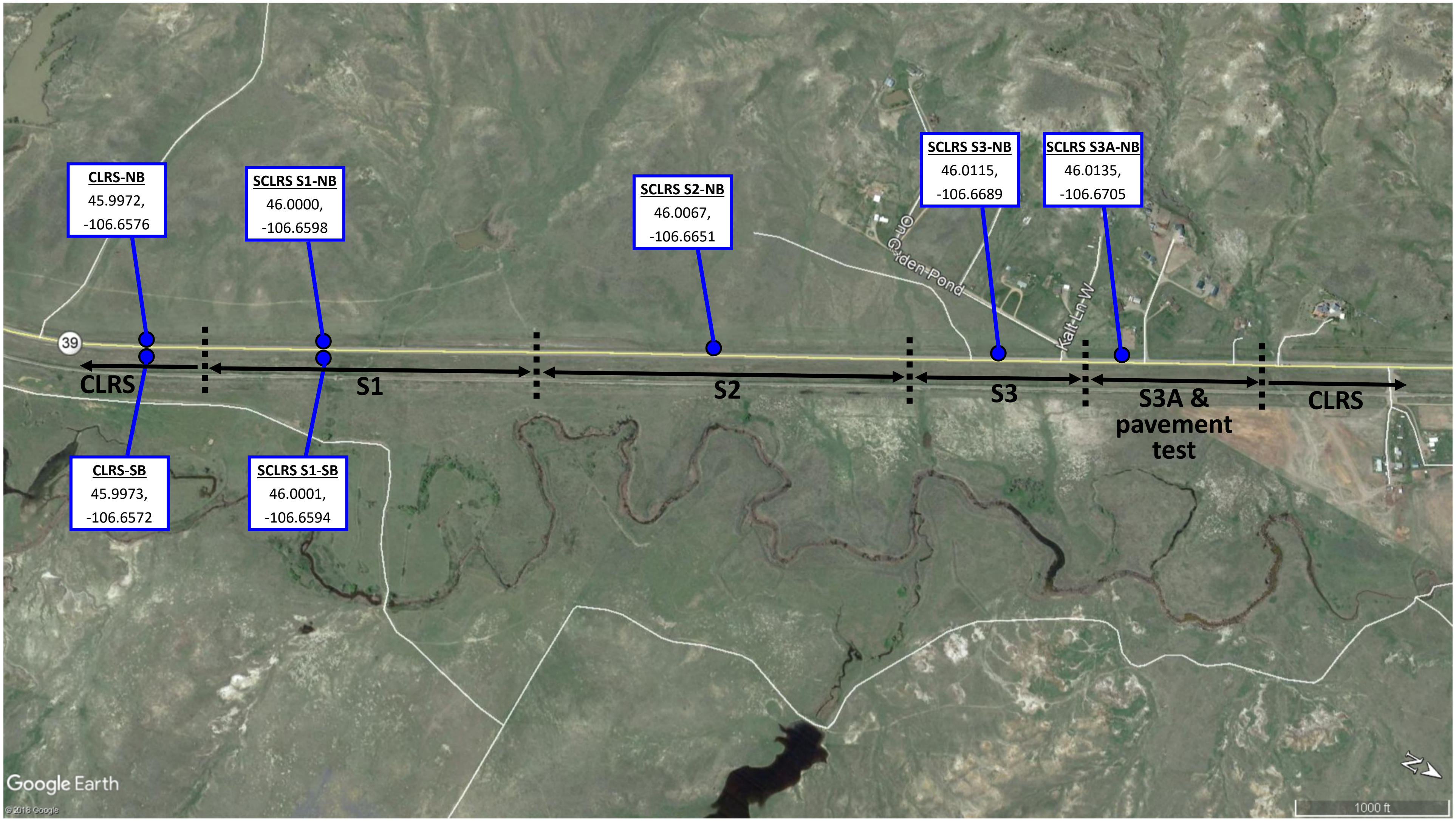


Notes: NB = northbound (i.e., measurement location when testing vehicles were traveling north)
SB = southbound (i.e., measurement location when testing vehicles were traveling south)
Each measurement location was 50 ft from the centerline. GPS coordinates listed.
Microphone at each measurement location was 5 ft above the road surface, and between 8 and 9.5 feet above the ground surface.

Big Sky Acoustics

FIGURE 1

Rumble Strip Wayside Noise Study
Rumble Strip Sections and Noise Level Measurement Locations

Appendix A

Photolog

Appendix A: Photolog

		
View to the north of the Standard CLRS and strike zone cone markers.	View to the north of SCLRS Design S1 (14”LF, 12”wide) and strike zone cone markers.	View to the north of SCLRS Design S2 (24”LF, 12”wide) and strike zone cone markers.
		
View to the north of SCLRS Design S3 (14”LF, 14”wide) and strike zone cone markers.	View to the north of SCLRS Design S3A (24”LF, 14”wide) and strike zone cone markers.	View of the MT-39 pavement (3/8” aggregate chipseal) installed in 2011.

Appendix A: Photolog

		
Looking east at representative SLM and microphone equipment set up in MT-39 ROW 50 feet from centerline (measurement location SCLRS S3A).	Passenger vehicle used for testing: 2018 Toyota 4Runner, gas powered, automatic transmission, approx. GVW 6,100 lbs.	Medium truck used for testing: 2007 Dodge Ram Dually 3500 Quad Cab, diesel powered, manual transmission approx. GVW 11,000 lbs.
		
Heavy truck used for testing: 2000 Volvo Model 999 Truck Tractor, diesel powered, manual transmission, approx. GVW 18,000 lbs. plus drill equipment.	MWHC and BSA vehicle drivers during testing.	MDT and BSA roadside crew during testing.

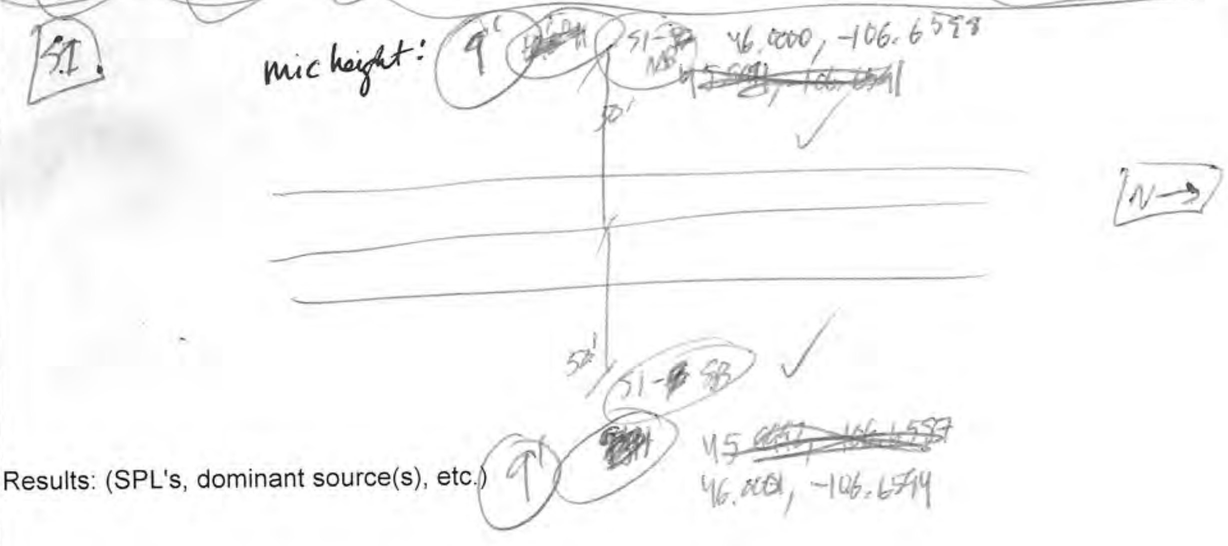
Appendix B

Field Notes

Big Sky Acoustics, LLC
Field Noise Level Measurement Data Form

Project: Rumble Strip - MDT		BSA Project #: 19134
Name: SC		Date: 7/29/19 - Tues
SLM: ~~h~~ NA	S/N:	Response:
Calibrator: NA	S/N:	
Location: Meas loc's setup NB/SB MT-39		
Calibration: NA	Before Meas:	After Meas:
Start Time: NA	End Time:	
Weather Conditions: N/A		
Ground Conditions/topography: level both sides of road, slope to borrow pit, ~~[illegible]~~ mic height adj to 5' above pavement		

Notes/observations (audible noises, line of sight, map, etc.)



Results: (SPL's, dominant source(s), etc.)

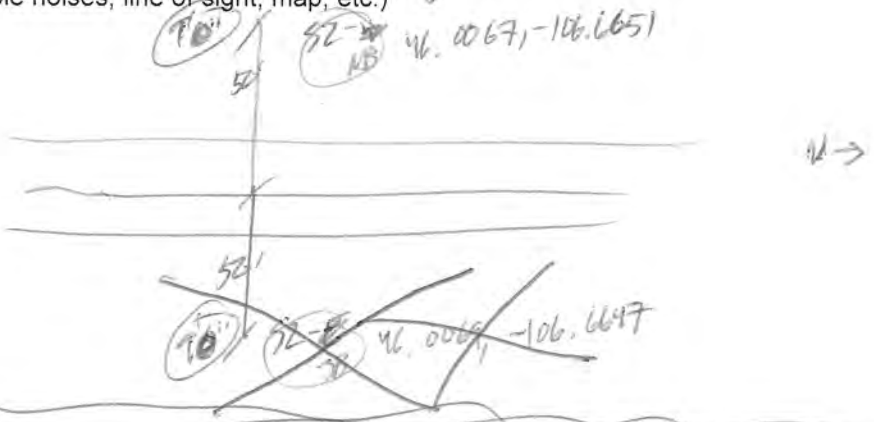
Big Sky Acoustics, LLC
Field Noise Level Measurement Data Form

(continued)

Project:		BSA Project #:
Name:		Date:
SLM:	S/N:	Response:
Calibrator:	S/N:	
Location:		
Calibration:	Before Meas:	After Meas:
Start Time:	End Time:	
Weather Conditions:		
Ground Conditions/topography:		

Notes/observations (audible noises, line of sight, map, etc.)

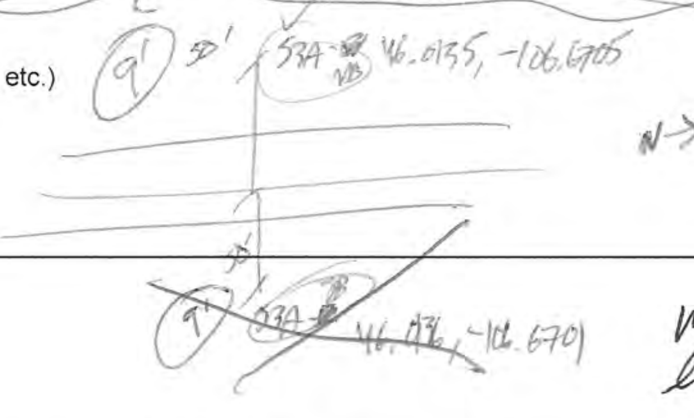
52



53

Results: (SPL's, dominant source(s), etc.)

53A



Meas locations Page 2 of 4

Big Sky Acoustics, LLC
Field Noise Level Measurement Data Form

Project: Buffer strip

BSA Project #: 19134

Name: [illegible] JC

Date: 7/30/19 - Wed

SLM: LD#1 w/#1 mic + preamp

S/N:

Response: A, f, w/s

Calibrator: LD

S/N:

Location:
Standard CLRS

Calibration:

Before Meas: ✓

After Meas: ✓

Start Time: 0724

End Time: 0819

Weather Conditions:
See below

Ground Conditions/topography:
level, slope to borrow pit, grass/weeds

Notes/observations (audible noises, line of sight, map, etc.)

Std

30 mph

(X) SHA-NB HT-073101 .004 72.3 - low hum power plant in dist, first
MT 073230 .005
Car 073319 .006

- trans is train cars → line starts w/ profile [illegible]

N→

|||| ||

HT - 073702 .007 (X) SHA-SB
MT - 073812 - .008
Car 073530 - .009

HT - 001 072408 - lowly hum rumble 70.1
MT 002 072539 - more engine 66.9
Car 003 072638 - some rumble - 65.5

50 mph

HT - 075816 016
MT - 075934 017
Car - 080020 018

(X) SHA - NB HT0747 .010
MT 074510 .011
Car074852 .012

N→

0750 67F, 66% RH
calm weather

Results: (SPL's, dominant source(s), etc.)

(X) SHA-SB HT .013
MT .014
Car .015

Big Sky Acoustics, LLC
Field Noise Level Measurement Data Form

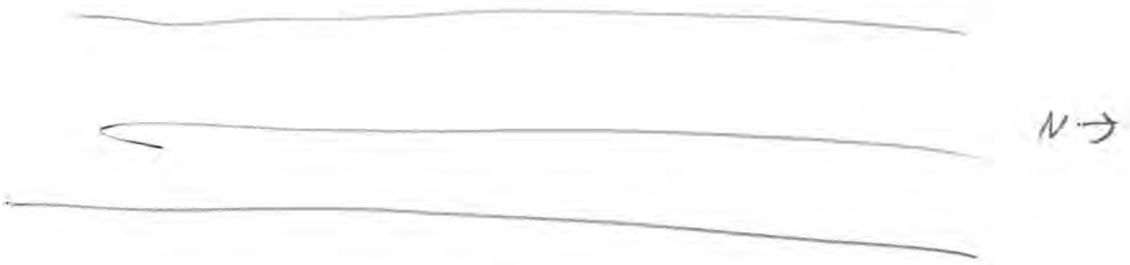
Project:		BSA Project #:
Name:		Date:
SLM:	S/N:	Response:
Calibrator:	S/N:	
Location: Std CLRS		
Calibration:	Before Meas:	After Meas:
Start Time:	End Time:	
Weather Conditions:		
Ground Conditions/topography:		

Notes/observations (audible noises, line of sight, map, etc.)

Sta 70mph

– sounds loud + typical

↖Sta-NB HT-.022 87
MT .023 86
Cnv .024 87



HT .025 ↙Sta-SB HT .019 86
MT .024 MT .020 55
Cnv .027 Cnv .021 55

Results: (SPL's, dominant source(s), etc.)

5

Big Sky Acoustics, LLC
Field Noise Level Measurement Data Form

Project: Rumble Strip

BSA Project #: 19134

Name:

Date: 7/30/19

SLM:

S/N:

Response:

Calibrator:

S/N:

Location:
SCLRS 51

Calibration: ✓

Before Meas: ✓

After Meas:

Start Time: 0844

End Time: 0954

Weather Conditions:
see below

Ground Conditions/topography:
level, slope to borrow pit, grass/weeds

Notes/observations (audible noises, line of sight, map, etc.)

57

30mph

HT - 085942 .034 0851 - MP
MT - .035
Car -

- insects .036

HT . 028 - ~~[illegible]~~ engine. N8 rumble.
MT . 029
Car - 030 - faint rumble

N →

51 - 5B HT - 031 - engine
MT - 032 - engine
Car - 033 - faint rumble

Results: (SPL's, dominant source(s), etc.)

~~[illegible]~~ 79°, 68%, calm weather
0840

Page 1 of 3
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6

Big Sky Acoustics, LLC
Field Noise Level Measurement Data Form

Project:

BSA Project #:

Name:

Date:

SLM:

S/N:

Response:

Calibrator:

S/N:

Location:
SCLRS S1

Calibration:

Before Meas:

After Meas:

Start Time:

End Time:

Weather Conditions:

Ground Conditions/topography:

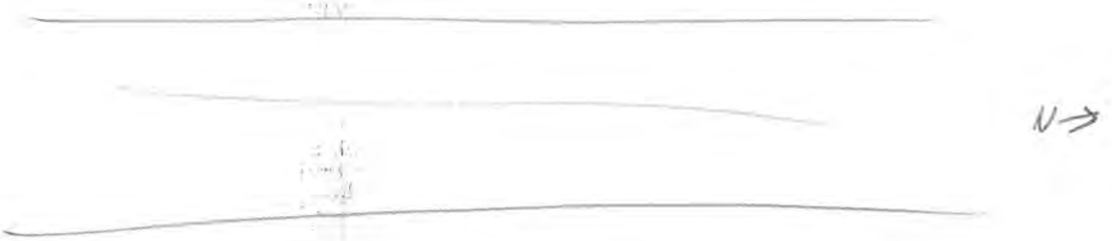
Notes/observations (audible noises, line of sight, map, etc.)

S1

50mph

@S1-NB

HT - 040
MT - 041
Car - 042



engine, no audible — HT - 043
- faint audible MT - 044
- faint rumble Car - 045

@S1-SB

HF - 037
MT 038
Car - 039

- ~~[illegible]~~ little audible; not much
- engine
- very little audible

Results: (SPL's, dominant source(s), etc.)

0915 - 84°F, 50%, (calm - 3mph), weather

Big Sky Acoustics, LLC
Field Noise Level Measurement Data Form

Project: Rumble Strip
BSA Project #:
Name:
Date: 7/30/19
SLM:
S/N:
Response:
Calibrator:
S/N:
Location: SCLRS S1
Calibration:
Before Meas:
After Meas:
Start Time:
End Time:
Weather Conditions:
Ground Conditions/topography:

Notes/observations (audible noises, line of sight, map, etc.)

S1

70mph

HT 052
on? N yes - MT 053
on? yes - Car 054 74
yes

@S1-NB
HT 046 - moving truck around
MT 047 - engine mostly
Car 048 - may not be team on strip 74

@S1-SB
HT - 049
MT - 050 - engine
Car - 051 - on it that time 78
- first rumble

- insects (both sides)
- strip pushing vehicles around
- "hard to stay on strip"

Results: (SPL's, dominant source(s), etc.)

0945 - 82°F, 53% RH, 1 mph weather

S1 Page 3 of 3

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Big Sky Acoustics, LLC
Field Noise Level Measurement Data Form

Project: Rumble Strip		BSA Project #: 19134
Name:		Date: 7/30/19
SLM:	S/N:	Response:
Calibrator:	S/N:	
Location: SCLRS 52		
Calibration:	Before Meas: ✓	After Meas: ✓
Start Time: 1103	End Time: 1142	
Weather Conditions: see below		
Ground Conditions/topography: level, slope to borrow pit, tall grasses/weeds		

Notes/observations (audible noises, line of sight, map, etc.)

52

30mph

HT - 055 - no rumble (NB) 72
MT - 056 - no rumble (NB) 64
Car - 057 - no rumble (NB) 62

HT -
MT -
Car -

⊗2-NB

HT - 058 (NB) 72
MT - 059 (NB) 67
Car - 060 (NB) 61

HT - 061 (SB) - 79 (passenger side)
MT - 062 (SB) - 70 "
Car - 063 (SB) - 63 "

Results: (SPL's, dominant source(s), etc.)

1100 - 87°F, 51%RH, calm

52 Page 1 of 3

Big Sky Acoustics, LLC
Field Noise Level Measurement Data Form

Project: [illegible]		BSA Project #:
Name:		Date: 7/30/19
SLM:	S/N:	Response:
Calibrator:	S/N:	
Location: SCLRS S2		
Calibration:	Before Meas:	After Meas:
Start Time:	End Time:	
Weather Conditions:		
Ground Conditions/topography:		

Notes/observations (audible noises, line of sight, map, etc.)

HT: 064 (NB) - 067 (SB) 070 (NB)
MT: 065 (NB) - 069 (SB) 071 (NB)
AV: 066 (NB) - 069 (SB) 072 (NB)

Results: (SPL's, dominant source(s), etc.)

10

Big Sky Acoustics, LLC
Field Noise Level Measurement Data Form

Project: Rumble		BSA Project #:
Name:		Date:
SLM:	S/N:	Response:
Calibrator:	S/N:	
Location: SCLRS 52		
Calibration:	Before Meas:	After Meas:
Start Time:	End Time:	
Weather Conditions:		
Ground Conditions/topography:		

Notes/observations (audible noises, line of sight, map, etc.)

HT - 073 (NB) - 076 (SB) 079 (NB)
mT - 074 (NB) - 077 (SB) 080 (NB)
Car - 075 (NB) - 078 (SB) 081 (NB)
- no variable for any vehicle

Results: (SPL's, dominant source(s), etc.)

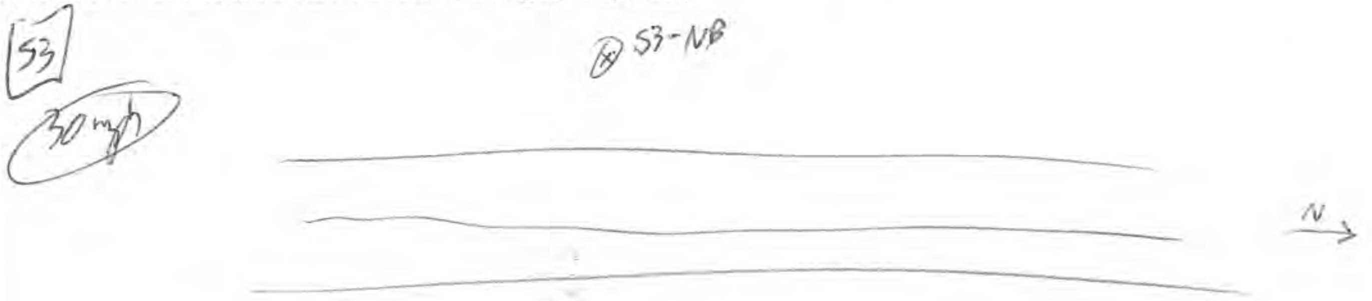
Big Sky Acoustics, LLC
Field Noise Level Measurement Data Form

Project: Rumble		BSA Project #: 19134
Name:		Date: 7/30/19
SLM:	S/N:	Response:
Calibrator:	S/N:	
Location: SCLRS S3		
Calibration: ✓	Before Meas: ✓	After Meas:
Start Time: 1206	End Time: 1244	

Weather Conditions:
see below

Ground Conditions/topography:
level, slope to borrow pit, tall grasses/weeds

Notes/observations (audible noises, line of sight, map, etc.)



HT - 082 (NB) - 085 - 088

MT - 083 (NB) - 086 - 089

Car - 084 (NB) - 087 - 090 (faint rumble)

- no rumble for any vehicles

-

Results: (SPL's, dominant source(s), etc.)

12

Big Sky Acoustics, LLC
Field Noise Level Measurement Data Form

Project: Rumble strip		BSA Project #:
Name:		Date: 7/30/19
SLM:	S/N:	Response:
Calibrator:	S/N:	
Location: SCLRS 53		
Calibration:	Before Meas:	After Meas:
Start Time:	End Time:	
Weather Conditions:		
Ground Conditions/topography:		

Notes/observations (audible noises, line of sight, map, etc.)

HT - 091 (NB) - 094 (NB) - 097

MT - 092 (NB) - 095 (NB) - 098

Car - 093 (NB) - 096 (NB) - 099

- no rumble

Results: (SPL's, dominant source(s), etc.)

1215 - 92°F, 41% RH, calm - 3mph

53 Page 2 of 3

Big Sky Acoustics, LLC
Field Noise Level Measurement Data Form

Project: Rumble
BSA Project #:
Name:
Date: 7/30/19
SLM:
S/N:
Response:
Calibrator:
S/N:
Location: SCLRS 53
Calibration:
Before Meas:
After Meas:
Start Time:
End Time:
Weather Conditions:

Ground Conditions/topography:

Notes/observations (audible noises, line of sight, map, etc.)

HT - 100 (NB) - 103 - 106
MT - 101 (NB) - 104 - 107
Car - 102 (NB) - 105 - 108 → little, faint rumble

- no rumble for vehicles
-

Results: (SPL's, dominant source(s), etc.)

53

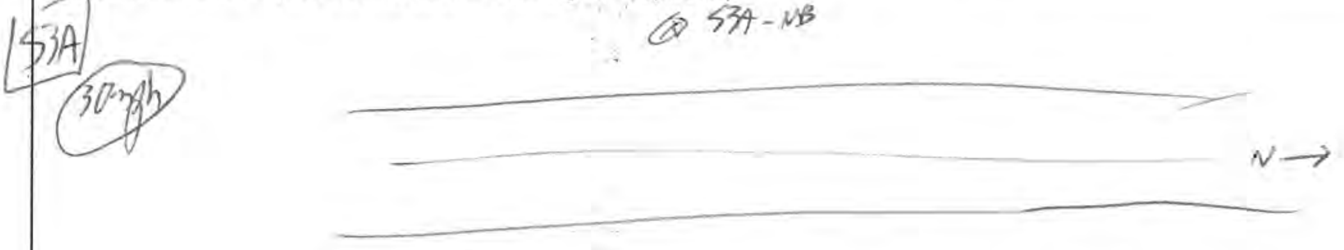
14

Big Sky Acoustics, LLC
Field Noise Level Measurement Data Form

Project: Rumble		BSA Project #:
Name: SC		Date: 7/30/19
SLM:	S/N:	Response:
Calibrator:	S/N:	
Location: SCLRS S3A		
Calibration:	Before Meas: ✓	After Meas: ✓
Start Time: 1301	End Time: 1335	
Weather Conditions: see below		
Ground Conditions/topography: level, slope to borrow pit, tall grasses/weeds		

Notes/observations (audible noises, line of sight, map, etc.)

@ S3A - NB



HT - 109 - louder; truck shaking — 112 - can hear rattle (faint) — 115

MT - 110 - — 113 — 116

Car - 111 - not much "rumble" — 114 — 117

- "can feel vibration more than others"

Results: (SPL's, dominant source(s), etc.)

1305: 92°F, 39% RH, calm - 3mph S

Page 1 of 3

S3A

Big Sky Acoustics, LLC
Field Noise Level Measurement Data Form

Project: Rumble Strip

BSA Project #:

Name:

Date: 7/30/19

SLM:

S/N:

Response:

Calibrator:

S/N:

Location: SCLRS S3A

Calibration:

Before Meas:

After Meas:

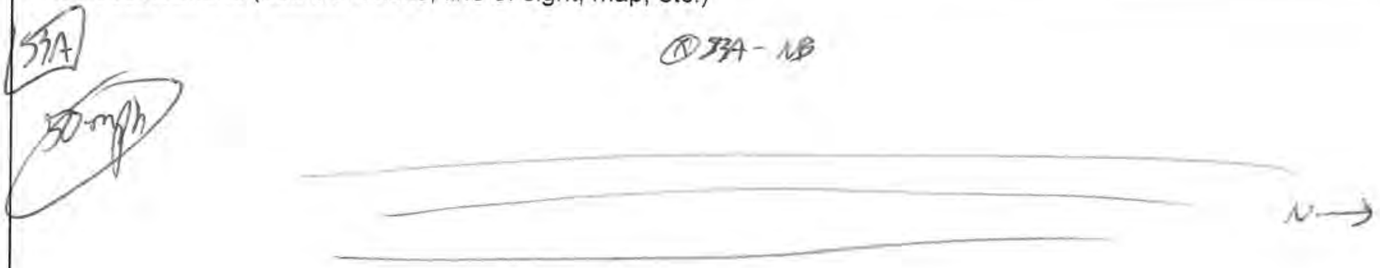
Start Time:

End Time:

Weather Conditions:

Ground Conditions/topography:

Notes/observations (audible noises, line of sight, map, etc.)



HT - 118 — 121 — 124

MT - 119 — 122 = 125

Car - 120 (rumble, but faint) — 123 — 126

Results: (SPL's, dominant source(s), etc.)

S3A

Big Sky Acoustics, LLC
Field Noise Level Measurement Data Form

Project: Rumble

BSA Project #:

Name:

Date: 7/30/19

SLM:

S/N:

Response:

Calibrator:

S/N:

Location: SCLRS S3A

Calibration:

Before Meas:

After Meas:

Start Time:

End Time:

Weather Conditions:

Ground Conditions/topography:

Notes/observations (audible noises, line of sight, map, etc.)

S3A

70mph

HT – 127 ~can see tires "bumping" – 130 – 133

MT – 128 – 131 – 134

Car – 129 – 132 – 135

- no "rumble"

"driver favorite" ⇒

Results: (SPL's, dominant source(s), etc.)

1330: 90°F, 40% RH, clm - 3mph S

Big Sky Acoustics, LLC
Field Noise Level Measurement Data Form

Project: Rumble Strip
BSA Project #: 19134
Name:
Date: 7/30/17
SLM:
S/N:
Response:
Calibrator:
S/N:
Location: 53A - NB Chipseal Pavement only
Calibration:
Before Meas: ✓
After Meas: ✓
Start Time: 1344
End Time: 1410
Weather Conditions: same as 53A
Ground Conditions/topography: same as 53A

Notes/observations (audible noises, line of sight, map, etc.)

Pavement & no Rumble Strip

@53A - NB

30 mph
HT - 136 (NB) - 139 (SB) - 142 (NB)
MT - 137 (NB) - 140 (SB) - 143 (NB)
Car - 138 (NB) - 141 (SB) - 144 (NB)

50 mph
HT - 145 (SB) - 148 (NB) - 151 (SB)
MT - 146 (SB) - 149 (NB) - 152 (SB)
Car - 147 (SB) - 150 (NB) - 153 (SB)

Results: (SPL's, dominant source(s), etc.)

70 mph
HT - 154 (NB) - 157 (SB) - 160 (NB)
MT - 155 (NB) - 158 (SB) - 161 (NB)
Car - 156 (NB) - 159 (SB) -

Cal chk: 1411 - 114.1 dB

Page 1 of 1

Chipseal Pavement

Rumble Strip Wayside Noise Study Fieldwork

Driver Notes

Date: 7/30/19

Passenger Vehicle
Equipment: 2018 Toyota 4 Runner

Rumble Strip Design	Speed	Car			Medium Truck			Heavy Truck			Notes & Met Data
		Time/ L_{max}	Time/ L_{max}	Time/ L_{max}	Time/ L_{max}	Time/ L_{max}	Time/ L_{max}	Time/ L_{max}	Time/ L_{max}	Time/ L_{max}	
SCLRS S1	30 mph	0847	0855	0900	0846	0854	0859	0844	0853	0858	hard to stay on strip steering wheel vib
	50 mph	0907	0912	0919	0906	0911	0918	0905	0910	0916	quieter, a bit than 30mph steering wheel vib pushing car off strip
	70 mph	0929	0941	0954	0928	0940	0951	0927	0939	0950	quieter than 30 mph louder than 50 mph higher freq than S2
SCLRS S2	30 mph	1105	1109	1111	1104	1108	1111	1103	1107	1110	Quietest yet (interior)
	50 mph	1115	1116	1120	1115	1116	1120	1114	1117	1119	very quiet
	70 mph	1132	1137	1142	1131	1136	1142	1141	1135	1130	lower freq than S1
SCLRS S3	30 mph	1207	1211	1214	1206	1211	1214	1206	1210	1213	more noise edge of strip - scalloped More noise/vib side front of seat
	50 mph	1219	1224	1228	1219	1224	1228	1218	1223	1227	same as 30 mph noise & vib in front of vehicle
	70 mph	1232	1238	1244	1232	1237	1243	1231	1236	~~[illegible]~~ 1242	this design didn't throw veh off strip like S1 did
SCLRS S3A	30 mph	1302	1305	1308	1301	1305	1308	1301	1304	1307	lots of vibration! driver favorite!
	50 mph	13	1317	1320	13	~~1319~~ 1317	~~1317~~ 1320	13	1316	1319	quieter & less vib than 30 mph
	70 mph	1327	1331	1335	1327	1331	1335	1326	1330	1334	good noise & vib louder than 50 mph a little less than 30 mph
Std CLRS	30 mph	0726	0732	0738	0725	0731	0737	0724	0730	0736	low rumble interior
	50 mph	0748	0753	0759 ✓	0747	0752	0758	0745	0750	0757	louder, shaking not see video
	70 mph	0805 ✓	0811 ✓	0819	0804	0810	0817 MDT	0802	0809	0816	rock & roll baby see video
Dry ~~Pa~~ Pavement	30 mph	1345	1347	1349	1345	1347	(ccafe arrived) 1349	1344	1346	1348	dry pavement for comparison to all strips
	50 mph	1351	1353	1355	1350	1352	1354	1350	1352	1354	
	70 mph	1400	1404	1408	1400	1403	1408	1359	1403	1407	

Rumble Strip Wayside Noise Study Fieldwork

Driver Notes

Date: 7/30/19

Rumble Strip Design	Speed	Car			Medium Truck			Heavy Truck			Medium Truck Equipment: 2007 Dodge Ram Dually 3500
		Time/ L_{max}	Time/ L_{max}	Time/ L_{max}	Time/ L_{max}	Time/ L_{max}	Time/ L_{max}	Time/ L_{max}	Time/ L_{max}	Time/ L_{max}	Notes & Met Data
SCLRS S1	30 mph				X	X	X				Very hard to Stay on
	50 mph				X	X	X				Smooth
	70 mph				X	X	X				Very Rough Pushed truck
SCLRS S2	30 mph				X	X	X				Smooth / Quiet
	50 mph				X	X	X				very little vibration
	70 mph				X	X	X				↓
SCLRS S3	30 mph				X	X	X				Smooth quiet - a little more vibration
	50 mph				X	X	X				than S2 To Smooth & quiet!
	70 mph				X	X	X				↓
SCLRS S3A	30 mph				X	X	X				Good * Sound & Vibrations
	50 mph				X	X	X				more quiet & smoother than 30mph
	70 mph				X	X	X				Better than ** 50 & 30 mph
Std CLRS	30 mph				X	X	X				Loud vibrations
	50 mph				X	X	X				↓
	70 mph				X	X	X				↓

Rumble Strip Wayside Noise Study Fieldwork Driver Notes											Date: 7/30/19
Rumble Strip Design		Car			Medium Truck			Heavy Truck			Heavy Truck Equipment: 2000 Volvo 999 Truck Tractor
	Speed	Time/ Lmax	Time/ Lmax	Time/ Lmax	Time/ Lmax	Time/ Lmax	Time/ Lmax	Time/ Lmax	Time/ Lmax	Time/ Lmax	Notes & Met Data
SCLRS S1	30 mph							✓	✓	✓	30 (quiet very smooth)
	50 mph							✓	✓	✓	smooth hear rumble strips better than 30mph
	70 mph							✓	✓	✓	rumble even louder pushing & pulling the truck
SCLRS S2	30 mph							✓	✓	✓	little vibration/ noise
	50 mph							✓	✓	✓	little vibration/ noise
	70 mph							✓	✓	✓	little vibration / noise
SCLRS S3	30 mph							✓	✓	✓	very quiet
	50 mph							✓	✓	✓	(Hardly noticable)
	70 mph							✓	✓	✓	
SCLRS S3A	30 mph							✓	✓	✓	Better than S1/S2/ & S3
	50 mph							✓	✓	✓	at all speeds in terms of rumble strips
	70 mph							✓	✓	✓	being more noticable inside truck for noise and vibration
Std CLRS	30 mph							✓	✓	✓	
	50 mph							✓	✓	✓	
	70 mph							✓	✓	✓	