EVALUATING THE PERFORMANCE OF SINUSODIAL RUMBLE STRIPS

TRB ADC 40: MID YEAR MEETING
JUNE 27TH, 2018

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Problem Statement

• Roadway departure crashes account for 66% of all highway fatalities in Oregon (FHWA, 2010).

• The noise and vibration generated by rumble strips (RS) alerts drivers when they are departing the traveled way.

• Shoulder rumble strips (SRS) reduce run-off-road (ROR) fatal injury crashes by 33% and all ROR crashes by 15% (Torbic et al, 2009).

• Even though they are inexpensive to install, easy to maintain, and have a very long service life, it is not always possible to install RS on many roadway segments due to noise concerns.
Project Scope

• The study evaluates the feasibility of using sinusoidal RS as a substitute for traditional milled RS on roadway segments with lane departure crash problems.

• A quantitative and empirical comparison of the in-vehicle noises and vibrations and roadside noises of sinusoidal and traditional RS will indicate if the sinusoidal pattern provides sufficient warning to drivers.

NCHRP 641 recommends a 6 to 12 dBA increase in noise to alert drivers that they are encroaching on a RS.
Rumble Strip Designs

Asphalt Shoulders

- Rounded
- Rectangular
- V-Shaped
- Tapered

Portland Cement Concrete Shoulders

- Corrugated

Rounded RS Designs (Bucko, 2001)
Rumble Strip Dimensions

RS Geometric Characteristics (Bucko, 2001)
## Tested Rumble Strip Geometry

<table>
<thead>
<tr>
<th>DIMENSION</th>
<th>DESCRIPTION</th>
<th>SITE A: SINUSOIDAL</th>
<th>SITE B: ROUNDED</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Gap between RS clusters</td>
<td>10’</td>
<td>10’</td>
</tr>
<tr>
<td>B</td>
<td>Length of RS cluster</td>
<td>28’</td>
<td>31’</td>
</tr>
<tr>
<td>C</td>
<td>Wavelength</td>
<td>16’”</td>
<td>12”</td>
</tr>
<tr>
<td>D</td>
<td>Length of individual RS mill</td>
<td>16”</td>
<td>8”</td>
</tr>
<tr>
<td>E-1</td>
<td><strong>Depth of RS mill at trough</strong></td>
<td>3/8”</td>
<td>1/2”</td>
</tr>
<tr>
<td>E-2</td>
<td>Depth of RS mill at crest</td>
<td>1/16”</td>
<td>0”</td>
</tr>
<tr>
<td>F</td>
<td>Distance between edge of lane line and inside edge of RS mill</td>
<td>12”</td>
<td>6”</td>
</tr>
<tr>
<td>G</td>
<td><strong>Width of RS mill</strong></td>
<td>14”</td>
<td>9.5”</td>
</tr>
<tr>
<td>H</td>
<td>Distance between outside edge of RS mill and edge of pavement</td>
<td>7’</td>
<td>8’</td>
</tr>
</tbody>
</table>

**RS Field Measured Geometric Characteristics**
Tested Rumble Strips

RS Comparison

Site A: Sinusoidal

Depth: 3/8”

14”

Site B: Rounded

Depth: 1/2”

9.5”
Research Design: Exterior Performance Measures

\[ \Delta \text{Traditional dB} = \text{RS Strike dB} - \text{Background dB} \quad (1) \]

\[ \Delta \text{Sinusoidal dB} = \text{RS Strike dB} - \text{Background dB} \quad (2) \]

\[ \text{Sinusoidal Noise Reduction} = \sum \Delta \text{Traditional dB} - \sum \Delta \text{Sinusoidal dB} \quad (3) \]

For all frequencies where RS strike dB > Background dB
Research Design: Interior Performance Measures

\[ \Delta \text{Traditional Alert dB} = \text{RS Strike dB} - \text{Alert Threshold dB} \]  
\[ (4) \]

\[ \Delta \text{Sinusoidal Alert dB} = \text{RS Strike dB} - \text{Alert Threshold dB} \]  
\[ (5) \]

\[ \text{Percent Reduction in Driver Alert} = 1 - \frac{\sum \Delta \text{Sinusoidal Alert dB}}{\sum \Delta \text{Traditional Alert dB}} \]  
\[ (6) \]

For all frequencies where RS strike dB > Background dB
Research Design: Vibration Performance Measure

Interior haptic feedback will be evaluated based on the procedure developed by Dulaski and Noyce in 2016.

The average acceleration will be tabulated for each axis (X, Y, and Z) for each acceleration signature as shown, as well as the variance and standard deviation.

Analysis of Variance (ANOVA) will be used to evaluate the difference between the strike and background condition.
Site Selection Guidelines based on AASHTO SIP Method

- Site should be away from intrusive noises, like railroads, construction sites, or airports.
- No Reflecting Surfaces
  - Includes parked vehicles, signboards, buildings, guardrails, etc.
  - 100' Radius
- Roadway Geometry
  - Level & Straight
  - Avoid Intersections or Ramps
- Roadway Surface
  - Homogenous Surface Condition & Type
  - Free of Gravel or Debris
- Clear Zone
  - 25' Microphone
  - 87'
  - 120°
  - 50' Microphone
  - No Obstructions
  - Flat & Acoustically Hard
  - Minimum Foliage

Based on AASHTO SIP Method
Site Selection

To Portland

Site A
Sinusoidal
Boring, OR

Site B
Rounded
Sandy, OR

Site Locations for Testing (© OpenStreetMap contributors)
Research Design

Interior Sound Equipment Diagram

Based on SAE Standard J1477: Measurement of Interior Sound Levels of Light Vehicles for automotive testing & Ziaran, 2013

Interior Set Up:
Interior Sound Measurement
- Microphone should be placed 28 in +/- 2 in above the centerline of the seat, but no closer than 6 in from walls or upholstery.

- The microphone should be facing forward, in the direction of travel, and the seat shall be in the middle position of horizontal and vertical adjustments.

Microphone tripod shall be secured using a bungee chord or tie down strap.

Driver’s Seat
Passenger Seat
Sound Analyzer
Laptop Interface
Microphone
Crossover Cable
5m Cable

28” +/- 2”
Interior Noise Instrumentation
Research Design

Interior Vibration Equipment Diagram

**Interior Set Up:**
**Interior Vibration Measurement**
- Accelerometer is attached to steering column using adhesive gel
- Cable should be routed along dash to minimize interference to driver

Based on Bucko, 2001 & Dulaski, 2006
Interior Vibration Instrumentation
Research Design

Exterior Sound Equipment Diagram

Based on AASHTO’s Statistical Isolated Pass-By (SIP) Method

Roadside Set Up:
Exterior Sound Measurement
- Use 100’ measuring tape, surveyor’s rod and level to locate Tripods
- Personnel and Equipment should be behind 50’ microphone to avoid interference

Meteorological Equipment
Wind Sensor Mounted on Tripod

Handheld Radar Gun

Cone to Indicate
Beginning of RS Strike

Cone to Indicate
End of RS Strike
Exterior Noise Instrumentation
Vehicle Types Tested: Passenger Car

2017 Ford Focus Hatchback
Vehicle Types Tested: Van

2015 Dodge Grand Caravan Striking the Sinusoidal RS
Vehicle Types Tested: Heavy Vehicle

Volvo VHD Dump Truck
Vehicle Types Tested: Heavy Vehicle

Heavy Vehicle Interior Microphone Setup
## Factor Groups

<table>
<thead>
<tr>
<th>VEHICLE TYPE</th>
<th>RUMBLE STRIP TYPE</th>
<th>CONDITION</th>
<th>EXTERIOR</th>
<th>INTERIOR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Passenger Car</td>
<td>Sinusoidal</td>
<td>Baseline</td>
<td>3</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Strike</td>
<td>3</td>
<td>13</td>
</tr>
<tr>
<td></td>
<td>Rounded</td>
<td>Baseline</td>
<td>3</td>
<td>13</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Strike</td>
<td>3</td>
<td>12</td>
</tr>
<tr>
<td>Van</td>
<td>Sinusoidal</td>
<td>Baseline</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Strike</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>Rounded</td>
<td>Baseline</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Strike</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>Heavy Vehicle</td>
<td>Sinusoidal</td>
<td>Baseline</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Strike</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Rounded</td>
<td>Baseline</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Strike</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td><strong>Subtotal</strong></td>
<td><strong>39</strong></td>
<td></td>
<td><strong>75</strong></td>
</tr>
<tr>
<td></td>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td><strong>114</strong></td>
</tr>
</tbody>
</table>

Total Data Collected
Exterior Measurement: Passenger Car

Passenger Car Frequency Comparison

Peak around 80 Hz

Strike

Baseline
Exterior Measurement: Passenger Car

Passenger Car dB Histogram Comparison

- Strike
- Baseline
- Additional High dB

Increase in specific dB
Exterior Measurement: Passenger Car

Strike Average 90.3 dB(A)
Baseline Average 83.9 dB(A)

Baseline
Strike

Passenger Car Rounded RS Exterior Sound Measurement
Exterior Measurement: Passenger Car

Strike Average 87.1 dB(A)
Baseline Average 85.3 dB(A)

Passenger Car Sinusoidal RS Exterior Sound Measurement
Interior Measurement: Passenger Car

Strike Average 104.8 dB(A)
Baseline Average 99.0 dB(A)
Average Alert 5.8 dB(A)

Passenger Car Sinusoidal RS Interior Sound Measurement
## Factor Groups Measurements

<table>
<thead>
<tr>
<th>VEHICLE TYPE</th>
<th>RUMBLE STRIP TYPE</th>
<th>CONDITION</th>
<th>EXTERIOR Avg dBA</th>
<th>INTERIOR Avg dBA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Passenger Car</td>
<td>Sinusoidal</td>
<td>Baseline</td>
<td>84.6</td>
<td>99.0</td>
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<tr>
<td></td>
<td></td>
<td>Strike</td>
<td>87.1</td>
<td>104.8</td>
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<td></td>
<td>Rounded</td>
<td>Baseline</td>
<td>83.9</td>
<td>100.4</td>
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<tr>
<td></td>
<td></td>
<td>Strike</td>
<td>90.3</td>
<td>111.8</td>
</tr>
<tr>
<td>Van</td>
<td>Sinusoidal</td>
<td>Baseline</td>
<td>85.9</td>
<td>96.9</td>
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<td></td>
<td></td>
<td>Strike</td>
<td>86.0</td>
<td>101.2</td>
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<td></td>
<td>Rounded</td>
<td>Baseline</td>
<td>89.4</td>
<td>96.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Strike</td>
<td>94.2</td>
<td>107.0</td>
</tr>
<tr>
<td>Heavy Vehicle</td>
<td>Sinusoidal</td>
<td>Baseline</td>
<td>88.5</td>
<td>101.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Strike</td>
<td>94.5</td>
<td>108.1</td>
</tr>
<tr>
<td></td>
<td>Rounded</td>
<td>Baseline</td>
<td>91.6</td>
<td>103.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Strike</td>
<td>95.0</td>
<td>104.0</td>
</tr>
</tbody>
</table>
Exterior Measurement Comparison

Exterior Measurement for Different Vehicle Type

Delta = Strike dBA – Baseline dBA

Delta Strike

PCERD
PCESD
VERD
VESD
HVERD
HVESD

Delta Strike

5.4798
3.06855
4.64734
-0.210619
2.21168
5.72873

Delta Strike

0
-2
-4
-6
-8
-10

0
2
4
6
8
10

Portland State University

Oregon State University
Interior Measurement for Different Vehicle Type

Interior Alert Levels

Delta Strike/No-Strike dB (A)

PCIRD  PCISD  VIRD  VISD  HMIRD  HMISD

Interior Measurement: Alert Levels
Questions?

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Exterior Measurement: Passenger Car

Time Series (3 seconds)

dB(A)

Rounded Strike
Sinusoidal Strike
Rounded Baseline
Sinusoidal Baseline

Passenger Car RS Exterior Comparison
Exterior Measurement: Van

Van RS Exterior Comparison

Time Series (3 seconds)

Rounded Strike
Sinusoidal Strike
Rounded Baseline
Sinusoidal Baseline

dB(A)
Exterior Measurement: Heavy Vehicle

Heavy Vehicle RS Exterior Comparison

Time Series (3 seconds)

dB(A)

Rounded Strike
Sinusoidal Strike
Rounded Baseline
Sinusoidal Baseline

Heavy Vehicle RS Exterior Comparison
Interior Measurement: Passenger Car

Strike Average 111.8 dB(A)
Baseline Average 100.4 dB(A)
Average Alert 11.4 dB(A)

Passenger Car Rounded RS Interior Sound Measurement
**Interior Measurement: Passenger Car**

### Time Series (~10 seconds)

- **Rounded Strike**
- **Sinusoidal Strike**
- **Rounded Baseline**
- **Sinusoidal Baseline**

**Passenger Car RS Interior Comparison**
Interior Measurement: Van

Van RS Interior Comparison

- Rounded Strike
- Sinusoidal Strike
- Rounded Baseline
- Sinusoidal Baseline

Time Series (~10 seconds)
Interior Measurement: Heavy Vehicle

Time Series (~10 seconds)

Heavy Vehicle RS Interior Comparison