Nebraska Transportation Center

MID-AMERICA TRANSPORTATION CENTER

NDOR Nebraska Department of Roads

Report SPR-P1(15) M037

Final Report
26-1121-3010-001

In-Vehicle Evaluation of Milled Rumble Strips at Pre- and Post-Chip Sealed Maintenance Periods

Ernest Tufuor
Graduate Research Assistant
Department of Civil Engineering
University of Nebraska-Lincoln

Laurence R. Rilett, Ph.D, P.E.
Director, Nebraska Transportation Center
Department of Civil Engineering
University of Nebraska-Lincoln

Christopher LeFrois
ITS Sr. Transportation Technology Engineer
Nebraska Transportation Center
University of Nebraska-Lincoln

2017

Nebraska Transportation Center
262 WHIT
2200 Vine Street
Lincoln, NE 68583-0851
(402) 472-1975

"This report was funded in part through grant[s] from the Federal Highway Administration [and Federal Transit Administration], U.S. Department of Transportation. The views and opinions of the authors [or agency] expressed herein do not necessarily state or reflect those of the U.S. Department of Transportation."

In-Vehicle Evaluation of Milled Rumble Strips at Pre- and Post-Chip Sealed Maintenance Periods

Ernest Tufuor
Graduate Research Assistant
Department of Civil Engineering
University of Nebraska-Lincoln

Laurence R. Rilett, Ph.D., P.E.
Director, Nebraska Transportation Center
Department of Civil Engineering
University of Nebraska-Lincoln

Christopher LeFrois
ITS Sr. Transportation Technology Engineer
Nebraska Transportation Center
University of Nebraska-Lincoln

Report on Research Sponsored by

Nebraska Department of Roads

Nebraska–Lincoln

January 2017

Technical Report Documentation Page

<table>
<tr><td>1. Report No.
SPR-P1(15)M037</td><td>2. Government Accession No.</td><td colspan="2">3. Recipient's Catalog No.</td></tr>
<tr><td colspan="2" rowspan="2">4. Title and Subtitle
In-Vehicle Evaluation of Milled Rumble Strips at Pre- and Post-Chip Sealed Maintenance Periods</td><td colspan="2">5. Report Date
January 2017</td></tr>
<tr><td colspan="2">6. Performing Organization Code</td></tr>
<tr><td colspan="2">7. Author(s)
Ernest Tufuor, Laurence Rilett and Christopher LeFrois</td><td colspan="2">8. Performing Organization Report No.
26-1121-3010-001</td></tr>
<tr><td colspan="2" rowspan="2">9. Performing Organization Name and Address
Nebraska Transportation Center
2200 Vine Street
P. O. Box 830851
Lincoln, NE 68583-0851</td><td colspan="2">10. Work Unit No. (TRAIS)</td></tr>
<tr><td colspan="2">11. Contract or Grant No.</td></tr>
<tr><td colspan="2" rowspan="2">12. Sponsoring Agency Name and Address
Nebraska Department of Roads
1500 Hwy. 2
Lincoln, NE 68502</td><td colspan="2">13. Type of Report and Period Covered
May 2016 – August 2016</td></tr>
<tr><td colspan="2">14. Sponsoring Agency Code
MATC TRB RiP No.36250</td></tr>
<tr><td colspan="4">15. Supplementary Notes</td></tr>
<tr><td colspan="4">16. Abstract
Driver fatigue and drowsiness can have a profound impact on safety. Centerline and shoulder rumble strips (RS) are popular countermeasures designed to produce audible and tactile warning when vehicles deviate from the travel lane onto the RS. This reduces the risk of lane departure crashes.
Studies show that the noise produced by RS is a function of many variables. RS depth is known to have the greatest impact on alerting drivers. However, chip-seal pavement maintenance operations have the tendency to reduce the original RS design depth, which may have an impact on the functional effectiveness of the RS. The purpose of this paper is to conduct a controlled experiment to understand the relationship between milled RS depth and noise and vibration in the vehicle cab. In-vehicle noise and vibration levels were collected on five different RS depths (i.e., 1/8", 1/4", 3/8", 1/2" and 5/8"), on three RS types (i.e., shoulder, single centerline, and double centerline), on three highways in the state of Nebraska, and using two vehicles travelling at speeds of 45 mph, 55 mph, and 65 mph. RS depths at 1/8" intervals were used to simulate the influence of a chip-seal on the RS effectiveness. On the basis of the in-vehicle sound and vibration levels of all the tested RS depths, it was shown in this research that a 1/8" reduction in the current milled RS design depth, as a result of chip-sealing, does not result in a practical reduction in the RS effectiveness at producing audible and tactile warnings to alert drivers. Re-milling of rumble strips after chip sealing is therefore not recommended if the chip seal reduced the rumble strip depth by 1/8".</td></tr>
<tr><td colspan="2">17. Key Words
Milled rumble strips, depths, vehicle type and speed, sound, vibration</td><td colspan="2">18. Distribution Statement</td></tr>
<tr><td>19. Security Classif. (of this report)
Unclassified</td><td>20. Security Classif. (of this page)
Unclassified</td><td>21. No. of Pages
93</td><td>22. Price</td></tr>
</table>

Table of Contents

List of Figures

List of Tables

Acknowledgments

The authors would like to thank the research sponsor, the Nebraska Department of Roads, for their support and we acknowledge the contribution of Phil TenHulzen during data collection.

Disclaimer

Abstract

Driver fatigue and drowsiness can have a profound impact on safety. Centerline and shoulder rumble strips (RS) are popular countermeasures designed to produce audible and tactile warning when vehicles deviate from the travel lane onto the RS. This reduces the risk of lane departure crashes.

Studies show that the noise produced by RS is a function of many variables. RS depth is known to have the greatest impact on alerting drivers. However, chip-seal pavement maintenance operations have the tendency to reduce the original RS design depth, which may have an impact on the functional effectiveness of the RS.

The purpose of this report is to conduct a controlled experiment to understand the relationship between milled RS depth and noise and vibration in the vehicle cab. In-vehicle noise and vibration levels were collected on five different RS depths (i.e., 1/8", 1/4", 3/8", 1/2" and 5/8"), on three RS types (i.e., shoulder, single centerline, and double centerline), on three highways in the state of Nebraska, and using two vehicles travelling at speeds of 45 mph, 55 mph, and 65 mph. RS depths at 1/8" intervals were used to simulate the influence of a chip-seal on the RS effectiveness. On the basis of the in-vehicle sound and vibration levels of all the tested RS depths, it was shown in this research that a 1/8" reduction in the current milled RS design depth, as a result of chip-sealing, does not result in a practical reduction in the RS effectiveness at producing audible and tactile warnings to alert drivers.

Re-milling of rumble strips after chip sealing is therefore not recommended if the chip seal reduced the rumble strip depth by 1/8".

Chapter 1 Introduction

1.1 Background

Reduced driver reaction time, vigilance and ability to read or process traffic information are strongly correlated to driver fatigue and drowsiness which can have a negative impact on road safety. Drivers in this situation may drift out of their travel lane which increases the risk of lane departure crashes, head on and opposite-direction sideswipe collisions (FHWA, 2013). Rumble strips (RS) are provided on shoulders and/or centerlines as a safety countermeasure. The theory is that they alert drivers by producing audible and tactile warnings as drivers depart from their travel lane and cross over the RS. Intuitively, the larger the difference between the sound and vibration in the vehicle on the travel lane versus on the RS, the more successful the countermeasure will be.

The threshold of human hearing ranges from 10-12 Watt/m^2 to a max of 10^4 Watt/m^2. Because this range is wide the intensity is typically provided using the logarithmic decibel scale (0 dB – 160 dB). For example, 160 dB is 10^{16} as loud as 1 dB (Outcalt 2001). Talking is about 40 dB, lawn mower is 70 dB which is about 8 times louder than 40 dB. The outputs of sound level meters are adjusted for both intensity and frequency. The ‘A-weighting’ scale (dBA) is often used because it mimics the human ear by filtering low frequency noise from high intensities to avoid ear damage. This study will adapt to dBA. It has been found that human perception of 1 dBA is imperceptible. A change of 3 dBA is barely noticeable, while a 6 dBA or greater change is clearly noticeable. Current practice suggests that if RS can generate 3 to 15 dBA of noise above ambient conditions, then it will arouse an inattentive or drowsy driver (Torbic 2009). Harwood et al (1993) concluded that a noise differential of 6 to 10 dBA was created by RS depending on the pavement type.

The vibration from a RS is felt by the driver through the vehicle steering wheel, seat, and floor. The threshold of vibration perceptibility is not well-defined (Meyer et al. 2002). It varies widely based on numerous factors such as driver fitness, expectations, surrounding conditions etc. Approximate estimation of public transport passenger comfort reaction to whole body vibration has been predicted by the International Standards Organization (ISO 2631-1). Whole body implies to vibration in all directions and the root-sum of the squares of vibration measurements is used. In this index, the “not uncomfortable” category has a range from 0 to 0.315 m/s^2, the “little to fairly uncomfortable” category has a range from 0.315 m/s^2 to 1 m/s^2, the “uncomfortable to very uncomfortable” category ranges from 0.8 m/s^2 to 2.5 m/s^2 and the “extremely uncomfortable” category is above 2 m/s^2. Note that the ranges of these categories overlap.

The sound and vibration levels are highly correlated to the RS width and depth and also the vehicle speed (Khan et al. 1995). FHWA found that RS depth and width have the greatest effect on the alerting properties (FHWA 2011). However, pavement maintenance operations, such as chip seals, may change the original dimensions of RS design and the functional effectiveness of the RS may be impacted. The goal of the research is to measure the effect of different RS depths on the alerting properties of the RS.

1.1.1 Why Nebraska?

In 2002, the Nebraska Department of Roads (NDOR) constructed center line RS on two highway locations as an experiment. From the examination of cross-over crashes, there was a 64% decrease in total accidents and a 100% decrease in fatal crashes over a three-year period (NDOR 2007). This positive result has motivated the utilization of RS by NDOR whenever viable. A policy for the installation of milled RS was passed in 2011. It states that “…RS are not required to be reinstalled until the next resurfacing project or as directed by the District Engineer” (NDOR 2016). In this respect, understanding the performance of un-restored RS during post-maintenance periods is critical.

Figure 1.1 shows the NDOR recommended milled RS design. The recommended milled RS dimension is 3/8", 1/2", or 5/8" deep (e.g. dimension D), spans 6" or 7" (e.g. dimension C) and is either 12" or 16" wide (e.g. dimension B) on 12" spacing (e.g. dimension E). Note that there is no common description of RS dimensions and that each Department of Transportation (DOT) can use different terminology. For example, the National Cooperative Highway Research Program (NCHRP 641) would refer to dimension C as width and dimension B as length. For simplicity and clarity purposes the terms adopted by the NCHRP 641 will be used in this report. These terms are introduced in section 2.1. Note that the NDOR policy only applies to edge line and shoulder RS. For centerline RS the approach is to use the same policy but reduce the width to 6". The centerline RS may be single (e.g. one 6" width RS on the centerline of the road) or double (e.g. two 6" RS spanning the centerline of the road).

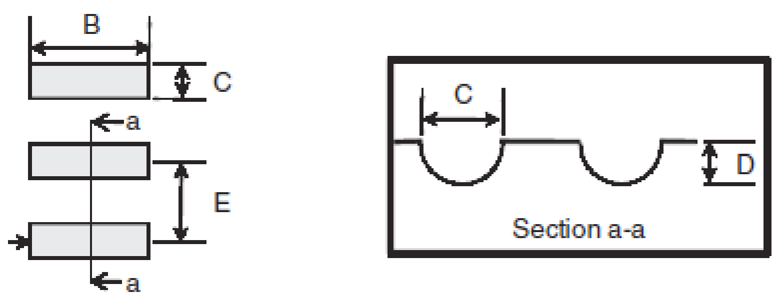


Figure 1.1 NDOR recommended milled RS

To date, there has been limited detailed research conducted on the relationship between RS depth and noise and vibration measurements within a cab. It is difficult to compare results of the existing research because of the varying location of the test instrument. There are two reasons why it is important to understand the relationship between RS depth, noise, and vibration in the Nebraska condition. The first is that NDOR has a choice on RS depth, and it is easy to hypothesize that the deeper the depth the more damage will be done to the pavement. Secondly, many common pavement maintenance practices, such as chip-sealing where a surface treatment combines one or more layers of asphalt with one or more layers of fine aggregate, may reduce RS depth. In this situation, it is unclear whether the RS will still be effective. Based on past experience, this study assumes that chip-sealing will reduce the RS depth by 1/8".

1.2 Research Objectives and Scope

This study measured the noise and vibration response as a function of RS depth, vehicle speed, and vehicle type on parallel-placed milled RS on asphalt pavement. The goal is to help provide an assessment of current NDOR policy on RS depth. The objective is to identify whether a decrease in the RS depth, in increments of 1/8" can still produce acceptable functional characteristics. The results will be used to determine when RS will need to be re-milled after pavement maintenance activities such as chip seals.

The research is focused on shoulder and centerline milled RS. NDOR's Pavement Manual considers 15 different flexible pavement treatments (NDOR 2002). The scope of this research is limited to Chip Seal flexible pavements and longitudinal RS that are placed parallel to the travel lane. In-cab vibration and noise measurements are compared as functions of RS depths, vehicle speed, and vehicle type.

1.3 Expected Benefits

This research provides the results between sound and vibration as a function of RS depth, vehicle speed and vehicle type and on milled RS. The results will be used to determine when RS will need to be re-milled after chip-sealing and to develop RS guidelines for highways expected to be chip-sealed in the future.

The research is also related to the US DOT's Strategic Goal of "enhancing safety". The findings will help provide operationally effective RS that serve the purpose of reducing accidents.

1.4 Report Organization

This report is organized into five chapters. Chapter 1 presents the background of the research, the problem, the research objectives and scope, the expected benefits, and the organization of the report. Chapter 2 provides an overview of the purpose, types and nomenclature of RS, the NDOR RS installation policy, pavement maintenance effects on RS performance, vehicle dynamics effects on vibration and noise levels and the magnitude and nature of crashes that can be prevented by RS. The data collection system is described in Chapter 3. Data analysis and key findings are discussed in Chapter 4. Chapter 5 provides the research conclusions and recommendations for future work.

Chapter 2 Literature Review

This chapter provides an overview of the purpose and types of RS, the NDOR installation policy, and maintenance and vehicle dynamic effects on the effectiveness of RS.

2.1 Purpose, Types and Nomenclature of RS

Hardwood (1993) describes a RS as a raised or grooved pattern installed on a pavement surface. A set of these can be placed parallel or perpendicular to the direction of travel. The latter placement type is used as a speed calming measure. This research is limited to the study of parallel placed RS with the purpose to alert drivers departing their travel lane. RS was first introduced in the United States in 1955 and was popularly referred to as 'singing shoulders'. There are four major categories of RS: raised, formed, rolled, and milled; which differ by shape, size, and installation method, as shown in table 2.1.

Table 2.1 Types of RS and installation (NCHRP 641, Hirasawa et al. 2005)

<table>
<tr><th>Installation</th><th>Raised</th><th>Rolled</th><th>Formed</th><th>Milled</th></tr>
<tr><td>Method</td><td>Use materials as strips that adhere to pavement surface</td><td>Grooves are formed in the hot asphalt surface with a roller or mold</td><td>Grooves in portland cement concrete surfaces</td><td>A milling machine cut grooves into pavement</td></tr>
<tr><td>When to apply?</td><td>Any time</td><td>During compaction of asphaltic pavement</td><td>During finishing process of the PCC surface</td><td>Any time</td></tr>
<tr><td>Remarks</td><td>Restricted to warmer climates</td><td colspan="2">Only applicable during construction or reconstruction stage</td><td>Easy to install and produces louder sounds and vibrations</td></tr>
</table>

Milled RS have been found to reduce injury crashes by 38%-50% and 37%-91% on rural and urban two-lane roads, respectively (FHWA 2011). Milled RS are the most common type used by NDOR. In 2004, NDOR evaluated the impact of RS and noted that milled RS resulted in a 64% reduction in cross-centerline accidents and 44% reduction in fatal and injury crashes with a benefit/cost ratio of 20 (NDOR 2015). Based on this positive result, NDOR began to install milled RS, where appropriate, on highways across Nebraska. The NDOR 2014 annual report indicates that over 2715 miles of Nebraska state highways have RS.

DOTs have a variety of terms that they use to describe the dimensions of RS. However, for simplicity and clarity purposes the following terms will be used in this report as adopted by the National Cooperative Highway Research Program (NCHRP 641). The nomenclature of the dimensions of RS placed on the shoulder is illustrated in figure 2.1.

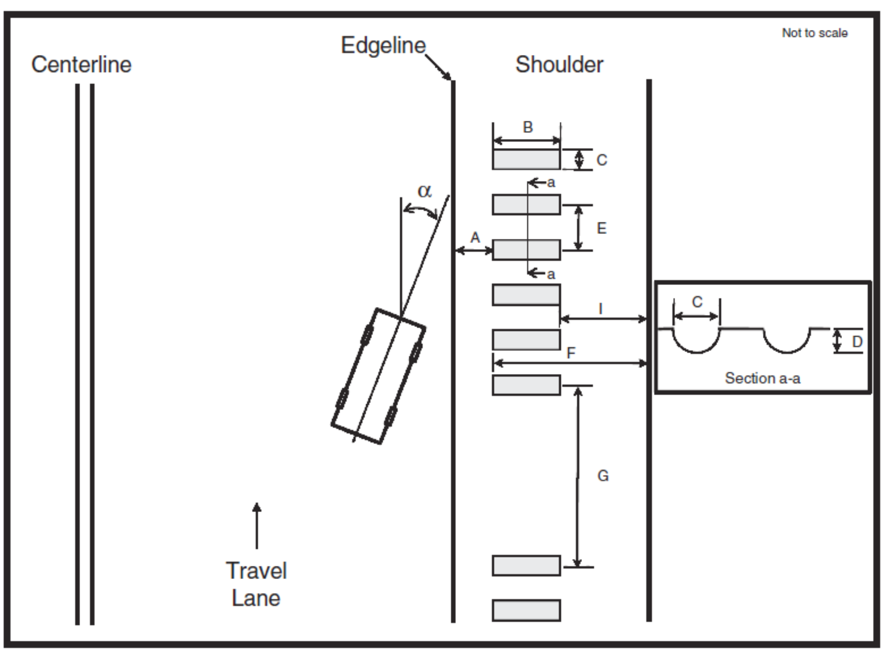


Figure 2.1 Parameters of shoulder RS.

SOURCE: (NCHRP 641)

The descriptions of the features are indicated in table 2.2. Note that if the RS is milled then the point D refers to depth, but if it is raised then it refers to height.

Table 2.2 Description of RS design parameters

Nomenclature		Description	Placement Types	
			Centerline	**Shoulder**
A	Offset	Distance between the edge of travel lane and the inside edge of the RS		√
B	Length	RS dimension measured lateral to the travel lane	√	√
C	Width	RS dimension measured parallel to the travel lane	√	√
D	Depth or Height	Vertical distance from the top of the travel lane to; a) the bottom of the RS if grooved or b) the top of a raised RS.	√	√
E	Spacing	Center-to-center distance between successive RS	√	√
F	Recovery area	Distance from the inside edge of the RS to the outside edge of the shoulder		√
G	Gap	Distance between groups of successive RS patterns	√	√
I	Clearance	F-B		√
α	Departure Angle	Degree of vehicle departure from the travel lane	√	√

NOTE: √ – parameter is critical

2.2 Rumble Strips Installation Policy

Different design and installation policies are adopted by various DOTs. The NDOR policy letter DES 14-01 (Appendix A) describes the policy regarding the installation of RS. The policy considers the installation of shoulder, edge line, and centerline RS to mitigate single vehicle run-off road and lane departure crashes. It provides a detailed outline on the guiding principles in installing RS. The policy further states that if maintenance operations cause a reduction in RS depth, the RS are not required to be reinstalled until the next resurfacing project. However, the RS may be restored earlier if directed by the District Engineer. To date, there has been no research to help guide this decision.

Table 2.3 summarizes some of the policies for the installation of milled RS in the United States. This is an extract from a survey conducted by NCHRP in 2009. The first and second columns indicate the state and the type of roadway. The third column provides some minimum requirements for installation and the fourth column presents the typical dimensions. It should be noted that because of the time frame and the research methodology adopted by the NCHRP, table 2.3 may not reflect the current policies of the states. However, table 2.3 does provide a good overview of the diverse nature of RS installation policies across states and cities.

Table 2.3 Summary of selected milled RS installation policies

State or City	Roadway Type	Shoulder width	Lateral clearance	Speed	Length	Width	Depth	Spacing
Alaska	Freeways, Expressways and two lane roads	6 ft	4 ft	45 mph	16 in.	7 in.	0.5 in.	12 in.
California	Rural freeways, expressways and two lane roads	4 ft	5 ft	-	12 in.	5 in.	0.32 in. ± 1.25 in.	12 in.
Florida	Freeways	-	-	-	16 in.	7 in. ± 0.5 in.	0.5 to 0.625 in.	12 in. ± 1 in.
Georgia	Freeways, multilane and two lane roads	4 ft	4 ft	-	16 in.	7 in.	0.5–0.625 in.	12 in.
Idaho	Freeways, multilane and two lane roads	3 ft	-	-	12– 18 in.	7 in. ± 0.5 in.	0.5–0.625 in.	12 in.
Iowa	Freeways, multilane and two lane roads	4 ft	-	-	16 in.	7 in.	0.5–0.625 in.	12 in.
Kansas	Rural highway	8-10 ft	-	-	16– 17 in.	7–8 in.	0.5 in.	12 in.

2.3 Pavement Maintenance Effects on Rumble Strips

It is known that the performance of milled RS as an alerting mechanism is directly correlated to RS depth and width (FHWA 2011). Intuitively, the pavement maintenance operations can negatively affect the operational effectiveness of RS by reducing the depth. The NDOR pavement maintenance manual (NDOR 2002) provides an overview of maintenance strategies and treatments for various pavement types. This report will be limited to flexible pavement as per the scope of the research. NDOR's flexible pavement maintenance decision matrix is as shown in figure 2.2.

There are many variables related to the selection, procedure, and materials for a particular treatment. However, all these treatments may influence the effectiveness of the RS. Invariably, edge/shoulder repair, such as patching, resealing, and overlays, will have the greater impact in reducing RS depth.

Flexible Pavement	Low		Moderate		High	
Distresses	Occasional	Frequent	Occasional	Frequent	Occasional	Frequent
Alligator Cracking[2]	3,1	3,6	6,3,11,4	6,5	13,6,11	15,13
Edge Cracking	1,2	2,1	2,13	2,13	13	13
Longitudinal Cracking	2,1	2,6,1	2,6	2,6	13,2,6	6,2,13
Random/Block Cracking	2,1	2,3	2,6	2,6	6,11,12	12,6,14
Raveling/Weathering	3,1,6	3,6,5	6,4	6,7	6,11,5	6,12,11
Distortion	1,8,13	13,1,8	8,13,2	8,13,6,2	8,11,6,13	8,14,13
Rutting	1	1	8 + 6	8 + 6	8 + 6, 12	8,14,12
Excess Asphalt	1	1,6	6,1,8	6,8	8 + 6	8 + 6 or 12
Transverse Cracking	2,1	2	2,6	2,6	2,6	2,6,13

Pavement Treatments

1 Do Nothing
2 Crack Seal/Fill
3 Fog Seal
4 Scrub Seal (Broom Seal)
5 Slurry Seal
6 Chip Seal/Armor Coat
7 Micro Surfacing
8 Mill
9 Cold-in-place Recycle
10 Hot-in-place Recycle
11 Thin Cold Mix Overlay
12 Thin Hot Mix Overlay[3]
13 Patching
14 Thick Overlay
15 Total Reconstruction

[1] Based on recommendations of the eight District Maintenance Superintendents and Materials & Research Division. Treatments are listed based on the frequency with which they were selected. Only treatments shown are those which were selected by more than two of the group. Other possible treatments are listed on the pages showing the distresses.

[2] Effectiveness of treatments other than 13, 14 & 15 will be minimal and short-lived.

[3] Pavement Extension Program (PEP) projects are typically 2 inches thick and are considered the maximum thickness of this treatment.

Figure 2.2 NDOR Maintenance decision matrix

SOURCE: NDOR 2002

Several DOTs either mill the RS before applying the chip seal or place the chip seal over an existing RS (FHWA, 2011). The authors indicated that;

Michigan DOT has found that milling rumble strips to 5/8" depth prior to applying the chip seal provides good quality rumble strip and often a second chip seal over these rumble strips has adequate alerting noise and vibration without the need for the rumble strips to be re-milled.

In Idaho, standard practice is to install rumble strips before applying a chip seal. While they have installed rumble strips after applying the chip seal, they found that the milling process causes chips to unravel.

In Washington, standard practice is to install rumble strips before applying a chip seal due to experiences with delamination when the chip seal is placed prior to milling in the rumbles.

However, Montana DOT regularly chip seals and then mills rumble strips. Where the depth of the existing rumble strip is 5/8" (or greater), Montana DOT can perform the chip seal and not have to re-mill the rumble strips. Where existing rumble strip depth is 3/8" (or less), the DOT re-mills the rumble strips.

2.4 Vehicle Dynamics Effect on Noise and Vibration Levels

There are a variety of studies where researchers collect noise (audible) and vibration (tactile) data using different types of motor vehicles (Elefteriadou et al. 2000, Outcalt 2001, Bucko et al. 2001, Gardner et al. 2007). This section gives a summary of some major studies where the vibration and noise levels were measured in the vehicle cab as the vehicle traversed on the RS.

Chen et al. (2003) noted that the effectiveness of the performance of RS can be determined by the following function:

$$P = f(a_{d-}a_r, t_{d-}t_r) \tag{2.1}$$

Where P is the effectiveness of the rumble strip

a_d is the mean audible index of travel lane

a_r is the mean audible index of RS

t_d is the mean tactile index of travel lane

t_r is the mean tactile index of RS.

Hirasawa et al. 2005 performed a study in Japan, where they collected audible and tactile data by using a passenger car (station wagon) to traverse three RS patterns at speeds of 40, 60, 80 and 100 km/h. It was found that the mean audible and tactile measurements were at least 15 dBA and 10 dB greater than what was measurement while the vehicle was in the travel lane for all speeds examined.

Finley et al. 2007 examined both passenger car and commercial truck variations on different RS types. The test speeds were 55 and 70 mph. It was found that the geometric dimensions of the RS had the greatest contributing effect on the audible alerting properties of the RS. For example, the test truck on a milled RS resulted in a sound change of 2 dB and 13 dB for width of 4" and 8" respectively.

The state of the vehicle's passenger-side window (i.e. up or down) is known to affect the in-vehicle noise levels of about 2 dBA and 5 dBA at a speed of 30 mph and 50 mph, respectively (Torbic 2009). Most often, the researchers place the sound level measuring instrument in the cab at the ear level of the driver to collect sound data. An accelerometer is also often used by researchers in collecting vibration data. The position of the accelerometer can be on the steering column (Hirasawa et al. 2005), the steering wheel (Bucko et al. 2001) or on the floor of the vehicle (Outcalt 2001). Because the location of the device affects the results, it is difficult to compare results of the various vibration studies (Torbic 2009). It is important to understand the relationship between RS depth, noise and vibration in a cab under the Nebraska conditions.

The vibration of the right front-wheel was measured by Tye (1976), and Chen (1994) uses International Roughness Index (IRI) scale. Elefteriadou et al. (2000) used simulation modeling and measured the vertical and angular acceleration of the motor vehicle. In all of these studies there is no distinctive answer in determining the optimum dimensions of RS. However, it can be gathered that: 1) there are differences in the sound and vibration levels between cars and trucks, 2) the deeper or wider the RS the higher the sound and vibration levels in the cab.

The International Standards Organization (ISO) evaluation of human exposure to whole body vibration gives the vibration bandwidths as shown in table 2.4. The table shows overlapping range of values, that may stem from the fact that vibration perceptibility is not well defined (Meyer 2002).

Table 2.4 Human exposure to vibration (Source: ISO 2631-1)

Range	**Human exposure**
Less than 0.315 m/s^2	Not uncomfortable
0.315 m/s^2 to 0.63 m/s^2	A little uncomfortable
0.5 m/s^2 to 1 m/s^2	Fairly uncomfortable
0.8 m/s^2 to 1.6 m/s^2	Uncomfortable
1.25 m/s^2 to 2.5 m/s^2	Very uncomfortable
Greater than 2 m/s^2	Extremely uncomfortable

Chapter 3 Data Collection System

3.1 Methodology

The research methodology examined the effect of three major treatment categories (i.e. vehicle speed, vehicle type and RS depth) on two response variables (i.e. in-cab noise and vibration levels). Table 3.1 presents these variables and their sub-categories.

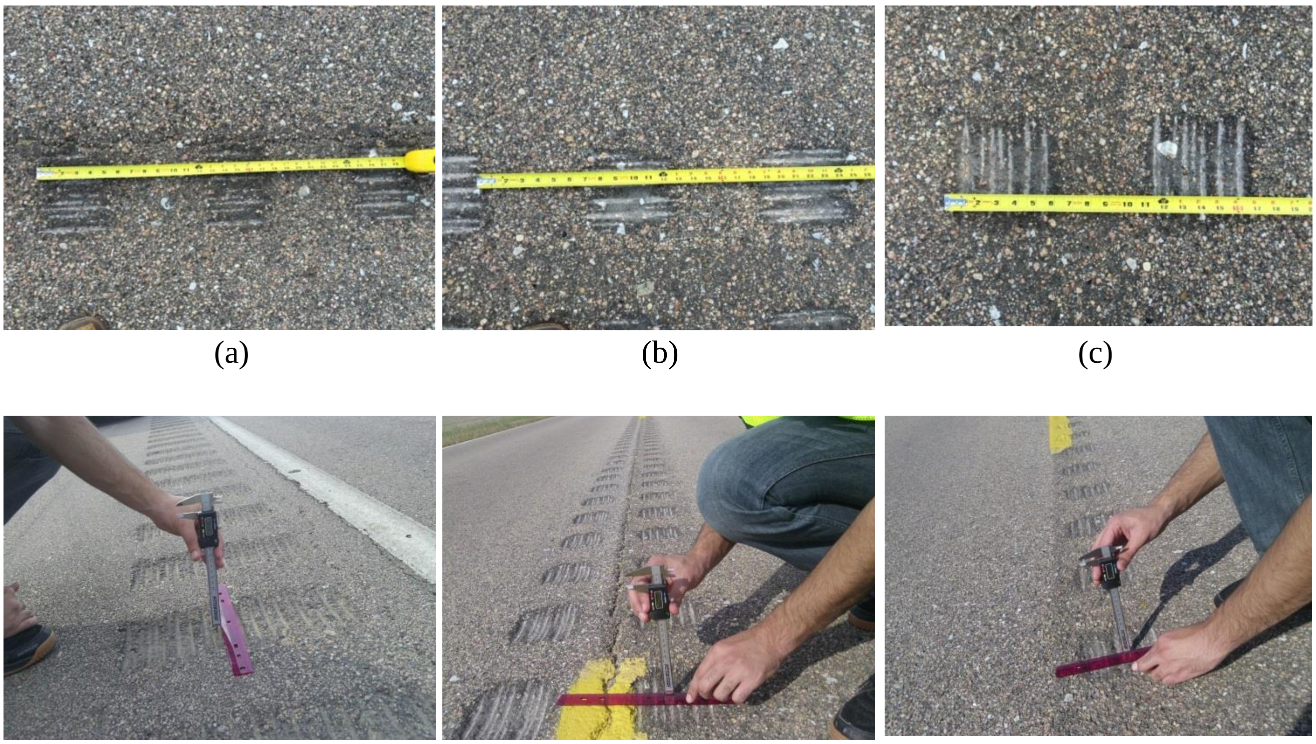
Table 3.1 Treatment and response variables

<table>
<tr><th>Treatment</th><th>Response 1</th><th>Response 2</th></tr>
<tr><td>Test Vehicle Speed
1. 45 MPH
2. 55 MPH
3. 65 MPH</td><td rowspan="3">Vehicle cab noise
(1 - when test vehicle is in travel lane and, 2 - when vehicle is on rumble strip)

A-weighted decibels (dBA)</td><td rowspan="3">Vehicle cab vibration
(1 - when test vehicle is in travel lane and, 2 - when vehicle is on rumble strip)

Vertical acceleration (m/s^2)</td></tr>
<tr><td>Rumble Strip Depth
1. 1/8 in.
2. 1/4 in.
3. 3/8 in.
4. 1/2 in.
5. 5/8 in.</td></tr>
<tr><td>Test Vehicles Type
1. Passenger Car
2. Pickup Truck</td></tr>
</table>

The tested RS had constant spacing and width. That is, 12" spacing (from center to center) and 6" wide for both single and paired RS as may be seen in figures 3.1 (a) and (b). The lateral spacing between paired RS in the centerline was also 6" as shown in figure 3.1 (c). Hence, the distance between the edges of the paired RS is about 18". The length of the shoulder RS was 16" but with the same spacing and width as the centerline. Typical measurements of RS depths are shown in figure 3.1 (d) to (f) and the dimensions summarized in Table 3.2. From figure 3.1, the pavement type may be seen as the flexible type with chip surface.



(a) (b) (c)

(d) (e) (f)

Figure 3.1 RS width and spacing for single centerline (a), double centerline-parallel to travel lane (b), perpendicular to travel lane (c) and depth measurements (d)-(f)

Table 3.2 Dimensions of Tested Rumble Strips

Location of Rumble Strips	**Dimensions**
1. Road Centerline **2.** Road Shoulders	1. 6" long, 6" wide, 12" spacing, and varying depths 2. 16" long, 6" wide, 12" spacing, and varying depths

3.2 Data Collection Instrument

The researcher developed a data collection system for obtaining the relevant field data. The system is portable and can be mounted on any vehicle. There were four (4) components in the system. The following provides detailed description of each of the components.

3.2.1 Noise Measurement

A Cel-63X sound meter was used to measure sound in decibels within the cab of the test vehicle. The sound level meter provides an octave band noise measurement that is compliant with international standards (CEL-63X User Manual). It has a digitally-derived true root-mean-square detection with 0.1 dB display resolution, a single measurement ranges up to 140.2 dBA, sampling rate of 67.2 kHz and a linearity range from 10 dB above noise floor (CEL-63X User Manual). It must be calibrated by the user before data collection. The instrument uses a data management software package to store and retrieve data. It was placed on the left side driver seat at approximately shoulder height as indicated by arrow A in figure 3.2.

3.2.2 Vibration Measurement

An Xsens MTi-G GPS, an inertial measurement unit, was used to measure the vibration in the form of vertical acceleration (in z-direction). It has a 3D orientation output with vibration measured at 10 kHz per channel equating to 60 kilo samples per seconds sampling rate (MTi-User Manual). The operating conditions are also suitable for the test locations and are designed to work with the precision specified in ISO 8041. In addition, the instrument is factory calibrated to continuously filter any biases that may affect the results (MTi-User Manual). The instrument was placed on the dashboard close to the steering wheel as indicated by arrow B in figure 3.2.

3.2.3 Video Cameras

A dual HD mirror cam video camera (F360) was used to capture in-vehicle activities and any surrounding interactions that may affect the measurements. It was located on the windshield above the rear-view mirror and was positioned to look back into the cab as indicated by arrow C in figure 3.2. A full HD contour camera with a waterproof case was used to capture the movement of the vehicle. It was placed on either the left or right fender of the front wheel (shown as D in figure 3.2) depending on whether the centerline or shoulder RS were being measured. In addition to the video output, the camera's inbuilt GPS provided visual confirmation of where and when the tire was making contact with the RS.

3.2.4 Computer/Timer

A laptop computer compactible to the instruments was used to synchronize the time stamp of all the components of the data collection system. The laptop time, which is automatically in sync with an internet time server (time.windows.com), was used as the base time. The laptop was placed on the lap of the data collector in the front passenger seat of the test vehicle. Snapshots of the locations where the instruments are placed during data collection are shown in figure 3.2.

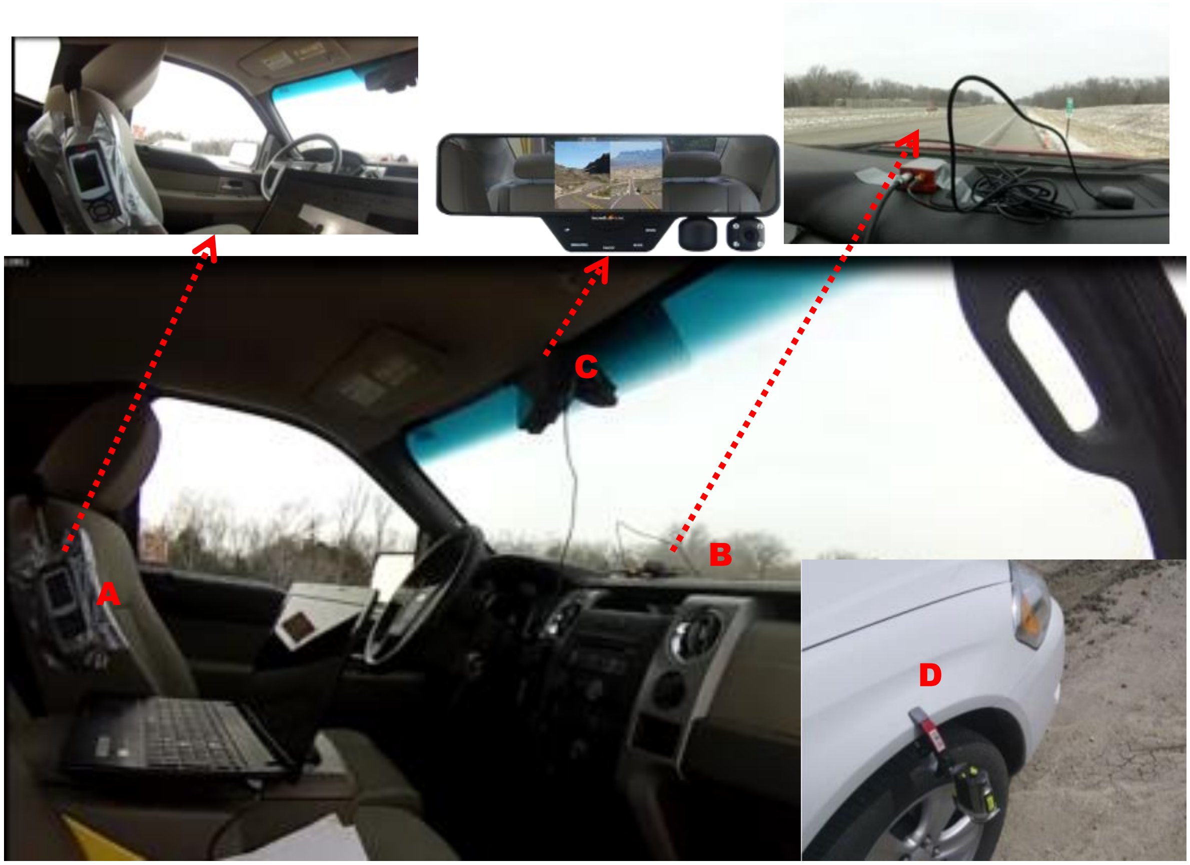


Figure 3.2 Data collection system

A closer view of the key data collection instruments is shown in figure 3.3. They are arranged in accordance to the labels in the data collection system setup shown in fig. 3.2.

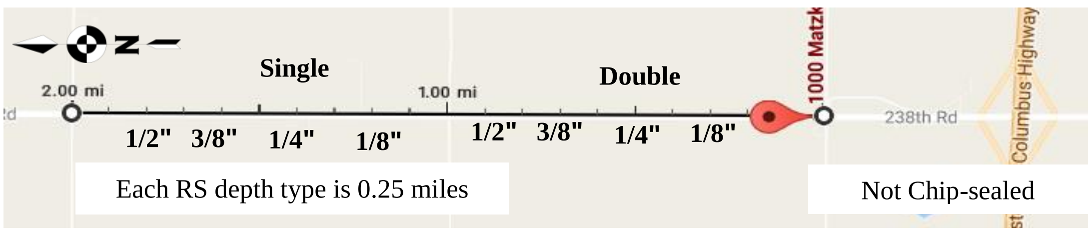
(a) SOURCE: (CEL-63X User Manual) (b) SOURCE: (MTi-G User Manual)

(c) SOURCE: (www.falconzero.com) (d) SOURCE: (http://eftm.com.au/)

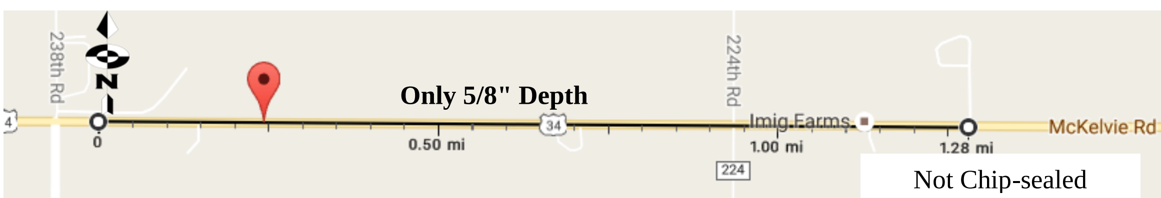
Figure 3.3 Sound meter (a), accelerometer (b), mirror cam (c), contour camera (d)

3.3 Data Collection Sites

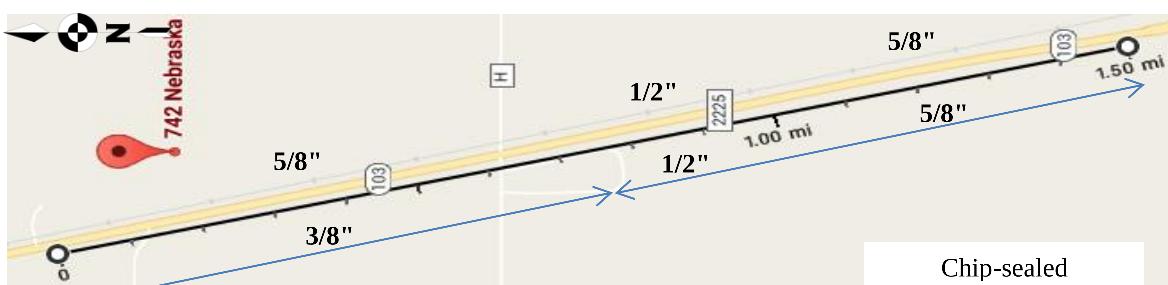
Data were collected on three roads in Nebraska as shown in figure 3.4. The sites were selected based on whether they had existing RS, and if not, whether RS of various depths could be installed. Test site 1 is 2.0 miles long and did not have existing RS. As part of this project a set of double and single RS of varying depths were milled near the centerline. Each set was arranged in ascending order of RS depth (1/8", 1/4", 3/8", and 1/2"). The dimensions for each RS was 6" long and 6" wide and were placed at 12" spacing. Test site 2 is 1.3 miles long and had existing milled RS on both shoulders of the highway. The RS had a 5/8" depth, a 16" length, a 6" width, and were installed at 12" spacing. Test site 3 is 1.5 miles long and has existing milled RS on both shoulders. The RS depths vary across the test section and had recently been chip-sealed. At the beginning of the test bed the RS were 5/8" deep, 16" long, and 6" wide on the northbound roadway. On the southbound roadway, the RS were 3/8"deep, 16" long, and 6" wide. From milepost 40.75, the RS changes to 1/2" deep and then ends with a depth of 5/8".



(a) Site 1: Milford 238th road – from Holdrege to Superior (milled centerline RS)



(b) Site 2: Highway 34 in Seward - milepost 303.0 to 304.28 (existing shoulders RS)



(c) Site 3: Nebraska highway 103 in Crete-milepost 40.0 to 41.50 (shoulders RS)

Figure 3.4 Site layout and depths of milled rumble strip.
SOURCE: google maps accessed on July 20, 2016

The driver of the test vehicle was instructed to drive on the RS near the center of each set of depth for at least 5 seconds and then return to the travel lane. The departure angle ranges from 5 to 10 degree. A typical field setup is shown in figure 3.5.

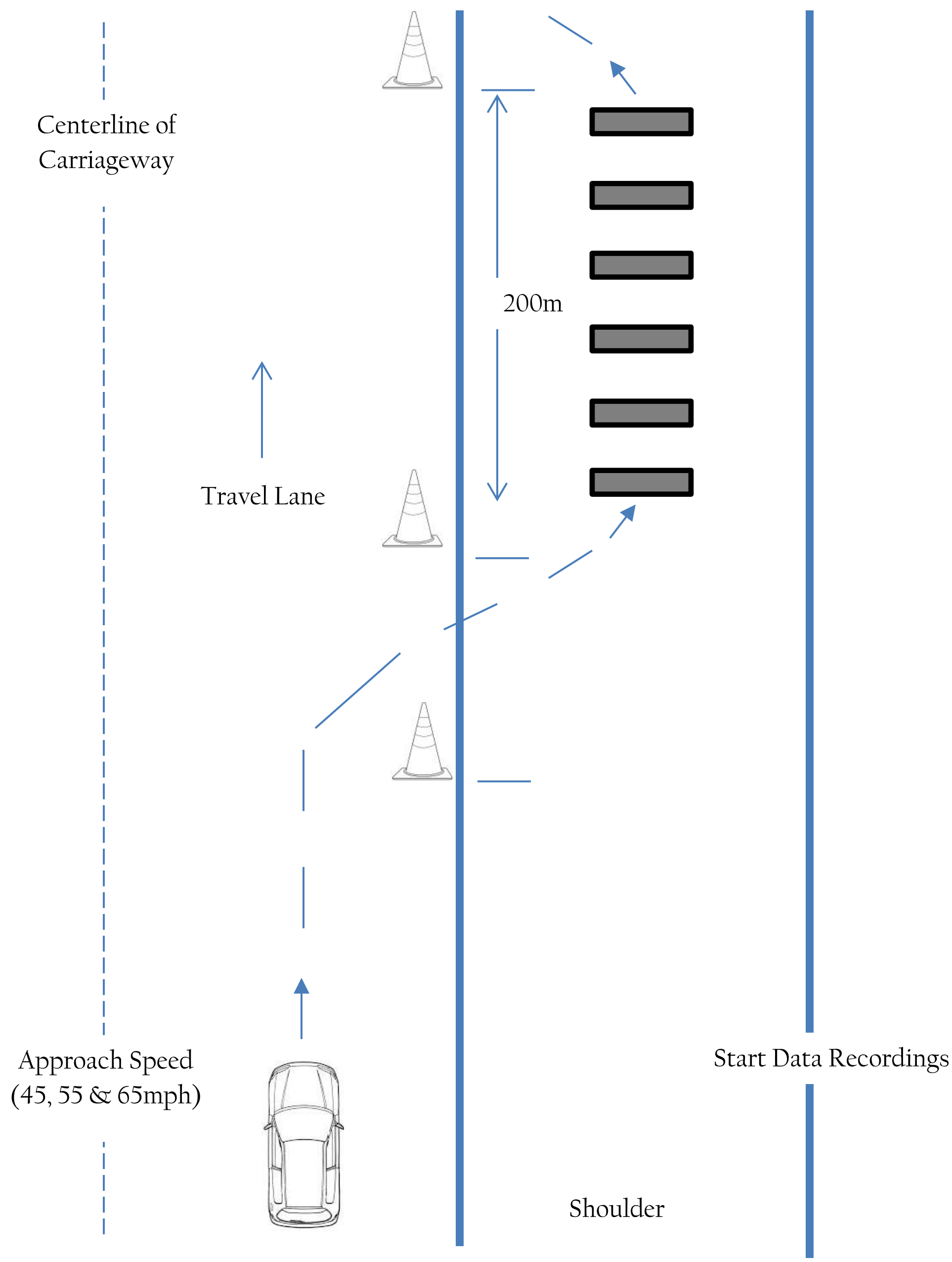


Figure 3.5 Field set up for data collection

A pre-test was conducted on the 18th April, 2016 in order to check the data collection system. The data collection was conducted on the 19th May, 2016 from 9:00am to 4:00pm. The weather was overcast and sunny with an average temperature of 66.9°F, 56% humidity, 10.5mph wind speed and barometric pressure of 30.09in Hg.

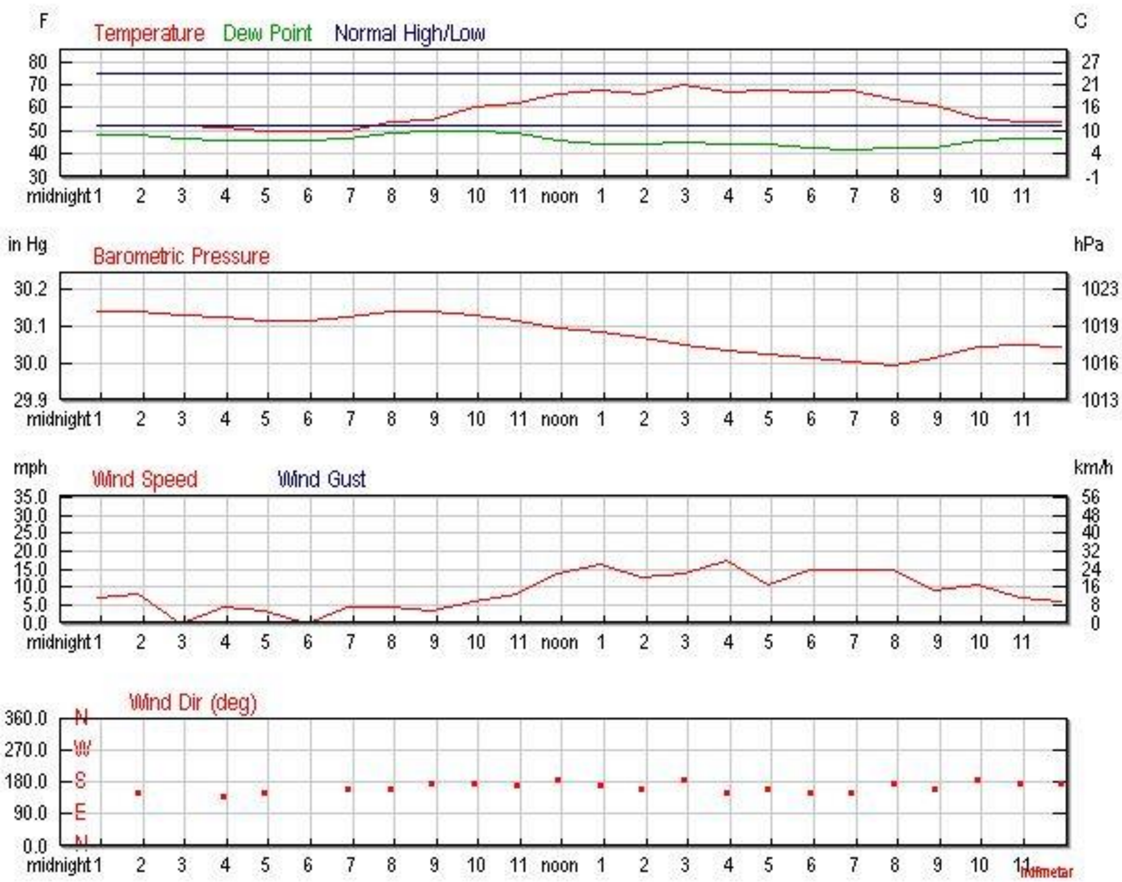


Figure 3.6 Weather conditions of test sites.
SOURCE: Weather underground (2016)

3.4 Data Collection Process

Two test vehicles were used in the study: a 2014 Chevrolet Impala and a 2014 Ford F150 pickup truck. Both vehicles were owned by NDOR, had low mileage (e.g. less than 30,000 miles), and were equipped with relatively new tires. These vehicles were selected to be representative of the two primary types of passenger vehicles found on Nebraska highways. During the data collection, the windows in the cab were rolled up and the radio turned off. This is not typical; however, in similar studies the radio is turned off to have a controlled test condition. Meyer et al (2002) tested two scenarios - (1) with radio on and (2) with radio off. The authors determined that though the radio increases the ambient noise level, the differences in the changes in sound level were similar; therefore, it is reasonable to assume that the differences in these ideal conditions are representative of the differences in a more realistic situation.

Both the sound meter and accelerometer were calibrated, and their time stamps were synchronized with the field video collecting system before data collection began. The laptop time, which was automatically synchronized with an internet time server located at time.windows.com, was used as the base time. All other units were synchronized to this time. The data from all the devices were stored during data collection. In addition, the data was displayed in real-time so that the researcher in the cab of the test vehicle could monitor the devices and ensure they were collecting data.

The test vehicles traversed each section at three speeds (45, 55, and 65 mph). A run was defined as a complete traversal (e.g. upstream to downstream) of a section. The driver was instructed to drive on the RS near the center of each set of depth for at least 5 seconds and then to return to the travel lane. This is referred to as a pass in this report. The driver was instructed to conduct as many passes as possible during a given run and each section had a minimum of two passes in a run. Each scenario (e.g. vehicle type, vehicle speed) had at least 3 runs.

Figure 3.7 shows a snapshot of the output of the data collection system during a test run. Part (a) shows the GPS output from the HD contour camera. This gives information on the speed, elevation, and distance travelled by the test vehicle. Part (b) shows the in-vehicle camera feed of the road section and in the cab. Part (c) indicates the view of the contact of the wheel with the RS, and part (d) indicates the vibration readings when the vehicle is in the travel lane (E) and on the RS (F).

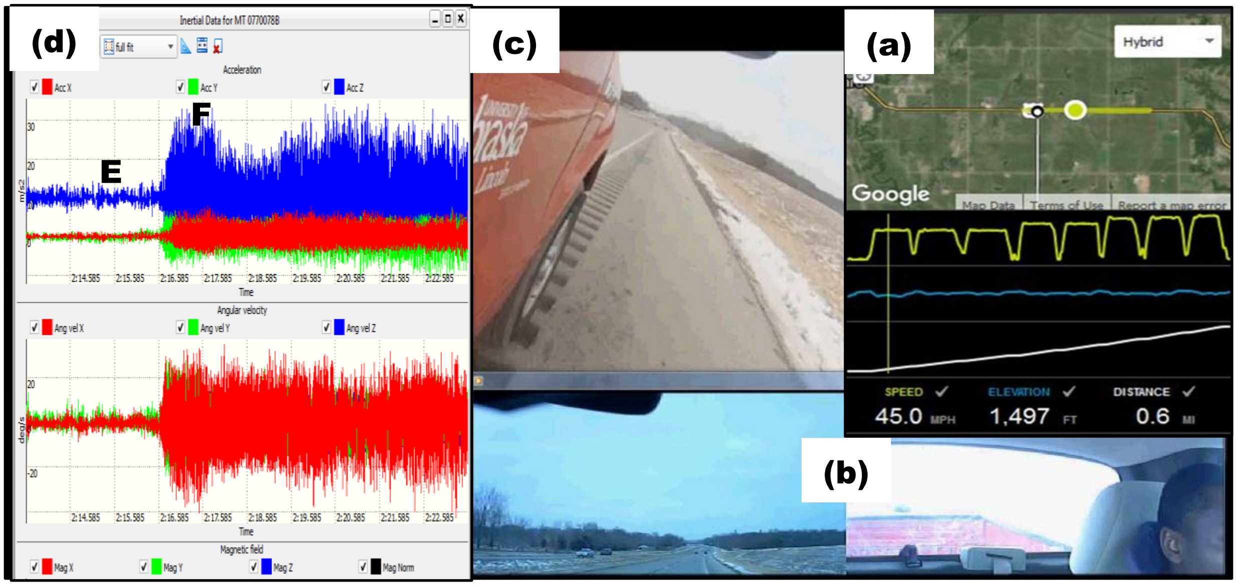


Figure 3.7 Snapshot of data collection system showing raw data for a given time

Once the data was collected, the first step was to disaggregate the data into two groups: (1) Group 1 was when the front tire was definitely off the RS (i.e. test vehicle was in the travel lane), and (2) Group 2 was when the test vehicle was definitely on the RS. To do this, the video was checked manually and the appropriate time periods were identified. The data was disaggregated accordingly and any data that did not belong to Group 1 or Group 2 was discarded. Table 3.3 gives information on the testing protocol for each of the three test sites.

Table 3.3 Testing protocol for each test site

Test Site	**Repetitive runs per vehicle**	**Number of Observations**			
		Group 1 (On Rumble Strips)		Group 2 (Off Rumble Strips)	
		Sound[1]	Vibration[2]	Sound[1]	Vibration[2]
1	Car • 7 runs (14 passes) at 45 mph • 7 runs (14 passes) at 55 mph • 5 runs (10 passes) at 65 mph Truck • 3 runs (6 passes) at 45 mph • 3 runs (6 passes) at 55 mph • 3 runs (6 passes) at 65 mph	24911	178340	18153	192114
2	Car • 4 runs (28 passes) at 45 mph • 2 runs (14 passes) at 55 mph • 2 runs (14 passes) at 65 mph Truck • 3 runs (21 passes) at 45 mph • 3 runs (21 passes) at 55 mph • 3 runs (21 passes) at 65 mph	7473	53502	5446	57634
3	Car • 3 runs (28 passes) at 45 mph • 2 runs (14 passes) at 55 mph • 2 runs (14 passes) at 65 mph Truck • 3 runs (21 passes) at 45 mph • 2 runs (14 passes) at 55 mph 3 runs (21 passes) at 65 mph	2242	16051	1634	17290

[1]Sound measured at 67.2 kHz
[2]Vibration measured at 10 kHz per channel equating to 60 kilo samples per seconds

Over 100,000 sound measurements and over 1,000,000 vibration measurements were recorded. Approximately 48% of this data was identified as belonging to Group 1 (i.e., on the RS) and 46% was determined to be in Group 2 (i.e., fully on the travel lane). The Group 1 noise and vibration data were further disaggregated by the five RS depths (i.e., 1/8", 1/4", 3/8", 1/2", and 5/8"). In addition, the six groups of data (i.e., travel land and five RS depths) were further disaggregated by the two vehicle types (i.e., car and truck), and the three vehicle speeds (i.e., 45 mph, 55 mph, and 65 mph). In total there were 36 data sets created.

It is important to note that during the data analysis the individual sections of the three test sites that had the same RS depth were analyzed separately (e.g., 5/8" RS depth on Highway 103 and 5/8" depth on Highway 34). It was found that there were no statistically significant differences in the data sets. It was concluded that the test site did not have an effect on the results and the data was subsequently aggregated by RS depth.

The second important point to note is, that the double centerline RS only acted as single RS from a data collection perspective because the vehicle tire could only make full contact with one RS at a time. For this reason, the data from the single and double RS were combined. That is, the 6" gap and 6" length of each RS implied 18" from edge to edge along the centerline of the carriageway. Meanwhile the widths of the front tire of the test vehicles are 8.9" and 9.6" for car and truck respectively. Consequently, this did not allow for full tire impact on both pairs of RS. Figure 3.8 shows the snapshot during data collection when the tire of the truck is on only one set of the paired RS. It was therefore reasonable to treat the paired type as a single RS. The only difference was that the paired version had twice the warning points at the same location on the carriageway.

Figure 3.8 Snap shot of test truck during data collection

Lastly, a pre and post chip-seal analysis was undertaken on test site 3. At this site, the shoulder RS were not completely filled during the chip-sealing, and therefore the same RS would have a depth of 1/2" close to the travel lane and 5/8" further from the travel lane. It was found that there was no statistical significant difference in the RS that had a milled 1/2" depth and the RS that had a 1/2" depth because of the chip-seal treatment. Consequently, the 1/2" depth RS measurements were aggregated. The decision to aggregate the data had no effect on the conclusions.

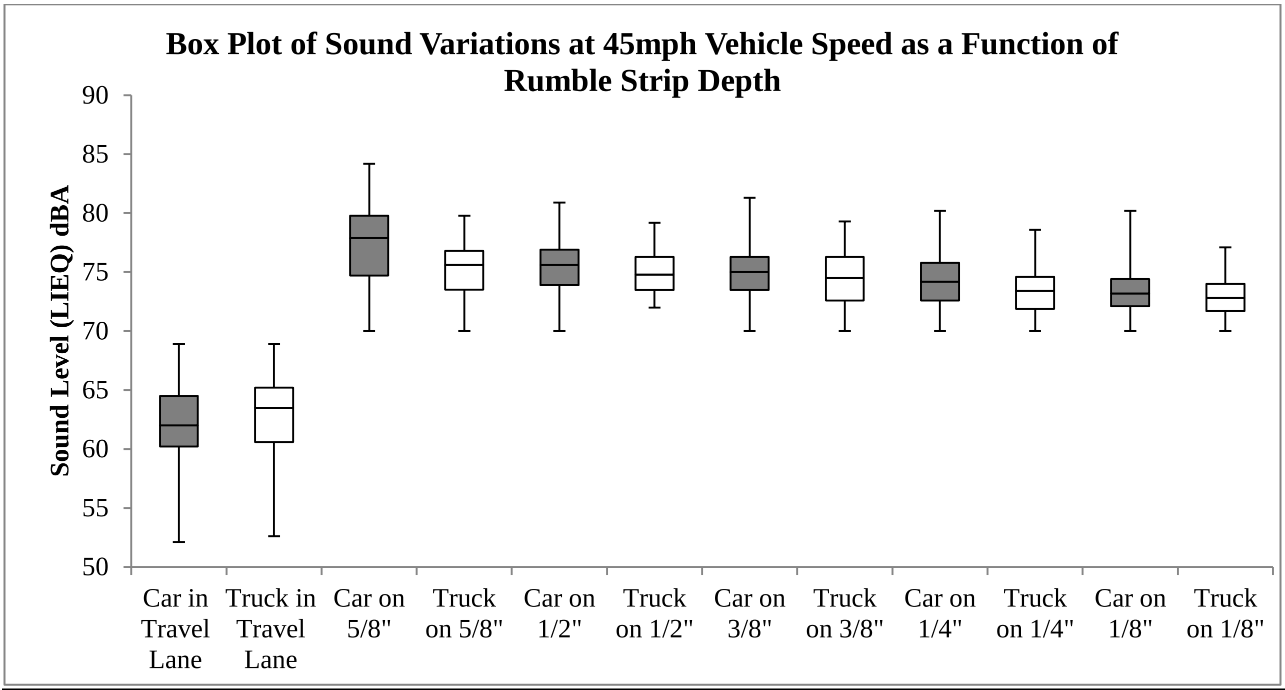
Chapter 4 Analysis and Results

This chapter presents the preliminary results of the sound and vibration data collection discussed in Chapter 3. It also analyzes and tests whether observed patterns are statistically significant and practically meaningful.

4.1 Preliminary Analysis of Results

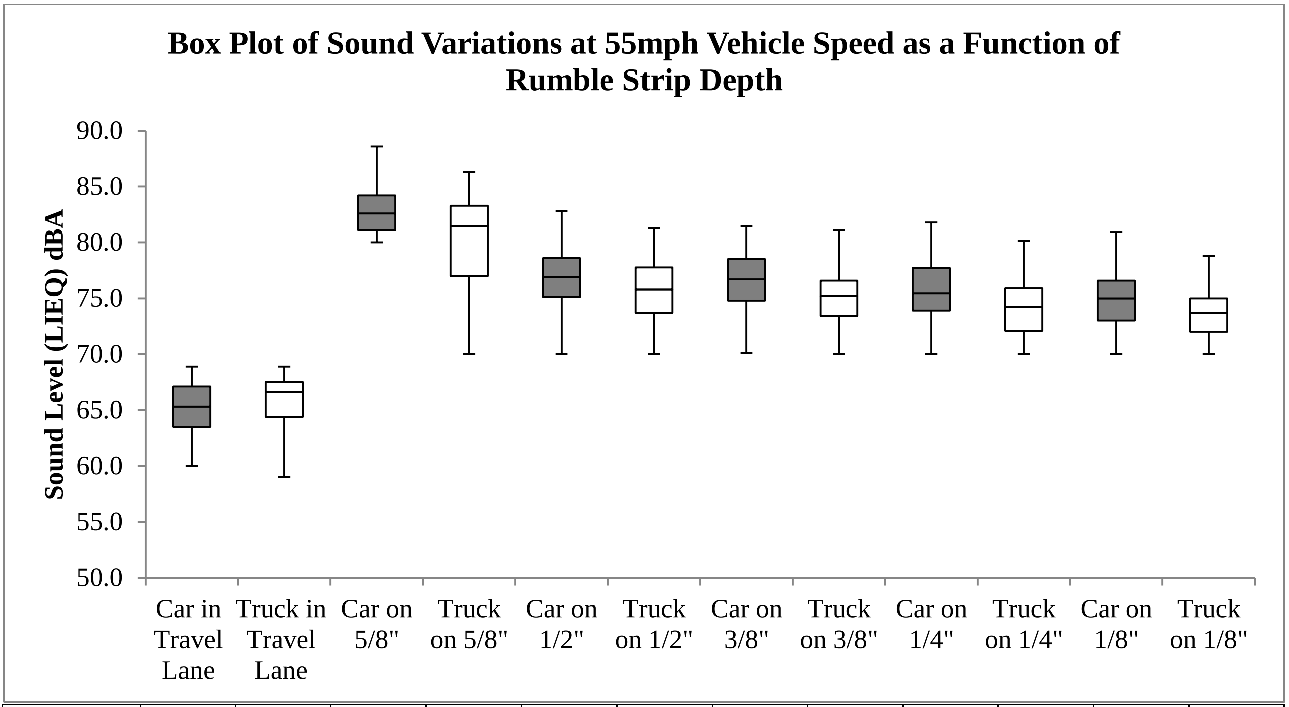
For ease of analysis, the sound and vibration responses to the effect of the independent variables (RS depth, vehicle speed, and vehicle type) for all the sites are presented as box plots as shown in figure 4.1, 4.2 and 4.3 for 45 mph, 55 mph and 65 mph, respectively. The centerline of the box plot shows the median. The bottom of the box represents the 25th percentile value while the top of the box represents the 75th percentile value.

It may be seen from the box plot that as speed increases so does the noise levels in the test vehicle. For example, for passenger car, the 1/2" RS results in a sound level of 75.6, 76.9 and 82.0 dBA for the 45, 55 and 65 mph speeds respectively. In addition, it may be seen that there is approximately 9-18 dBA increase in the in-cab noise level when the vehicle is traveling on the RS as compared to the base case (e.g. on the travel lane). Based on standard noise theory (Outcalt 2001) this difference would be noticeable by a typical driver. Anecdotally, the driver and the data collector both noted the change in noise level when the test vehicle was on the RS. It may be seen that there is a difference of approximately 2-5 dBA in responses when the sound levels from the various RS depths are compared. Not surprisingly, the deeper the RS the higher the sound levels. Both the test driver and data collector noted that it was difficult to ascertain the depth of the RS based on the noise level in the cab. It may also be seen that the car experiences higher in-vehicle noise levels when traveling on the RS compared to the truck. Interestingly, when the vehicles are on the travel lane this phenomenon is reversed as the truck experiences higher in-cab noise levels than the car.



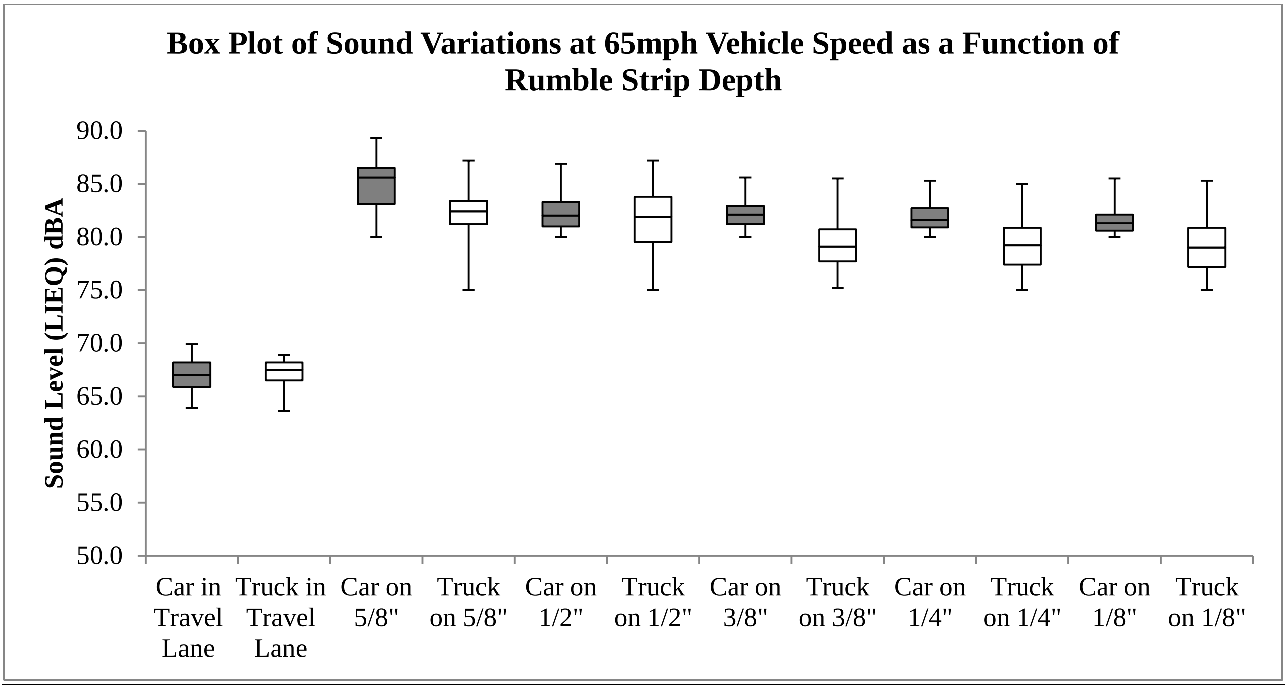
Minimum	52.10	52.60	70.00	70.00	70.00	72.00	70.00	70.00	70.00	70.00	70.00	70.00
First Quartile	60.20	60.58	74.70	73.53	73.90	73.50	73.50	72.60	72.60	71.90	72.10	71.70
Median	62.00	63.50	77.90	75.60	75.60	74.80	75.00	74.50	74.20	73.40	73.20	72.80
Third Quartile	64.50	65.20	79.80	76.80	76.90	76.30	76.30	76.30	75.80	74.60	74.40	74.00
Maximum	68.90	68.90	84.20	79.80	80.90	79.20	81.30	79.30	80.20	78.60	80.20	77.10
Mean	62.30	62.65	77.19	75.14	75.29	74.91	74.89	74.42	74.20	73.37	73.36	72.87
Standard Deviation	3.31	3.85	3.39	2.30	2.21	1.77	2.03	2.22	2.22	1.79	1.78	1.56
Skewness	-0.12	-0.73	-0.45	-0.44	-0.37	0.22	-0.15	-0.14	0.18	0.15	0.76	0.20
Count	11056	12869	1748	1863	1932	1890	1770	1891	1625	1862	1967	1444

Figure 4.1 Sound variations at 45 mph on travel lane and on RS of varying depth.



Minimum	60.00	59.00	80.00	70.00	70.00	70.00	70.10	70.00	70.00	70.00	70.00	70.00
First Quartile	63.50	64.40	81.10	77.00	75.10	73.70	74.80	73.40	73.90	72.10	73.00	72.00
Median	65.30	66.60	82.60	81.50	76.90	75.80	76.70	75.20	75.45	74.20	75.00	73.70
Third Quartile	67.10	67.50	84.20	83.30	78.60	77.75	78.50	76.60	77.70	75.90	76.60	75.00
Maximum	68.90	68.90	88.60	86.30	82.80	81.30	81.50	81.10	81.80	80.10	80.90	78.80
Mean	65.18	65.73	82.83	80.07	76.72	75.62	76.57	75.09	75.62	74.11	74.86	73.51
Standard Deviation	2.31	2.53	1.98	4.13	2.61	2.72	2.43	2.51	2.51	2.40	2.38	1.95
Skewness	-0.30	-1.11	0.52	-0.71	-0.42	-0.26	-0.29	0.00	-0.05	0.07	0.05	-0.05
Count	9986	10256	1493	1313	1424	1210	1494	1219	1476	1291	1445	1373

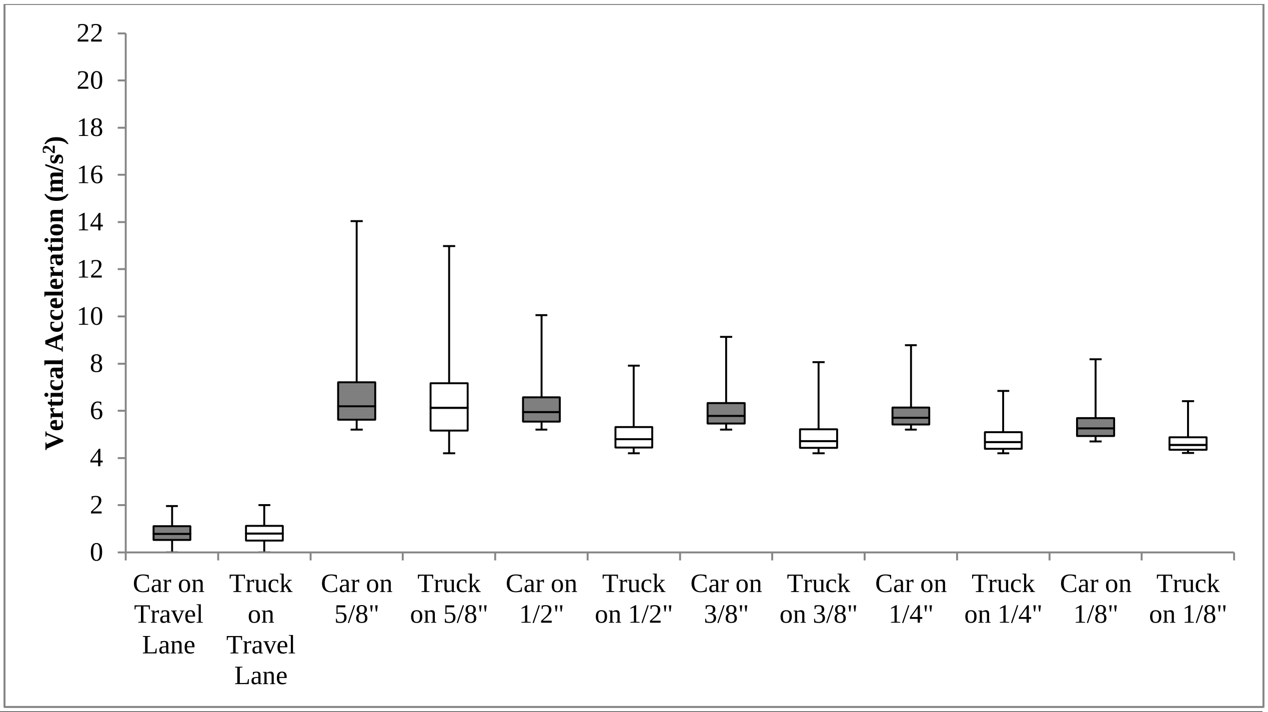
Figure 4.2 Sound variations at 55 mph on travel lane and on RS of varying depth.



Minimum	63.90	63.60	80.00	75.00	80.00	75.00	80.00	75.20	80.00	75.00	80.00	75.00
First Quartile	65.90	66.50	83.10	81.20	81.00	79.50	81.20	77.70	80.90	77.40	80.60	77.20
Median	67.00	67.50	85.60	82.40	82.00	81.90	82.10	79.10	81.60	79.20	81.30	79.00
Third Quartile	68.20	68.20	86.50	83.40	83.30	83.80	82.90	80.70	82.70	80.88	82.10	80.85
Maximum	69.90	68.90	89.30	87.20	86.90	87.20	85.60	85.50	85.30	85.00	85.50	85.30
Mean	66.98	67.16	84.78	82.17	82.26	81.59	82.10	79.32	81.82	79.27	81.48	79.15
Standard Deviation	1.51	1.35	2.20	2.02	1.52	2.83	1.18	2.27	1.20	2.35	1.14	2.43
Skewness	-0.10	-0.91	-0.69	-0.78	0.56	-0.30	0.25	0.42	0.47	0.25	1.00	0.42
Count	8254	9856	1492	1118	1408	1406	1499	1123	1482	1364	1315	1446

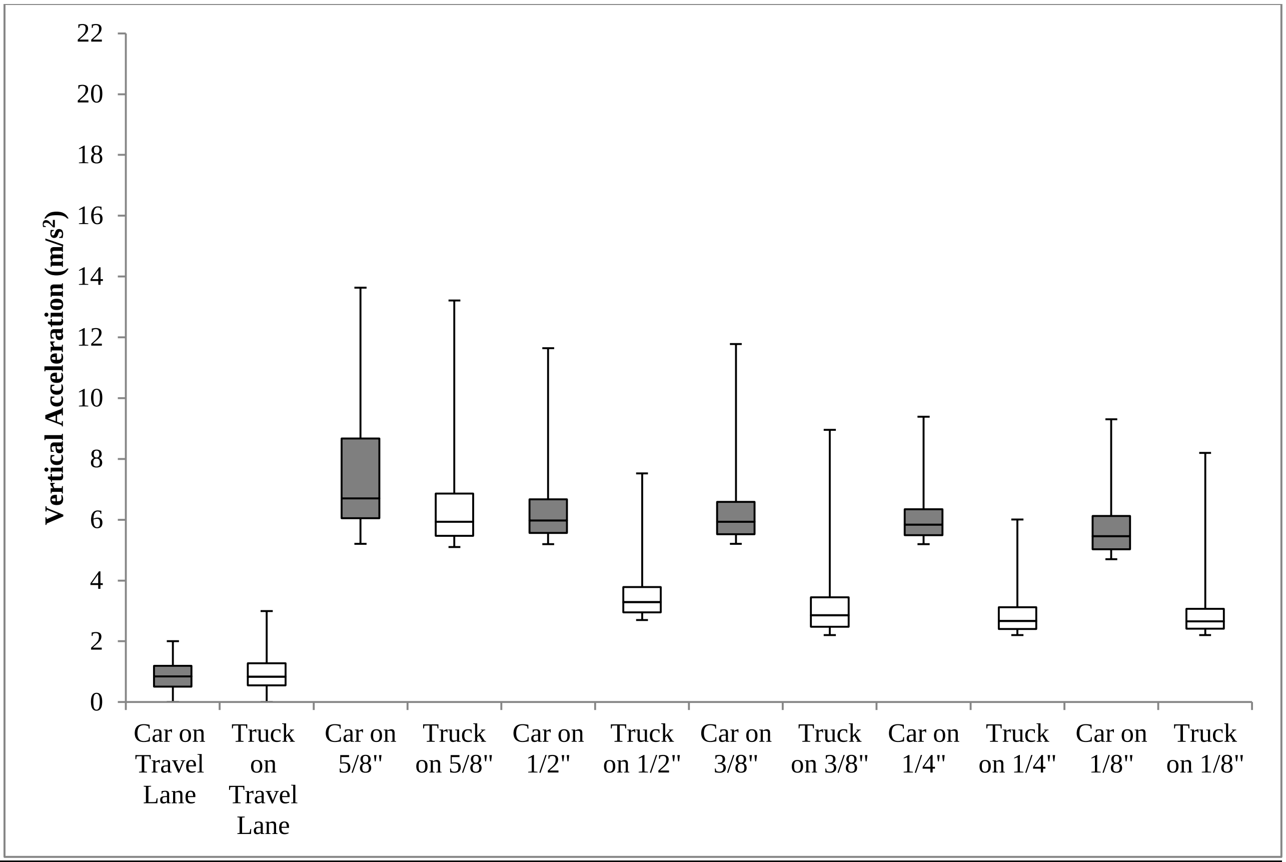
Figure 4.3 Sound variations at 65 mph on travel lane and on RS of varying depth.

Figures 4.4, 4.5 and 4.6 show the vibration measurement box plots for the 45 mph, 55 mph, and 65 mph travel speeds, respectively. The box plots show that as the speed of the car increases so too does vibration in the cabs, and this growth is at an increasing rate. For example, the difference in vibration between 45 and 55 mph is approximately 2%, but between 55 and 65 mph it is from 10% to 14%. The opposite was found for trucks where higher speeds resulted in lower in-vehicle vibrations. The decrease occurred at a declining rate as the speed increased. For example, trucks on the 3/8" RS result in vertical acceleration of 4.71, 2.86 and 2.68 m/s^2 for speeds of 45, 55 and 65 mph, respectively. The plots also show vibration differences between successive RS depths. For example, a vehicle speed of 45 mph results in a difference ranging between 0.08 to 0.24 m/s^2 for car and 0.03 and 1.34 m/s^2 for truck. The vibration difference is greater between 5/8" and 1/2" RS. Interestingly, the test car experiences higher vibrations on the RS compared to the truck. When the vehicle is on the travel lane the test truck experiences slightly higher vibrations as compared to the test car.



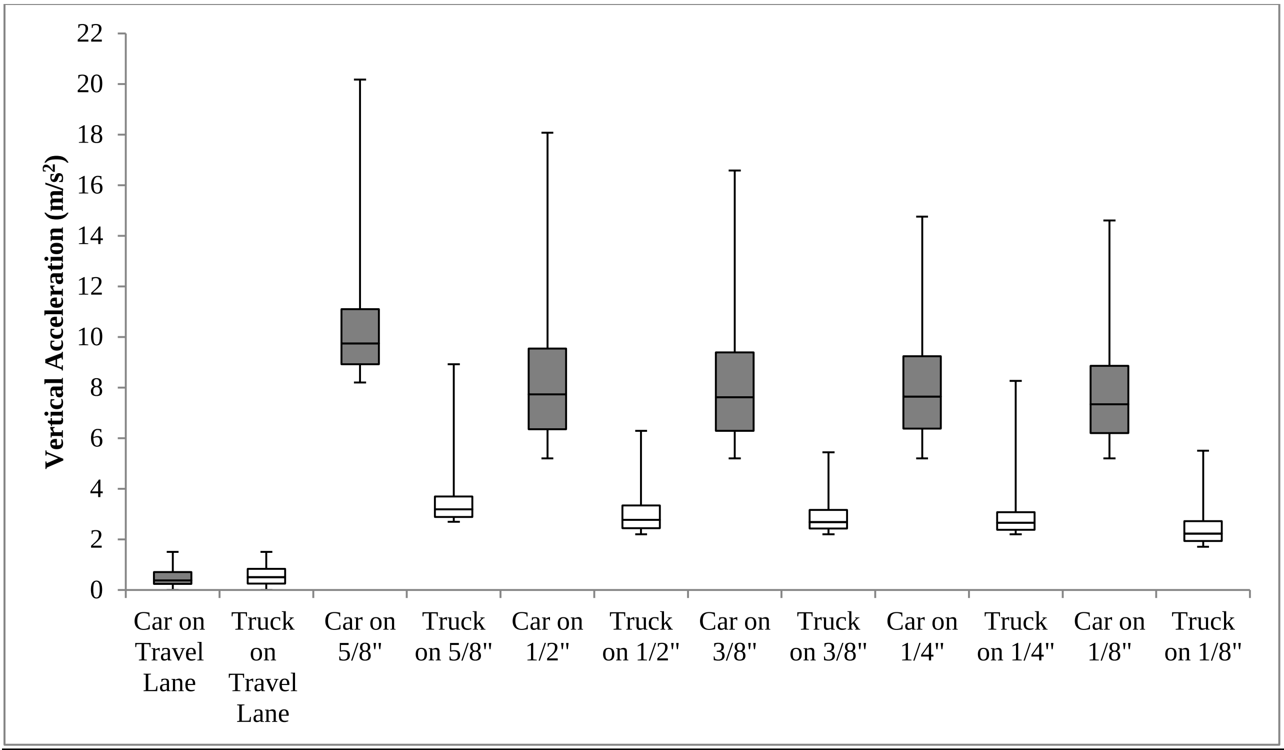
Minimum	-0.80	-0.80	5.20	4.20	5.20	4.20	5.20	4.20	5.20	4.20	4.70	4.21
First Quartile	-0.28	-0.29	5.62	5.16	5.54	4.44	5.46	4.43	5.42	4.39	4.94	4.35
Median	-0.02	0.00	6.19	6.13	5.95	4.79	5.78	4.71	5.70	4.68	5.26	4.55
Third Quartile	0.31	0.33	7.21	7.17	6.57	5.31	6.32	5.21	6.14	5.10	5.69	4.87
Maximum	1.16	1.20	14.04	12.98	10.06	7.92	9.14	8.07	8.78	6.84	8.19	6.41
Mean	0.02	0.04	6.58	6.26	6.13	4.96	5.96	4.89	5.87	4.80	5.43	4.65
Standard Deviation	0.43	0.44	1.25	1.34	0.77	0.66	0.66	0.62	0.61	0.52	0.63	0.40
Skewness	0.33	0.34	1.35	0.56	1.26	1.26	1.33	1.38	1.40	1.15	1.32	1.47
Count	72856	79501	16990	16286	16325	16570	16037	16945	16400	16323	16761	16312

Figure 4.4 Vertical accelerations at 45 mph off and on RS of varying depth.



Minimum	-0.80	-0.80	5.20	5.10	5.20	2.70	5.20	2.20	5.20	2.20	4.70	2.20
First Quartile	-0.29	-0.24	6.05	5.47	5.56	2.96	5.52	2.48	5.49	2.41	5.03	2.41
Median	0.04	0.04	6.70	5.93	5.98	3.29	5.93	2.86	5.84	2.67	5.46	2.66
Third Quartile	0.40	0.47	8.67	6.86	6.67	3.78	6.59	3.45	6.34	3.12	6.13	3.07
Maximum	1.20	2.20	13.63	13.21	11.64	7.53	11.78	8.96	9.39	6.01	9.30	8.20
Mean	0.07	0.18	7.50	6.43	6.22	3.49	6.17	3.10	6.03	2.85	5.66	2.82
Standard Deviation	0.47	0.62	2.14	1.41	0.87	0.73	0.87	0.84	0.71	0.61	0.81	0.56
Skewness	0.26	1.04	1.31	2.00	1.44	1.67	1.55	1.70	1.48	1.60	1.16	1.59
Count	70562	78015	15752	16410	15856	15734	16249	15610	15519	15596	16175	15588

Figure 4.5 Vertical accelerations at 55 mph off and on RS of varying depth.



Minimum	-0.30	-0.30	8.20	2.70	5.20	2.20	5.21	2.20	5.20	2.20	5.20	1.70
First Quartile	-0.06	-0.05	8.92	2.89	6.35	2.45	6.29	2.43	6.38	2.38	6.20	1.93
Median	0.08	0.20	9.75	3.19	7.73	2.78	7.62	2.68	7.65	2.65	7.34	2.23
Third Quartile	0.41	0.54	11.10	3.70	9.54	3.34	9.39	3.16	9.24	3.07	8.86	2.71
Maximum	1.20	1.20	20.17	8.92	18.07	6.29	16.58	5.44	14.75	8.26	14.60	5.50
Mean	0.20	0.26	10.24	3.46	8.11	2.99	8.01	2.86	7.96	2.81	7.69	2.41
Standard Deviation	0.35	0.38	1.76	0.87	2.12	0.73	2.06	0.58	1.92	0.59	1.83	0.63
Skewness	0.91	0.53	1.41	2.43	0.73	1.52	0.72	1.31	0.63	2.31	0.75	1.41
Count	68392	76524	16310	16369	16199	15285	15132	15673	16286	15044	15317	15233

Figure 4.6 Vertical accelerations at 65 mph off and on RS of varying depth.

4.2 Statistical Analysis of Results

The data in figures 4.1 through 4.3 and 4.5 through 4.7 were analyzed subsequently in order to test whether the identified patterns were statistically significant and, if so, whether they were practically meaningful. The following comparisons were evaluated: (a) sound and vibration changes relative to the travel lane (off-RS) and on-RS conditions, (b) the differences in response between the various RS depths, and (c) the effect of vehicle speed and vehicle type on the sound and vibration levels.

4.2.1 Analysis A – Travel Lane versus Rumble Strips

4.2.1.1 Sound Variations

As discussed earlier it was found that in-cab sound level increases with RS depth. The in-vehicle sound levels ranges from 66.4 dBA to 84.8 dBA for a speed of 65 mph, ranges from 64.5 dBA to 82.8 dBA for a speed of 55 mph, and ranges from 62.3 dBA to 77.2 dBA for a speed of 45 mph as shown in figures 4.1, 4.2 and 4.3 respectively.

The differences between the in-vehicle sound levels when the test vehicle is in the travel lane and on various depths of the RS are shown in figure 4.7. It is apparent that the sound change within the cab of the test vehicle rises with increasing RS depth. For example, the 1/8" depth has the lowest sound change for all scenarios. Secondly, at all conditions, the test car tends to experience lower in-cab sound changes than the test truck.

Figure 4.7 shows the difference in sound levels observed on the RS and the travel lane for the two vehicle types and three speeds as a function of RS depth. The difference in the sound level ranges from 8.97 dBA (e.g. car traveling at 55 mph on 1/8" RS as compared to the travel lane) to 17.8 dBA (e.g. car traveling at 65 mph on 5/8" RS as compared to the travel lane). As before, the greater difference was for the 5/8" RS depth.

From a practical perspective, the minimum change of 8.97 dBA is clearly noticeable and the in-cab noise is approximately twice the sound in the cab when the vehicle is in the travel lane (Outcalt 2001). It is concluded that all the RS depths tested would be sufficient with respect to in-cab sound from a safety perspective. On average, this sound difference can be likened to changes in sound that ranges from a normal speech at 3 ft (1 m) to that of a vacuum cleaner at 10 ft (3 m) (CALTRANS 1998).

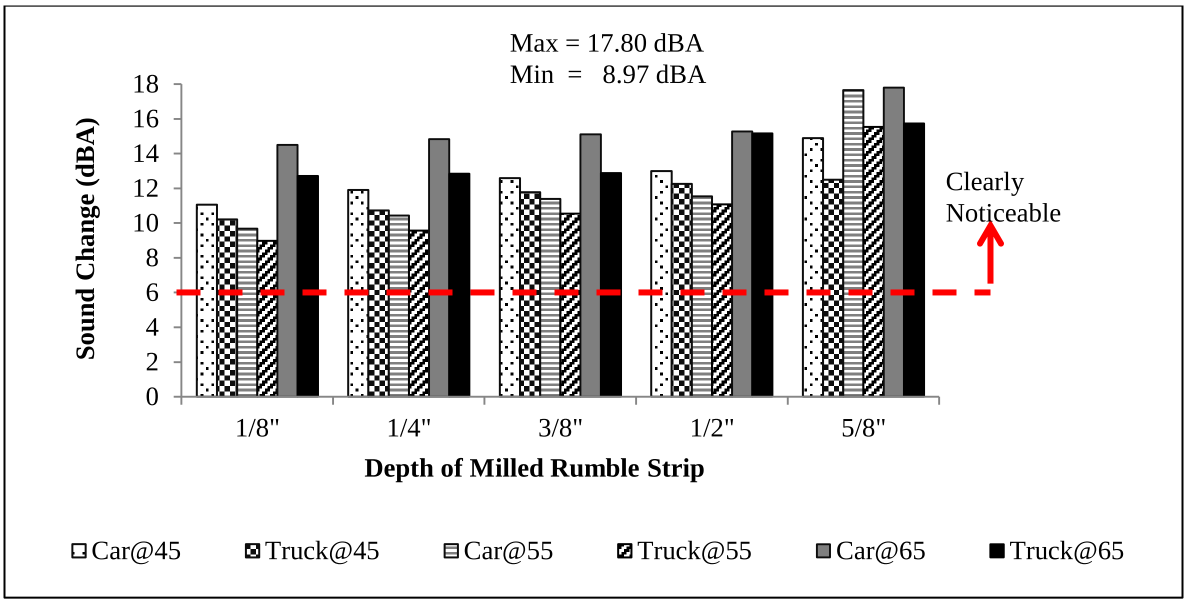


Figure 4.7 Changes in sound levels between when vehicle is on travel lane and when on RS

Each of the differences (i.e. between travel lane and RS) shown in figure 4.7 was found to be statistically significant, as measured by a two-tailed t-test at a 95% level of significance as shown in table 4.1.

Table 4.1 Two sample t-test comparing sound responses off and on RS

Rumble Depth	Off Rumble Strips		1/8"		1/4"		3/8"		1/2"		5/8"	
Vehicle Type	**Car**	**Truck**	**Car**	**Truck**	**Car**	**Truck**	**Car**	**Truck**	**Car**	**Truck**	**Car**	**Truck**
65 mph Vehicle Speed												
Mean Sound Level (dBA)	66.98	67.16	81.48	79.15	81.82	79.26	82.10	79.31	82.26	81.59	84.77	82.17
Standard Deviation	1.5	1.3	1.1	2.4	1.2	2.4	1.2	2.3	1.5	2.8	2.2	2.0
t-stat			209	97	212	104	230	100	206	117	219	225
Remarks			Sig.	Sig.	Sig	Sig.	Sig.	Sig.	Sig.	Sig.	Sig.	Sig.
55 mph Vehicle Speed												
Mean Sound Level (dBA)	65.18	65.73	74.85	73.5	75.62	74.1	76.57	75.08	79.72	75.61	82.82	80.07
Standard Deviation	2.3	2.5	2.4	2.0	2.5	2.4	2.4	2.5	2.6	2.7	2.0	4.1
t-stat			97	61	97	63	116	69	107	69	194	98
Remarks			Sig.	Sig.	Sig.	Sig.	Sig.	Sig.	Sig.	Sig.	Sig.	Sig.
45 mph Vehicle Speed												
Mean Sound Level (dBA)	62.3	62.65	73.35	72.86	74.19	73.37	74.89	74.42	75.29	74.91	77.18	75.14
Standard Deviation	3.3	3.9	1.8	1.6	2.2	1.8	2.0	2.2	2.2	1.8	3.4	2.3
t-stat			117	100	124	101	137	105	136	113	134	127
Remarks			Sig.	Sig.	Sig.	Sig.	Sig.	Sig.	Sig.	Sig.	Sig.	Sig.

NOTE: *Sig.* implies Significant at 95% confidence interval

4.2.1.2 Vibration Variations

As discussed earlier, the in-vehicle vibration measured in vertical acceleration, ranges from 0.02 m/s^2 to 0.26 m/s^2 for the baseline (no RS) and 2.41 m/s^2 to 10.24 m/s^2 for the on-RS periods. Figure 4.8 shows the changes in the vertical acceleration measured in each vehicle type between the RS and travel lane for various RS depths; and two trends may be identified. Firstly, as the RS depth increases so do the vibration. For example, the 5/8" RS has the highest difference for all scenarios. The change in vibration is approximately linear for depths from 1/8" to 1/2" but there is a noticeable discontinuity at 5/8". Secondly, the truck tends to experience lower in-cab vibration differences as compared to the car, all else being equal. For example, as shown in figure 4.8, the vehicle speed of 45 mph results in vibration differences that ranges from 5.4 m/s^2 to 6.5 m/s^2 for car and ranges from 4.6 m/s^2 to 6.2 m/s^2 on the RS depths.

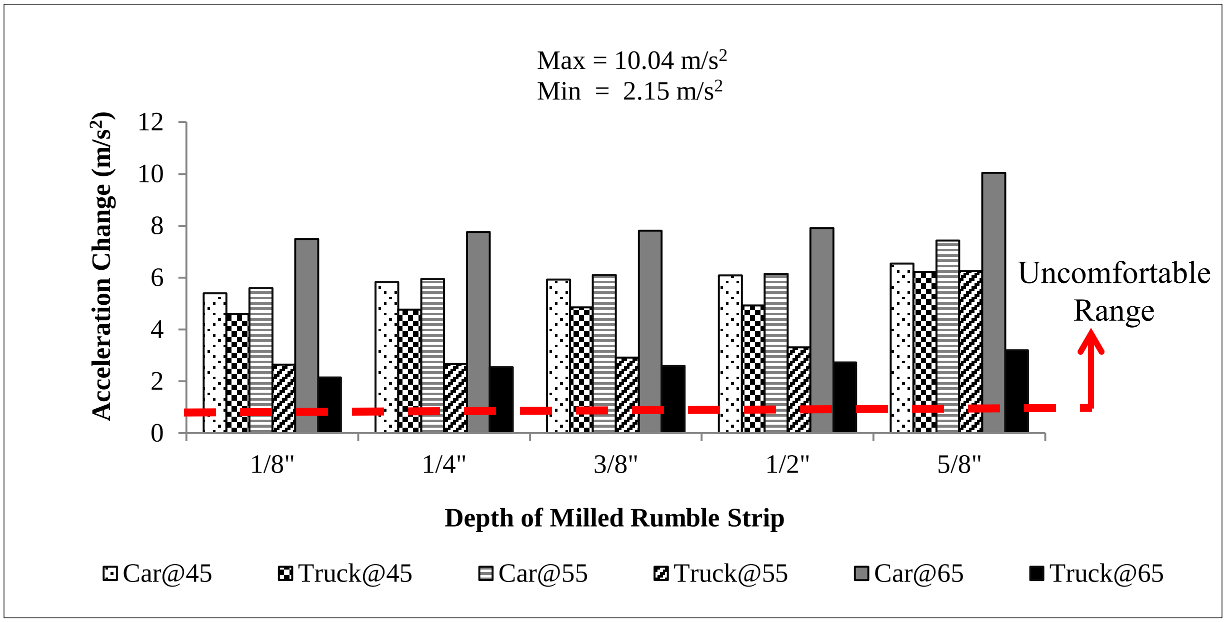


Figure 4.8 Changes in vertical acceleration between when vehicle is on travel lane and when vehicle is on RS.

Figure 4.8 shows the difference in vibration levels observed on the RS and the travel lane for the two vehicle types and three speeds as a function of RS depth. Each of the differences (i.e. between travel lane and RS) was found to be statistically significant, as measured by a two-tailed t-test at a 95% level of significance as shown in table 4.2.

Table 4.2 Two sample t-test comparing vibration responses off and on RS

Rumble Depth	Off Rumble Strips		1/8"		1/4"		3/8"		1/2"		5/8"	
Vehicle Type	**Car**	**Truck**	**Car**	**Truck**	**Car**	**Truck**	**Car**	**Truck**	**Car**	**Truck**	**Car**	**Truck**
65 mph Vehicle Speed												
Mean Vertical Acc. (m/s^2)	0.20	0.26	7.69	2.41	7.96	2.81	8.01	2.86	8.11	2.99	10.24	3.46
Standard Deviation	0.35	0.38	1.83	0.63	1.92	0.59	2.06	0.58	2.12	0.73	1.76	0.87
t-stat			244	146	287	121	250	128	250	97	234	137
Remarks			Sig.	Sig.	Sig.	Sig.	Sig.	Sig.	Sig.	Sig.	Sig.	Sig.
55 mph Vehicle Speed												
Mean Vertical Acc. (m/s^2)	0.07	0.18	5.66	2.82	6.03	2.85	6.17	3.10	6.22	3.49	7.50	6.43
Standard Deviation	0.47	0.62	0.81	0.58	0.72	0.61	0.87	0.84	0.87	0.73	2.14	1.41
t-stat			234	183	251	169	245	198	294	191	178	154
Remarks			Sig.	Sig.	Sig.	Sig.	Sig.	Sig.	Sig.	Sig.	Sig.	Sig.
45 mph Vehicle Speed												
Mean Vertical Acc. (m/s^2)	0.02	0.04	5.43	4.65	5.87	4.80	5.96	4.89	6.13	4.96	6.58	6.26
Standard Deviation	0.43	0.44	0.63	0.40	0.61	0.52	0.66	0.62	0.77	0.66	1.25	1.34
t-stat			214	137	240	222	221	202	237	233	242	539
Remarks			Sig.	Sig.	Sig.	Sig.	Sig.	Sig.	Sig.	Sig.	Sig.	Sig.

NOTE: Sig. implies Significant at 95% confidence interval

While all else was equal, the difference in the vibration level between the travel lane and RS was much greater for the car than the truck. Even though there are no commonly accepted standards with respect to human perceptibility of vibration (Meyer et al. 2002) all of the differences shown in figure 4.8 would be within the “noticeable” range based on similar studies (Bucko et al. 2001). For example, the minimum change (2.15 m/s^2) is within the range of “very uncomfortable” level proposed by ISO2631 (1997) for a passenger bus. It was concluded that all RS depths met the safety criteria with respect to vibration. Anecdotally, the test driver and data collector noticed the difference in vibration as the vehicle moved from the travel lane onto the RS and felt that all RS depths were successful in notifying the vehicle occupants that they had departed the travel lane.

As discussed earlier the difference in vibration relation between the car and truck is clearly noticeable in figure 4.8. As speed increases so does the vibration level decreases for the truck but increases for the car on all RS depths.

4.2.2 Analysis B – Effect of Rumble Strip Depth on In-vehicle Cab Sound and Vibration

4.2.2.1 In-Vehicle Sound Response

As discussed previously, the sound level increases as the RS depth increases. Table 4.3 provides the t-test statistical test results for a comparison of RS sound for RS that differed in depth by 1/8". T-test assuming unequal variance was used since the two samples are from different populations with unknown variance. In general, the differences in volume resulting from a 1/8" change in depth were statistically significant at the 95% level of confidence. There was one exception at 55 mph (car: 1/2" to 3/8") and two exceptions at 65 mph (truck: 3/8" to 1/4" and truck: 1/4" to 1/8") where no statistical significant difference was found.

With respect to table 4.3, at 45 mph the average difference was 2 dBA, at 55 mph the average difference was 5 dBA, and at 65 mph the average difference was 2 dBA. From a practical sense, this level of sound difference would be barely noticeable by the average driver (Outcalt 2001). Similarly, the difference between the deepest RS at 5/8" and the shallowest RS at 1/8" is approximately 4.5 dBA, which would also be barely noticeable by the average driver (Outcalt 2001).

It was hypothesized that while the differences, in general, are statistically significant, they are not significant from a practical perspective. It would be expected that a maintenance activity that reduced the RS depth by 1/8" would only have a marginal effect on the RS depth with respect to in-vehicle cab sound level.

Table 4.3 Two sample t-test comparing sound responses from RS of varying depths

Vehicle Type	**Car**		**Truck**		**Car**		**Truck**		**Car**		**Truck**		**Car**		**Truck**	
Rumble Depth	**5/8"**	**1/2"**	**5/8"**	**1/2"**	**1/2"**	**3/8"**	**1/2"**	**3/8"**	**3/8"**	**1/4"**	**3/8"**	**1/4"**	**1/4"**	**1/8"**	**1/4"**	**1/8"**
65 mph Vehicle Speed																
Mean Sound (dBA)	84.8	82.3	82.2	81.6	82.3	82.1	81.6	79.3	82.1	81.8	79.3	79.3	81.8	81.5	79.3	79.2
Standard Deviation	2.2	1.5	2.0	2.8	1.5	1.2	2.8	2.3	1.2	1.2	2.3	2.4	1.2	1.1	2.4	2.4
t-stat	28.3		4.7		2.1		14.1		4.0		0.3		4.6		0.7	
Remarks	Significant		Significant		Significant		Significant		Significant		Not Significant		Significant		Not Significant	
55 mph Vehicle Speed																
Mean Sound (dBA)	82.8	76.7	80.1	75.6	76.7	76.6	75.6	75.1	76.6	75.6	75.1	74.1	75.6	74.9	74.1	73.5
Standard Deviation	2.0	2.6	4.1	2.7	2.6	2.4	2.7	2.5	2.4	2.5	2.5	2.4	2.5	2.4	2.4	2.0
t-stat	56.1		30.9		1.3		4.0		8.3		7.9		6.6		5.3	
Remarks	Significant		Significant		Not Significant		Significant		Significant		Significant		Significant		Significant	
45 mph Vehicle Speed																
Mean Sound (dBA)	77.2	75.3	75.1	74.9	75.3	74.9	74.9	74.4	74.9	74.2	74.4	73.4	74.2	73.4	73.4	72.9
Standard Deviation	3.4	2.2	2.3	1.8	2.2	2.0	1.8	2.2	2.0	2.2	2.2	1.8	2.2	1.8	1.8	1.6
t-stat	19.3		2.7		5.2		4.9		8.9		10.8		10.4		5.9	
Remarks	Significant		Significant		Significant		Significant		Significant		Significant		Significant		Significant	

4.2.2.2 In-Vehicle Vibration Response

Table 4.4 shows the statistical differences of the vertical accelerations produced on successive RS depths. The change in in-vehicle vibration for each 1/8” change in RS depth was found to be statistically significant at the 95 % level of confidence. The only non-statistically significant results were at a vehicle speed of 65 mph (car and truck: 3/8" to 1/4") and at 55 mph (car: 1/2" to 3/8"). From a practical perspective, the differences in vibrations between successive RS depths would not be noticeable based on the ISO scale (ISO2631 1997). The only exception would be the differences in vibration levels when the RS depth changes from 5/8" to 1/2". In this situation the vertical acceleration difference ranges between 1 m/s^2 – 3 m/s^2. This range corresponds to the bandwidth defined as "fairly uncomfortable" to "extremely uncomfortable" on the ISO2631 bandwidth. Further investigation on the aerodynamics and vehicle mechanics effects on vibration is recommended.

It is hypothesized that while the differences, in general, are statistically significant, they are not significant from a practical perspective. It would be expected that a maintenance activity that reduced the RS depth by 1/8" would only have a marginal effect on the RS depth with respect to in-vehicle cab vibration.

Table 4.4 Two sample t-test comparing acceleration responses to successive RS depths

Vehicle Type	**Car**		**Truck**		**Car**		**Truck**		**Car**		**Truck**		**Car**		**Truck**	
Rumble Depth	**5/8"**	**1/2"**	**5/8"**	**1/2"**	**1/2"**	**3/8"**	**1/2"**	**3/8"**	**3/8"**	**1/4"**	**3/8"**	**1/4"**	**1/4"**	**1/8"**	**1/4"**	**1/8"**
65 mph Vehicle Speed																
Vertical Acceleration (m/s^2)	10.24	8.11	3.46	2.99	8.11	8.01	2.99	2.86	8.01	7.96	2.86	2.81	7.96	7.69	2.81	2.41
Standard Deviation	1.76	2.12	0.87	0.73	2.12	2.06	0.73	0.58	2.06	1.92	0.58	0.59	1.92	1.83	0.59	0.63
t-stat	40.12		13.12		2.11		3.61		1.23		1.61		6.69		15.78	
Remarks	Significant		Significant		Significant		Significant		Not Significant		Not Significant		Significant		Significant	
55 mph Vehicle Speed																
Vertical Acceleration (m/s^2)	7.50	6.22	6.43	3.49	6.22	6.17	3.49	3.09	6.17	6.02	3.09	2.85	6.02	5.66	2.85	2.82
Standard Deviation	2.14	0.87	1.41	0.73	0.87	0.87	0.73	0.84	0.87	0.71	0.84	0.61	0.71	0.81	0.61	0.56
t-stat	27.40		66.98		1.40		17.56		4.34		11.27		10.84		1.69	
Remarks	Significant		Significant		Not Significant		Significant		Significant		Significant		Significant		Significant	
45 mph Vehicle Speed																
Vertical Acceleration (m/s^2)	6.58	6.13	6.26	4.96	6.13	5.96	4.96	4.89	5.96	5.87	4.89	4.80	5.87	5.43	4.80	4.65
Standard Deviation	1.25	0.77	1.34	0.66	0.77	0.66	0.66	0.62	0.66	0.61	0.62	0.52	0.61	0.63	0.52	0.40
t-stat	12.12		54.23		4.54		2.03		2.55		2.81		12.67		3.84	
Remarks	Significant		Significant		Significant		Significant		Significant		Significant		Significant		Significant	

4.2.3 Analysis C – Effect of Vehicle Type

Table 4.5 shows the statistical differences of the in-cab sound level responses between the test car and truck for different speeds and RS depths. It was found that all the differences between the in-cab sound levels of the test vehicles for all combinations were statistically significant at the 95% confidence level. On the RS, in-car sound levels were higher than truck and ranges from 0.67 to 2.79 dBA for vehicle speed of 65 mph, ranges from 1.35 to 2.75 dBA for vehicle speed of 55 mph and ranges from 0.38 to 2.04 dBA for vehicle speed of 45 mph. It was hypothesized that while the in-cab sound differences between the test vehicles are statistically significantly different for the tested conditions, practically they were not.

Table 4.5 Two sample t-test comparing sound responses between car and truck

Rumble Depth	In Travel Lane		1/8"		1/4"		3/8"		1/2"		5/8"	
Vehicle Type	**Car**	**Truck**	**Car**	**Truck**	**Car**	**Truck**	**Car**	**Truck**	**Car**	**Truck**	**Car**	**Truck**
65 mph Vehicle Speed												
Mean Sound Level (dBA)	66.98	67.16	81.48	79.15	81.82	79.26	82.10	79.31	82.26	81.59	84.77	82.17
Standard Deviation	1.51	1.35	1.14	2.42	1.19	2.35	1.18	2.26	1.52	2.82	2.2	2.01
t-stat	2.81		18.48		21.39		22.67		5.22		31.29	
Remarks	Significant		Significant		Significant		Significant		Significant		Significant	
55 mph Vehicle Speed												
Mean Sound Level (dBA)	65.18	65.73	74.85	73.5	75.62	74.1	76.57	75.08	79.72	75.61	82.82	80.07
Standard Deviation	2.31	2.53	2.38	1.95	2.51	2.39	2.43	2.51	2.61	2.71	1.97	4.13
t-stat	4.56		12.53		12.46		12.66		8.38		22.29	
Remarks	Significant		Significant		Significant		Significant		Significant		Significant	
45 mph Vehicle Speed												
Mean Sound Level (dBA)	62.3	62.65	73.35	72.86	74.19	73.37	74.89	74.42	75.29	74.91	77.18	75.14
Standard Deviation	3.31	3.85	1.78	1.55	2.21	1.78	2.03	2.22	2.21	1.76	3.39	2.3
t-stat	3.08		6.14		9.57		5.25		4.26		21.7	
Remarks	Significant		Significant		Significant		Significant		Significant		Significant	

Table 4.6 shows the statistical differences of the in-cab vibration responses between the test car and truck for different speeds and RS depths. The differences between the in-cab vertical accelerations for all combinations were statistically significant. At a speed of 45 mph on the RS depths, the car acceleration is 0.32 to 1.17 m/s^2 higher than the truck. The quantum of acceleration differences increases with speed. For example, at a vehicle speed of 55 mph, the in-cab vibration differences on the various RS ranges from 1.07 to 3.17 m/s^2. Similarly, for a vehicle speed of 65 mph the range is from 5.12 to 6.78 m/s^2. Interestingly, the in-vehicle vertical acceleration in the test truck decreases as speed increases whereas the opposite is true for the test car as noted by Meyer et al. 2002. It was hypothesized that the in-cab vibration differences between the test vehicles are statistically significant and practically noticeable.

Table 4.6 Two sample t-test comparing vibration responses between car and truck

Rumble Depth	In Travel Lane		1/8"		1/4"		3/8"		1/2"		5/8"	
Vehicle Type	**Car**	**Truck**	**Car**	**Truck**	**Car**	**Truck**	**Car**	**Truck**	**Car**	**Truck**	**Car**	**Truck**
65 mph Vehicle Speed												
Acceleration (m/s^2)	0.20	0.26	7.69	2.41	7.96	2.81	8.01	2.86	8.11	2.99	10.24	3.46
Standard Deviation	0.35	0.38	1.83	0.63	1.92	0.59	2.06	0.58	2.12	0.73	1.76	0.87
t-stat	35.07		155.4		150.48		138.58		121.3		139.01	
Remarks	Significant		Significant		Significant		Significant		Significant		Significant	
55 mph Vehicle Speed												
Acceleration (m/s^2)	0.07	0.17	5.66	2.82	6.02	2.85	6.17	3.09	6.22	3.49	7.50	6.43
Standard Deviation	0.47	0.62	0.81	0.56	0.71	0.61	0.87	0.84	0.87	0.73	2.14	1.41
t-stat	34.65		103.25		112.03		107.04		101.04		18.33	
Remarks	Significant		Significant		Significant		Significant		Significant		Significant	
45 mph Vehicle Speed												
Acceleration (m/s^2)	0.02	0.04	5.43	4.65	5.87	4.80	5.96	4.89	6.13	4.96	6.58	6.26
Standard Deviation	0.43	0.44	0.63	0.4	0.61	0.52	0.66	0.62	0.77	0.66	1.25	1.34
t-stat	5.64		18.45		32.91		29.72		32.26		11.00	
Remarks	Significant		Significant		Significant		Significant		Significant		Significant	

4.2.4 Analysis D – Effect of Vehicle Speed

Tables 4.7 and 4.8 shows the statistical differences of the sound and vibration responses as a function of RS depths. This was done by comparing outcomes for the following test vehicle speeds: (1) 65 mph versus 55 mph and (2) 55 mph versus 45 mph. It was found that, with the exception of vibration responses between the test truck at 65 mph and 55 mph, all of the comparisons between tested speeds for in-vehicle sound and vibration levels were statistically significant at the 95% significance level.

As previously discussed, in-vehicle sound levels increase with increasing vehicle speed but there is no general trend in the amount of increase between tested scenarios. The in-cab sound level difference between speeds of 65 mph and 55 mph ranges from 1.95 to 6.62 dBA for the test car and 2.14 to 5.97 dBA for the truck. There are generally small differences between in-cab sound level for vehicle speeds between 55 mph and 45 mph. For example, with the exception of the 5/8" RS depth, all other RS depths showed in-cab sound levels ranging from 1.42 dBA to 1.68 dBA for the test car and 0.64 dBA to 0.74 dBA for the truck. It was hypothesized that there are statistically significant differences in the in-cab sound levels at different vehicle speeds on RS depths and the difference is practically noticed at higher speeds.

In table 4.8 it may be seen that in-cab vertical acceleration increases with increasing car speeds and decreasing truck speeds as previously discussed. The in-cab vertical acceleration difference between vehicle speeds of 65 mph and 55 mph ranges from 1.84 m/s^2 to 2.74 m/s^2 for the test car and ranges from 0.04 m/s^2 to 2.97 m/s^2 for the truck. Similar to the sound levels, the practical vibration differences between 55 mph and 45 mph vehicle speeds are minimal in the test car and noticeable in the truck. It is hypothesized that there are generally statistically significant differences in the in-cab vibration level at different vehicle speeds on RS depths. The practical difference is noticed at high speeds for car and low speeds for truck.

Table 4.7 Two sample t-test comparing changes in in-vehicle sound response to speed change

Rumble Depth	In Travel Lane			1/8"			1/4"			3/8"			1/2"			5/8"		
	65	**55**	**45**	**65**	**55**	**45**	**65**	**55**	**45**	**65**	**55**	**45**	**65**	**55**	**45**	**65**	**55**	**45**
	CAR																	
Mean Sound Level (dBA)	66.98	65.18	62.30	81.48	74.86	73.36	81.82	75.62	74.20	82.10	76.57	74.89	82.26	76.72	75.29	84.78	82.83	77.19
Standard Deviation	1.51	2.31	3.31	1.14	2.38	1.78	1.20	2.51	2.22	1.18	2.43	2.03	1.52	2.61	2.21	2.20	1.98	3.39
t-stat	23.03		28.98	71.06		15.69	61.04		13.61	62.2		18.42	52.87		13.63	20.82		54.74
Remarks	Significant		Significant	Significant		Significant	Significant		Significant	Significant		Significant	Significant		Significant	Significant		Significant
	TRUCK																	
Mean Sound Level (dBA)	67.16	64.54	62.65	79.15	73.51	72.87	79.27	74.11	73.37	79.32	75.09	74.42	81.59	75.62	74.91	82.17	80.03	75.14
Standard Deviation	1.35	3.80	3.85	2.43	1.95	1.56	2.35	2.40	1.79	2.27	2.51	2.22	2.83	2.72	1.77	2.02	2.83	2.30
t-stat	17.56		11.41	41.15		6.76	37.75		6.91	29.21		5.73	39.64		5.86	20.55		46.64
Remarks	Significant		Significant	Significant		Significant	Significant		Significant	Significant		Significant	Significant		Significant	Significant		Significant

Table 4.8 Two sample t-test comparing changes in in-vehicle vibration response to speed change

Rumble Depth	In Travel Lane			1/8"			1/4"			3/8"			1/2"			5/8"		
	65	**55**	**45**	**65**	**55**	**45**	**65**	**55**	**45**	**65**	**55**	**45**	**65**	**55**	**45**	**65**	**55**	**45**
	CAR																	
Vertical Acceleration (m/s^2)	0.20	0.07	0.02	7.69	5.66	5.43	7.96	6.03	5.87	8.01	6.17	5.96	8.11	6.22	6.13	10.24	7.50	6.58
Standard Deviation	0.35	0.47	0.43	1.83	0.81	0.63	1.92	0.72	0.61	2.06	0.87	0.44	2.12	0.87	0.77	1.76	2.14	1.25
t-stat	54.86		20.97	52.25		6.77	53.88		4.62	46.09		5.76	49.86		2.64	45.89		18.39
Remarks	Significant		Significant	Significant		Significant	Significant		Significant	Significant		Significant	Significant		Significant	Significant		Significant
	TRUCK																	
Vertical Acceleration (m/s^2)	0.26	0.18	0.03	2.41	2.82	4.65	2.81	2.85	4.80	2.86	3.10	4.89	2.99	3.49	4.96	3.46	6.43	6.26
Standard Deviation	0.38	0.62	0.44	0.63	0.58	0.40	0.59	0.61	0.52	0.58	0.84	0.62	0.73	0.73	0.66	0.87	1.41	1.34
t-stat	31.50		49.98	-20.19		-49.93	-1.55		-73.42	-9.45		-64.08	-15.33		-54.03	-63.59		4.08
Remarks	Significant		Significant	Significant		Significant	Not Significant		Significant	Significant		Significant	Significant		Significant	Significant		Significant

Chapter 5 Conclusions and Recommendations

This report presented the results of a comparative analysis of sound and vibration data collected on varying depths of milled RS on three highways in the state of Nebraska. The goal was to determine the functional effectiveness of milled RS with respect to RS depth. The results will inform road maintenance policy with respect to chip-seal overlays that affect RS depth, in addition to providing input on RS design depth. The results of the study showed that:

1. On the basis of the in-vehicle sound and vibration levels of all the tested RS depths, it can be hypothesized that a 1/8" reduction in the current milled RS design depth, as a result of chip-sealing, does not result in a practical reduction in the RS effectiveness at producing audible and tactile warnings to alert drivers.
2. There are statistically significant differences between the in-vehicle noise levels and vibration levels when vehicles are on a travel lane and when they are on a RS. The difference is clearly noticeable by the average driver at speeds of 45 mph, 55 mph, and 65 mph.
3. The deeper the RS, the higher the alerting properties. It was found that, in general, there are statistically significant differences between RS with a 1/8" depth difference. However, the sound differences are practically imperceptible for the average driver. Similarly, the vibration differences are barely noticeable except for the transition between a 5/8" to1/2" RS depth.
4. There are statistically significant differences between the sound and the vibrations produced in a car from those produced in a truck. The differences of in-vehicle noise between the vehicles are not practically noticeable whereas the vibration differences

would be. The difference of in-vehicle vibration increases with increasing speeds at an increasing rate.

5. The in-vehicle sound level increases with increasing speed on both the travel lane and on the RS. There are statistical significant differences between the test speeds, and these differences would be noticed by an average driver.

In conclusion, chip sealing that reduces the RS depth of 1/8" or less does not affect the RS alerting properties and therefore re-milling will not be recommended. However, it will be useful to repeat the studies for different RS designs (e.g., mumble strips, sinusoidal, etc.), pavement types, vehicle types, vehicle speeds, and other maintenance treatments. Also a before and after study on the same test site is recommended.

References

1. Bucko, Troy, and Ahmad Khorashadi. 2001. "Evaluation of Milled-In Rumble Strips, Rolled-In Rumble Strips and Audible Edge Stripe." California Department of Transportation.

2. CALTRANS Technical Noise Supplement, 1998. “Statewide Investigation of Noise Abatement Alternatives.” http://www.strongsville.org/content/documents/ODOT_Ch_3_Fundamentals_of_Highway_Traffic_Noise.pdf . Ohio Department of Transportation. Accessed on Jul 5, 2016.

3. CEL-63X User Manual. http://www.enviroequipment.com/rentals/PDF/CEL-63x-User-Manual.pdf Accessed on 15th January, 2016

4. Chen, Chung S. "A study of effectiveness of various shoulder rumble strips on highway safety." Virginia Department of Transportation. 1994.

5. Chen, Chung, Emmanuel O. Darko, and Tanqueray N. Richardson. "Optimal continuous shoulder rumble strips and the effects on highway safety and the economy." *Institute of Transportation Engineers. ITE Journal* 73.5 (2003): 30.

6. Elefteriadou, Lily, M. El-Gindy, D. Torbic, P. Garvey, A. Homan, Z. Jiang, B. Pecheux, and R. Tallon. *Bicycle-tolerable shoulder rumble strips*. No. PTI 2K15. 2000.

7. Federal Highway Administration (FHWA) Technical Advisory, Center Line Rumble Strips. 2011. http://safety.fhwa.dot.gov/roadway_dept/pavement/rumble_strips/t504040/ Accessed Jul 5, 2016.

8. Finley, Melisa Dayle, and Jeffrey David Miles. "Exterior noise created by vehicles traveling over rumble strips." *Transportation Research Board 86th Annual Meeting*. No. 07-2555. 2007.

9. Gardner, Lucas W., Margaret Joanna Rys, and Eugene Russell. *Comparison of football shaped rumble strips versus rectangular rumble strips*. No. K-TRAN: KSU-00-4P2. Kansas Department of Transportation, 2007.

10. Harwood, F. and R. Holcom. *Interior Vehicle Noise from Shoulder Rumble Strips*. Research Report R-1326, Materials and Technology Division, Michigan Department of Transportation, 1993.

11. Hirasawa, Masayuki, Motoki Asano, and Kazuo Saito. *"Study on development and practical use of rumble strips as a new measure for highway safety."* Journal of the Eastern Asia Society for Transportation Studies 6 (2005): 3697-3712.

12. International Organization for Standardization (1997). *Mechanical vibration and shock: evaluation of human exposure to whole-body vibration—part 1*: general requirements. ISO 2631–1. Geneva: International Organization for Standardization.

13. Khan, A. M., and A. Bacchus. "Economic feasibility and related issues of highway shoulder rumble strips." Transportation research record (1995): 92-101.

14. Meyer, Eric, and Scott Walton. *"Preformed rumble strips."* Rep. for Midwest Smart Zone Deployment Initiative, 2002.

15. MTi User Manual. https://www.xsens.com/wp-content/uploads/2013/12/MTi-User-Manual.pdf Accessed on 15th January, 2016

16. Nebraska Department of Roads (NDOR). *2014 Annual Report.* NDOR, 2015. http://www.transportation.nebraska.gov/docs/annual-report.pdf Accessed on 13th June, 2016.

17. Nebraska Department of Roads (NDOR). *Pavement Maintenance Manual*. NDOR, 2002. http://www.transportation.nebraska.gov/docs/pavement.pdf Accessed on 13th June, 2016.

18. Nebraska Department of Roads (NDOR). *The Roadrunner*. Communication Division, NDOR, 2007. Lincoln.

19. Nebraska Department of Roads (NDOR) *Roadway Design Manuals.* NDOR, 2016. http://roads.nebraska.gov/business-center/rd-manuals/ Accessed July 5, 2016.

20. Outcalt, W., *Bicycle-Friendly Rumble Strips*. Report No. CDOTDTD-R-2001-4. Colorado Department of Transportation. May 2001.

21. Potter, R.C, Fidell, S.A, Myles, M.M, Keast, D.N. *Effectiveness of audible warning devices on emergency vehicles*. No. DOT-TSC-OST-77-38 Final Report, 1977.

22. Russell, E. R., M. J. Rys, and T. S. Brin, *U.S. Experience with Centerline Rumbles Strips on Two-lane Roads: Pattern Research and North American Usage.* Mid-continent Transportation Research Symposium, Ames, IA, 2003. http://www.ctre.iastate.edu/pubs/midcon2003/RussellRumble.pdf Accessed Jul 6, 2016.

23. Torbic, Darren J. *Guidance for the design and application of shoulder and centerline rumble strips*. NCHRP Vol. 641. Transportation Research Board, 2009.

24. Tye, Edward J. *Devices to Prevent Run-Off-Road Accidents*. No. FHWA-CA-76-01 Final Rpt.. 1976.

25. Weather Underground (2016). https://www.wunderground.com/history/airport/KLNK/2016/5/19/DailyHistory.html?req_city=Lincoln&req_state=NE&req_statename=&reqdb.zip=68501&reqdb.magic=1&reqdb.wmo=99999 *Accessed on 13th June, 2016*

Appendices

A. NDOR Policy for the Installation of Rumble Strips and Stripes

B. Setup and Data Collection Manual

   1. Equipment Checklist
   2. Field Setup
   3. Data Collection
   4. Site Record Sheet
   5. Recording Sound and Vibration
   6. Retrieving Collected Data

C. Recorded Sound and Vibration Levels at Test Sites – Raw Data

   1. Recorded Sound Levels at Various Locations
   2. Measured Vibration Readings at Various Locations

D. Picture Gallery

Appendix A NDOR Policy for the Installation of Rumble Strips and Stripes

Nebraska Department of Roads

Roadway Design Division – Policy Letter

Policy Number: **DES 14–01**

Approval Date: 6/18/14 By: [signature] Roadway Design Engineer

Approval Date: 6-18-14 By: [signature] Traffic Engineer

Approval Date: 6-19-14 By: John J. Perry FHWA, NE Safety/ITS Engineer

Roadway Design Policies incorporated into & superseded by this policy letter:
DES 06-03: "Milled-in Rumble Strips on Shoulders 6' & Wider", dated June 21, 2006
DES 11-01: "Policy for the Installation of Centerline Rumble Strips", dated June 13, 2011

Roadway Design Manual Chapter affected by this policy letter: **Chapter Eight: Surfacing**
Section 6: Rumble Strips

POLICY FOR THE INSTALLATION OF RUMBLE STRIPS & STRIPES

Background

The Nebraska Interagency Safety Committee has determined that reducing the occurrence of vehicles deviating from their assigned lane by leaving the roadway, encroaching on, or crossing into opposing traffic lanes is one of the critical emphasis areas for the Nebraska Strategic Highway Safety Plan. Installation of **shoulder rumble strips**, **edge line rumble stripes**, and **centerline rumble strips** are cost effective measures recognized by Federal and state transportation agencies for alerting errant drivers of lane departure, potentially mitigating run off the road (ROR) and lane departure crashes.

Purpose

The purpose of this policy is to establish guidelines for the installation of rumble strips, edge line rumble stripes, and centerline rumble strips as mitigation measures for ROR crashes and for cross lane departure crashes on Nebraska highways.

Definitions

Shoulder rumble strips are milled into the shoulder surfacing. When a vehicle crosses a rumble strip, it shakes and the vibration causes a noise, alerting the driver that the vehicle is leaving the travel lane. Rumble strips are typically a 5/8 inch dip spanning 6 inches, and either 12 inches or 16 inches wide on 12 inch spacing.

Edge line rumble stripes are relatively narrow, 8 inches wide on 12 inch spacing, placed in the location of the white edgeline and are generally used where the surfaced shoulders are less than 6 feet in width.

Sent to: NDOR Roadway Design, NDOR "Distribution B", and selected consultants.

Installation should follow the Special Plans Section of the Nebraska Department of Roads Standard/Special Plans Book. The appropriate pay item is "Rumble Strip, Asphalt" and/or "Rumble Strip, Concrete". Rumble stripes will be paid for as rumble strips.

Average Daily Traffic (ADT): The total volume of traffic in a time period greater than one day and less than one year (measured in whole days), divided by the number of days in the chosen time period. The result is given in Vehicles per Day (VPD).

Future

When rumble strips, edge line rumble stripes or centerline rumble strips are placed they will be perpetuated on subsequent projects and not be obliterated without their function being replaced with a similarly effective mitigation measure for ROR departures (ex. lighting). Since the installation will substantially modify the ROR crash history, use of the warrants to justify continued use of the rumble stripes would be inaccurate. In the event that department maintenance operations or activities obliterate the rumble strips/stripes, they are not required to be reinstalled until the next resurfacing project. Rumble strips/stripes may be restored earlier if directed by the District Engineer.

Shoulder Rumble Strips

After reviewing the crash data and research literature, the NDOR has determined the following to be guiding principles for the installation of shoulder rumble strips on the state highway system.

- Shoulder rumble strips will be constructed on the shoulders, including the median shoulders, for all Interstate and expressway projects (new construction, reconstruction, and 3R).
- Shoulder rumble strips should be constructed on 6 foot wide or wider surfaced shoulders for all new construction and reconstruction projects on rural high-speed two-way two-lane highways.
- Shoulder rumble strips should be constructed on 3R projects over one-half mile in length on rural high-speed highways with continuous surfaced shoulder widths of 6 feet or greater.
- Existing rumble strips will be perpetuated on 3R projects over one-half mile in length. When project lengths are less than one-half mile, the rumble strips may be added to another project in the area to reduce mobilization fees.
- Projects with surfaced shoulders with curb and flume will be reviewed for inclusion of milled in rumble strips by Roadway Design.

Shoulder rumble strips may be placed at the direction of the Traffic Engineer or designee to address other traffic operations issues beyond those presented here.

Sent to: NDOR Roadway Design, NDOR "Distribution B", and selected consultants.

Edge Line Rumble Stripes

After reviewing the crash data and research literature, the NDOR has determined the following to be guiding principles for the installation of rumble stripes on the state highway system.

- Roadway type – Rural two-lane undivided with two way traffic.
- Lane width –12 feet with 2 feet integral shoulders for a 28 feet minimum total top width; Edge Line Rumble Stripes may be installed on shoulders up to 6 feet in width when recommended by Traffic.
- Pavement section with a recommended minimum overlay thickness of 2.5 inches of pavement and the surface in good condition.
- ADT in excess of 500 VPD.
- On curves with a ROR crash history.
- Crash history evaluation period of at least three years.
- Posted speed limit of 50 mph or greater.

Edge line rumble stripes may be placed at the direction of the Traffic Engineer or designee to address other traffic operations issues beyond those presented here.

Centerline Rumble Strips

After reviewing the crash data and research literature, the NDOR has determined the following to be guiding principles for the installation of centerline rumble strips on the state highway system.

- Roadway type – Rural two-lane undivided with two way traffic.
- Lane width – no less than 11 ft.; the lane width will be 12 ft. minimum where edgeline rumble stripes are present.
- Pavement section with a recommended minimum overlay thickness of 2.5 in. of pavement and the surface in good condition.
- ADT in excess of 1,500 VPD.
- Posted speed limit of 50 mph or greater.
- Evaluation period of at least three years and minimum length of segment of three miles.
- Cross lane departure and opposite direction sideswipe crashes greater than 0.4 crashes per mile per year evaluated for a minimum three mile segment for a minimum of three years where the combination of cross lane departure and opposite direction sideswipe crashes exceeds 1.0 crash per year per hundred million vehicle miles traveled.
- Segments may be added for continuity when the gap between highway segments with centerline rumble strips is less than 5 miles in length.
- Highway segments in excess of 10 miles in length that warrant the installation of centerline rumble strips under the preceding warrants will be reviewed to determine if the entire segment warrants the installation of centerline rumble strips. Gaps in excess of 5 miles in a segment that exhibit no cross lane departure and opposite direction sideswipe crashes may be omitted from the roadway to receive centerline rumble strips.

Sent to: NDOR Roadway Design, NDOR "Distribution B", and selected consultants.

Centerline rumble strips may also be placed to delineate geometric features of the roadway which may differ from the overall character of the roadway. Examples would be the delineation of broken back curves with intersections in the intermediate tangent, entrances to rural roundabouts, or approaches to channelized rural intersections.

Centerline rumble strips may be placed at the direction of the Traffic Engineer or designee to address other traffic operations issues beyond those presented here.

References include the following:

- NCHRP Report 641, Guidance for the Design and Application of Shoulder and Centerline Rumble Strips, 2009.
- Low Cost Treatments for Horizontal Curve Safety, FHWA, 2006.
- Shoulder and Edge Line Rumble Strips, FHWA Technical Advisory T 5040.39, November 7, 2011
- NCHRP Synthesis 339, Centerline Rumble Strips, 2005

Sent to: NDOR Roadway Design, NDOR "Distribution B", and selected consultants.

Appendix B Setup and Data Collection Manual

1.1 Equipment Checklist

☐ Laptop with functional data analysis software (MT Manager & Casella Insight) for the vibration meter

1. Fully charged and include a charger

☐ Vibration meter & accessories

1. Xsens MTi-G Motion Tracker
2. GPS Antenna
3. USB cable (for both power and data)

Fig. 1: Vibration Meter

☐ Sound level meter & accessories

1. CEL-63X meter
2. Removable microphone with amplifier
3. Acoustic calibrator
4. Windshield
5. Charger and 3 AA batteries

Fig. 2: Sound Level Meter

☐ Dual HD Mirror Cam Video Recorder

1. F360 HD Mirror Camera
2. Memory/SD card
3. Power cord
4. USB cord

Fig. 3: F360 Mirror Camera

☐ Full HD Contour Camera

1. Contour Camera with water proof case
2. Camera Mount/Clamp
3. Charging Unit & Batteries

☐ Traffic Cones with good reflectors (6 no.)

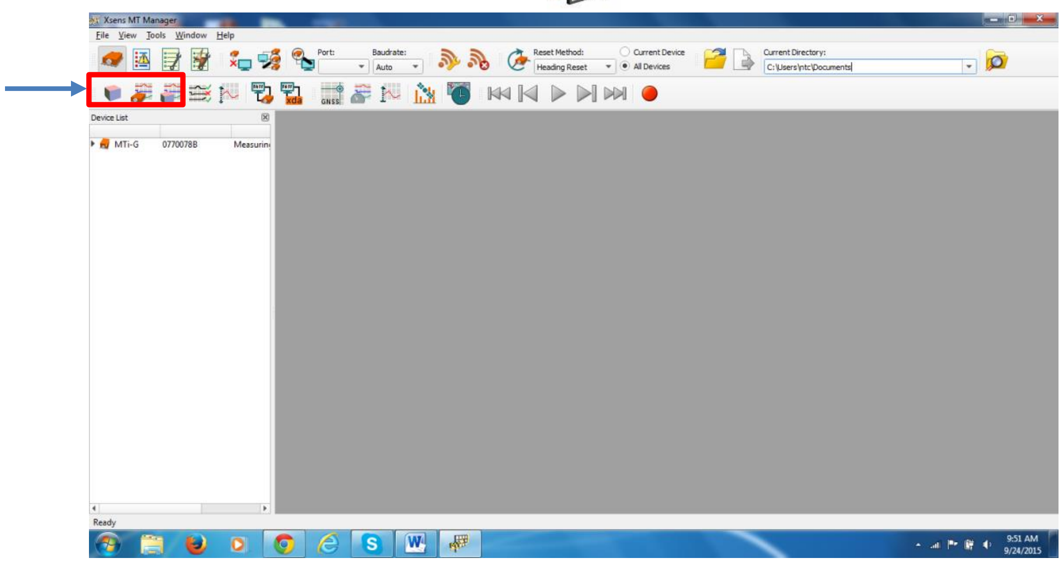
Fig. 4: F360 Mirror Camera

1.2 Field Setup

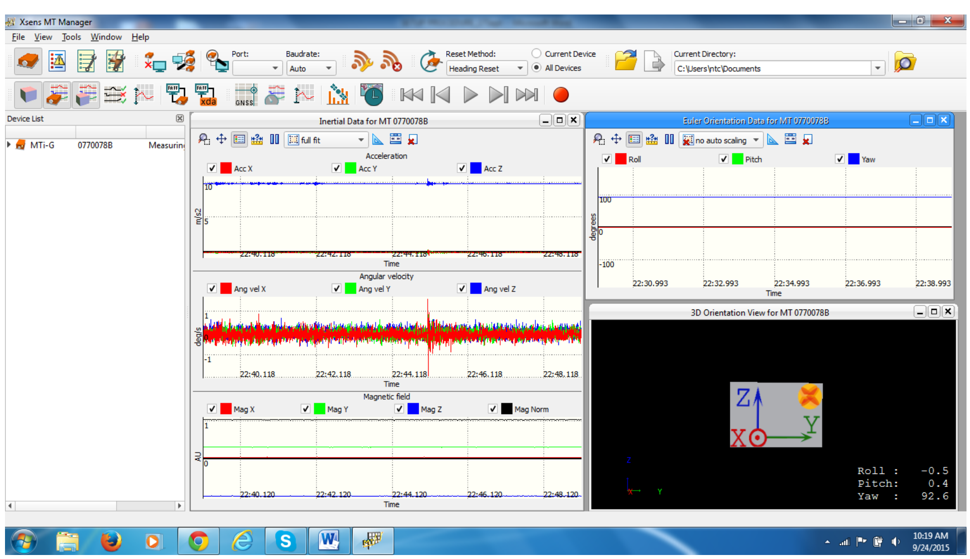
(In - Test Vehicle)

1. **Vibration Meter**
   a. Connect GPS Antenna to the Motion tracker. Make sure the sleeve of the connector is locked by turning-in the round nut

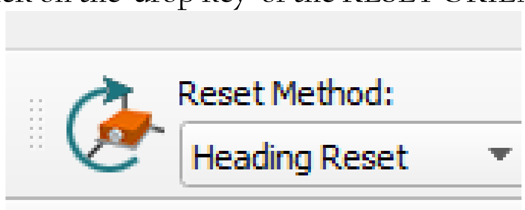
   b. Connect tracker via USB cable to the PC. This will be detected on the desktop
   c. Open the MT Manager software on the desktop
      1. Double click on this icon  to open up the screen below:



      2. Click on the following 3 icons: ‘3D Orientation, Inertia Data and the Orientation Data’ as highlighted and marked with an arrow above. These will activate the following screen



d. To check if the system is properly connected and the tracker is running: move the tracker around to view the corresponding display on the desktop.
e. Firmly affix the tracker with the GPS antenna on the dash board of the vehicle. Use a solid tape to prevent any isolated movement.
f. Note the position of the tracker for repeated runs.
g. Set all coordinates to zero (x, y, & z) by following the steps below:
    1. Click on the 'drop key' of the RESET ORIENTATION icon on the tool bar



    2. Change the reset method from 'Heading Reset' to 'Alignment Reset'
    3. Click on the icon to reset.
    4. The coordinates on the 3D orientation screen will all be reset to zeros.

2. **Sound Level Meter**
   a. Install batteries and place the removable microphone (with amplifier) on the CEL 63X sound meter. Make sure the red point on the microphone flashes with the red power key.

   b. Calibrate the sound meter
      1. Put ON the meter and fit the acoustic calibrator fully over the removable microphone.
      2. Press the ON key of the calibrator
      3. The meter automatically detects the signals and activates the calibration screen
      4. Press B to start calibration.
      5. It auto calibrates and display PASSED when finished.

6. Press A to exit and return to the stop screen
7. Switch off and remove the calibrator

c. Put the windshield on the microphone
d. Affix the sound level meter on the driver seat close to the ear level. Fix to avoid any displacement during data collection.

3. Video Camera (F360) for Approach Vehicles

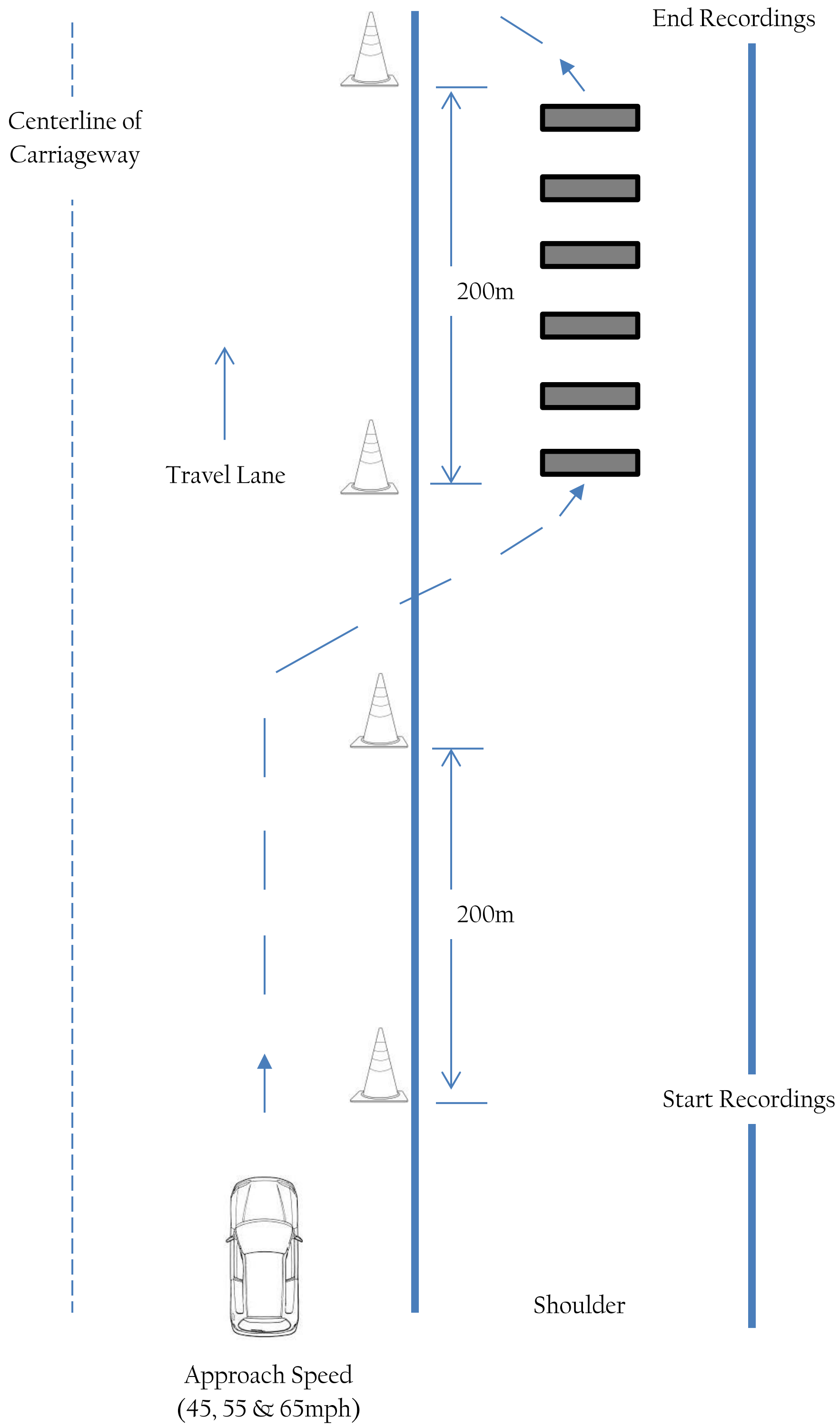
a. Insert SD card and plug in the unit to the vehicle 12v output socket. If the vehicle has no output, use the USB cable and link to your PC.
b. The Unit automatically turns on. When using the USB cable, the start screen will state two options, 'Mass Storage' and PC camera'.
c. Click on the Mode button to display the camera view.
d. This may start to record if the red recording icon is flashing. Immediately Press the Menu/Rec key to stop recording.
e. Check if the time and date synchronizes with the PC's
    - Long press the Menu/Rec button. This will get you to the Menu Screen. Press again to enter the Settings Screen where the first option will be the Time/Date settings.
    - Set time and date by using the Up or Down keys if not in sync with the PC.
f. Press the Mode key to get back to the video screen. The screen should be able to display dual views, time and date stamp.
g. Use the adjustable clamps to securely mount the F360 unit in a position that can display both front and rear views of the vehicle. The driver's mirror position is recommended.
h. The two cameras can be adjusted (through 180^{o}) to a position that will best capture approaching traffic.

4. Video Camera for Test Vehicle Movement on Rumble Strips

a. Place the contour camera in the mount on the vehicle front fender.
    - Note that the camera should be in its protected case
b. The lens of the camera should point in a direction for a good view of the tire and road surface interaction.

The site layout for a typical setup for the test is illustrated as follows:

1. Shoulder Rumble Strip Test Layout



2. Centerline Rumble Strip Layout

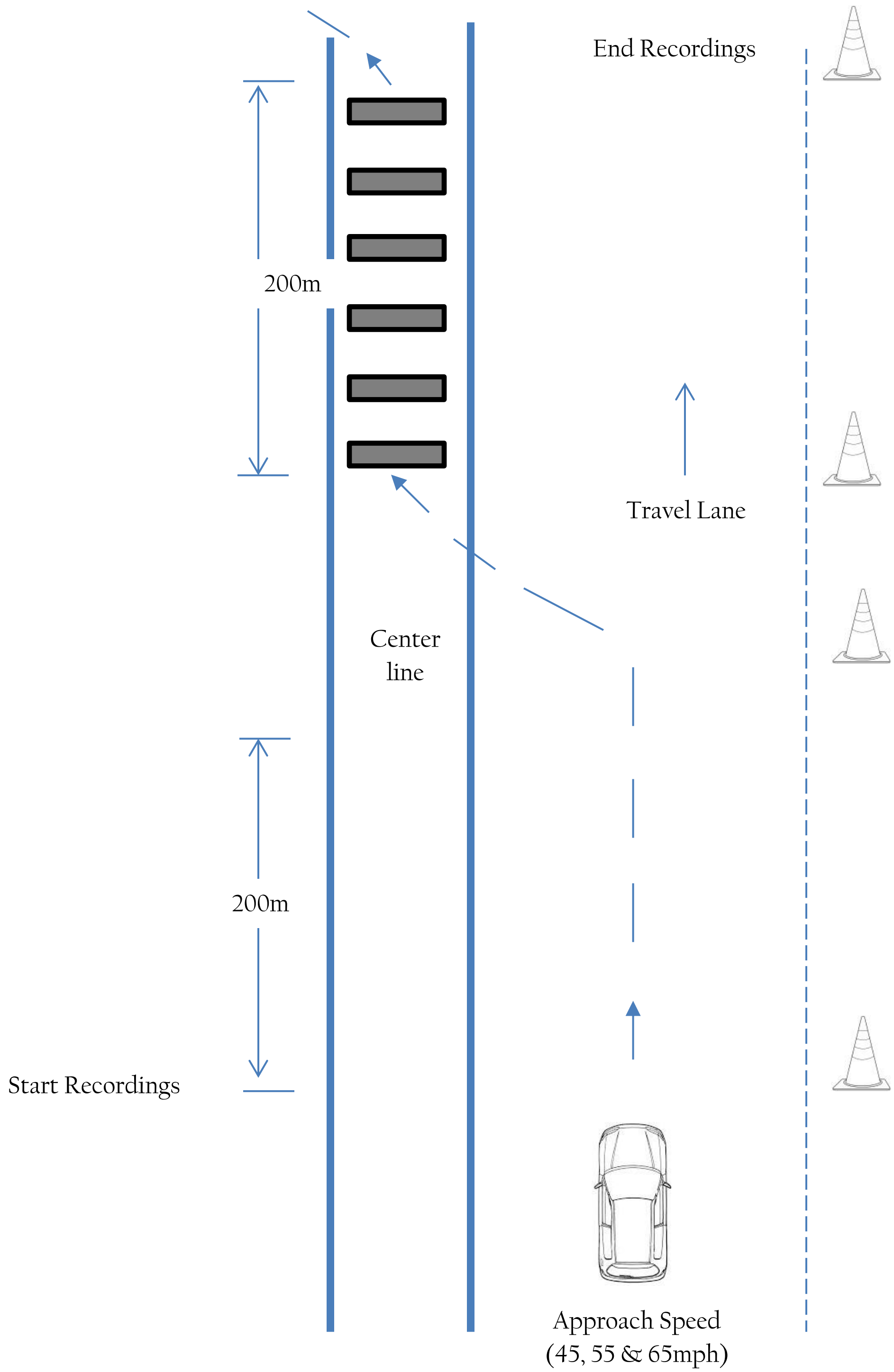


Figure 5: Illustration of Field Setup for Data Collection

1.3 Data Collection

Four (4) Officers will be the minimum requirement for data collection. Each of their specific roles is outline below:

Officer 1: -Driver of the test vehicle. -Should have a good understanding of the test by knowing the speed required (cruise control), the point of diverging from the travel lane onto the rumble strips and when to return back.

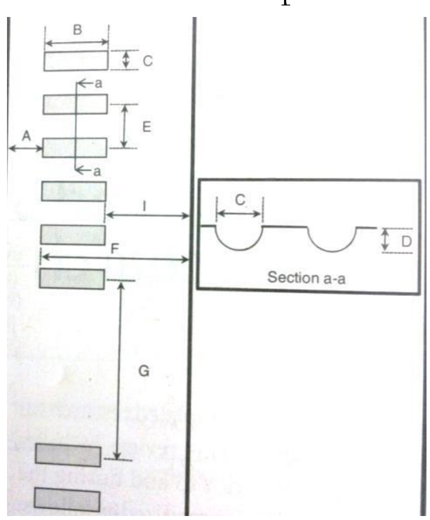
Officer 2: -Sit with the driver in the test vehicle. -Operate the PC and the measuring instruments. -Should be conversant with the test procedure, the software and the instruments. – Should know when to start the test and end.

Officers 3&4: -Should be flagmen located at good positions (approx. 200m) to the start of the test field and also at the end of the test position. -Should have successfully completed the safety test conducted by NTC and know the basic safety precautions of being flagmen.

Other officers may be deployed to assist in data collection and safety precautions.

A. MEASURING THE DESIGN PARAMETERS OF THE STRIPS

1. The quota sampling method which is based on the analyst's own judgement and the stratified probability sampling will be adopted.
    a. Group the rumble strips within the test region into three sections each of length 50m.
    b. Within each group; mark out 10 strips, of which 5 are in good condition and the remaining in worse condition
2. Measure the dimensions of the selected rumble strips as described below and fill in the record sheet.



(NCHRP Report 641: Fig 6)

1.4 Site Record Sheet

Road Name:

Location/section:

Bench mark:

Weather Condition:

Time of the Day 00hr00min:

Date:

All measurements in metrics (cm)

		Offset	Length	Width	Depth ***(milled/rolled)*** ***or*** Height ***(raised type)***	Spacing	Recovery Area	Gap	Lateral Clearance	Remarks
		A	B	C	D	E	F	G	I	
Within (1-50m)										
Strips in Good Condition	1									
	2									
	3									
	4									
	5									
Bad Condition	6									
	7									
	8									
	9									
	10									
	Averages									
Within (50-100m)										
Strips in Good Condition	1									
	2									
	3									
	4									
	5									
Bad Condition	6									
	7									
	8									
	9									
	10									
	Averages									
Within (100-150m)										
Strips in Good Condition	1									
	2									
	3									
	4									
	5									
Bad Condition	6									
	7									
	8									
	9									
	10									
	Averages									

1.5 Recording Sound and Vibration Measurements

1. The contour camera at the fender of the vehicle is switched on to record by sliding forward the button on top of the casing.
2. Vehicle needs to gain momentum at a cruise speed of 45, 55 or 65mph before reaching the start point for recording (Figure 5).
3. Officer 2 writes down the date, speed and time and undertake the following steps before the start point:
    a. Click the record button in the MT manager software on the PC (arrow A)

    b. A successful click will change the ***measuring*** status (arrow B) to ***recording***
    c. Press on the Play/Stop key on the Sound level meter to start recording. A 120 secs record note will appear prior to the measurement. Press REC
    d. Officer 2 should record a voice note of the date, speed and time. Press Play/Stop key when completed.
    e. The screen changes from red to green bars at the top and bottom to start measuring.
    f. Click on the MENU/REC key on the F360 Cam Video Recorder to start recording. A flashing red light will show on the display screen.

4. How to STOP recordings at the end of each run:
    a. Click on the REC button in the MT Manager software on the PC to stop the sensor from recording
    b. Click on the PLAY/STOP key on the sound level meter. A screen will pop out asking you to stop recording. Click YES and write the RUN NUMBER on the top right corner of the blue displayed screen (i.e. Run 0…). Press the EXIT key to return to the stop mode (red bars at the top and bottom of screen)
    c. Click on MEN/REC key on the F360 Cam to pulse recording.

5. Start the recording process again for the subsequent RUNS.

6. Note that each run is recorded separately by carefully undertaking this process. Failure to stop recordings after each run will give a continuous data that may be difficult to separate or distinguished.

1.6 Retrieving Collected Data

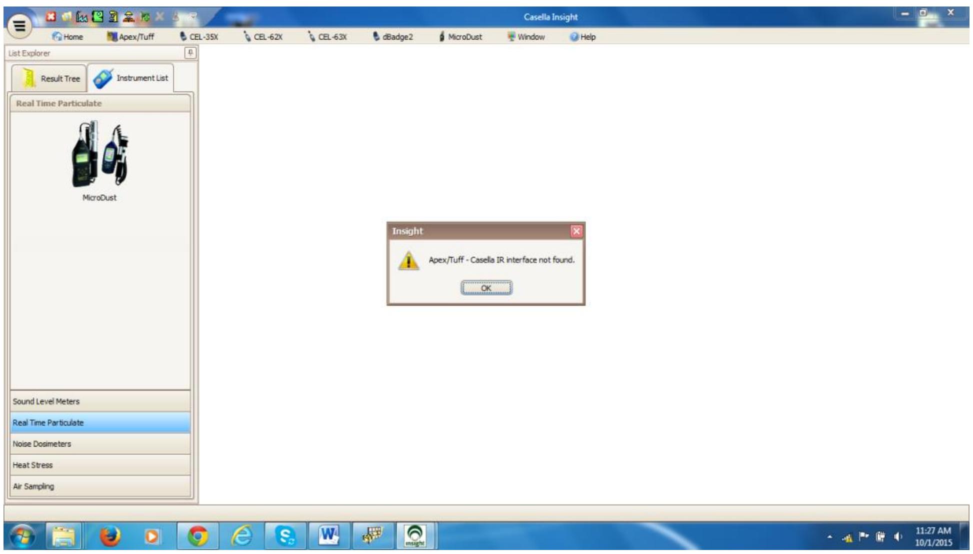
-From Sound Level Instrument (CEL-63X)

1. Switch on the sound level instrument and connect it to the PC via the USB cable
2. Ignore the Auto play screen that pops up after the connection
3. Open the Casella Insight Data Management software

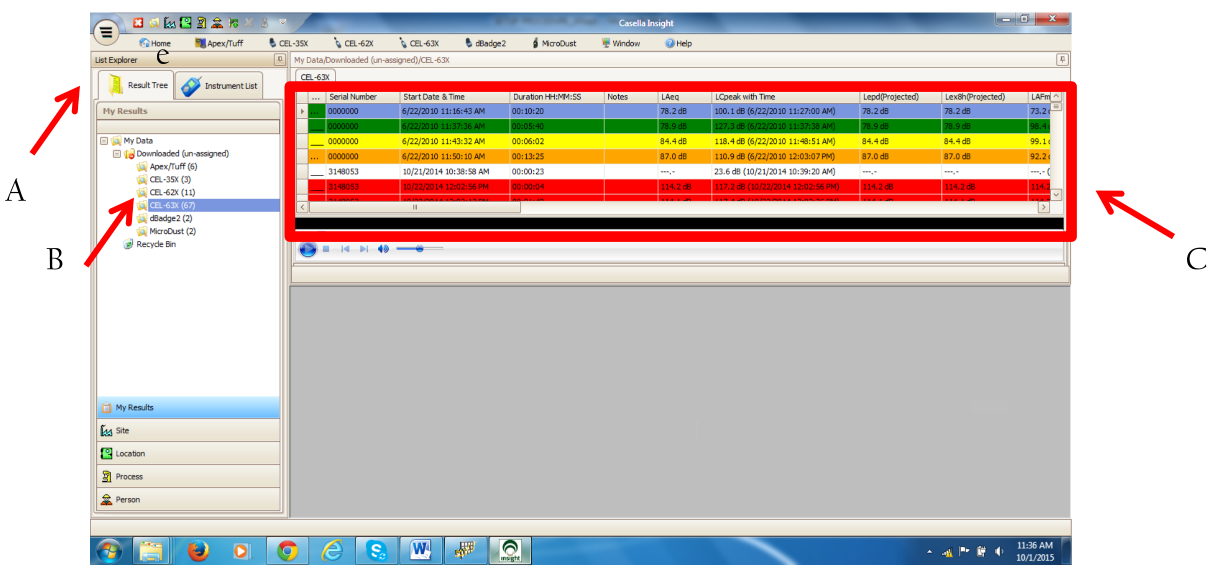
    a. Double click on 

 from the desktop to open the software.

    b. This screen shows up. Clicks on OK twice



    c. Click on the RESULT TREE (A) and select CEL 63X – (B)



d. The AREA Mark (C) shows all the recorded data stored on the sound meter. The color codes indicate the exposure level of the results (i.e. above or below threshold values)

e. Data is sorted by date and time of recording. It also gives the voice notes recorded during the beginning of a RUN.

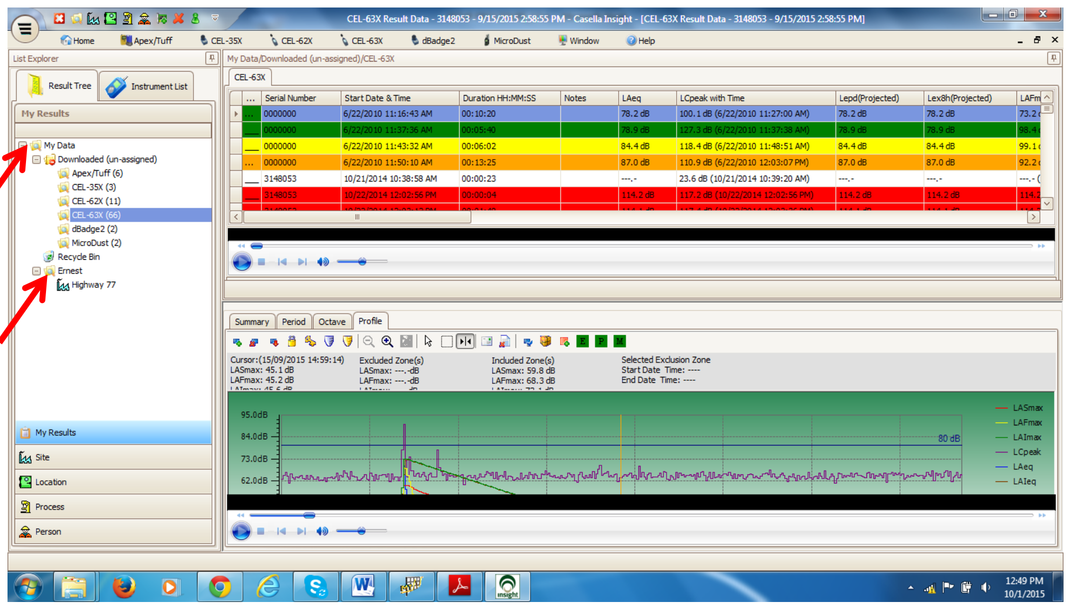
f. Double click on any line data to show the results SUMMARY, PERIOD, OCTAVE & PROFILE

g. To export the data into an excel format:

   i. Create a new folder – Right click on the MY DATA (marked A) & add folder

A

B



   ii. The new folder is added (Marked B). Right lick on the new folder and add a Site (use name of location as site name: e.g. Highway 77)

   iii. Copy all recordings in the CEL-63X folder into their corresponding site locations.

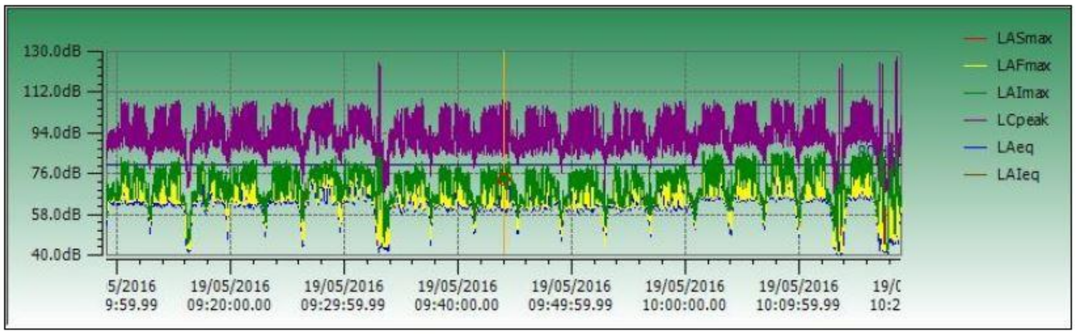
   iv. Right click on the site and EXPORT Data to a known location on the PC.

   v. Generate a Report for this site by right clicking on any of the data line to select GENERATE REPORT FOR THIS RESULTS. Follow the wizard to print out your report. A sample report is as shown below:

NEBRASKA TRANSPORTATION CENTER & NDOR

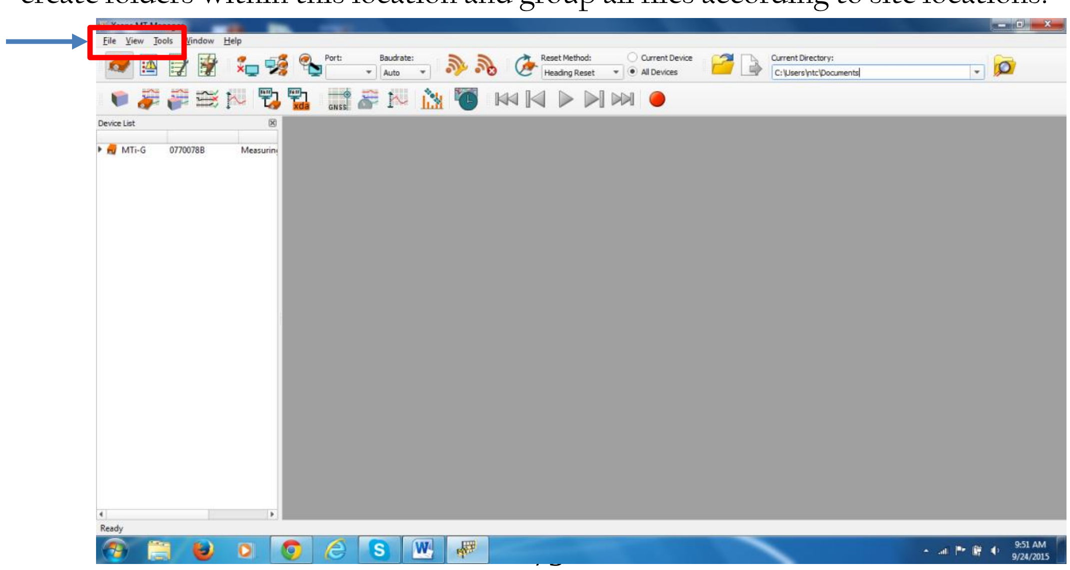
Report on Rumble Strips

Instrument Model	CEL-632A		
Duration	01:09:52 HH:MM:SS	Start Date & Time	5/19/2016 9:09:07 AM
End Date & Time	5/19/2016 10:18:59 AM	Result	Cumulative

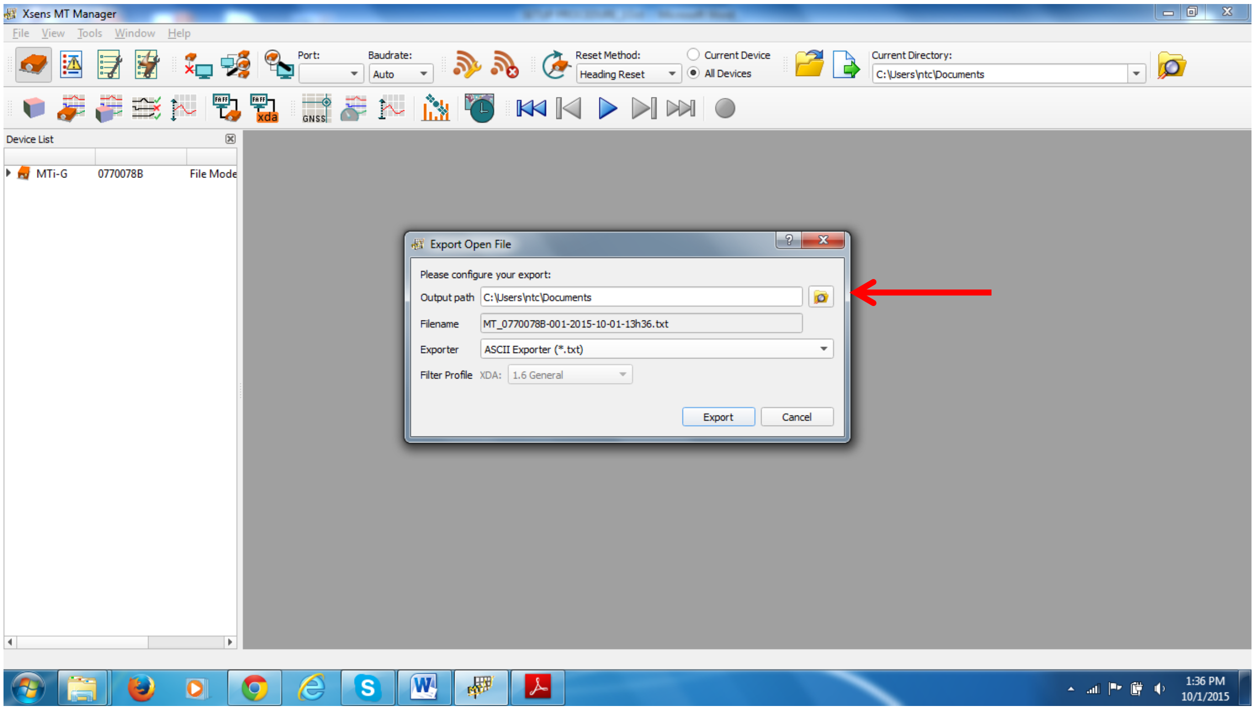


-Retrieving Data from Vibration Sensor (Xsens MTi-Motion Tracker)

1. Open the MT Manager Software
2. Click on the FILE tap at the top right corner of the screen to select OPEN FILE
3. This opens up the location of all the recorded measurements on site. It is advisable to create folders within this location and group all files according to site locations.



4. Double click on any of the recorded files to open it up within the MT Manager.
5. Click on File again and select EXPORT Data. Select the appropriate location for the exported file.



6. The exported file will be a text file (*.txt). We can then open this any statistical software to analyze the data.

Appendix C Recorded Sound and Vibration Levels at Test Sites

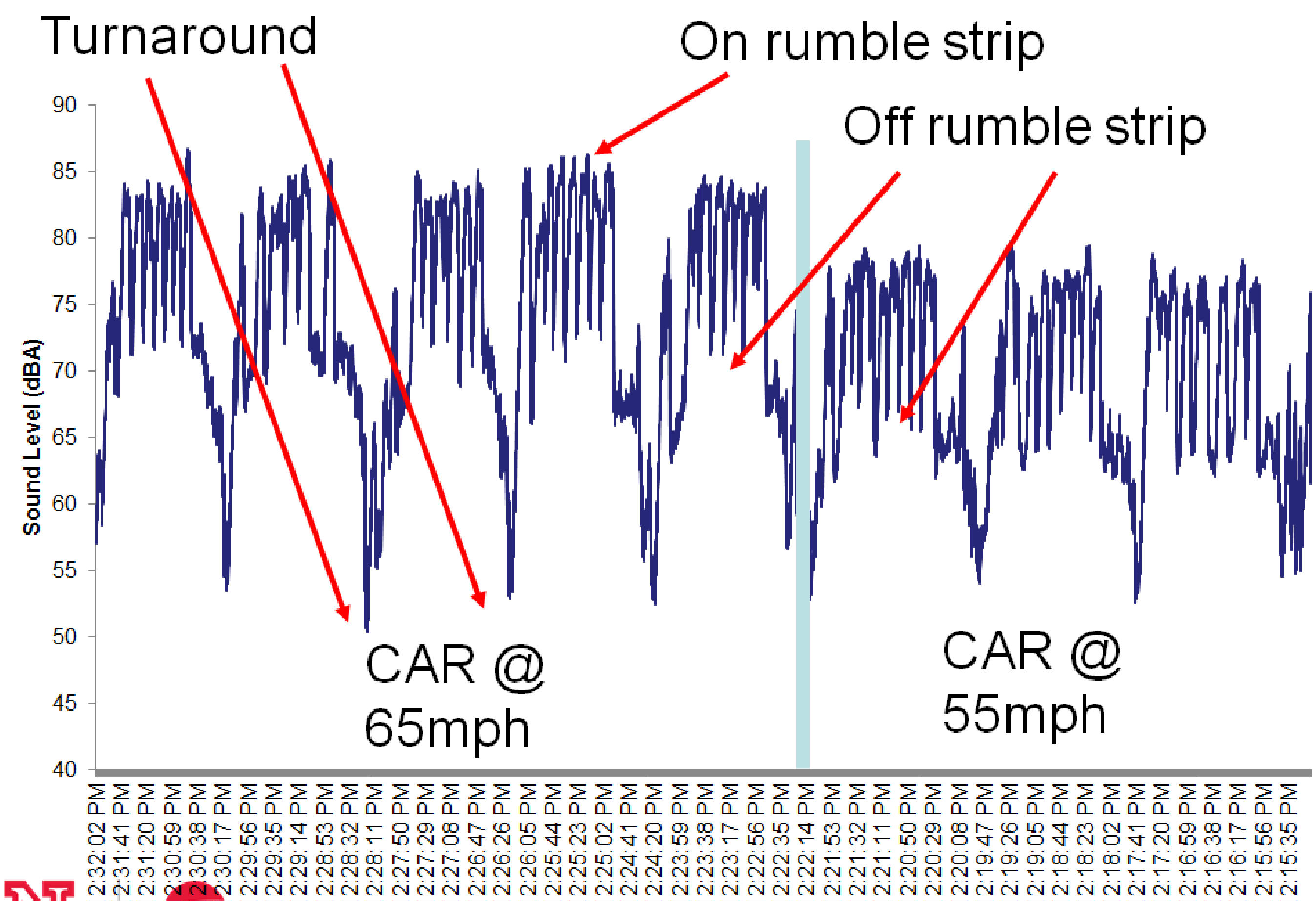
The time for the data collection and the vehicle type used at each test site is shown below.

Test no.	Test sites	Testing time on 5/19/2016	Vehicle type
1	238th road (Milford near Midwest Machinery)	09:13 to 10:21 am	car
2	Highway 34 near Seward	11:05 to 11:23 am	car
3	Highway 34 near Seward	12:15 to 12:32 pm	truck
4	238th road (Milford near Midwest Machinery)	12:38 to 1:11 pm	truck
5	Highway 103 near Crete	2:03 to 2:22 pm	truck
6	Highway 103 near Crete	2:31 to 2:51 pm	car
7*	Highway 77 (Homestead hwy Sth 12st -in Princeton)	3:22 to 3:30 pm	car
8*	Highway 77 (Homestead hwy Sth 12st -in Princeton)	3:44 to 3:53 pm	truck

*Additional test site that is not included in the data analysis. This is an old type RS configuration

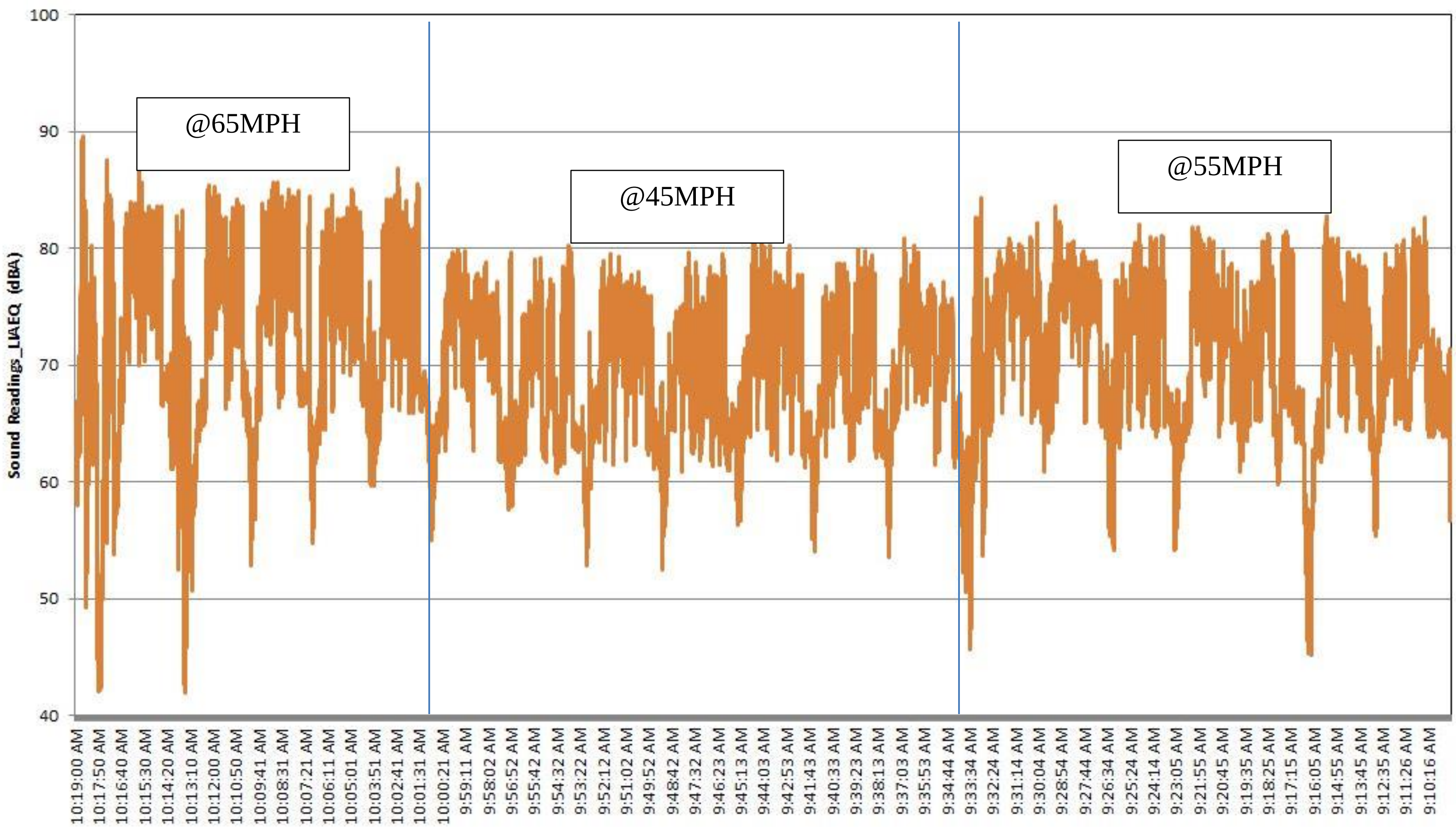
The measured sound levels for the various test numbers are graphically represented as follows:

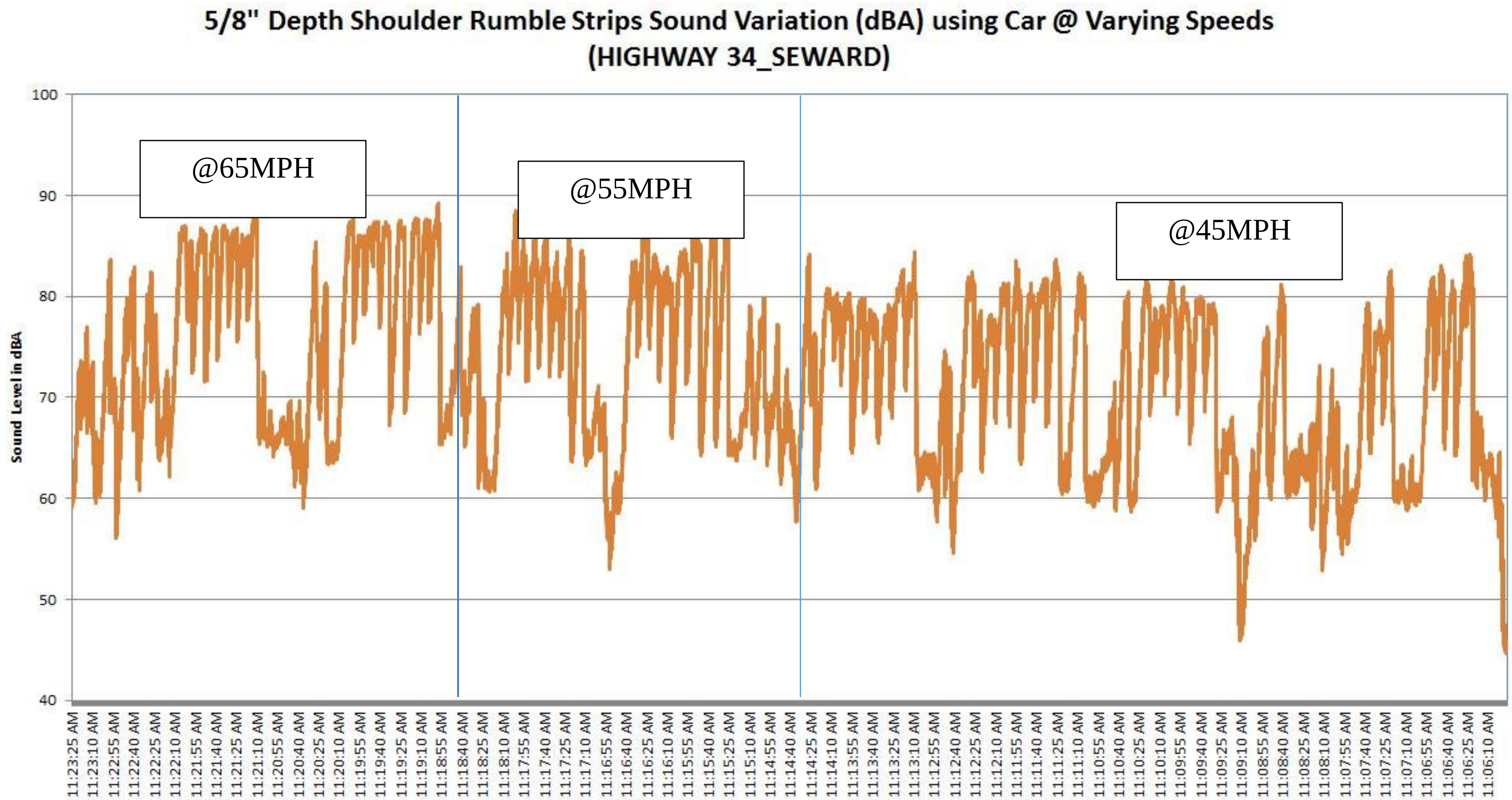
1. Recorded Sound Levels at Various Locations



Nebraska Transportation Center | Mid-America Transportation Center

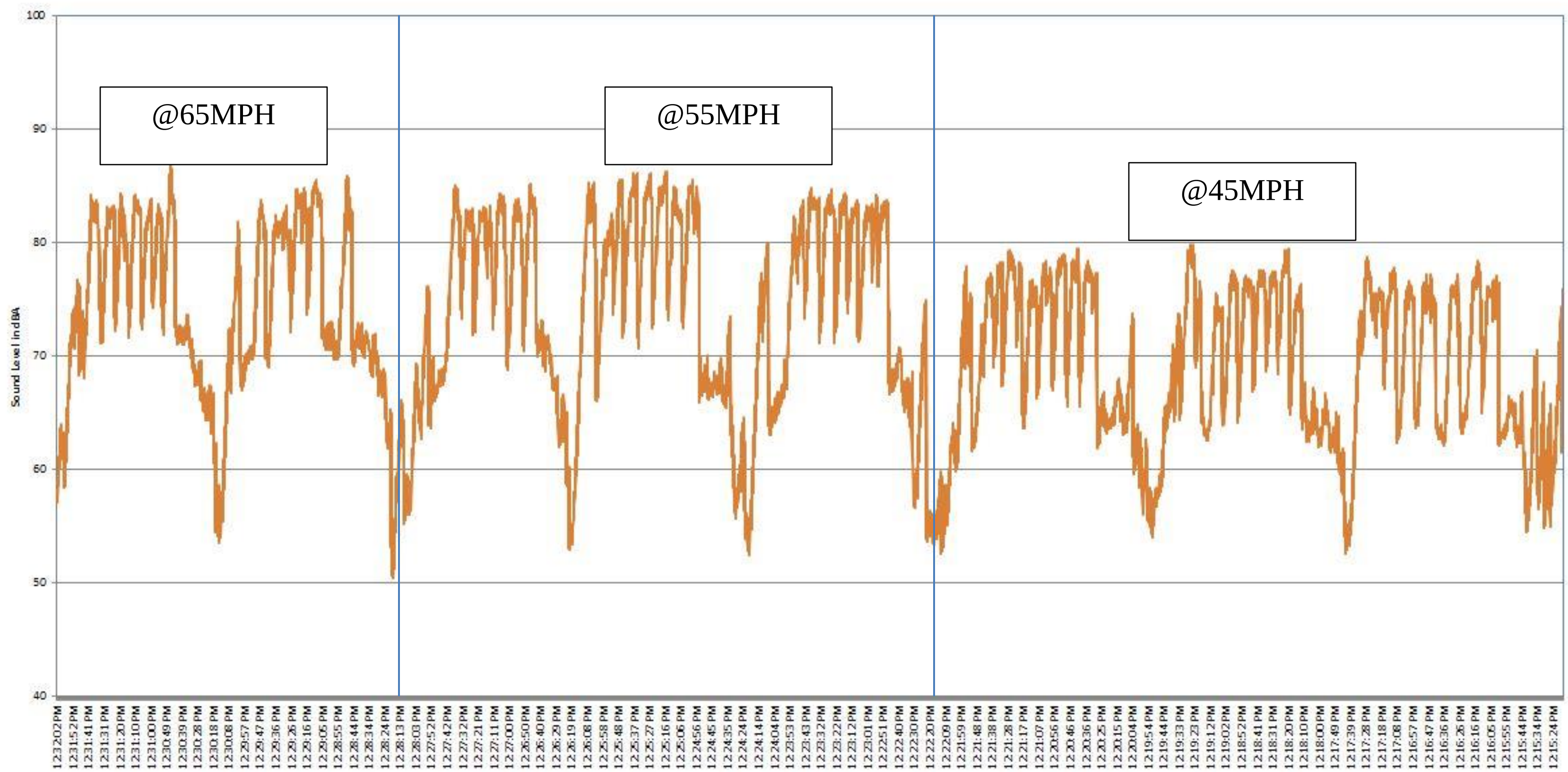
Centerline Rumble Strips Sound Variation (dBA) using Car @ different speeds and varying Depth (MILFORD)



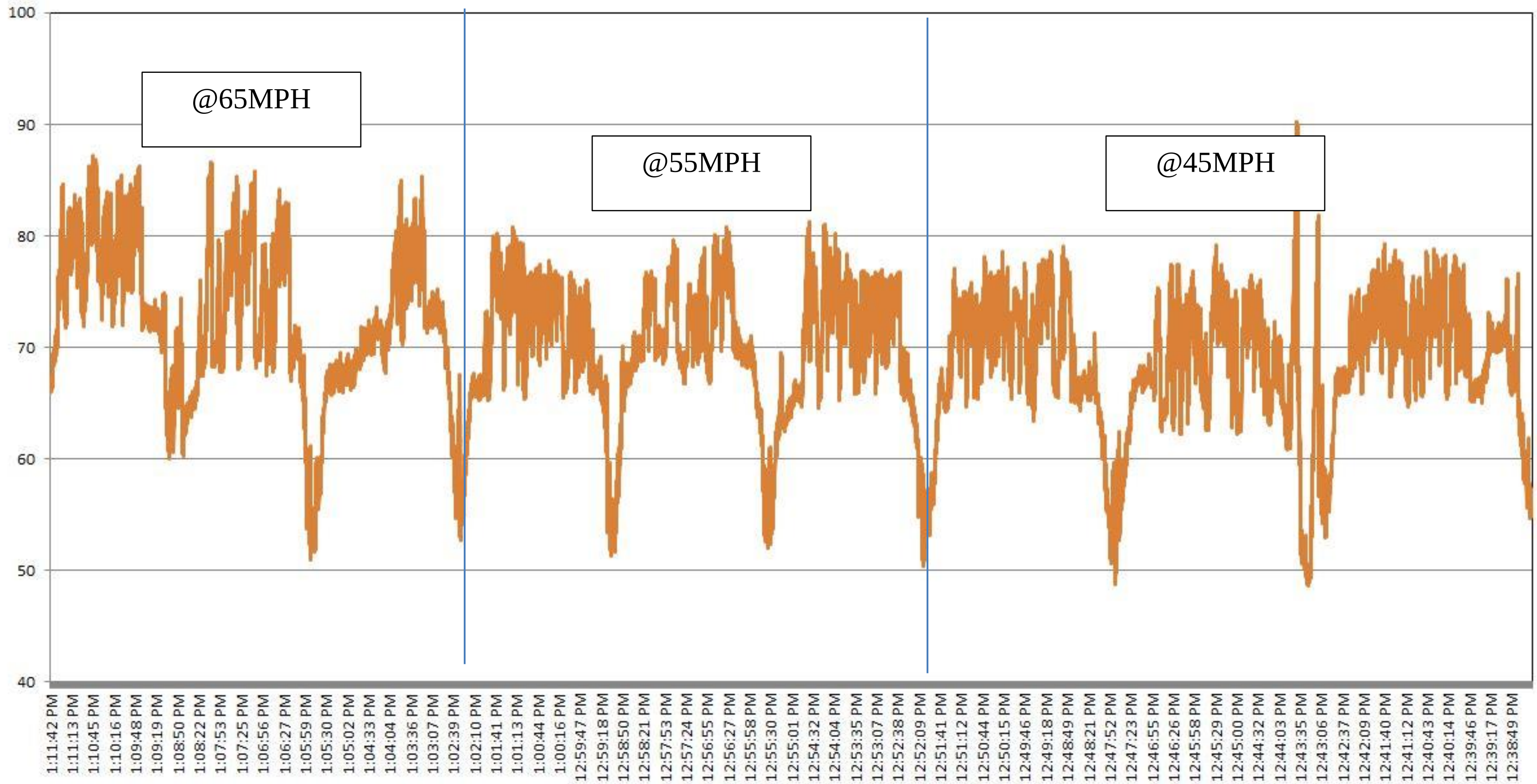


5/8" Depth Shoulder Rumble Strips Sound Variation (dBA) using Car @ Varying Speeds
(HIGHWAY 34_SEWARD)
@65MPH
@55MPH
@45MPH
Sound Level in dBA

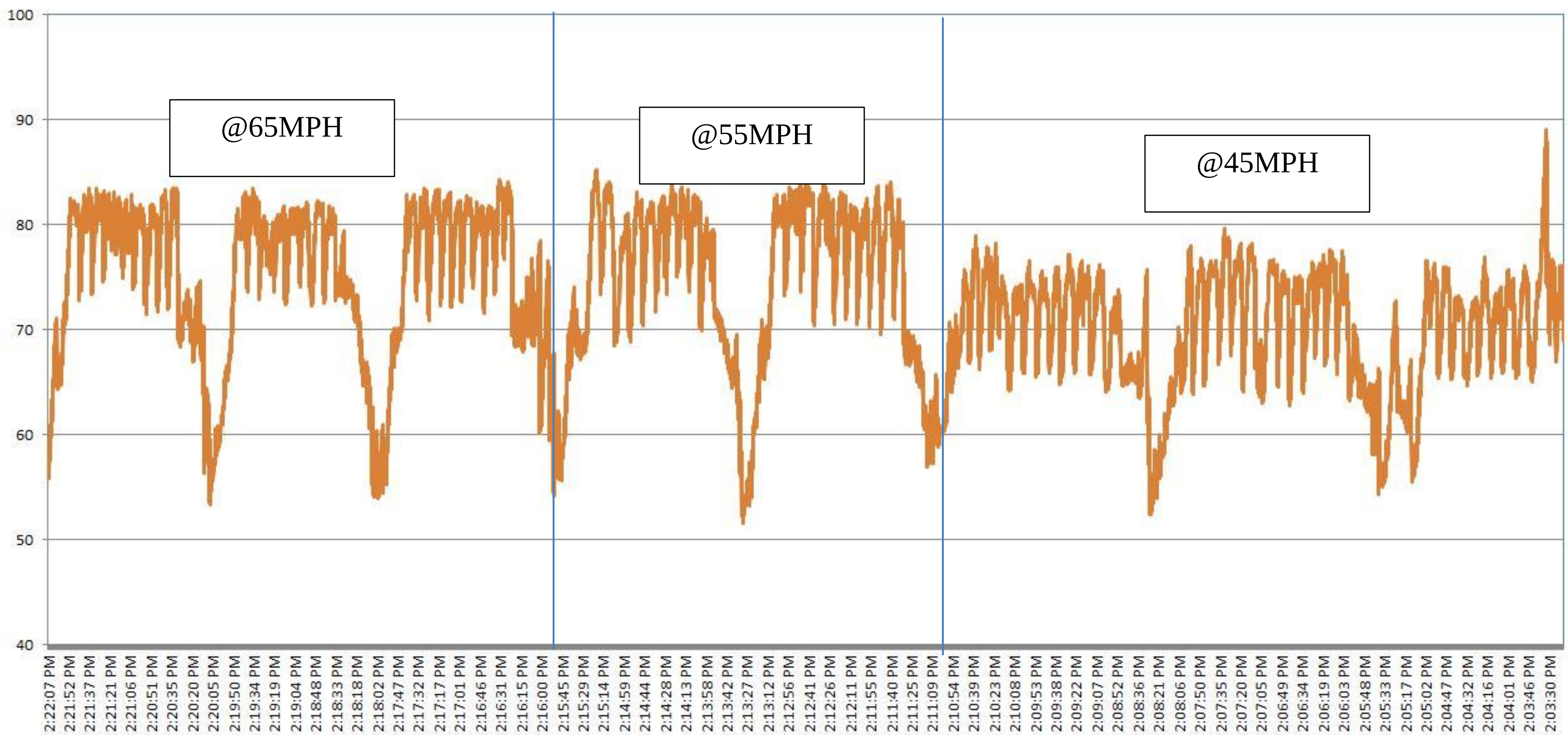
5/8" Depth Shoulder Rumble Strips Sound Variation (dBA) using Truck @ Varying Speeds (HIGHWAY 34_SEWARD)



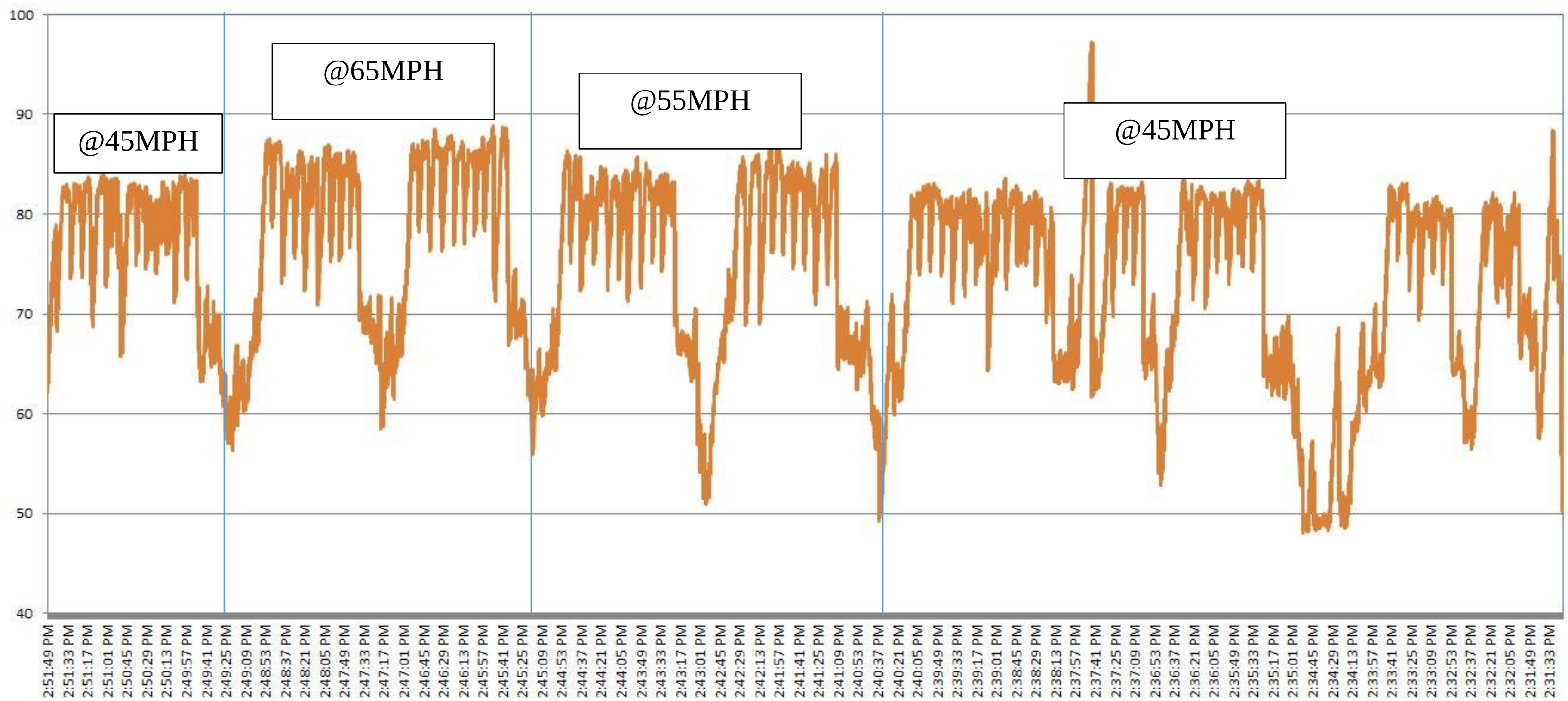
Centerline Rumble Strip Sound Variation (dBA) using Truck @ different Speeds and varying Depths (MILFORD)



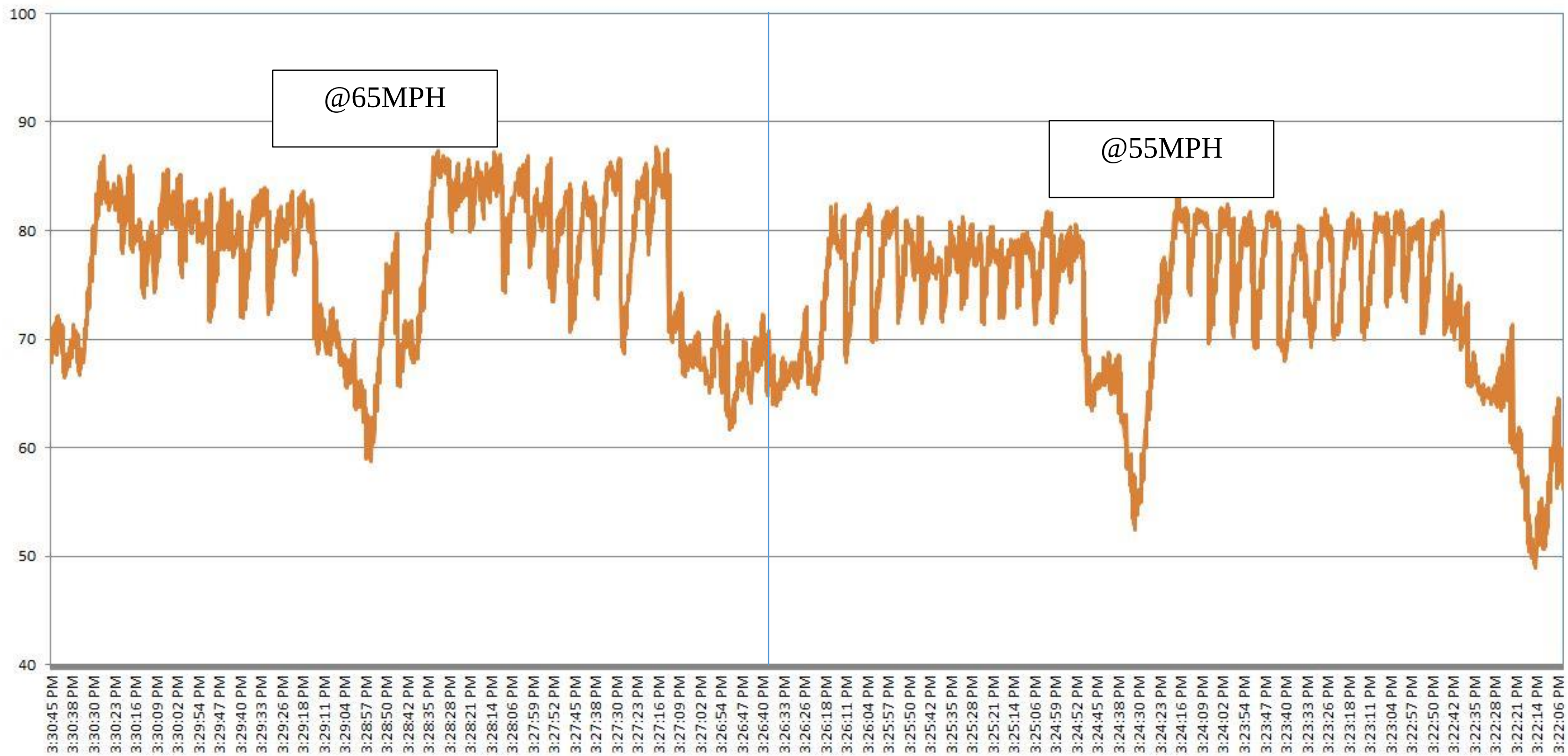
Shoulder Rumble Strip Sound Variation (dBA) using Truck @ different Speeds and varying Depths
(HIGHWAY 103_SOUTH CRETE)



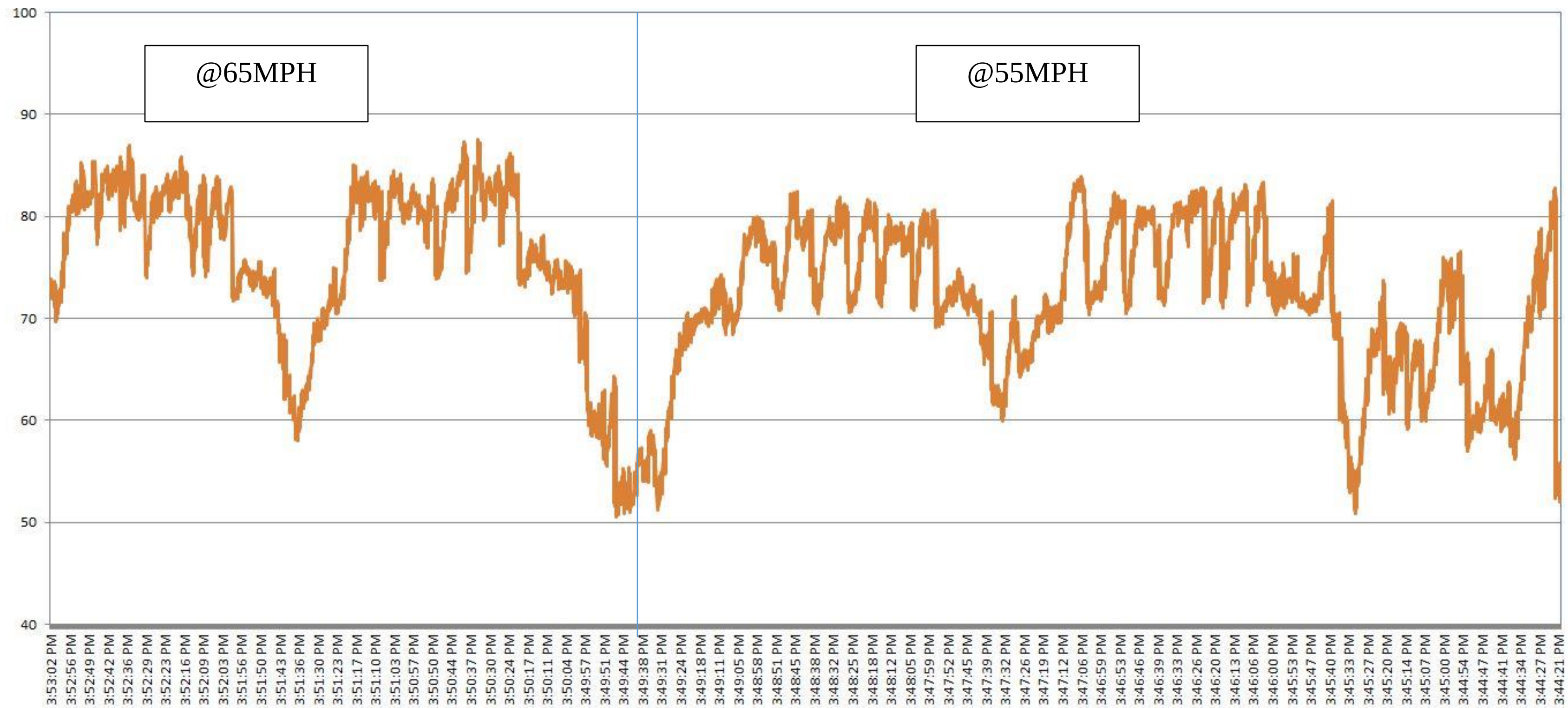
Shoulder Rumble Strip Sound Variation (dBA) using Car @ different Speeds and varying Depths
(HIGHWAY 103_SOUTH CRETE)



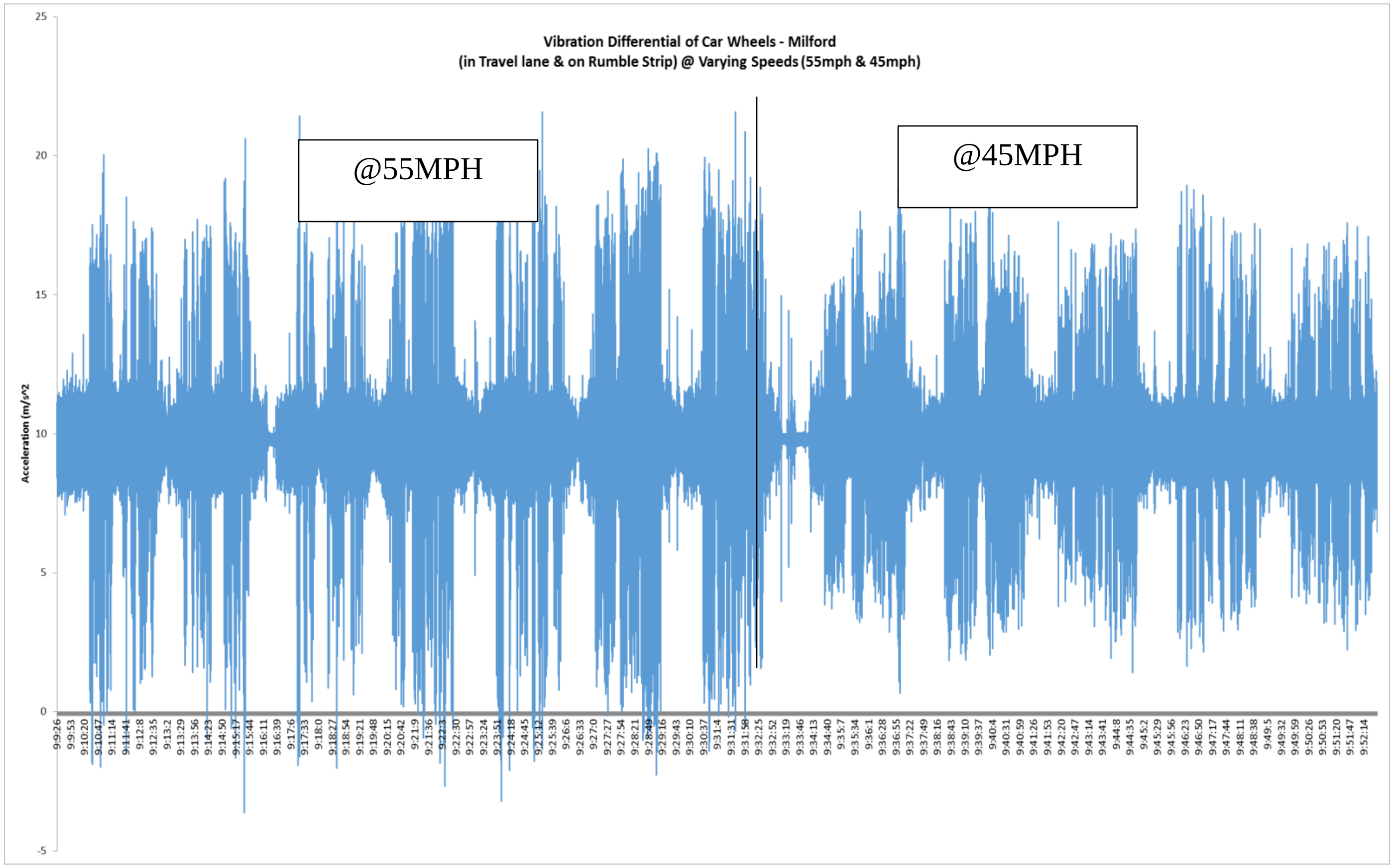
5/8" Old Type Shoulder Rumble Strip Sound Variation (dBA) using Car @ different Speeds (HIGHWAY 77_PRINCETON)

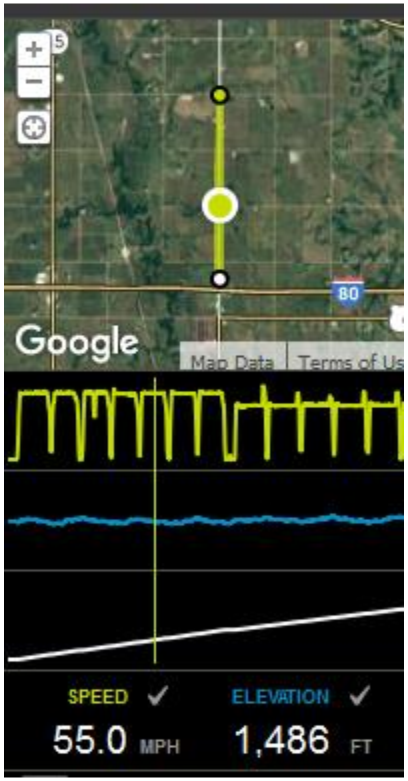


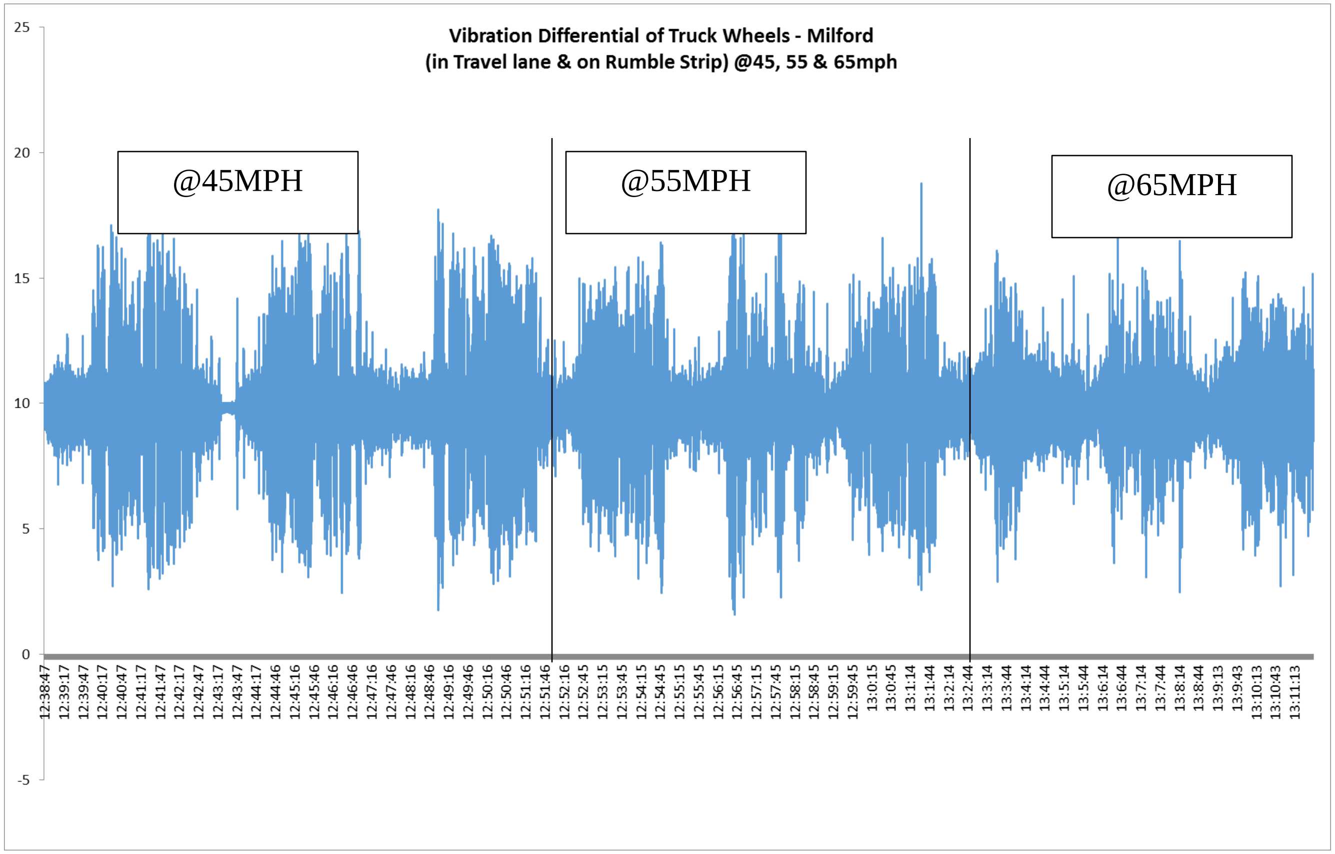
5/8" Old Type Shoulder Rumble Strip Sound Variation (dBA) using Truck @ different Speeds
(HIGHWAY 77_PRINCETON)



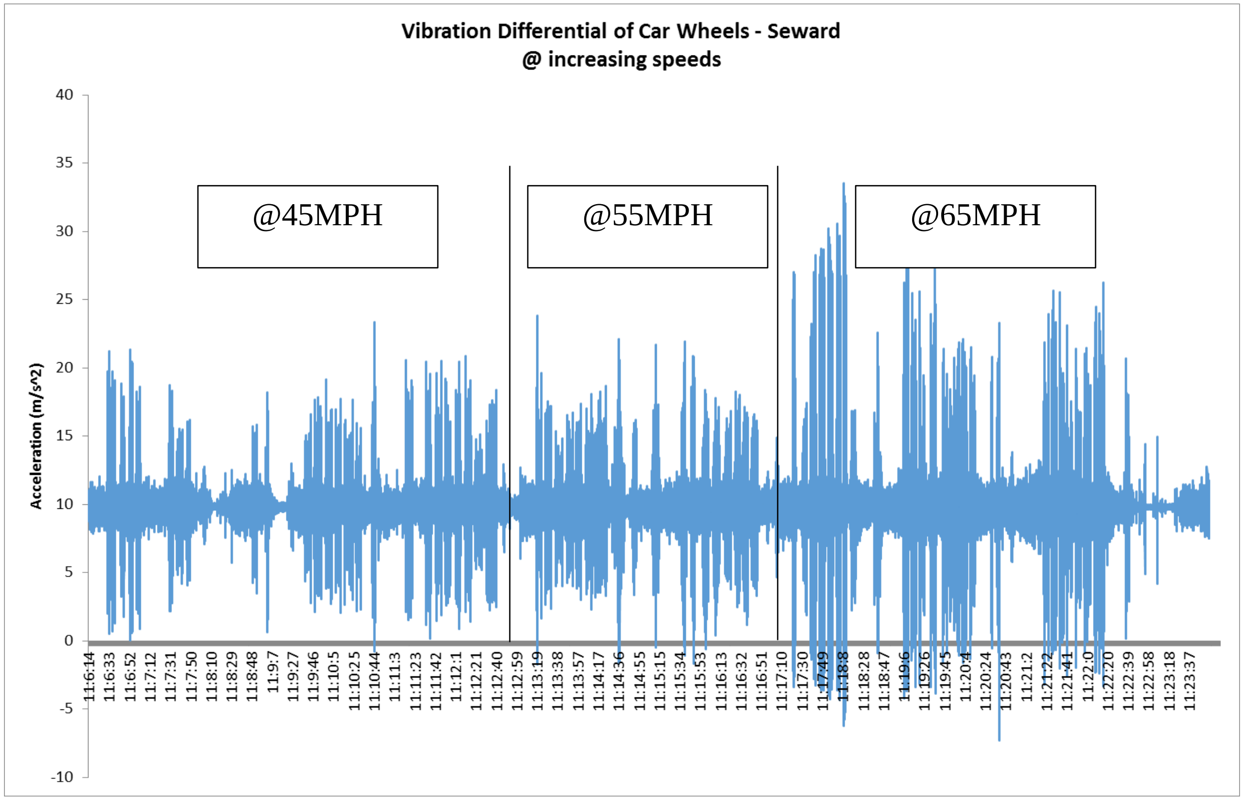
2. Measured Vibration Levels at Various Locations





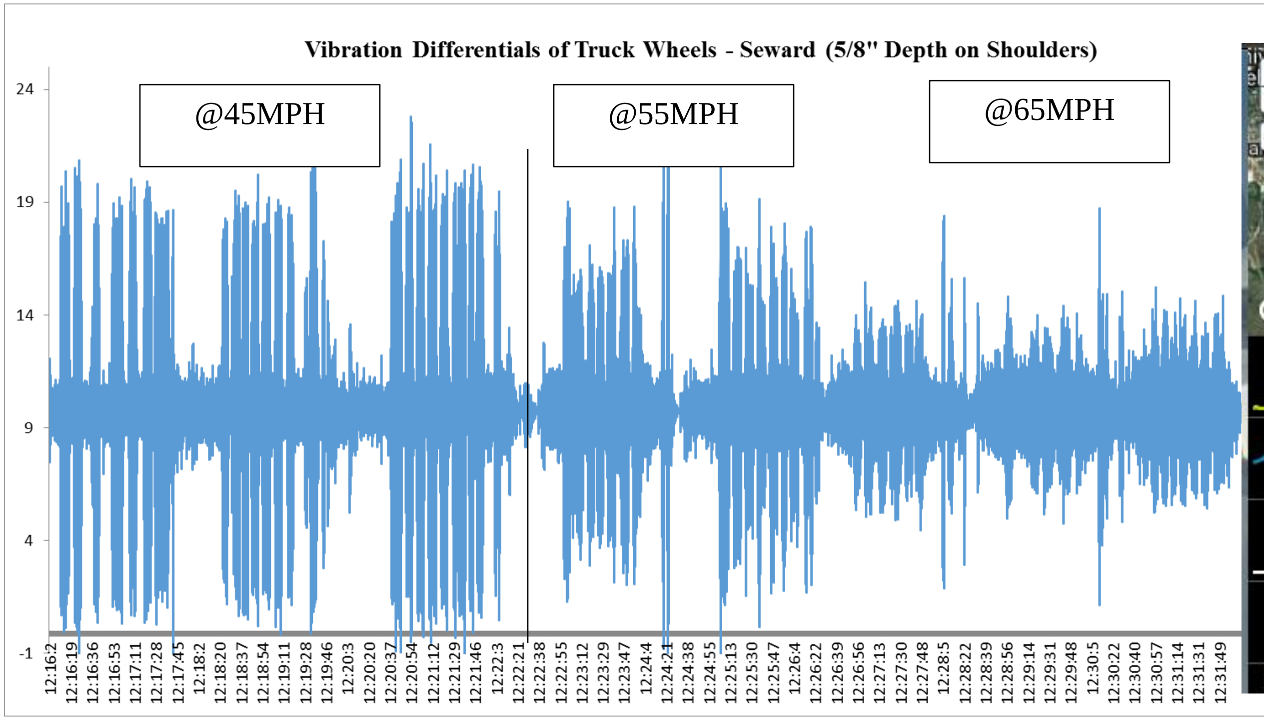

Vibration Differential of Truck Wheels - Milford
(in Travel lane & on Rumble Strip) @45, 55 & 65mph
@45MPH
@55MPH
@65MPH
25
20
15
10
5
0
-5
12:38:47
12:39:17
12:39:47
12:40:17
12:40:47
12:41:17
12:41:47
12:42:17
12:42:47
12:43:17
12:43:47
12:44:17
12:44:46
12:45:16
12:45:46
12:46:16
12:46:46
12:47:16
12:47:46
12:48:16
12:48:46
12:49:16
12:49:46
12:50:16
12:50:46
12:51:16
12:51:46
12:52:16
12:52:45
12:53:15
12:53:45
12:54:15
12:54:45
12:55:15
12:55:45
12:56:15
12:56:45
12:57:15
12:57:45
12:58:15
12:58:45
12:59:15
12:59:45
13:0:15
13:0:45
13:1:14
13:1:44
13:2:14
13:2:44
13:3:14
13:3:44
13:4:14
13:4:44
13:5:14
13:5:44
13:6:14
13:6:44
13:7:14
13:7:44
13:8:14
13:8:44
13:9:13
13:9:43
13:10:13
13:10:43
13:11:13


Hybrid
Google
Map Data
Terms of Use
Report a map error
SPEED
ELEVATION
DISTANCE
45.0 MPH
1,497 FT
0.6 MI
VIDEO INSET
CLOSE

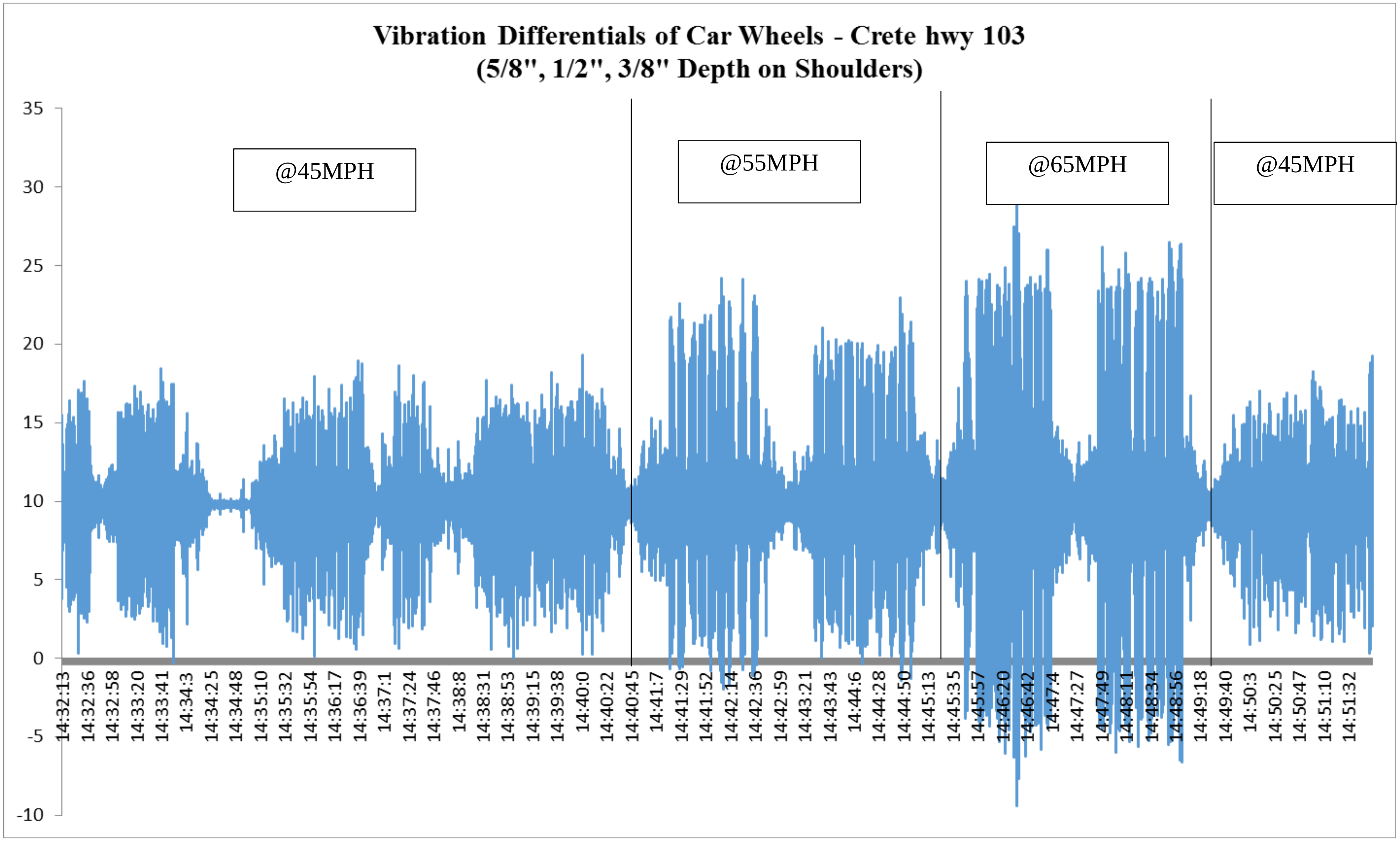


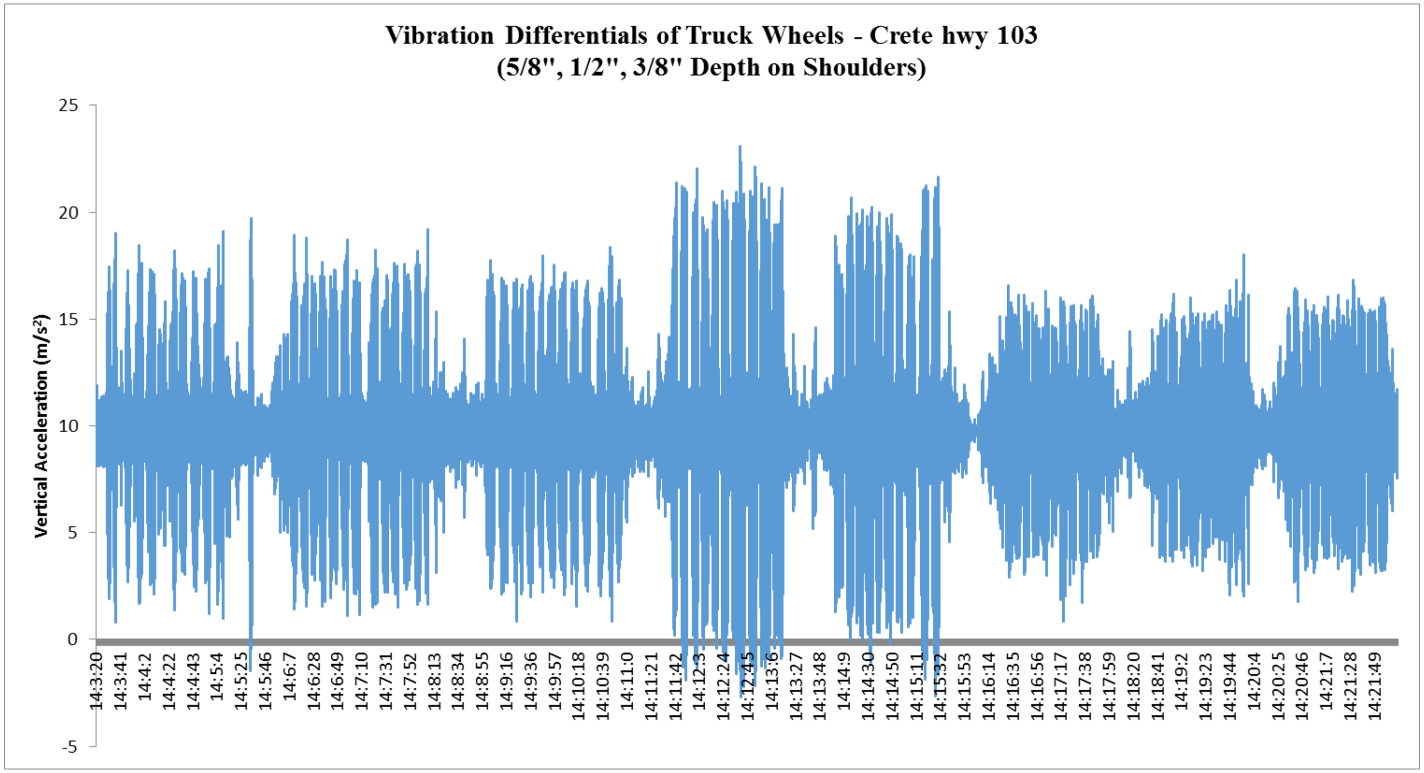
Vibration Differential of Car Wheels - Seward
@ increasing speeds
Acceleration (m/s^2)
@45MPH
@55MPH
@65MPH
40
35
30
25
20
15
10
5
0
-5
-10

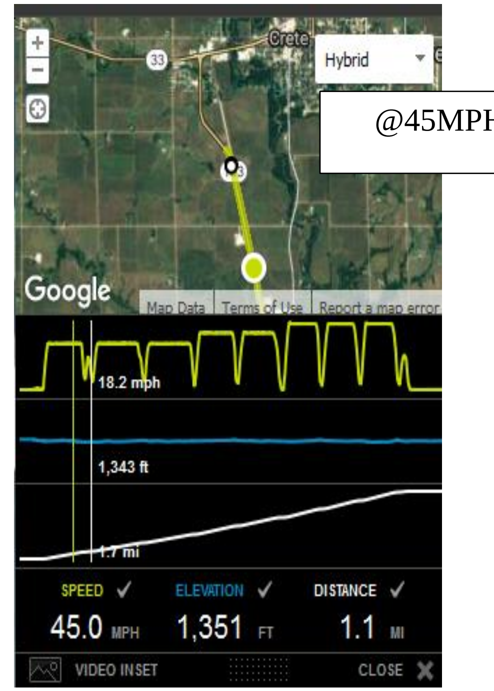
Hybrid
Google
Map Data
Terms of Use
Report a map error
SPEED
55.0 MPH
ELEVATION
1,526 FT
DISTANCE
6.2 MI
VIDEO INSET
CLOSE

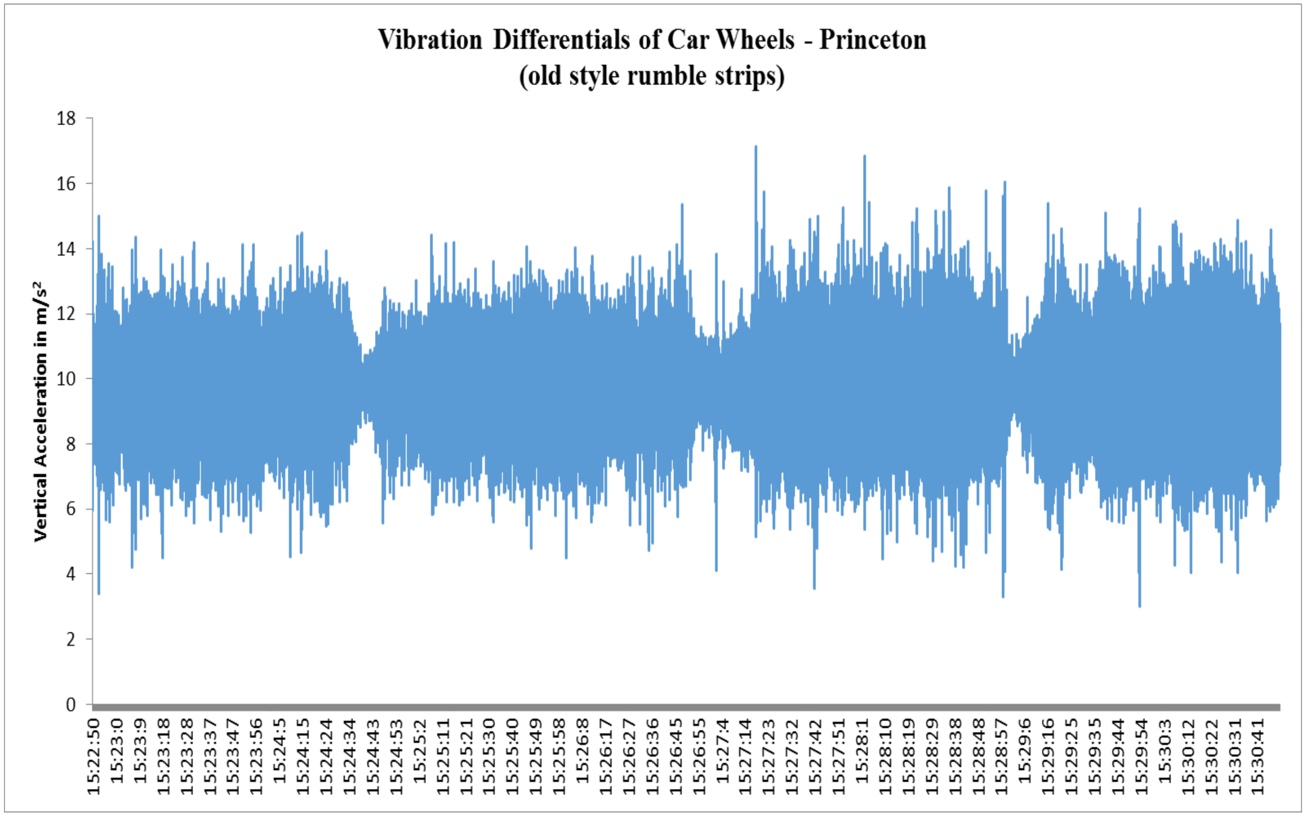

Vibration Differentials of Truck Wheels - Seward (5/8" Depth on Shoulders)
@45MPH
@55MPH
@65MPH
24
19
14
9
4
-1

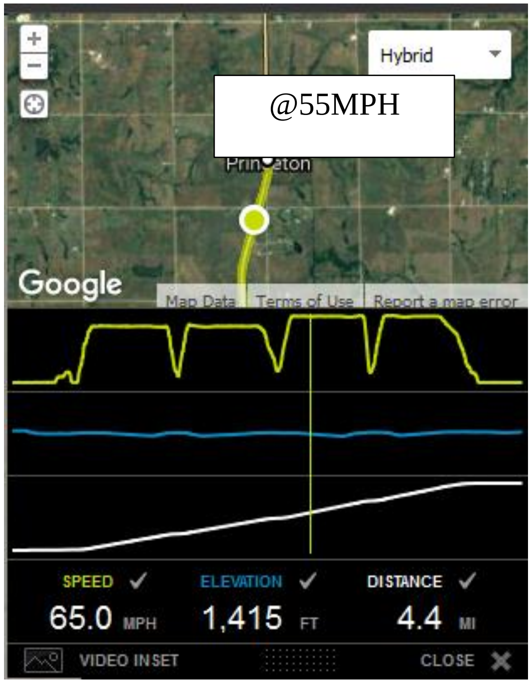

Hybrid
Google
Map Data
Terms of Use
Report a map error
SPEED
ELEVATION
DISTANCE
45.0 MPH
1,518 FT
2.0 MI
VIDEO INSET
CLOSE

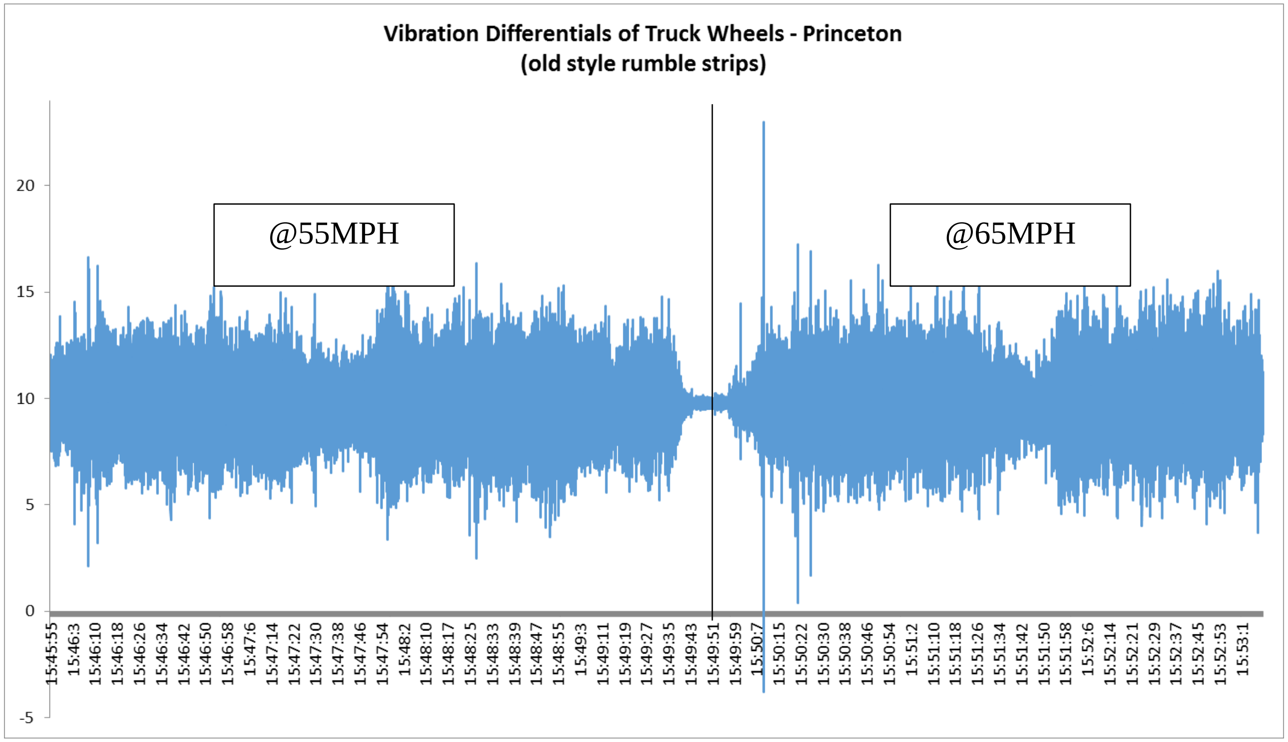

Vibration Differentials of Car Wheels - Crete hwy 103
(5/8", 1/2", 3/8" Depth on Shoulders)
@45MPH
@55MPH
@65MPH
@45MPH
35
30
25
20
15
10
5
0
-5
-10
14:32:13
14:32:36
14:32:58
14:33:20
14:33:41
14:34:3
14:34:25
14:34:48
14:35:10
14:35:32
14:35:54
14:36:17
14:36:39
14:37:1
14:37:24
14:37:46
14:38:8
14:38:31
14:38:53
14:39:15
14:39:38
14:40:0
14:40:22
14:40:45
14:41:7
14:41:29
14:41:52
14:42:14
14:42:36
14:42:59
14:43:21
14:43:43
14:44:6
14:44:28
14:44:50
14:45:13
14:45:35
14:45:57
14:46:20
14:46:42
14:47:4
14:47:27
14:47:49
14:48:11
14:48:34
14:48:56
14:49:18
14:49:40
14:50:3
14:50:25
14:50:47
14:51:10
14:51:32

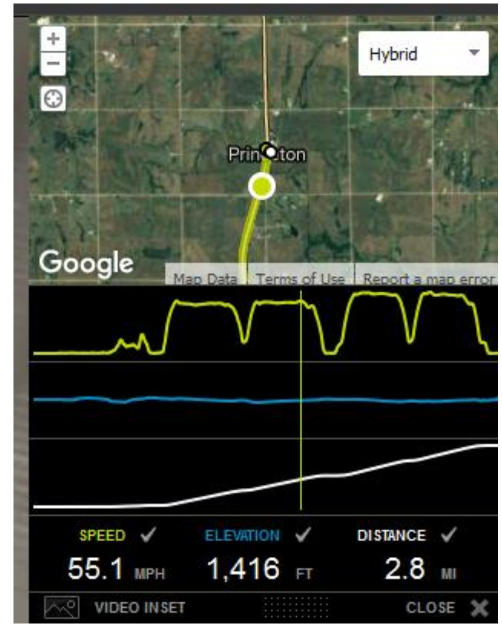

Vibration Differentials of Truck Wheels - Crete hwy 103
(5/8", 1/2", 3/8" Depth on Shoulders)
Vertical Acceleration (m/s²)
25
20
15
10
5
0
-5
14:3:20
14:3:41
14:4:2
14:4:22
14:4:43
14:5:4
14:5:25
14:5:46
14:6:7
14:6:28
14:6:49
14:7:10
14:7:31
14:7:52
14:8:13
14:8:34
14:8:55
14:9:16
14:9:36
14:9:57
14:10:18
14:10:39
14:11:0
14:11:21
14:11:42
14:12:3
14:12:24
14:12:45
14:13:6
14:13:27
14:13:48
14:14:9
14:14:30
14:14:50
14:15:11
14:15:32
14:15:53
14:16:14
14:16:35
14:16:56
14:17:17
14:17:38
14:17:59
14:18:20
14:18:41
14:19:2
14:19:23
14:19:44
14:20:4
14:20:25
14:20:46
14:21:7
14:21:28
14:21:49


Crete
Hybrid
Google
Map Data
Terms of Use
Report a map error
18.2 mph
1,343 ft
1.7 mi
SPEED
ELEVATION
DISTANCE
45.0 MPH
1,351 FT
1.1 MI
VIDEO INSET
CLOSE
@45MPH


Vibration Differentials of Car Wheels - Princeton
(old style rumble strips)
Vertical Acceleration in m/s²
18
16
14
12
10
8
6
4
2
0


Hybrid
@55MPH
Princeton
Google
Map Data
Terms of Use
Report a map error
SPEED
65.0 MPH
ELEVATION
1,415 FT
DISTANCE
4.4 MI
VIDEO INSET
CLOSE


Vibration Differentials of Truck Wheels - Princeton
(old style rumble strips)
@55MPH
@65MPH
20
15
10
5
0
-5
15:45:55
15:46:3
15:46:10
15:46:18
15:46:26
15:46:34
15:46:42
15:46:50
15:46:58
15:47:6
15:47:14
15:47:22
15:47:30
15:47:38
15:47:46
15:47:54
15:48:2
15:48:10
15:48:17
15:48:25
15:48:33
15:48:39
15:48:47
15:48:55
15:49:3
15:49:11
15:49:19
15:49:27
15:49:35
15:49:43
15:49:51
15:49:59
15:50:7
15:50:15
15:50:22
15:50:30
15:50:38
15:50:46
15:50:54
15:51:2
15:51:10
15:51:18
15:51:26
15:51:34
15:51:42
15:51:50
15:51:58
15:52:6
15:52:14
15:52:21
15:52:29
15:52:37
15:52:45
15:52:53
15:53:1


Hybrid
Princeton
Google
Map Data
Terms of Use
Report a map error
SPEED
ELEVATION
DISTANCE
55.1 MPH
1,416 FT
2.8 MI
VIDEO INSET
CLOSE

APPENDIX D: Picture Gallery of RS Dimension Measurement