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Directional Rumble Strips for Reducing Wrong-Way-Driving Freeway Entries

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Final Report

CTS 18-04

Technical Report Documentation Page

1. Report No. CTS 18-04	2.	3. Recipients Accession No.
4. Title and Subtitle Directional Rumble Strips for Reducing Wrong-Way-Driving Freeway Entries		5. Report Date February 2018 6.
7. Author(s) Huaguo Zhou, Chennan Xue, Lingling Yang, and Albert Luo		8. Performing Organization Report No.
9. Performing Organization Name and Address Department of Civil Engineering 238 Harbert Engineering Center Auburn University, Auburn, AL 36849-5337 Department of Mechanical Engineering Southern Illinois University Edwardsville Edwardsville, IL 62026-1805		10. Project/Task/Work Unit No. CTS #2015039 11. Contract (C) or Grant (G) No. DTRT13-G-UTC35
12. Sponsoring Organization Name and Address Roadway Safety Institute Center for Transportation Studies University of Minnesota 200 Transportation and Safety Building 511 Washington Ave. SE Minneapolis, MN 55455		13. Type of Report and Period Covered Final Report 14. Sponsoring Agency Code
15. Supplementary Notes http://www.roadwaysafety.umn.edu/publications/		

16. Abstract (Limit: 250 words)

This report presents the evaluation results of five types of directional rumble strips (DRS) based on extensive field tests conducted at the National Center for Asphalt Technology (NCAT) in Auburn, Alabama. The ultimate goal of this study is to develop a low-cost safety countermeasure by capturing a driver's attention through elevated in-vehicle sound and vibration for wrong-way (WW) driving while providing normal sound and vibration levels for right-way (RW) driving. Tests of sound and vibration generated by different DRS were performed with full-size passenger vehicles for six categories of speed: 10, 15, 20, 25, 35, and 45 mph. For each type of DRS concept design, three initial tests were performed with vehicles traveling on normal pavement (ambient condition), followed by three to five tests on the DRS in both WW and RW directions. The study identified three final design patterns (C, D Configuration 3, and E.1) that can generate elevated sound and vibration for WW drivers. The field test results also showed that speed had a significant impact on sound and vibration. Considering that travelling speed will be different on DRS by WW and RW drivers, additional speed studies were conducted to estimate the WW and RW driving speeds at the proposed DRS implementation spots on off-ramps. Based on the results, recommendations were developed to implement the final three DRS designs on off-ramps that can achieve the maximum safety benefits by alerting WW drivers through in-vehicle elevated sound and vibration.

17. Document Analysis/Descriptors Rumble strips, Sound, Vibration, Wrong way driving, Highway safety		18. Availability Statement No restrictions. Document available from: National Technical Information Services, Alexandria, Virginia 22312	
19. Security Class (this report) Unclassified	20. Security Class (this page) Unclassified	21. No. of Pages 105	22. Price

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FINAL REPORT

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February 2018

Published by:

Roadway Safety Institute
Center for Transportation Studies
University of Minnesota
200 Transportation and Safety Building
511 Washington Ave. SE
Minneapolis, MN 55455

ACKNOWLEDGMENTS

The funding for this project was provided by the United States Department of Transportation's Office of the Assistant Secretary for Research and Technology for the Roadway Safety Institute, the University Transportation Center for USDOT Region 5 under the Moving Ahead for Progress in the 21st Century (MAP-21) Act.

The project team would like to thank Jason Nelson for arranging the field tests at the test track of the National Center for Asphalt Technology (NCAT) in Auburn, Alabama. Authors would also like to thank the students at Auburn University who helped with the field-data collection, including Dan Xu, Raghu Baireddy, Lingxi Zhu, and Beijia Zhang.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

DOT	Department of Transportation
DRS	Directional Rumble Strips
FFT	Fast Fourier Transform
FHWA	Federal Highway Administration
MUTCD	Manual on Uniform Traffic Control Devices
NCAT	National Center for Asphalt Technology
RW	Right-Way
TRS	Transverse Rumble Strips
WW	Wrong-Way
WWD	Wrong-Way Driving

EXECUTIVE SUMMARY

This report presents evaluation results of directional rumble strips (DRS) designed to deter wrong-way (WW) freeway entries. Five conceptual designs of DRS (named A to E) with various configurations (e.g., 1, 2, 3…) were proposed based on state DOT design guidelines, current practices, and feedback from a national survey. Each concept design was expected to generate elevated sound and vibration for wrong-way driving (WWD) and normal level of sound and vibration for right-way (RW) traffic on off-ramps.

In addition to a comprehensive literature review, a national survey was performed to collect opinions on conceptual designs from transportation practitioners and vendors who are knowledgeable about rumble strip design, manufacturing, and installation. Based on the survey and literature review results, a total of five patterns and eight configurations was developed for field evaluation.

The initial field tests were conducted to collect sound and vibration generated by the proposed DRS configurations at the National Center for Asphalt Technology (NCAT) of Auburn University. Six speed categories were set at 10, 15, 20, 25, 35, and 45 mph for the testing vehicles. At least six field measurements were taken for each speed category in both directions. The generated sound and vibration for the WWD were compared with the ambient conditions and existing Transverse Rumble Strip (TRS) stimuli levels. The results indicated that all the tested patterns can generate an adequate sound increase in the WW direction to alert drivers to slow down (7.2 to 16.6 dBA increases). Pattern D Configuration 3 and Pattern E produced a comparable vibration increase of 0.26 g (2.57 m/s^2) and 0.23 g (2.30 m/s^2), respectively. Then, statistical analyses were conducted to examine if there was a significant difference in the sound and vibration between RW and WW directions. Pattern C generated significantly different sound and vibration signals between RW and WW directions when driving from 10 to 25 mph. Pattern E was found to generate significantly different vibration at 45 mph.

After initial field tests, three final conceptual DRS designs were selected for field verification, specifically Patterns C, Pattern D Configuration 3, and Pattern E. Pattern C was designed based on TRS, but the spacing between the strips was changed to generate different rhythms of sound and vibration. Pattern D Configuration 3, which was modified based on the advance warning markings for speed humps, has the increasing thickness and length of each strip. Pattern E has a right-angled triangle cross-section, which can produce the most recognizable sound and vibration from the WWD direction among the three patterns. Further field verification results indicated that all three tested DRS can generate recognizable interior sound and a moderate amount of vibration to alert WW drivers.

Considering the specialty of each pattern, specific segments of off-ramps were then recommended for further implementation. Pattern D Configuration 3 was suggested for installation close to the stop bar at an off-ramp terminal. In comparison, Pattern C could be implemented on the straight long segment of an off-ramp. It works similarly to existing TRS for RW drivers to remind them to slow down when they are approaching the stop bar or traffic signal. It can generate louder sound and more severe vibration for WW drivers who tend to drive at a higher speed when they think they are driving on an on-ramp. Based on the further field verification results, Pattern E was modified to have double strips at the inside of the travel lane, which can generate elevated sound and vibration to drivers when they drive in the wrong direction.

The three final DRS design patterns: C, D Configuration 3, and E.1 are recommended for field implementation on different off-ramps in the future. Pattern C is recommended to be installed in the middle point of the straight long segment of an off-ramp; Pattern D Configuration 3, with high-visibility reflective painting applied on the edge facing the WW direction, can be installed near the stop bar of off-ramps. The modified Pattern E.1 is suitable for installation before the sharp curve of off-ramps to provide visual cues about the curve ahead in addition to providing recognizable sound and vibration to WW drivers. Practical impacts will be further assessed by implementing them on off-ramps in the next project.

CHAPTER 1: **INTRODUCTION**

1.1 BACKGROUND

Wrong-way driving (WWD) on freeways has been identified as a serious traffic safety problem. Drivers who make wrong-way (WW) entries onto freeways pose a serious risk to the safety of other motorists and themselves. This study investigated the feasibility of novel designs for directional rumble strips (DRS) to discourage WW entries onto freeway off-ramps. The purpose of this study was to provide recommendations to engineers in the selection and use of DRS that will generate gentle interior sound and vibration for right-way (RW) drivers and provide elevated sound and vibration for WW drivers.

The initial field tests completed in fall 2015 evaluated the effectiveness of five types of DRS concept designs. The initial data analysis evaluated sound and vibration generated by five patterns with different configurations in both WW and RW directions. The initial test results found that three patterns (i.e., Pattern C, Pattern D Configuration 3, and Pattern E) could generate elevated sound and vibration for WW drivers. Further field verification of these three patterns was conducted in 2017 to evaluate the effectiveness of those three recommended DRS patterns. Based on verification results, recommendations were developed for implementation of the final three DRS design patterns.

1.2 STUDY OBJECTIVES

The objectives of this study were to

- develop conceptual DRS designs based on a comprehensive literature review and a national survey;
- evaluate sound and vibration generated by different DRS patterns in both RW and WW directions;
- select the most effective DRS design patterns; and
- develop the general implementation guidelines for the recommended DRS.

CHAPTER 2: **LITERATURE REVIEW**

2.1 WRONG-WAY DRIVING ISSUES

Drivers who make WW entries onto freeways pose a serious risk to the safety of other motorists and themselves. The National Transportation Safety Board (NTSB) reported that the primary origin of WW movement occurs when a driver enters from an exit ramp (NTSB 2012). WWD crashes are relatively infrequent but are more likely to produce serious injuries and fatalities compared with other types of crashes. A recent study of the Fatality Analysis Reporting System (FARS) showed that WWD caused between 300 and 400 annual traffic fatalities from 2004 to 2011 in the United States (Zhou et al. 2012). This number of fatalities has been consistent, even though total traffic fatalities declined by 4% over the eight-year period from 2004 through 2011.

As early as the 1970s, WWD freeway entries raised the attention of transportation agencies. The Virginia Department of Transportation (DOT) performed on-site investigations in the state and proposed countermeasures in terms of geometric design, pavement marking, and roadway signage (Vaswani 1974, NCHRP 1976). California DOT (1978) developed the counter and surveillance system for off-ramps and recommended placing DO NOT ENTER and WW signs, along with the WW pavement lights (a row of red lights embedded in the pavement across the off-ramp). In most recent practices, many agencies committed to upgrade signage along freeways, such as larger versions of DO NOT ENTER and WW signs (Arizona DOT 2014), lower mounting height (Ohio DOT 2012), and solar-powered flashing signs (Washington State DOT 2011, Florida DOT 2014, Rhode Island 2015, Missouri DOT 2014). Some high-technology countermeasures also emerged to reverse the troubling trend of WW freeway entries. The Intelligent Transportation System (ITS) was employed to detect WW drivers immediately upon entry, notify the traffic management center and public safety dispatch of the WW entry point, and inform the errant driver of his or her potentially fatal mistake via visual and/or audible warnings to prompt drivers into corrective action (New York DOT 2013, Sarah and Reza 2015).

Despite decades of improvements on design, marking, and signage at freeway interchanges, more efforts should still be taken to mitigate the WWD issue. The latest study by the NTSB (2012) also concluded that there is a need "to establish—through traffic control devices and improved highway designs—distinctly different views for motorists approaching entrance and exit ramps."

2.2 TRANSVERSE RUMBLE STRIPS

Transverse rumble strips (TRS) are a type of warning system that provides motorists with audible, visual, and tactile signals when approaching a decision point. Some countries have used TRS as a safety feature. Austria, for example, applied TRS at tunnel entrances. France installed "noisy transverse strips" to alert drowsy drivers (CEDR 2010). China installed TRS in southern areas to help reduce vehicle speeds at critical locations on rural roads, such as the crosswalks (Liu et al. 2011). The Transportation Association of Canada published "Best Practice Guidelines for the Design and Application of Transverse Rumble Strips" (Bahar et al. 2005), which provides an overall summary of extensive research and practices.

In the United States, TRS are mainly installed on approaches to intersections, toll plazas, horizontal curves, and work zones (FHWA 2014). According to a Minnesota DOT synthesis (Corkle et al. 2001), 56 of the 68 Minnesota counties responded to a survey on the use of TRS. Most of these counties (48 of the 56) use two sets of rumble strips prior to an intersection or change in traffic control. Texas DOT states that TRS should only be used at high incident and special geometric locations (Texas DOT 2006). Besides the regular TRS locations, Maryland DOT also suggests that TRS may be useful to address the need for a reduced speed zone with a posted speed reduction of 20 mph or greater or an entrance to a town, business district, or location, where significant pedestrian activity is anticipated. Also, the TRS may be used in work zones in advance of detours, flaggers, lane transitions, lane closures, temporary traffic signals, and locations with major reductions in speed limits (SHA 2011).

2.3 DESIGN GUIDELINES OF TRS

Transportation agencies and DOTs usually release their design guidelines for different rumble strips and update them as circumstances change. The 1993 synthesis provided typical values for TRS summarized from the design practices of 24 state transportation agencies (Harwood 1993). The result shows that the TRS design practices vary widely.

In Minnesota, an approach to a stop-controlled intersection can have up to five sets of TRS, but a minimum of three sets are recommended. The length of each TRS panel is about 5 ft (MnDOT 1999). Jefferson County, Montana, installed the TRS in a stop-controlled T-intersection (a total of four sets of TRS were installed). The TRS have an 11.8-in. offset from the travel lane edge, 3.9 in. width, 0.6 in. thickness, and 7.9 in. spacing (MDT 2004). In Iowa, until 2006, three sets of TRS were required (Iowa DOT 2006). This standard was altered in April 2006 and again in May 2007 to require only two sets of TRS, thus removing the TRS closest to the intersection. Currently, each TRS panel is 24 ft long and consists of 25 grooves placed at 1 ft intervals perpendicular to the centerline (USDOT/FHWA 2012). Michigan DOT required occasional usage of trunk-line TRS. The rectangle cross section is 4 in. wide and 0.5 in. deep; the grooves are separated by 8-in. spacing (MDOT 2011). In Maryland, milled TRS are applied to the pavement with pavement marking material; moreover, they are created by stacking two pieces of formed pavement marking material to obtain the desired thickness (SHA 2011). Table 2.1 details the configurations of TRS in several states.

Texas DOT issued design guidelines for both standard and alternative patterns. The alternative TRS only run the width of a vehicle’s wheel path to reduce driver’s swerving maneuvers (TxDOT 2006). Dimensions of the TRS are shown in Figure 2.1.

According to Arizona DOT 2014 revisions to its TRS details (ADOT 2014), the TRS are installed in three sets before the decision point; moreover, the gap among the sets range from 125 to 200 ft, corresponding to the approach speed of 35 to 55 mph. The guideline provides two different set designs for snow and non-snow zones, as shown in Figure 2.2. The non-snow zone TRS are made by raised pavement makers, and the snow zone TRS are cut-grooved and measure 15 degrees with the lateral axis.

Table 2.1 TRS configurations of several states

State	Raised (R) or Grooved (G)	Strips in each set	Length (ft)	Width (in.)	Spacing (in.)	Thickness (in.)	Offset (in.)	Ref.
Minnesota	G	6	3.3*2	5.9±0.2	5.9	0.4±0.1	7.9 from centerline 19.7 from shoulder	MnDOT 1999
Michigan	G	25	-	4	8	0.5	12	MDOT 2011
Maryland	R	10	-	-	54 or 72	5+5 10+5	-	SHA 2011
Montana	G	16	12	4	8	5/8	12	MDT 2004
Oregon	G	11	10	5(1/2)	12.5	1/2	12*(Lane width-10ft)/2	Oregon DOT 2013
Arizona	G	6	Lane width/cos (15 degree)	4	12	3/8	0	ADOT 2014
Texas	R	5	4*2	-	24	-	6-12	TxDOT 2006
New Hampshire	G	11 (minimum)	-	-	-	-	3/8	State of New Hampshire, 2013

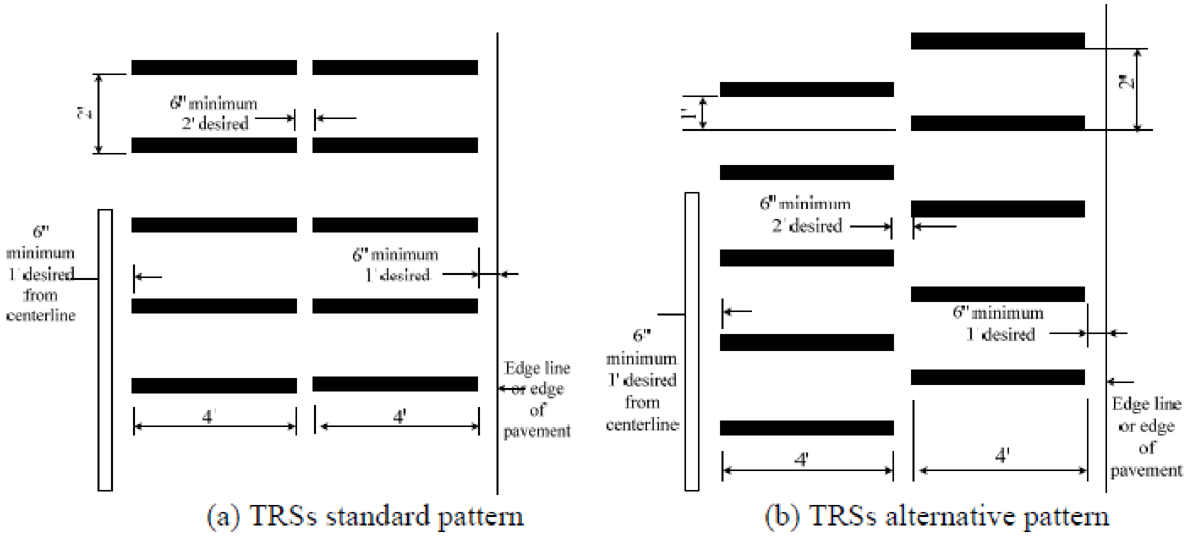


Figure 2.1 Texas DOT TRS designs (TxDOT 2006)

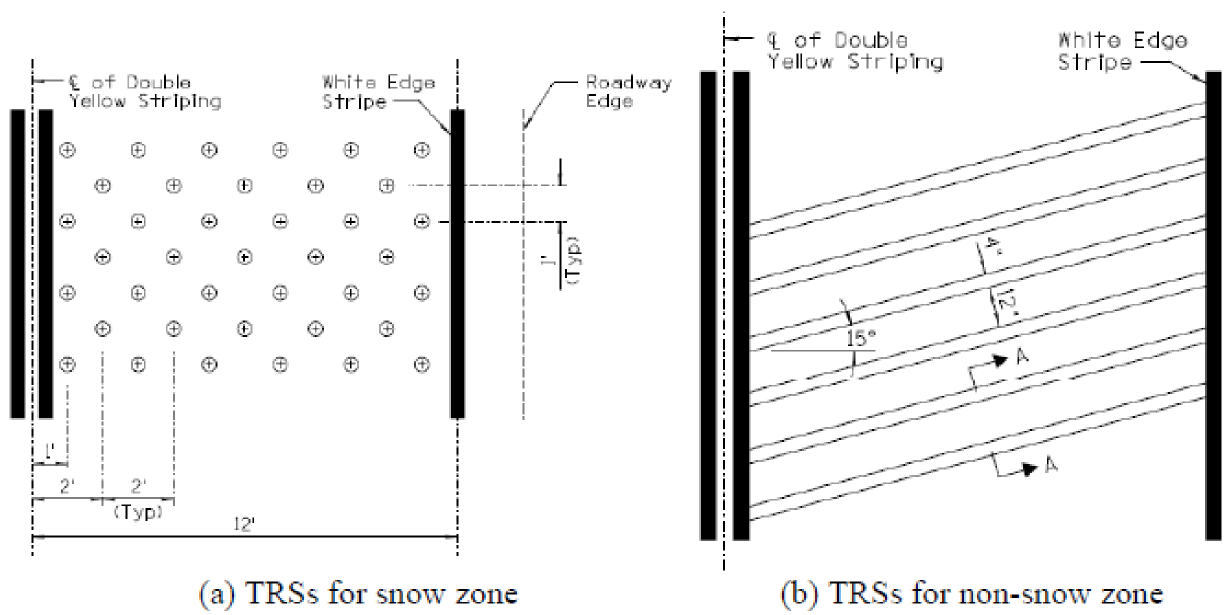


Figure 2.2 Arizona DOT TRS details (ADOT 2014)

2.4 EVALUATION OF TRS EFFECTIVENESS

The primary goal of TRS design and application is to improve roadway safety through reductions in crash number and severity. Therefore, the ultimate measure of effectiveness (MOE) would be an evaluation or analysis of changes in crash experience. A study by the Virginia DOT documented a 37% reduction in total crash frequency and a 93% reduction in fatal crashes for the stop-controlled intersections (VDOT 1983). The crash rate for rear-end and ran-stop-sign accidents was reduced by 89% (FHWA 1998). NCHRP Synthesis 191 summarized 10 before-and-after studies that investigated the safety effectiveness of TRS. The reported crash reduction ranges from 14% to 100% (Harwood 1993). The most recent study examined the impacts of TRS based on Minnesota DOT and Iowa DOT data sets from rural intersections with minor-leg stop controls (FHWA 2012). For four-leg intersections, there was a statistically significant reduction in KA and KAB crashes (K=fatal, A=incapacitating injury, and B=non-incapacitating injury). For three- and four-leg intersections combined, there was a statistically significant increase in PDO crashes (about 19%) and a statistically significant reduction in KAB crashes (about 21%) and KA crashes (about 39%) (C=possible injury, and PDO=property damage only).

The attention-getting effects of rumble strips were normally measured by sound levels in contrast with baseline conditions. Some researchers considered increases of 4 dB or greater to be sufficient to alert drivers coming into contact with rumble strips (Watts 1977, Elefteriadou et al. 2000, Miles and Finley 2007). The study by Outcalt regarded a sound level of a 6-dB change as a "clearly noticeable change" and 10 dB changes as twice as loud according to human perception of changes (Outcalt 2001). Tests by Walton and Meyer revealed an average increase in sound from TRS (10 dB for cars and 4 dB for trucks and dump [Walton and Meyer 2002]). Lank and Steinauer reported that the A-weighted volume in the area of the TRS is, on average, 10 dBA above the basic sound level without TRS (Lank and Steinauer 2011). Horowitz and Nothbohm also measured the sound and vibration level generated by permanent cut-in-pavement (CIP) rumble strips and adhesive rumble strips (Horowitz and Notbohm 2005). The average sound level for both standard CIP strips at 40 and 55 mph was found to be, respectively, 75.2 and 75.8 dB and 70.9 and 76.8 dB for the adhesive rumble strips. Schrock et al. tested 10 different configurations of four to six strips (24- and 36-in. spacing plastic TRS and CIP strips spaced at 18-in. intervals) and found that in-vehicle sound levels ranged from 79.4 to 85.0 dB for a truck and from 75.7 to 85.7 dB for a passenger car (Schrock et al. 2010).

In summary, there have been quite a few studies on sound and vibration evaluation of TRS. A similar field test method will be adopted for testing DRS in this study. The literature review results found no previous studies on application of TRS on off-ramps to deter WW freeway entries. However, the attention-getting effects of rumble strips might be effective to remind impaired drivers that they are driving in the wrong direction, if the field test can provide evidence that it can generate enough sound and vibration for WW drivers.

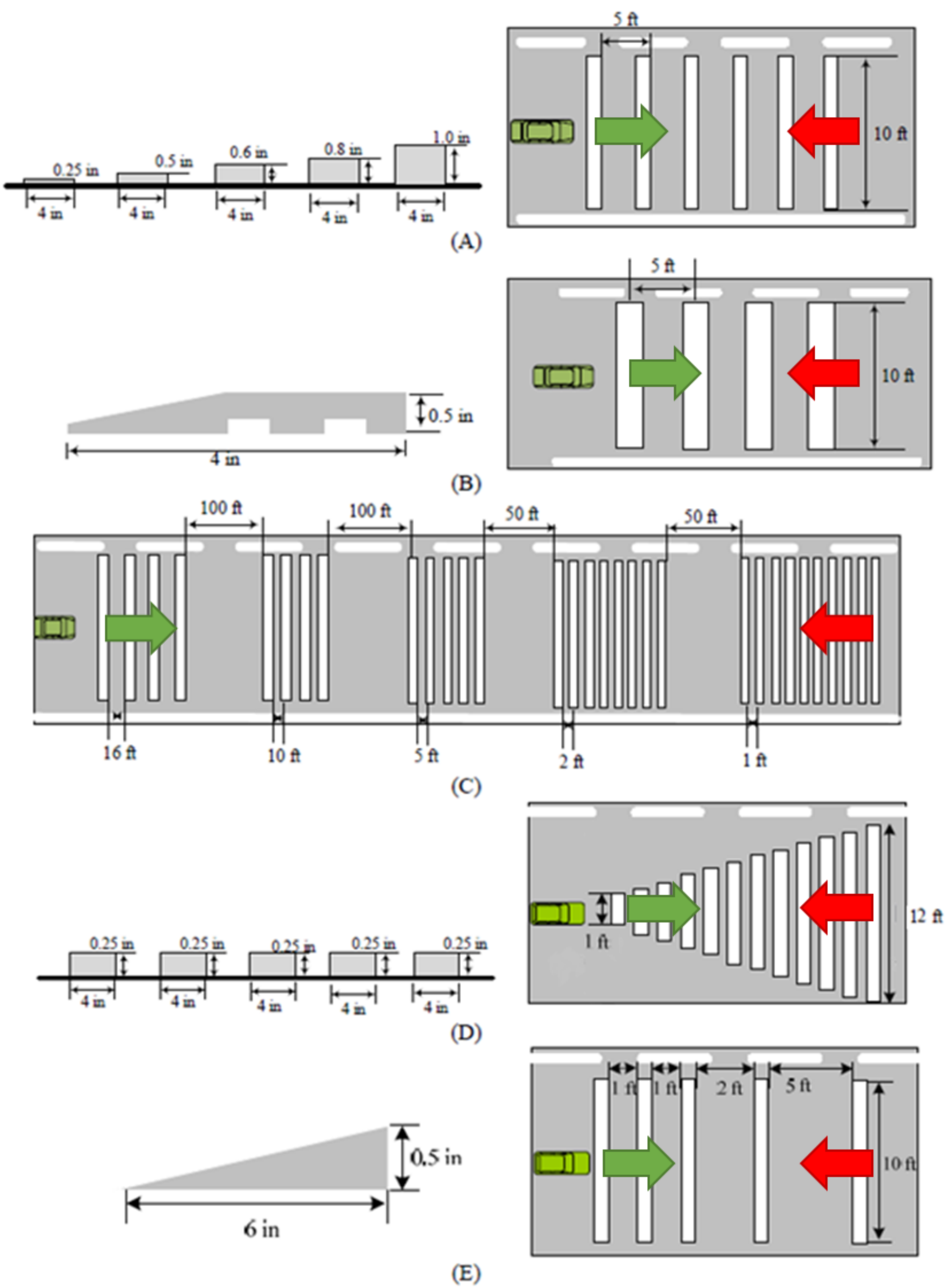
CHAPTER 3: **DIRECTIONAL RUMBLE STRIP DESIGNS**

3.1 INITIAL DESIGNS OF DRS

DRS can be regarded as a variation of TRS. When vehicles roll over the rumble strips from either direction, the conventional TRS provides motorists with the same levels of sound and vibration. In this project, the DRS was designed to generate elevated sound and vibration to warn WW drivers and normal sound and vibration to slow down traffic for the RW direction when they are approaching exit-ramp terminals. Tables 3.1 and 3.2 summarize the layout and configurations of TRS currently under implementation based on state DOT guidelines, practices in Alabama, and rumble strip vendors. The state DOT design guidelines summarize best practices by more recent leaders in TRS practice and research, including Minnesota, Maryland, Oregon, Arizona, Texas, Michigan, Montana, New Hampshire, etc. Alabama practices are summarized by field reviews of over 10 TRS sites. Recommendations from vendors (e.g., ATM, SWARCO, Ennis-Flint, TAPCO, etc.) are also considered at the initial design stage.

These dimensions provide references for the configuration and layout of DRS designs. In this project, the maximum length of strips was designed to be 10 or 12 ft to fit one traffic lane. The width ranged from 4 to 6 in., and the thickness ranged from 0.25 to 1.0 in. Spacing among strips was designated at 1 ft, 2 ft, and 5 ft for the best sound and vibration effects.

To achieve the goal of different sound and vibration depending on travel directions, five conceptual designs of DRS have been selected from the pools of proposals, which are illustrated in Figure 3.1. Pattern A utilizes the removable rumble strips as the DRS. Thickness of the strip gradually increases from 0.25 to 1.0 in. by combining different thicknesses of tapes. In Pattern B, the raised wedge strips may offer audible and tactile signals of DRS. The 20-degree angle enables a gradual climb. The 90-degree edge makes it possible to create a more alarming feel for drivers traveling in the wrong direction. Pattern C attempts to create different audible and physical warnings by a varied number of strips and spacing among them. For Pattern D, the specifically shaped rumble strip features a set of triangles that provides visual effects. The length of the strips decreases from 12 to 1 ft. For the wrong direction, the drivers encounter decreasing strip length, and the arrow gives a visual warning to the WW drivers. In Pattern E, the triangle strips are designed to offer audible and tactile signals of DRS.



Note: Green Arrow = Right Direction; Red Arrow = Wrong Direction.

Figure 3.1 Conceptual designs of DRS

Table 3.1 Layout of TRS

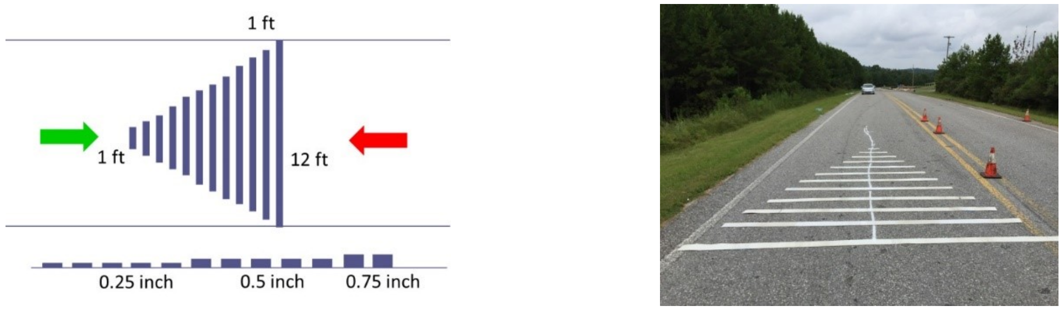
Resources	Number of sets	Length between set 1 & 2 (ft)	Length between set 2 & 3 (ft)	Length between set 3 & 4 (ft)	Length between set 4 & 5 (ft)
State Guidelines	2, 3, 4, 5	15-160	15-175	50-250	15
Alabama Practices	5	90, 100	80-100	40, 45, 50	40, 45, 50
Vendors	1, 2, 3, 4	90-500	328-500	656	-

Table 3.2 Configurations of DRS

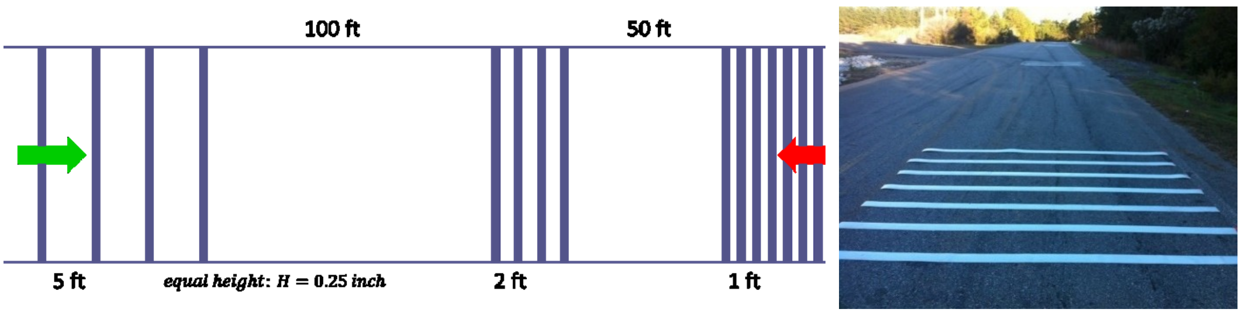
Resources	Strips in each set	Length (ft)	Width (in.)	Spacing (ft)	Thickness (in.)	Offset (in.)
State Guidelines	6-25	8-12	4, 5.5, 5.9 ± 0.2	5.9, 12, 54, 72	0.375-15	6-12
Alabama Practices	5	9, 12, 24	5.5-9.0	8.0-10.0	0.05-0.21	0
Vendors	6, 10	2, 3, 4	4, 6	12, 18, 24, 36, 60, 72, 120	0.25, 0.375, 0.5	0
This project	4, 5, 6, 7, 12	10, 12	4, 5	12, 24, 60, 120	0.25, 0.5	0

3.2 FINAL DESIGNS FOR VERIFICATION TEST

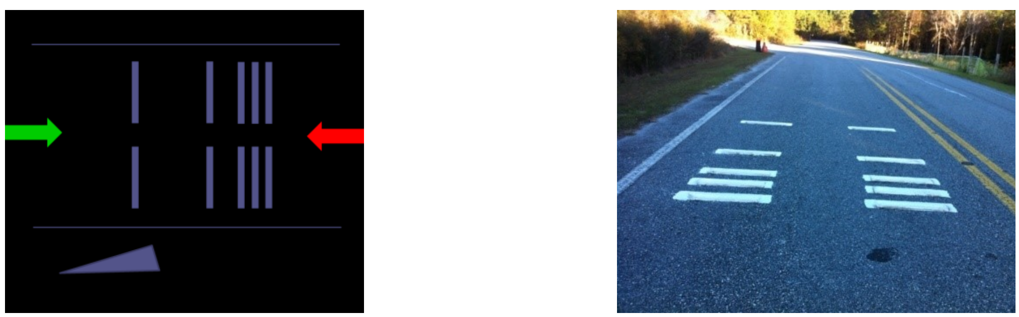
Five DRS design patterns with different configurations (thickness of rumble strips) were tested in the early stage of this project. Three patterns (i.e., C, D Configuration 3, and E) were recommended for further verification. Pattern D Configuration 3 was modified based on the advance warning markings for speed humps (see 3B-31 in the MUTCD), which has a triangle appearance as the length of the strip gradually increases from 1 to 12 ft. The thickness of the strip with a length from 1 to 5 ft is equally 0.25 in. The 6- to 10-ft strips have the same thickness of 0.5 in. The remaining two strips (11 and 12 ft long) are both 0.75 in. thick. In Figure 3.2-a, the green arrow indicates the RW driving direction. When an RW driver drove through, the first five strips had an equal thickness of 0.25 in. The thickness of the following five strips were increased to 0.5 in., while the last two were 0.75 in. thick. Pattern C is similar to the TRS but has different spacing. Three groups of strips with different spacings of 1, 2, and 5 ft, respectively, were placed apart with 100 and 50 ft spacing, as shown in Figure 3.2-b. All the strips had the same thickness of 0.25 in. Pattern E (Figures 3.2-c) has a cross section of the rectangular triangle. The width of the strip was also 6 in., and the thickness was about 0.5 in. A new Pattern E.1 (Figure 3.2-d) was developed to double the number of strips on the inside of the travel lane to increase vibration for WW drivers.



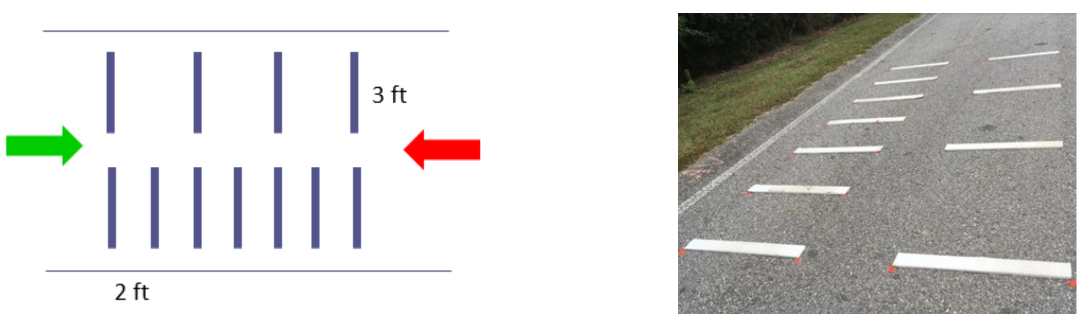
(a) Pattern D Configuration 3



(b) Pattern C



(c) Pattern E



(d) Pattern E.1

Figure 3.2 DRS patterns for verification test

CHAPTER 4: **SURVEY RESULTS**

A national survey was initiated to collect the comments and suggestions for conceptual designs from transportation professionals who are knowledgeable about rumble strip design, manufacturing, and installation. The survey questionnaire (see Appendix A) consists of two major parts. Part One provides a brief introduction of the background and objective of the project; Part Two includes five questions related to DRS conceptual design. Question 1 highlights the feasibility of using DRS as a warning system to discourage WW drivers. Question 2 asks participants to rate the proposed DRS patterns on a scale of 1 ("Absolutely Inappropriate") to 7 ("Absolutely Appropriate"). For each pattern, the generalized diagram was provided, and a brief illustration was used to further clarify the concept. Question 3 ranks the properties of the DRS based on the expectation of their potential to reduce WWD. The priority is scaled from 1 to 5, representing "Low Priority" to "High Priority." Questions 4 and 5 encourage participants to provide more ideas and concepts about DRS and should provide the materials, cost, and installation procedures as well.

The Auburn University Institutional Review Board (IRB) reviewed and approved the survey. The online survey was created by Qualtrics software and then distributed to transportation professionals from pavement marking vendors, state DOTs and local agencies. The authors of previous studies related to rumble strip designs or field tests were also selected for the survey contact list. A total of 242 transportation professionals and experts in rumble strip design and testing were selected for conducting the online survey. Survey questionnaires were sent via email to the selected 242 transportation professionals to collect their views on different DRS conceptual designs. A total of 26 responses were obtained, which constitutes an 11% return rate. As shown in Figure 4.1, among the respondents, 38% were from pavement marking vendors (*n*=10), 15% were from state DOTs (*n*=4), 12% from manufacturers (*n*=3), 8% from consultants (*n*=2), and 19% (*n*=5) were researchers at universities. In addition, phone interviews were conducted with several pavement-marking vendors who manufactured TRS products, including Advanced Traffic Markings (ATM), Ennis-Flint, SWARCO, Peek Pavement Marking, TAPCO (Traffic & Parking Control Co.), Garden State Highway Products, etc.

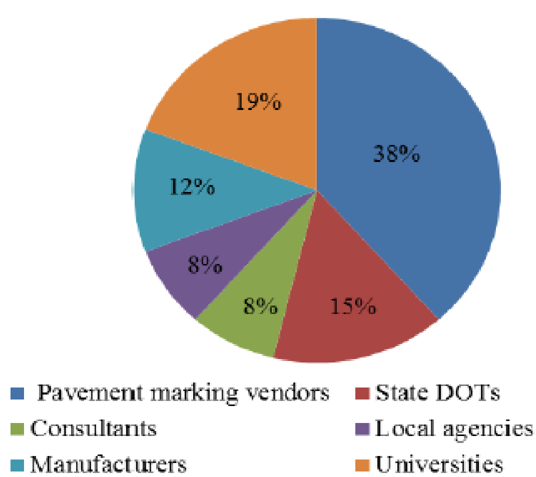


Figure 4.1 Response distribution

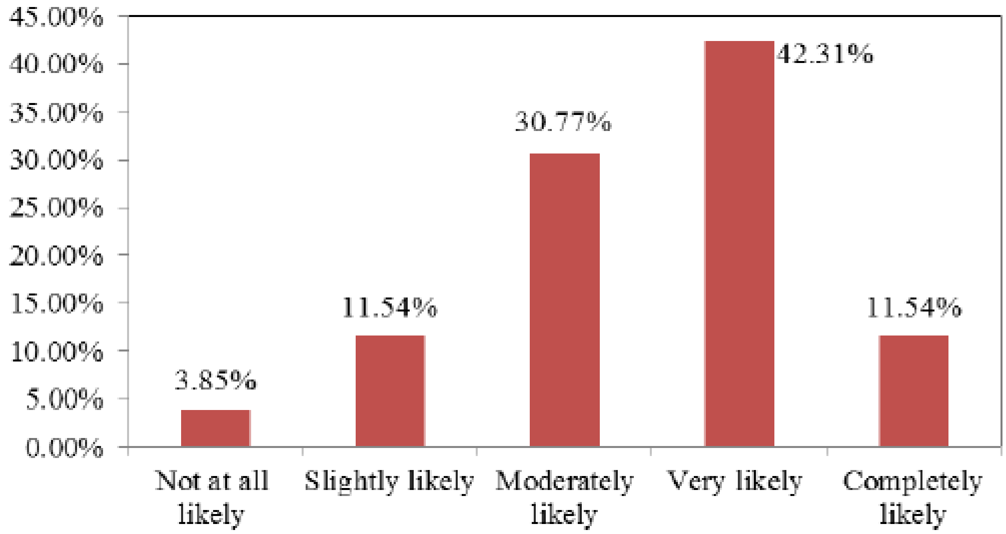


Figure 4.2 Survey results about feasibility of DRS for WWD

For the first question, participants were asked to rate the feasibility of the DRS application. As shown in Figure 4.2, 42.31% of participants thought it was "very likely" to use DRS as a warning system on off-ramps for deterring WWD. 30.77% of respondents agreed "moderately likely," and only 3.85% of participants considered "not at all likely."

Participants were also required to rate the proposed design of DRS with the scale of 1 to 7, representing "absolutely inappropriate" to "absolutely appropriate." As shown in Table 4.1, Pattern B (the raised wedge design of DRS) was expected to be the most appropriate pattern among all the designs. Pattern A (overlapped removable rumble strips as DRS), and Pattern D (triangle shaped DRS with decreasing length of strips) received the second-place rating, and Pattern C (DRS with verified number of strips and spacing) was scored as 3.3.

Table 4.1 Rank of DRS conceptual designs

Pattern	B	A	D	C
Score	4.0	3.5	3.5	3.3

As per the expectations regarding properties of the DRS and their potential to reduce WWD, the expectation ranking is listed in Table 4.2 based on the scale of 1 to 5 of "low priority" to "high priority." The result reveals that a minimum level of sound and vibration was the first concern of DRS properties. The optimum dimensions and visual attentiveness were also important to the developed DRS. Then, the DRS were also expected to exert less sound impact on adjacent residents. Besides the listed properties, other aspects were suggested, such as skid resistance, effect on motorcycle, and low or moderate cost.

The final part of the survey encouraged participants to give some ideas or suggestions about the DRS conceptual design. Ennis–Flint recommended a thermoplastic profiled retroreflective rumble in a directional chevron, approximately $9 per ft, and 250–375 mil thickness. Peek Pavement Marking, LLC suggested red retroreflective color for the raised wedge design on the WW side, with low cost. Traffic Calming Solutions proposed it would be possible to modify its Paver Rumble Strips to work with the Pattern A design, which are currently installed by contractors for approximately $100 per lineal foot (width). All these suggestions and recommendations will be considered for DRS designs and field tests in a later phase.

Table 4.2 Expectations of DRS Success

No.	Prosperities	Score*
1	Minimum level of stimuli (i.e., sound and vibration) necessary to alert inattentive drivers	3.9
2	Optimum dimensions (e.g., length, width, depth, spacing)	3.8
3	Visual attentiveness (e.g., retro-reflecting properties and coloring)	3.8
4	Impact of sound produced by rumble strips on adjacent residents	3.7
5	Accommodation to motorists' demands in adverse weather conditions, such as snow, fog, and rain	3.5
6	Effect on maintenance activities	3.5
7	Effect on pavement performance	3.0

*Note: 1 = lowest; 5 = highest.

CHAPTER 5: **FIELD TEST METHOD**

5.1 TEST LOCATION

The DRS field tests were conducted at the pavement test track of the National Center for Asphalt Technology (NCAT) at Auburn University. Different patterns of DRS were deployed on the entrance ramp at the Auburn University Erosion and Sediment Control Testing Facility (AU-ESCTF) at NCAT. Figure 5.1 shows the testing location, which has two 12 ft lanes and closed facilities during the study period. The testing road has a 1,091-ft tangent section, which provides appropriate space to install different DRS patterns (25 to 190 ft) and accommodates the need for frequent acceleration and deceleration of the testing vehicle.

Figure 5.1 Test location at NCAT

5.2 EQUIPMENT AND MEASUREMENT

Sound and vibration inside the vehicle were measured by full-size passenger cars (Ford Fusion and Nissan Altima). The acoustical signature was recorded by an Extech HD600 Sound Level Meter, which displays 10 decibel readings during any 1 s period. The vibration data was recorded using a Measurement Specialists 35201A accelerometer, which operates at 100 samples per second. This device allows researchers to measure acceleration rates along the longitudinal, lateral, and gravitational axes. The field test equipment is shown in Figure 5.2.

Sound level meter and accelerometer location inside the vehicle is shown in Figure 5.3. The sound-level meter was located at an average driver's ear height, and the tri-axial accelerometer was fixed between the driver and the passenger's seat. Both the sound level meter and accelerometer were controlled by a laptop computer via the equipment software and serial port. After conditioning the sound and vibration signals, all information was logged directly into Microsoft Excel for later analysis. While the tests were conducted, the air-conditioner, stereo, and any other sound-producing sources were turned off, and the windows were rolled up to eliminate as much background sound as possible.

(a) Extech HD600 (b) Measurement Specialists 35201A

Figure 5.2 Sound level meter (a) and accelerometer (b)

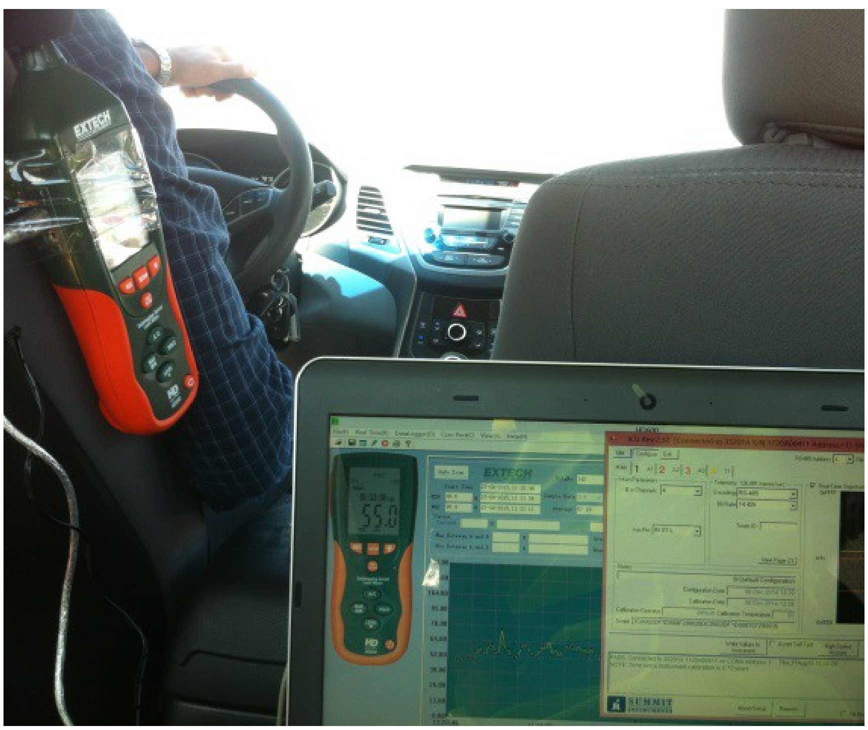


Figure 5.3 Locations of sound level meter and accelerometer in the full-size passenger car

5.3 DRS INSTALLATIONS

Two types of rumble strips were purchased from vendors to constitute different configurations of DRS. The black TAPCO rumble strips were produced at 23.5 in. × 3.5 in. × 0.5 in. and applied to the pavement using mixed epoxy provided by the manufacturer. The removable rumble strips from ATM are nonreflective, self-adhesive, and come in 50 ft rolls. The white removable rumble strips were first cut to the appropriate length using tin snips. The adhesive, which was pre-applied to the strip by the manufacturer, was exposed by removing the protective backing. These two types of rumble strips were used for testing all the patterns except Pattern E, which needed to be custom manufactured. The mold was made of wood covered with aluminum foil. Thermoplastic was used to make the strips.

The DRS was installed following the standard procedure when pavement was dry, and its temperature just before installation was warmer than 10° C (50° F). The pavement was swept with a push broom to remove loose debris. Once the pavement was clean, it was marked using masking tape to indicate the proper placement for the strips.

5.4 TEST SCHEMES

Using the vehicle and equipment setup, sound and vibration data were collected for both RW and WW directions for different DRS patterns. The experimental vehicle traveled through both directions at speeds of 10 mph, 15 mph, 20 mph, 25 mph, 35 mph, and 45 mph, respectively. These are the typical approach speeds at different segments of off-ramps. The sound and vibration measurements were then taken for both DRS patterns and ambient condition. The ambient condition was defined as the test vehicle traveling at a specified speed along the roadway section before DRS implementation. The rumble strip condition refers to the same road segment with installation of the DRS patterns. At least six test runs were completed for each DRS configuration for each direction and speed category.

As listed in Table 5.1, initial data collection was performed from August 27 to 29 and November 22 to 24, 2015. During the first test, five different configurations were evaluated for the speed range of 25 mph, 35 mph, and 45 mph. In the second test, six configurations were installed and tested for all speed ranges. At the end of the first test, the collected data were examined to determine which configurations performed the best in order to plan more focused testing during the second test. The Pattern B Configuration 2 and Pattern D Configuration 1 were not tested for more speed ranges in the second stage due to the unsatisfactory results.

The verification test was performed on November 19, 2016, and November 1, 2017. On November 19, 2016, the verification test verified the test results of Pattern C, Pattern D Configuration 3, and Pattern E based on the recommendations from initial test results. The modified Pattern E.1 was tested on November 1, 2017.

Table 5.1 DRS field test schemes

Date	Test patterns and configurations	Test speed (mph)	Total runs
August 27-29, 2015	Pattern B Configuration 1	25, 35, 45	18
	Pattern B Configuration 2	25, 35, 45	18
	Pattern C	25, 35, 45	18
	Pattern D Configuration 1	25, 35, 45	18
	Pattern D Configuration 2	25, 35, 45	18
	Ambient Condition	25, 35, 45	9
November 22-24, 2015	Pattern B Configuration 1	10, 15, 20, 25, 35, 45	72
	Pattern B Configuration 3	10, 15, 20, 25, 35, 45	72
	Pattern C	10, 15, 20, 25, 35, 45	72
	Pattern D Configuration 2	10, 15, 20, 25, 35, 45	54
	Pattern D Configuration 3	10, 15, 20, 25, 35, 45	72
	Pattern E	10, 15, 20, 25, 35, 45	72
	Ambient Condition	10, 15, 20, 25, 35, 45	27
November 19, 2016	Pattern C	10, 15, 20, 25, 35, 45	60
	Pattern D Configuration 3	10, 15, 20, 25, 35, 45	60
	Pattern E	10, 15, 20, 25, 35, 45	60
	Ambient Condition	10, 15, 20, 25, 35, 45	36
November 1, 2017	Pattern E.1	10, 15, 20, 25, 35, 45	60
	Ambient Condition	10, 15, 20, 25, 35, 45	36

CHAPTER 6: **FIELD TEST RESULTS**

6.1 INITIAL FIELD TEST RESULTS

Four types of DRS designs were evaluated under the early stage: Pattern B (the raised wedge design of DRS), Pattern C (DRS with verified number of strips and spacing), and Pattern D (triangle-shaped DRS with decreasing length of strips), and Pattern E (a simple triangle design provided by the Peek Pavement Marking, LLC). The rumble strips used for Pattern B Configuration 1 to Configuration 3 was the TAPCO rumble strips, with dimensions of 23.5 in. × 3.5 in. × 0.5 in. Pattern C and Pattern D Configuration 1 to Configuration 3 were formed by the ATM removable rumble strips, which are approximately 0.25 in. thick and 4 in. wide. Pattern E was tested through the custom-designed strips, with a triangle cross section, which has a width of 6 in. and height of 0.5 in.

The sound and vibration data were analyzed in the R statistical analysis software. When multiple observations of the same condition were made, the average of the maximum values was used. The sound level increases were noticeable, considering the 6 dBA of human perception thresholds. The vibration increases were noticeable, considering human perception threshold (2.5 to 4.25 m/s^2). T-test was used to compare the two different data sets to determine if the difference is statistically significant. The following subsections analyze the physical and attention-getting characteristics for each configuration in the early stage of the study.

6.1.1 Pattern B Configuration 1

This DRS configuration consists of a 12 ft-long 4 in.-wide black rubber with five raised ridges spaced at 5 ft intervals (Figure 6.1). The strips were applied to the pavement using mixed epoxy (provided by TAPCO). For the RW direction, vehicle tires roll over the strips with a smooth transition via a 20-degree edge. From the WW direction, the 90-degree edge of the strips may provide an alarming effect for drivers.

Figure 6.1 Pattern B Configuration 1

Table 6.1 displays the values of the sound and vibration measurements for Pattern B Configuration 1. For the sound levels, both the RW and WW had 8 to 10 dBA increases above the baseline condition. For the vibration levels, both the RW and WE had 0.1 to 0.2g increases above the baseline condition. However, there was no noticeable difference for the RW and WW sound and vibration signals.

Table 6.1 Sound and vibration level of Pattern B Configuration 1

	Speed (mph)	10	15	20	25	35	45
Sound (dBA)	Ambient	53	55.5	57.7	62.2	64.2	67.3
	RW	62.1	64.8	68.7	70.4	72.6	79
	WW	61.8	63.8	68.9	70.7	72.5	77.8
	RW vs. Ambient	9.1	9.3	11	8.2	8.4	11.7
	WW vs. Ambient	8.8	8.3	11.2	8.5	8.3	10.5
	WW vs. RW	–0.3	–1	0.2	0.3	–0.1	–1.2
Vibration (g)	Ambient	1.014	1.022	1.026	1.03	1.025	1.061
	RW	1.151	1.169	1.141	1.151	1.224	1.171
	WW	1.171	1.135	1.152	1.18	1.181	1.234
	RW vs. Ambient	0.137	0.147	0.115	0.121	0.199	0.11
	WW vs. Ambient	0.157	0.113	0.126	0.15	0.156	0.173
	WW vs. RW	0.02	-0.034	0.011	0.029	-0.043	0.063

6.1.2 Pattern B Configuration 2

Pattern B Configuration 2 (Figure 6.2) attempted to increase the WW stimuli by adding five more strips based on Pattern B Configuration 1. The white removable rumble strips are 0.4 in. wide, 0.25 in. thick, and spaced at 1 ft intervals. Sound and vibration results in Table 6.2 reveal that the maximum sound level increased by 7.2 to 9.7 dBA under different speeds. However, the sound level difference between RW and WW was still inadequate as expected. Similarly, the vehicle body vibration was observed at certain speeds for both directions. But, in most cases, the differences of WW versus RW were neither statistically significant nor noticeable.

Figure 6.2 Pattern B Configuration 2

Table 6.2 Sound and vibration level of Pattern B Configuration 2

	Speed (mph)	25	35	45
Sound (dBA)	Ambient	64.0	64.0	67.1
	RW	73.7	73.6	74.3
	WW	73.0	73.4	74.8
	RW vs. Ambient	9.7	9.6	7.2
	WW vs. Ambient	9.0	9.4	7.7
	WW vs. RW	-0.7	-0.2	0.5
Vibration (g)	Ambient	1.03	1.025	1.061
	RW	1.203	1.220	1.188
	WW	1.267	1.192	1.191
	RW vs. Ambient	0.173	0.195	0.127
	WW vs. Ambient	0.237	0.167	0.130
	WW vs. RW	0.064	-0.028	0.003

6.1.3 Pattern B Configuration 3

Pattern B Configuration 3 had multiple spacings based on Configuration 1 (Figure 6.3). The WW direction encountered decreased spacing from 5 to 1 ft. Table 6.3 shows comparisons of in-cab sound levels relative to levels experienced on smooth pavement. The sound levels for both the RW and WW were from 10.8 to 13.7 dBA, which is noticeably greater than in the ambient conditions. No in-vehicle sound comparisons that yielded RW and WW differences that were noticeable. The vibration differences were inadequate compared with the vibration perception threshold (2.5 to 4.25 m/s^2). Figure 6.4 displays the sound and vibration signal profile under speeds of 45 mph. Based on the sound waveforms, it appears that the strips provided significantly higher sound than that of the baseline conditions in the DRS areas (from 50 to 100 ft). Vertical vibration fluctuated from 0.8 to 1.2 *g* due to the DRS installment. Generally, sound signals for RW and WW had similar curve trends, and the vibration in the WW was a bit greater than in the RW direction. The RW and WW stimuli did not have obvious differences.

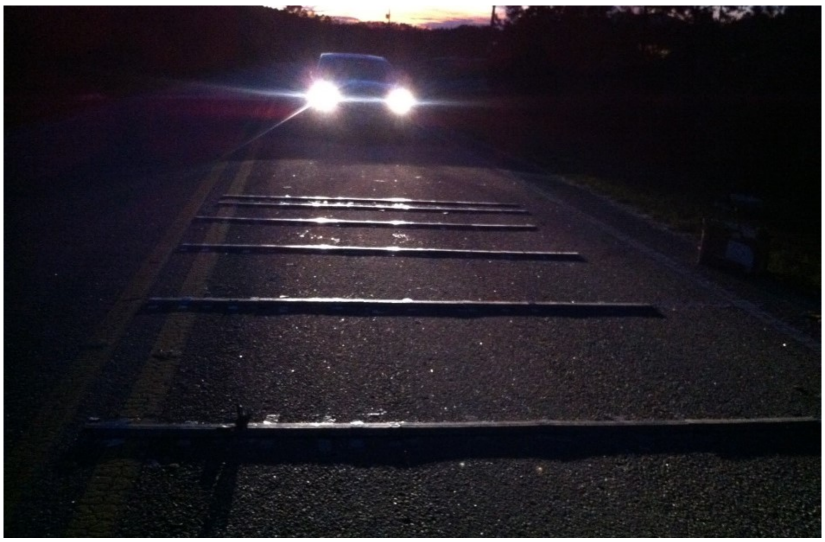
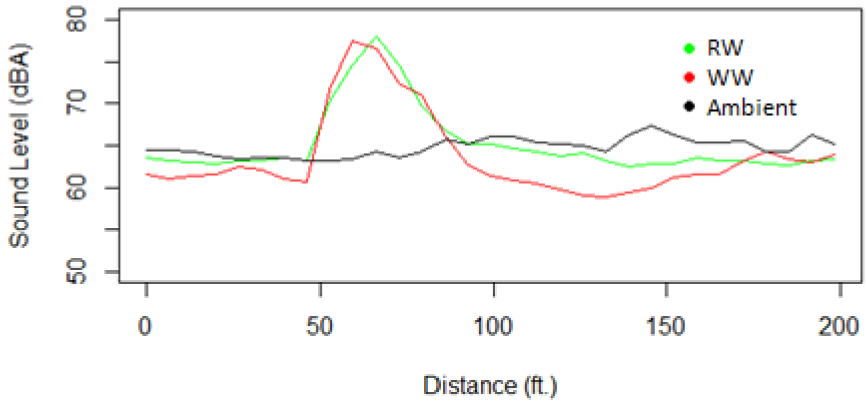


Figure 6.3 Pattern B Configuration 3

Table 6.3 Sound and vibration level of Pattern B Configuration 3

	Speed (mph)	10	15	20	25	35	45
Sound (dBA)	Ambient	52.3	54.6	57.7	64.4	64.2	67.3
	RW	65.0	67.1	70.2	71.1	75.9	78.0
	WW	64.4	68.3	68.5	71.2	74.1	77.5
	RW vs. Ambient	12.7	12.5	12.5	6.7	11.7	10.7
	WW vs. Ambient	12.1	13.7	10.8	6.8	9.9	10.2
	WW vs. RW	-0.6	1.2	-1.7	0.1	-1.8	-0.5
Vibration (g)	Ambient	1.014	1.022	1.026	1.03	1.025	1.061
	RW	1.227	1.213	1.206	1.209	1.202	1.120
	WW	1.192	1.221	1.211	1.219	1.155	1.152
	RW vs. Ambient	0.213	0.191	0.180	0.179	0.177	0.059
	WW vs. Ambient	0.178	0.199	0.185	0.189	0.130	0.091
	WW vs. RW	-0.035	-0.005	0.005	0.010	-0.047	0.032



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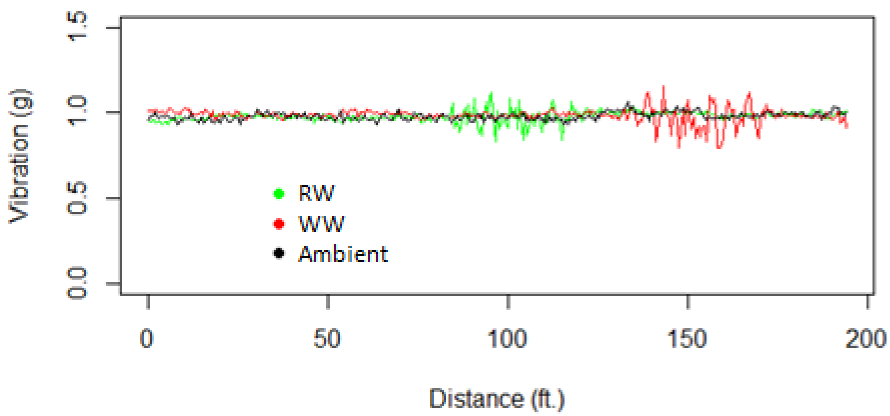


(b)

Figure 6.4 Signal profile for Pattern B Configuration 3 under 45 mph (a: sound level; b: vibration)

6.1.4 Pattern C

Figure 6.5 is a generalized diagram of Pattern C, which had multiple spacings among strips. This pattern contained three groups, with 100 and 50 ft in between groups. Each group contained four, four, and seven rumble strips, spaced 5 ft, 2 ft and 1 ft edge to edge. These strips stretched across the entire width of the lane with the length of 10 ft. Table 6.4 lists the sound and vibration data collected in the field. Figure 6.6 describes the sound and vibration signals along the distance for the speed of 20 mph. For the sound signals, when the vehicle drove along the RW, the peak values showed an increasing trend for each group of strips. The WW curve showed a reverse trend. This phenomenon can also be observed from the vibration profile. From left to right, the vibration signal became denser for each group of strips with verified spacing and number of strips.

Figure 6.5 Pattern C

Table 6.4 Sound and vibration level of Pattern C

	Speed (mph)	10	15	20	25	35	45
Sound (dBA)	Ambient	52.3	54.6	57.7	64.4	64.2	67.3
	RW	76.5	66.1	69.8	69.1	74.6	80.1
	WW	62.2	65.9	68.6	70.9	73.7	78.8
	RW vs. Ambient	24.2	11.5	10.9	8.1	10.4	12.8
	WW vs. Ambient	9.9	11.3	12.1	9.9	9.5	11.5
	WW vs. RW	-14.3	-0.2	-1.2	1.8	-0.9	-1.3
Vibration (g)	Ambient	1.025	1.022	1.030	1.03	1.034	1.061
	RW	1.123	1.159	1.179	1.157	1.217	1.152
	WW	1.112	1.120	1.156	1.139	1.209	1.123
	RW vs. Ambient	0.098	0.137	0.149	0.127	0.183	0.091
	WW vs. Ambient	0.098	0.098	0.126	0.109	0.175	0.062
	WW vs. RW	-0.001	-0.039	-0.023	-0.018	-0.008	-0.029

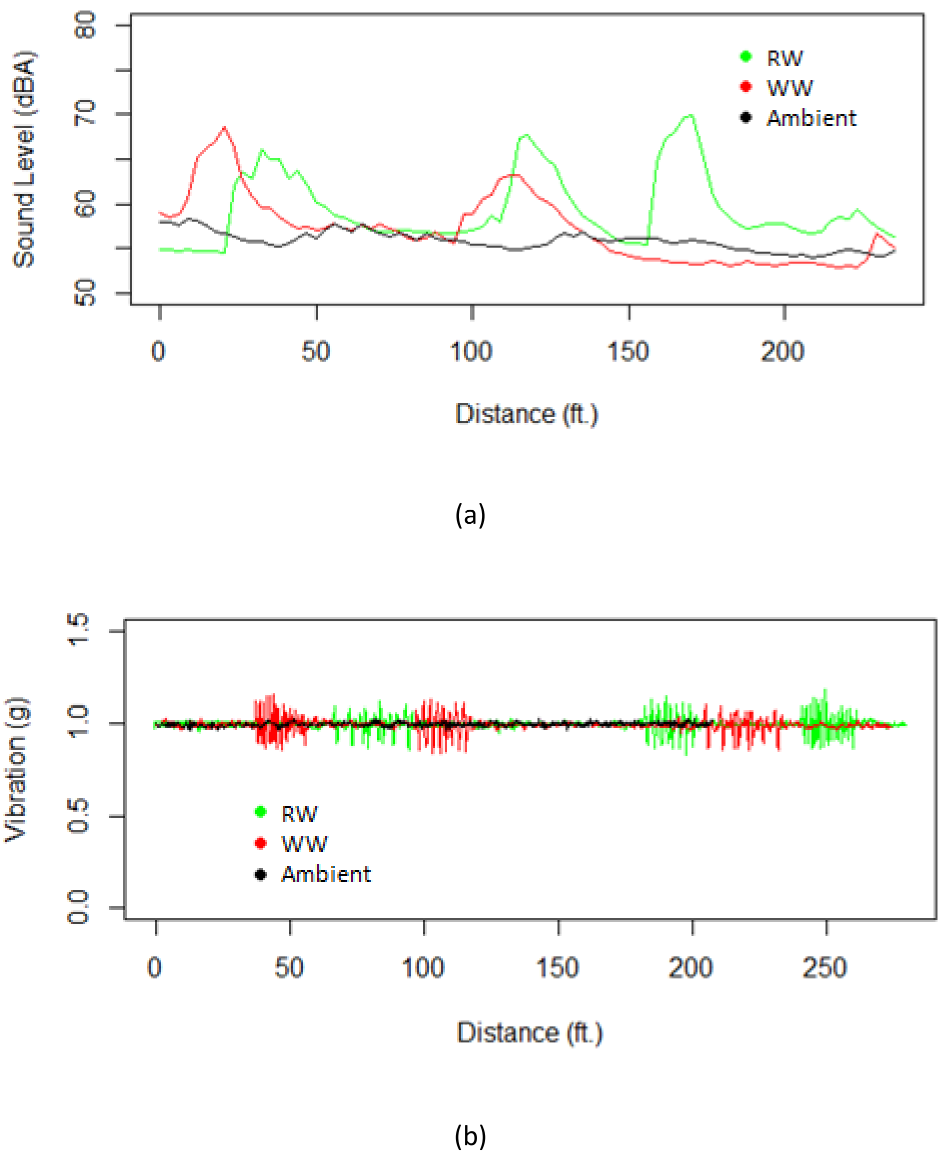


Figure 6.6 Signal profile for Pattern C at 20 mph (a: sound level; b: vibration)

6.1.5 Pattern D Configuration 1

Pattern D (Figure 6.7) constituted a lane direction arrow using the ATM removable rumble strips. The length of the strips decreased from 12 ft to 1 ft with the spacing of 5 ft among the strips. Sound and vibration data of 25 mph, 35 mph, and 45 mph were collected in the first field testing period. The results in Table 6.5 indicated 7.2 to 11.3 dBA sound-level increases. The vibration in both RW and WW directions had a noticeable increase from the ambient condition. However, no noticeable difference was observed for the RW and WW sound and vibration levels.

Figure 6.7 Pattern D Configuration 1 (left: daytime, right: nighttime)

Table 6.5 Sound and vibration level of Pattern D Configuration 1

	Speed (mph)	25	35	45
Sound (dBA)	Ambient	65.1	64.2	67.3
	RW	76.4	76.5	77.3
	WW	77.5	75.4	74.5
	RW vs. Ambient	11.3	12.3	10
	WW vs. Ambient	12.4	11.2	7.2
	WW vs. RW	1.1	-1.1	-2.8
Vibration (g)	Ambient	1.03	1.025	1.061
	RW	1.228	1.17	1.182
	WW	1.215	1.181	1.111
	RW vs. Ambient	0.198	0.145	0.121
	WW vs. Ambient	0.185	0.156	0.05
	WW vs. RW	-0.013	0.011	-0.071

6.1.6 Pattern D Configuration 2

Figure 6.8 shows the DRS direction arrow in both day and night conditions. During the night, the arrow also had good visibility for WW drivers. Compared with Configuration 1, Configuration 2 verifies the spacing among the strips to be 1 ft; the other parameters (length, width, number of strips) remain the same as in Configuration 1. Table 6.6 lists the sound and vibration data. It was observed that the sound increase ranged from 7.5 to 12.1 dBA, and both the RW and WW sound increases were significantly greater than the background sound. However, the sound level was not significantly different for the RW and WW directions. The vibration also showed no significant difference of RW and WW stimuli in most cases. Figure 6.9 demonstrates that the sound and vibration signals of the RW and WW directions have similar curve profiles. Both the RW and WW signals show a similar waveform.

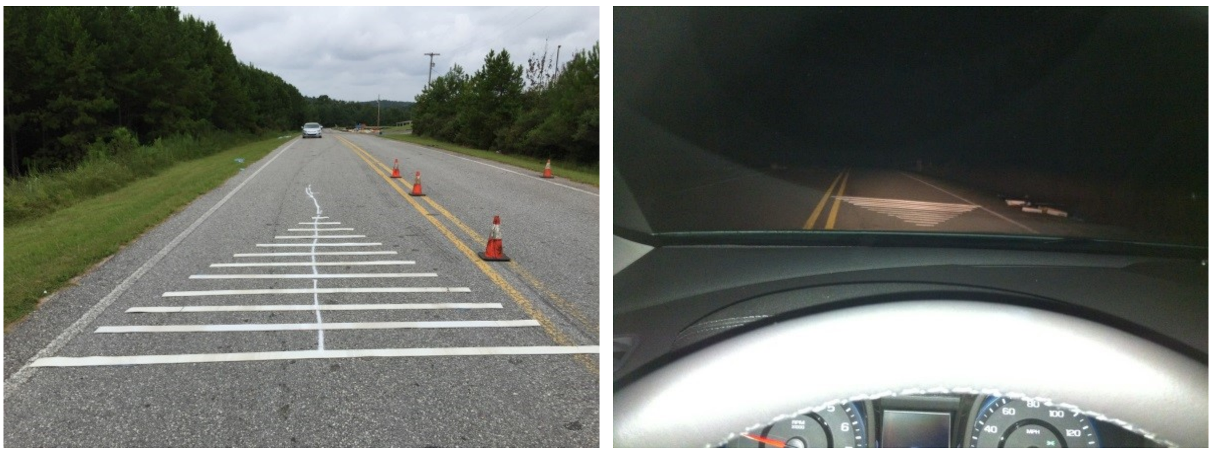
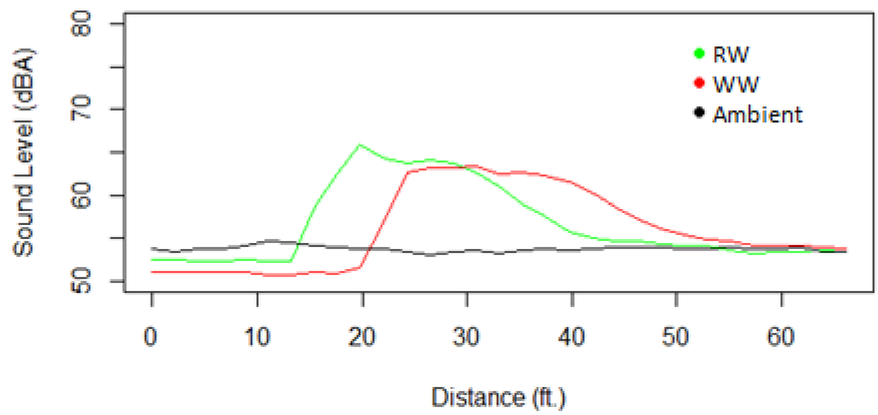


Figure 6.8 Pattern D Configuration 2 (left: daytime, right: nighttime)

Table 6.6 Sound and vibration level of Pattern D Configuration 2

	Speed (mph)	10	15	20	25	35	45
Sound (dBA)	Ambient	52.3	54.6	57.7	61	64.2	67.3
	RW	64.4	65.9	67.3	69.1	74.6	79.2
	WW	64	63.4	68.2	68.5	74.2	75.3
	RW vs. Ambient	12.1	11.3	9.6	8.1	10.4	11.9
	WW vs. Ambient	11.7	8.8	10.5	7.5	10	8
	WW vs. RW	-0.4	-2.5	0.9	-0.6	-0.4	-3.9
Vibration (g)	Ambient	1.014	1.022	1.026	1.03	1.025	1.061
	RW	1.123	1.114	1.124	1.123	1.153	1.153
	WW	1.133	1.118	1.122	1.157	1.223	1.142
	RW vs. Ambient	0.109	0.092	0.098	0.093	0.128	0.092
	WW vs. Ambient	0.119	0.096	0.096	0.127	0.198	0.081
	WW vs. RW	0.01	0.004	-0.002	0.034	0.07	-0.011



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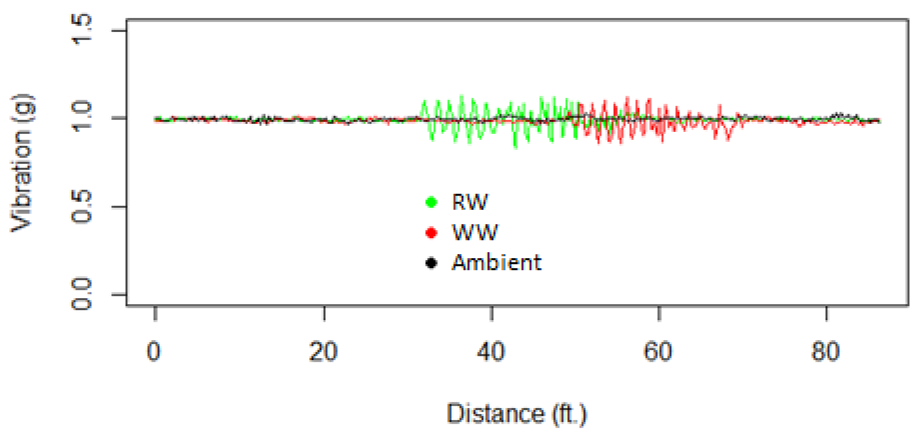


(b)

Figure 6.9 Sound and vibration signal profile for Pattern D Configuration 2 at 20 mph (a: sound level; b: vibration)

6.1.7 Pattern D Configuration 3

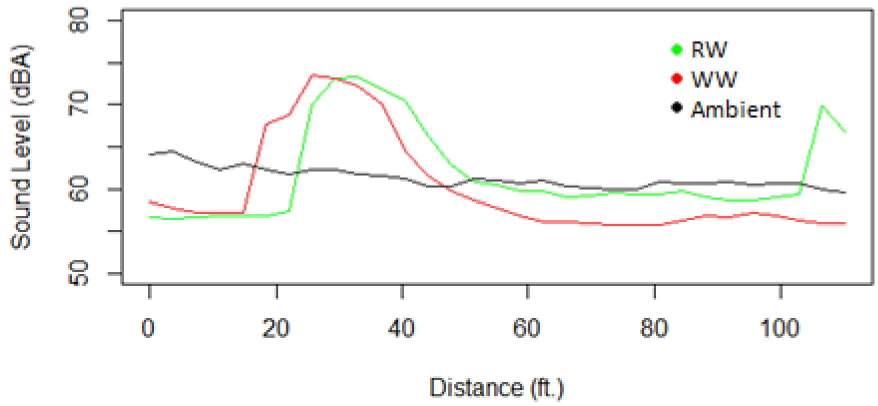
Pattern D Configuration 3 (Figure 6.10) was featured as multiple thicknesses of strips. The first seven strips (length from 1 to 7 ft) retained the single thickness of 0.25 in. The 8th to 10th strips (length of 8 ft, 9 ft, 10 ft) had a double thickness by overlapping two layers of strips. The last two strips (length of 11 ft and 12 ft) had a thickness of 0.75 ft with three layers of strips. Table 6.7 details the sound and vibration data. The sound level increases ranged from 8.9 to 19.2 dBA under different testing speeds. The sound- and vibration-level increase was significantly greater than other tested configurations, especially at low speed. Figure 6.11 displays the sound signal for the speed of 25 mph and the vibration curve of 45 mph. The slight difference of RW and WW signals can be observed from the profiles.

According to driver perceptions, the Pattern D Configuration 3 was the only pattern for which the driver could feel a different sound and vibration in the field test. Louder sound and denser vehicle body vibration were experienced for driving in the WW direction.

Figure 6.10 Pattern D Configuration 3

Table 6.7 Sound and vibration level of Pattern D Configuration 3

	Speed (mph)	10	15	20	25	35	45
Sound (dBA)	Ambient	52.3	54.6	57.7	64.4	64.2	67.3
	RW	70.4	73.6	72.2	73.3	78	79.6
	WW	69.4	73.8	73.8	73.4	78.4	80
	RW vs. Ambient	18.1	19	14.5	8.9	13.8	12.3
	WW vs. Ambient	17.1	19.2	16.1	9	14.2	12.7
	WW vs. RW	-1	0.2	1.6	0.1	0.4	0.4
Vibration (g)	Ambient	1.014	1.022	1.026	1.03	1.025	1.024
	RW	1.309	1.307	1.225	1.199	1.303	1.181
	WW	1.385	1.358	1.255	1.217	1.28	1.22
	RW vs. Ambient	0.295	0.285	0.199	0.169	0.278	0.157
	WW vs. Ambient	0.371	0.336	0.229	0.187	0.255	0.196
	WW vs. RW	0.076	0.051	0.03	0.018	-0.023	0.039



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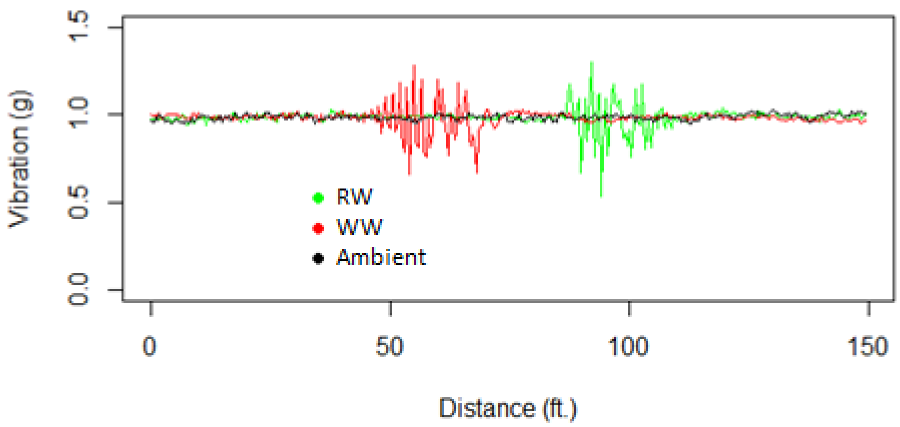


(b)

Figure 6.11 Sound and vibration signal profile for Pattern D Configuration 3 (a: 25 mph sound level; b: 45 mph vibration)

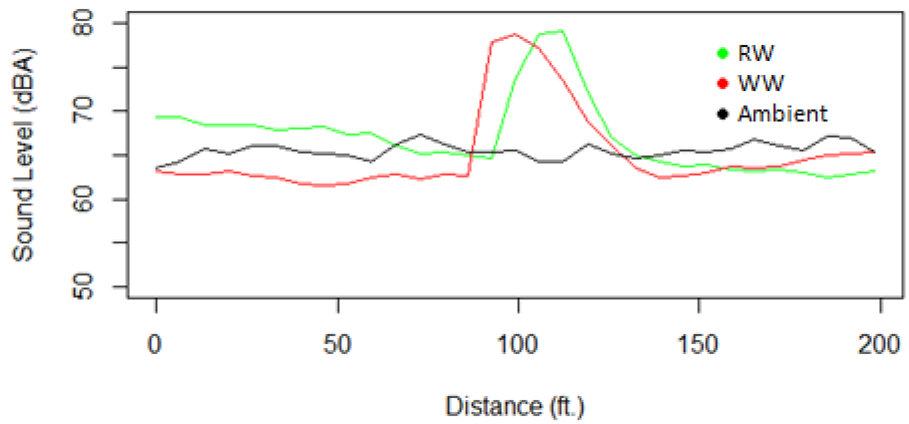
6.1.8 Pattern E

Pattern E (Figure 6.12) was a simple triangle design provided by the Peek Pavement Marking, LLC. The raised strips were installed by a particular machine of the vendor. The five strips were spaced at 1 ft, 1 ft, 2 ft, and 5 ft to increase the signals for the WW direction. The strips only cover the width of vehicle wheel path in the field test to save time of installation. If the test results show positive effects, this configuration will be compared with the one that covered the whole lane width in a later study. Table 6.7 lists the sound and vibration test results. The sound increase was 11 to 17.2 dBA for different speeds, which were considerable increases above the background sound. The vibration increase was 0.131 to 0.319 g more than the baseline conditions, which were comparable with the vibration perception threshold of 0.260 to 0.430 g. Figure 6.13 describes the sound and vibration curves for the speed of 45 mph. The curve trend was generally the same for both RW and WW directions.

Figure 6.12 Pattern E

Table 6.8 Sound and vibration level of Pattern E

	Speed (mph)	10	15	20	25	35	45
Sound (dBA)	Ambient	52.5	55.5	57.7	61.0	64.2	67.3
	RW	65.0	66.5	72.4	78.2	77.3	79.0
	WW	69.1	69.4	72.4	74.6	76.9	78.8
	RW vs. Ambient	12.5	11.0	14.7	17.2	13.1	11.7
	WW vs. Ambient	16.6	13.9	14.7	13.6	12.7	11.5
	WW vs. RW	4.1	2.9	0.0	-3.6	-0.4	-0.2
Vibration (g)	Ambient	1.014	1.022	1.026	1.030	1.025	1.061
	RW	1.333	1.309	1.327	1.257	1.230	1.212
	WW	1.267	1.241	1.309	1.272	1.305	1.192
	RW vs. Ambient	0.319	0.287	0.301	0.227	0.205	0.131
	WW vs. Ambient	0.253	0.219	0.283	0.242	0.280	0.151
	WW vs. RW	-0.066	-0.068	-0.018	0.015	0.075	0.020



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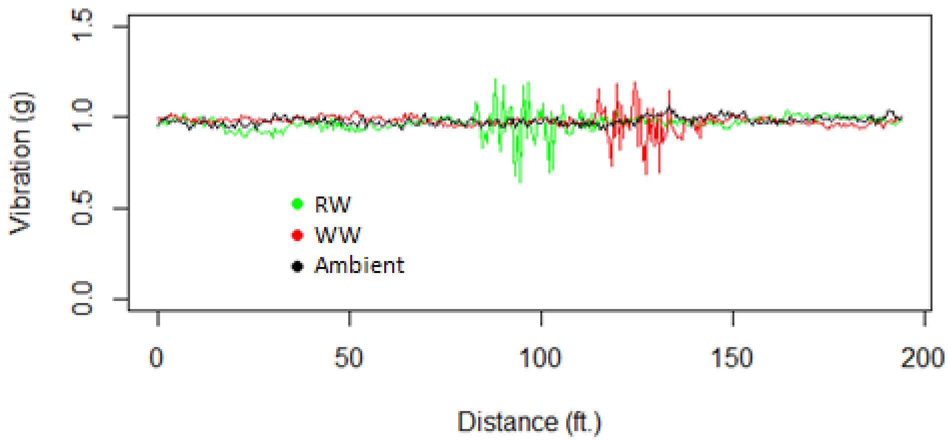


(b)

Figure 6.13 Sound and vibration signal profile for Pattern E at 45 mph (a: sound level; b: vibration)

6.1.9 Statistical Analysis Results

Tables 6.9 and 6.10 present the outcomes of the t-tests at 95% confidence level. The highlighted results show the statistical differences of the two data sets between RW and WW. The results provided evidence that Pattern C generated significant different sound and vibration signals for the RW and WW directions at speeds of 10 to 25 mph. Pattern E showed a statistically vibration difference at 45 mph. Even though Pattern E and Pattern D Configuration 3 could not generate significantly different sound and vibrations between RW and WW, they both were found to be able to generate the largest increase in sound and vibration over the baseline conditions.

Table 6.9 Statistical test results of sound level comparison

Pattern	10 mph	15 mph	20 mph	25 mph	35 mph	45 mph
Pattern B Configuration 1	0.7629	0.5837	0.7393	0.9050	0.5895	0.9514
Pattern B Configuration 2	-	-	-	0.9690	0.7956	0.4834
Pattern B Configuration 3	0.4034	0.5331	0.7912	0.7630	0.07198	0.1786
Pattern C	0.0035	0.0010	0.0004	0.0004	0.0710	0.5110
Pattern D Configuration 1	-	-	-	0.8548	0.6821	0.05645
Pattern D Configuration 2	0.9655	0.6338	0.6338	0.9696	0.5527	0.0322
Pattern D Configuration 3	0.4925	0.7364	0.6256	0.2301	0.06954	0.3395
Pattern E	0.9034	0.8384	0.5754	0.7072	0.6646	0.1062

Table 6.10 Statistical test results of vibration comparison

Pattern	10 mph	15 mph	20 mph	25 mph	35 mph	45 mph
Pattern B Configuration 1	0.6304	0.6975	0.0916	0.0697	0.6316	0.0007
Pattern B Configuration 2	-	-	-	0.4306	0.0339	0.0050
Pattern B Configuration 3	0.6805	0.0697	0.6839	0.0232	0.5813	0.0412
Pattern C	0.0000	0.0000	0.0093	0.0002	0.0745	0.8249
Pattern D Configuration 1	-	-	-	0.7311	0.9351	0.1508
Pattern D Configuration 2	0.3785	0.4818	0.0012	0.5039	0.763	0.6898
Pattern D Configuration 3	0.6203	0.6077	0.1410	0.3577	0.7251	0.7251
Pattern E	0.7382	0.9057	0.2580	0.2660	0.7300	0.0194

6.1.10 Recommendations for Further Verification Test

After the initial field test, Pattern C, Pattern D Configuration 3, and Pattern E were recommended for further optimization based on their attention-getting effects and visual attentiveness. All the tested patterns generated adequate sound changes in the WW direction to alert drivers (7.2 to 16.6 dBA increases over the ambient condition). Pattern D Configuration 3 and Pattern E produced noticeable vibration changes compared with the vibration perception threshold. The statistical test provided evidence that Pattern C generated significantly different sound and vibration signals for the RW and WW directions at speeds of 10 to 25 mph. Pattern E showed a statistically significant vibration difference at 45 mph.

6.2 VERIFICATION TEST RESULTS

This section presents the procedure of data analysis methodology and results in the field verification study.

6.2.1 Comparisons of Sound and Vibration at the Same Speed

The analysis results of the verification tests were consistent with the initial tests. Both testing results indicated that all three recommended patterns can generate adequate sound and vibration in the WW direction to alert drivers with a minimum increase of 7.2 dBA in sound and 0.2 g increase in vibration over the ambient condition. Additional t-tests were conducted to verify if there was a significant difference at a confidence level of 95% in sound and vibration generated by DRS between RW and WW directions. According to *p*-values, Pattern C showed a significant difference in sound and vibration levels between RW and WW at speeds (10, 15, 20 and 25 mph) with *p*-values less than 0.05. Pattern D Configuration 3 showed no significant difference between RW and WW directions for both sound and vibration at the same speed. Pattern E was only significantly different in the vibration at a speed of 45 mph (*p*-value = 0.0011,) but not significantly different in the sound levels. However, the modified Pattern E.1 did show a significantly different vibration at speeds of 35 mph or lower and different sound levels at speeds of 10 and 15 mph.

The verification study found that Pattern C and the newly modified Pattern E.1 can generate elevated sound and vibration to WW drivers when assuming they would drive at the same speed (less than 35 mph) in both directions. However, additional speed study found that speeds in WW and RW directions could be significantly different at different spots of ramps where DRS are installed. Field testing results in this study indicate that vehicle speed has a strong correlation with the sound and vibration generated by DRS. Generally, higher speeds can result in louder sound and more severe vibrations to drivers

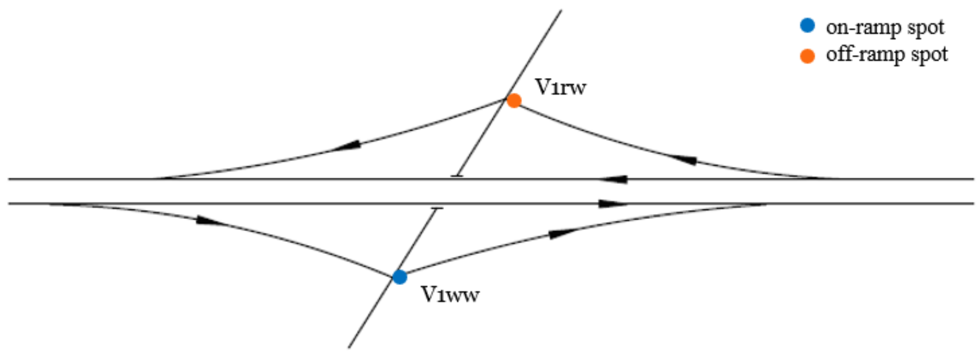
Table 6.11 Statistical test results of sound and vibration comparison

	Pattern	10 mph	15 mph	20 mph	25 mph	35 mph	45 mph
Sound (dBA)	Pattern D Configuration 3	0.6049	0.5130	0.6291	0.2666	0.1839	0.1174
	Pattern C	0.0146	0.0000	0.0372	0.0006	0.0850	0.5478
	Pattern E	0.2682	0.1072	0.3895	0.5236	0.4343	0.4116
	Pattern E.1	0.0272	0.0398	0.0896	0.3558	0.4217	0.4849
Vibration (g)	Pattern	10 mph	15 mph	20 mph	25 mph	35 mph	45 mph
	Pattern D Configuration 3	0.0849	0.1272	0.0825	0.1026	0.1971	0.0744
	Pattern C	0.0001	0.0000	0.0000	0.0010	0.6523	0.6473
	Pattern E	0.1730	0.2787	0.0952	0.5943	0.1764	0.0011
	Pattern E.1	0.0029	0.0065	0.0214	0.0476	0.0116	0.0647

6.2.2 Speed Analysis at Different Spots on Ramps

Sound and vibration analysis results indicated that vehicle speed had a significant impact on the differences in sound and vibration levels. Considering drivers are likely driving at different speeds at the same spot on the off-ramp when driving in WW and RW, a pilot speed study was conducted at three ramps to record average speed at specific spots along off- and on-ramps. A pocket radar (Traffic Advisor Model PR1000-TA) was used to estimate the average RW and WW driving speed on off-ramps. Three spots on both the on- and off-ramps were selected. The first spot is close to the stop bars of on- and off-ramp terminals (Figure 6.13-a). The RW speed (V_{1rw}) was measured close to the stop bar of the off-ramp terminal. The WWD speed (V_{1ww}) on off-ramps was assumed to be the same as the speed at the corresponding spot of the on-ramps. The second spot is the middle point of on and off-ramps (Figure 6.13-b). The RW speed (V_{2rw}) on off-ramps was collected. The WWD speed (V_{2ww}) was assumed to be the same as the RW speed measured at the middle point of the on-ramp. The third spot was selected at ramps of partial cloverleaf interchanges (Figure 6.13-c). The RW driving speed (V_{3rw}) was collected at the tangent of the incoming curve, while the speeds obtained at the tangent after the curve of an on-ramp was assumed the same as the WWD speeds.

Figure 6.14 and Table 6.11 present a summary of the speed study results. The first spot measured was 12 ft from the stop bar at the signalized intersections of on- and off-ramp terminals. Results showed that the mean speed is 16.1 mph at the on-ramp while only 9.8 mph at the same spot of the off-ramp. The second spot was the middle point of the straight segment (180 ft from the stop bar) of the ramps. The study found that the mean speed at this spot of the on-ramp is 33.6 mph when compared 25.6 mph on the off-ramp. The third spot is located at the starting point of the tangent of curves at a partial cloverleaf interchange. The results showed that the mean speeds of 17.7 and 15.8 mph are similar on both on- and off-ramp curve with a radius of 106 ft. The speed study results can help develop recommendations of proper locations for installing DRS based on approximate mean driving speed by RW and WW drivers.



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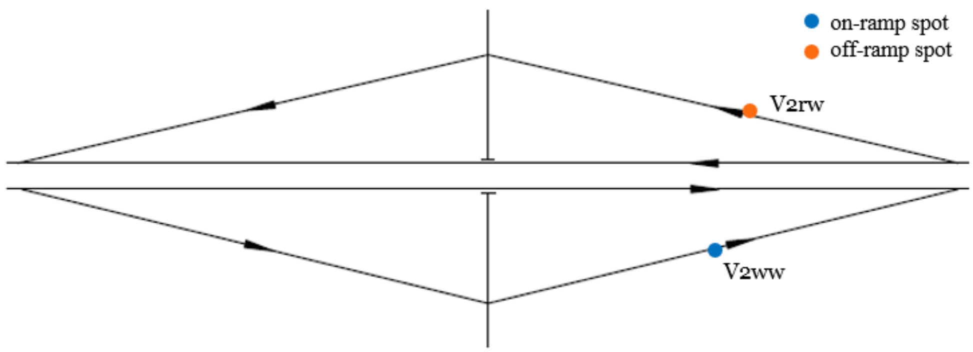

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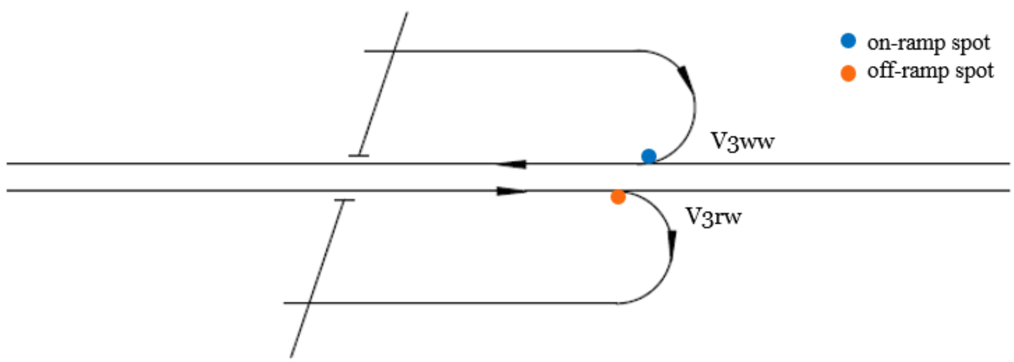

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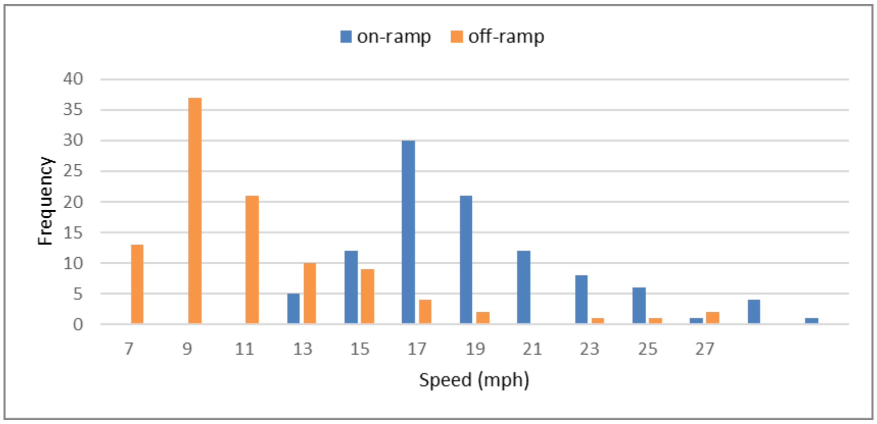
Figure 6.14 Description of spots on ramps and speeds measured



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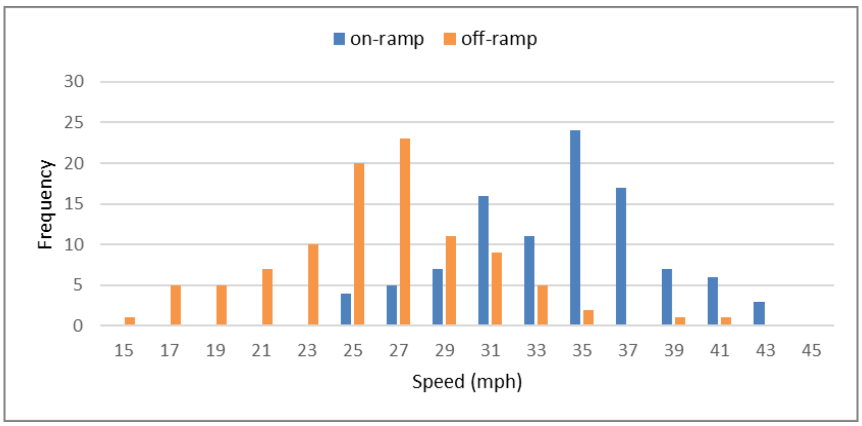

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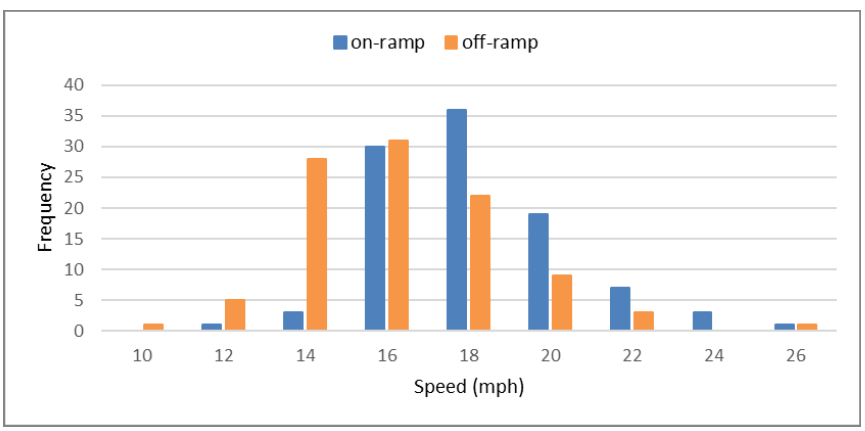


(c)

Figure 6.15 Speed distributions on ramps

Table 6.12 Speed characteristics on ramps

Location	Speed	On-ramp (mph)	Off-ramp (mph)
Terminal	85th	18.0	10.0
	Mean	16.1	9.8
	Max	28.0	27.0
	Min	10.0	7.0
Middle of Straight Segment	85th	38.0	30.0
	Mean	33.6	25.6
	Max	42.0	41.0
	Min	25.0	15.0
Tangent of Curves	85th	20.0	18.0
	Mean	17.7	15.8
	Max	25.0	25.0
	Min	11.0	10.0

6.2.3 Sound and Vibration Analysis Using Waveform and Fast Fourier Transform

In the initial field testing study, only the maximum value of sound and vibration along the time domain was investigated, which might ignore important characteristics of the sound or vibration generated by each pattern. For example, the statistical analysis only compared the maximum sound and vibration levels for the same speed between WW and RW directions, which might not represent the total amount of sound and vibration received by drivers in the real world. As such, in the verification test study stage, sound was further evaluated in the form of the waveform in the time domain and vibration was analyzed by the fast Fourier transform (FFT) method.

For sound data, waveforms in the time domain were used to identify the relative loudness of sound in the air as perceived by the driver. The waveform of sound showed the volumes caused by DRS that can be heard by drivers when driving through the strips.

Unlike sound, vibration required additional detailed analysis because different vibration patterns may have similar expressions in a waveform. Thus, FFT was employed to evaluate vibration amplitude as a function of frequency. Fourier analysis converts a signal from its original domain (e.g., time domain in this study) to a representation in the frequency domain. As a complicated vibration can be treated as a combination of many vibrations that have different frequencies and amplitudes, the *x*-axis in the FFT plot stands for different frequencies ranging from low to high, while the *y*-axis represents the amplitude of each frequency. The equation below shows how to simplify a complicated vibration signal to a series of basic sine and cosine signals. The vibration signals occuring through the DRS can be presented as $f(x)$. The sum of numbers of sine and cosine signals with different phases kx (i.e., 1/2 π , π , 3/2 π …) plus an offset (a_0) can be calculated, which is equal to the original signal $f(x)$. In this study, a MATLAB program was developed to help process a large amount of field data using FFT.

$$f(x) = \frac{a_0}{2} + \sum_{k=1}^{n} (a_k \cos kx + b_k \sin kx)$$

where,

- $f(x)$ = original signal
- a_0 = offset phase
- a_k, b_k = amplitude of each signal
- kx = 1/2 π , π , 3/2 π …

In the following sections, analysis results by the waveform and FFT were presented to compare the sound and vibration for WW drivers and RW drivers by three different types of DRS when they are implemented at different stops of off-ramps. The mean speeds of WW and RW driving are estimated based on the data in Table 6.12. WW and RW speed in Pattern C were determined to be 35 and 25 mph, respectively, when it is installed at the middle point of a straight long off-ramp segment. WW speed is close to 15 mph, while RW speed could be 10 mph in Pattern D Configuration 3 when it is installed close to the off-ramp terminal. WW speed would be close to 20 mph, and RW speed is close to 15 mph in Pattern E.1 when it is used at the tangent segment before the curves.

6.2.3.1 Pattern C

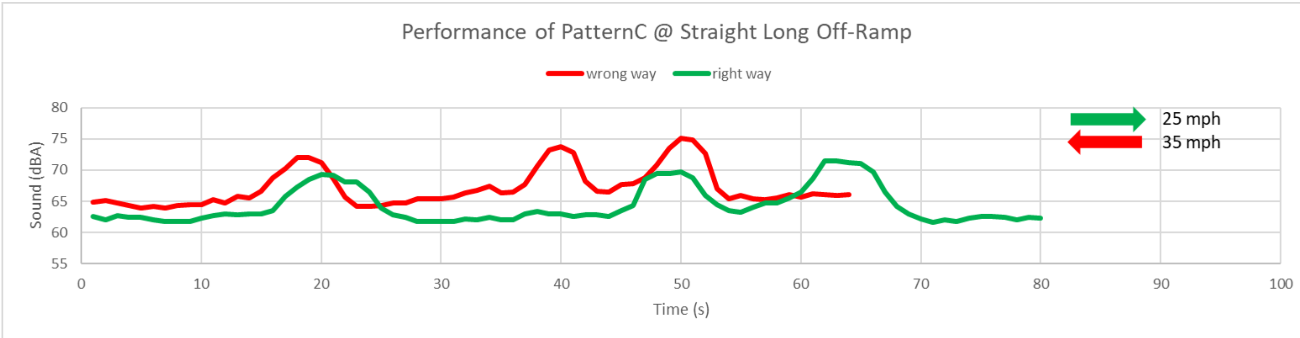
Figure 6.16 illustrates the waveform of sound generated by DRS Pattern C when it is installed at the middle point of a straight and long off-ramp segment. RW drivers were assumed to drive around 25 mph, while WW drivers were accelerating to an approximate speed of 35 mph. As shown in Figure 6.16 (a), the WW driver would receive a 10 dBA louder sound on average than RW driver. From FFT results, the WW driver would receive more vibration at three groups of strips (C5=5-ft spacing, C2=2-ft spacing, and C1=1-ft spacing) than RW drivers. The study also found that the smaller spacing between the strips can generate louder sound and more severe vibration on DRS.

6.2.3.2 Pattern D Configuration 3

The waveform on sound levels in Pattern D Configuration 3, as shown in Figure 6.17 (a), indicated that the WW drivers could hear an average 10% louder sound than RW drivers. WWD speed was estimated to be 15 mph, and RW driving speed was approximately 10 mph when DRS is installed close to the stop bar of an off-ramp. From the vibration FFT plot [Figure 6.17 (b)], RW drivers would receive the vibration at around a peak of 8 Hz, while WW drivers would receive the vibration concentrating around a frequency of 20 Hz, which also implied that the WW driver would receive a more severe vibration.

6.2.3.3 Pattern E.1

Pattern E.1 is designed to be installed before the curve on the off-ramp to provide visual attentiveness of a curve ahead. From the speed data collected on the sharp curves with a turning radius of 106 ft, the mean speed ahead of the curve was nearly 15 mph on the off-ramp, and approximately 20 mph on the on-ramp. Figure 6.18 presents the sound waveform and FFT plot on vibration. The WW driver can hear a louder sound and feel more severe vibration in terms of both frequency and amplitude. During field tests, drivers could hear a significantly louder sound and feel a much stronger vibration when driving in the WW direction than in the RW direction.



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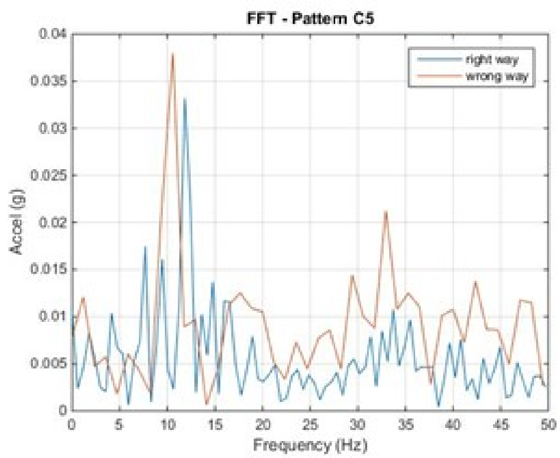

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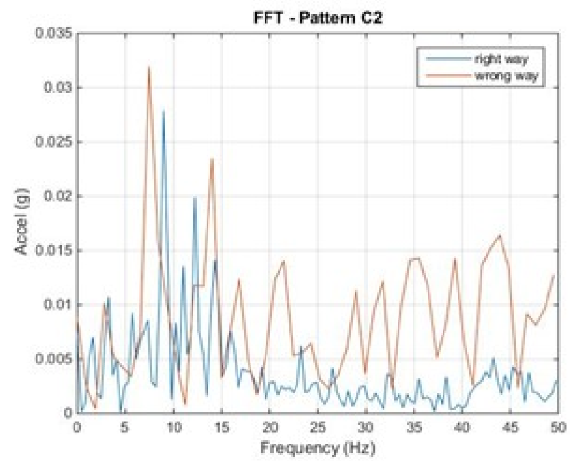

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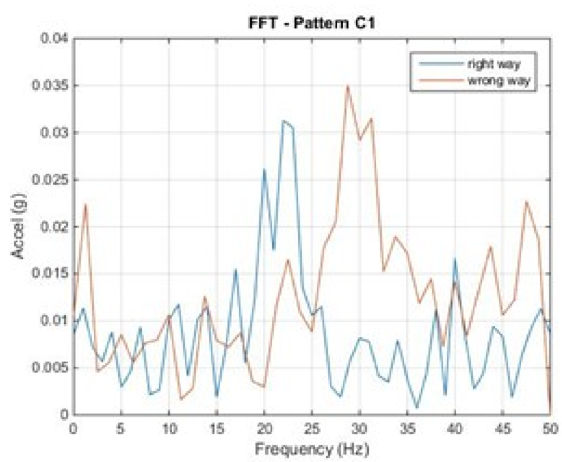
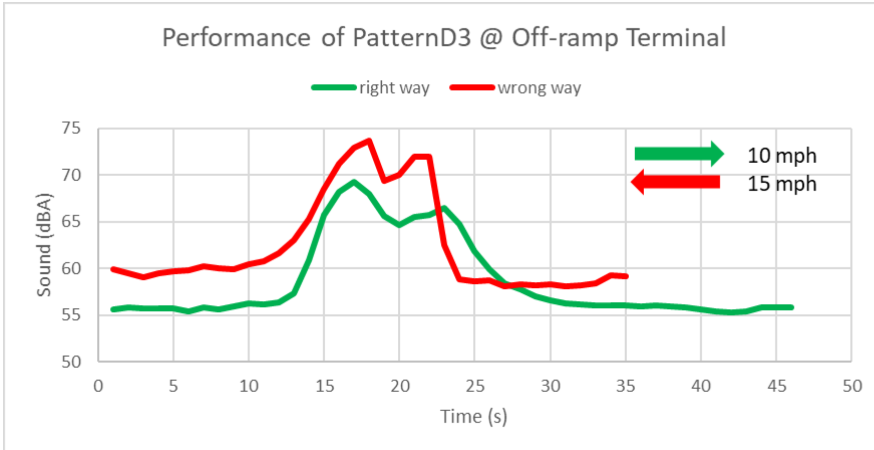


(d)

Figure 6.16 Pattern C: Sound waveform (a) and FFT spectrum analysis (b) 5-ft (c) 2-ft (d) 1-ft



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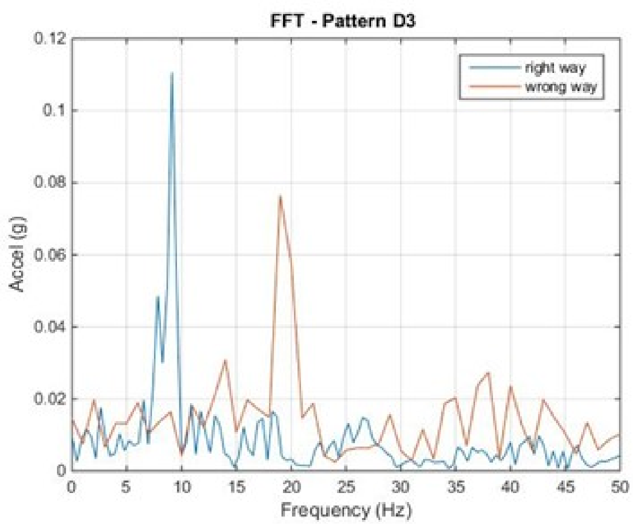
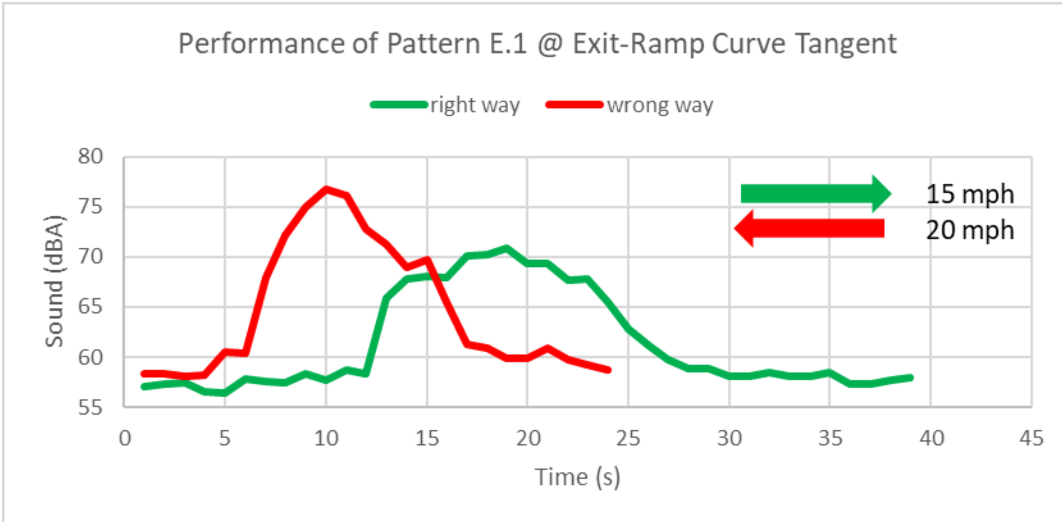


(b)

Figure 6.17 Pattern D Configuration 3: Sound waveform (a) and FFT spectrum analysis (b)



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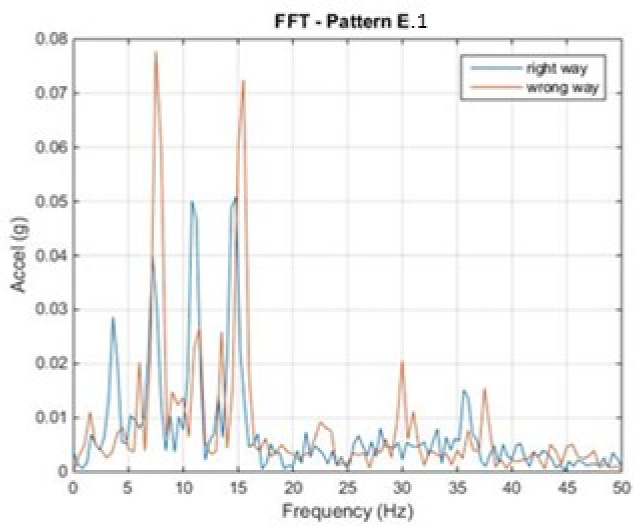


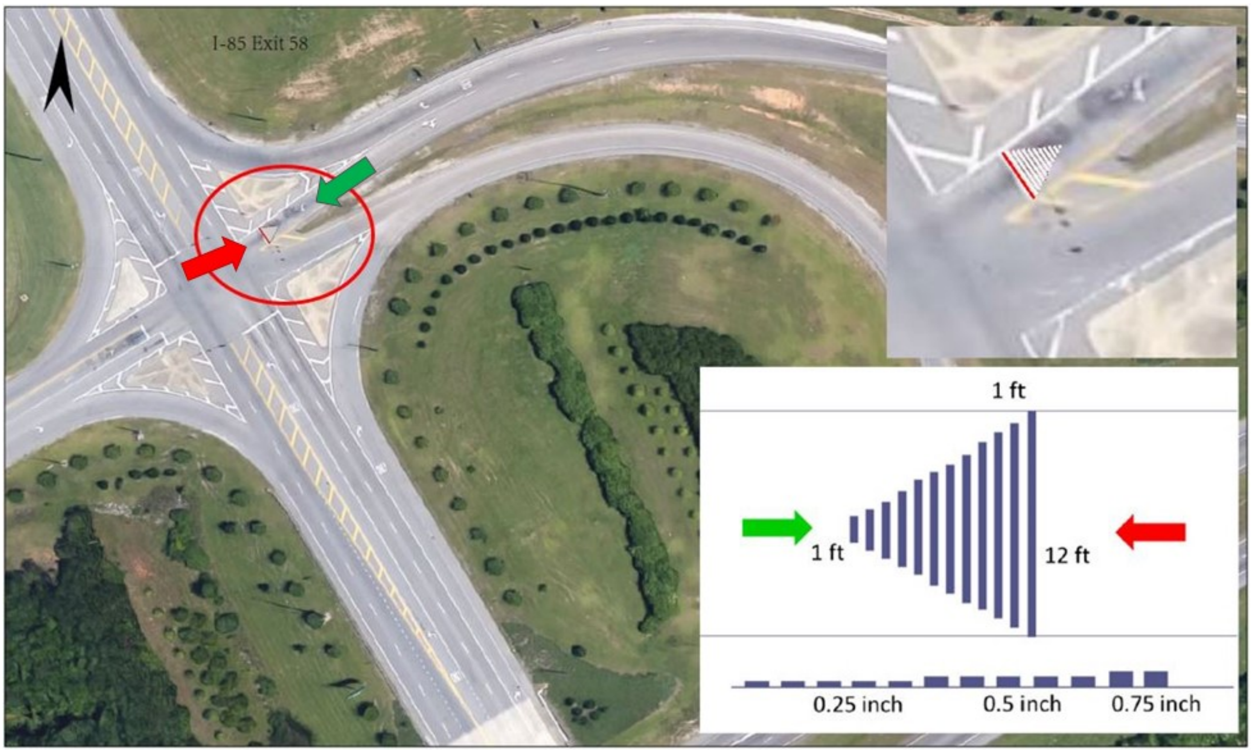
(b)

Figure 6.18 Pattern E.1: Sound waveform (a) and FFT spectrum analysis (b)

CHAPTER 7: **GENERAL GUIDELINES FOR IMPLEMENTATION**

According to the field test analysis results, the recommendations for implementing the three final types of DRS are summarized as follows. Three example locations were selected for each scenario.

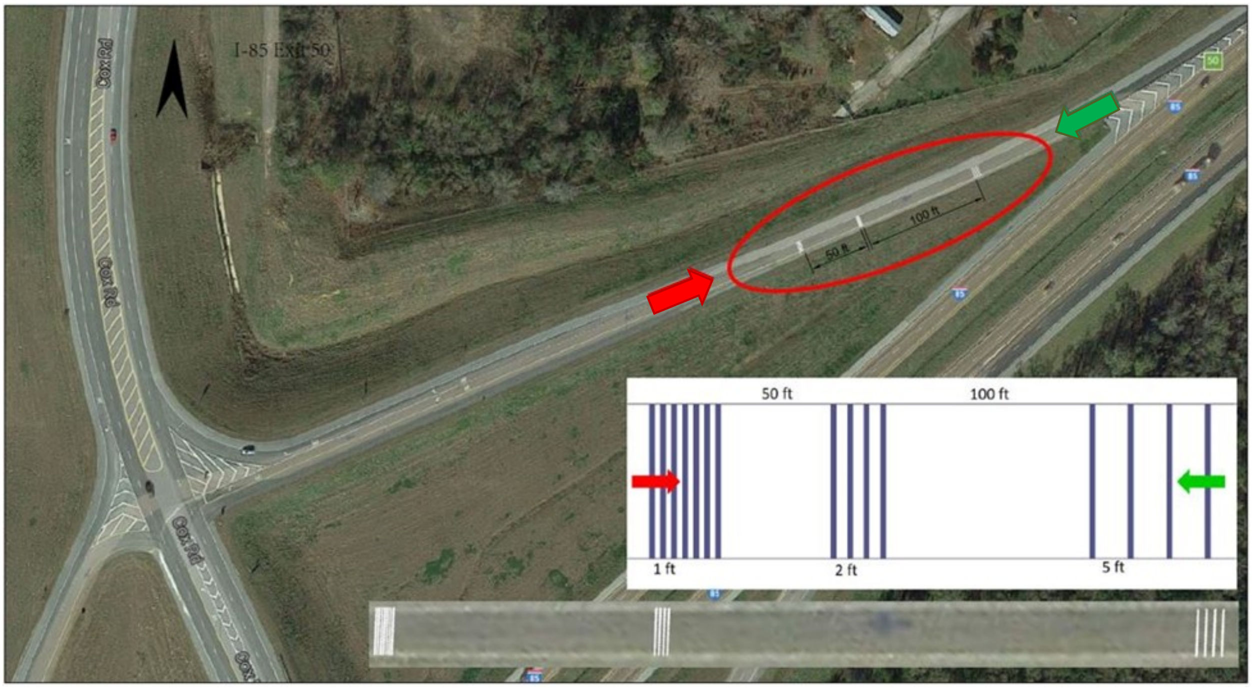
Figure 7.1 shows an off-ramp terminal that is close to the on-ramp entrance at Exit 58 of I-85. Drivers who are not familiar with this location, especially at night or under poor illumination conditions, could drive WW onto the freeway. In this case, Pattern D Configuration 3 can be implemented with the thickest strip as the stop bar, which could be painted with a red retroreflective on the edge facing potential WW drivers. Based on the configuration of strip thickness, RW drivers would perceive a gradually increasing amount of sound and vibration, while WW drivers would receive an immediate alert, which contains a louder sound and more severe vibration.



Note: Green Arrow = Right Direction; Red Arrow = Wrong Direction.

Figure 7.1 Proposed implementation of Pattern D Configuration 3

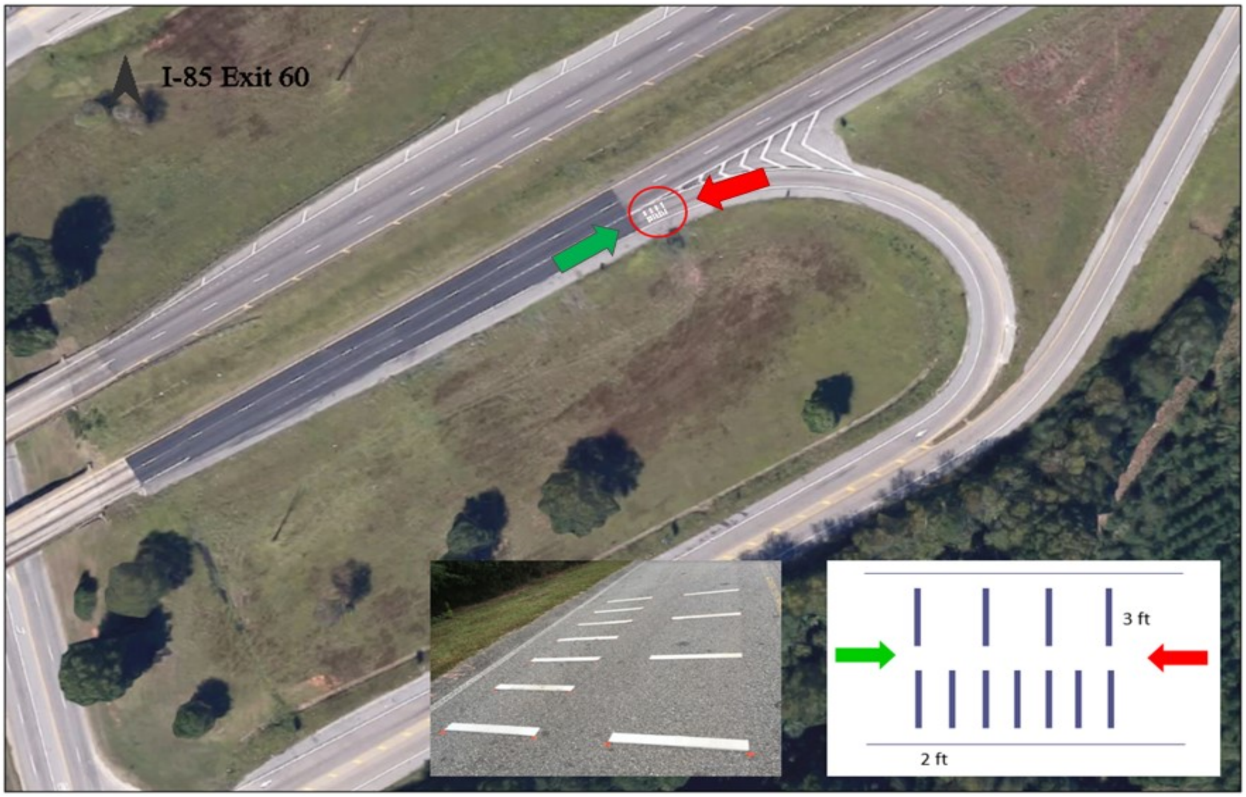
Figure 7.2 presents an example of a potential implementation of Pattern C at the middle part of a straight long segment of off-ramps at Exit 50 of I-85. Based on the testing results, the WW drivers can hear an average of 10 dBA louder sound than RW drivers. Further, the WW vibration has a higher frequency and larger amplitude. Moreover, WW drivers will perceive a different rhythm of sound and vibration due to the diverse spacing among the three strip groups. In this example location, this pattern is expected to produce louder sound and more severe vibration at the beginning when WW drivers drive through the first strip group with dense spacing (1 ft). RW drivers would experience the increasing loudness of sound and severity of vibration, which can be an advanced alert for the intersection ahead to slow them down.



Note: Green Arrow = Right Direction; Red Arrow = Wrong Direction.

Figure 7.2 Proposed implementation of Pattern C

In addition to deterring the WWD, Pattern E.1, as shown in in Figure 7.3, can provide visual attentiveness of the curve ahead and slow down RW driving at Exit 60 of I-85. Pattern E.1 was recommended to be installed on the tangent segment before the curve. Field test experience suggests that this pattern can provide the most recognizable increase of sound and vibration to WW drivers.



Note: Green Arrow = Right Direction; Red Arrow = Wrong Direction.

Figure 7.3 Proposed implementation of Pattern E.1

CHAPTER 8: **CONCLUSIONS**

A comprehensive evaluation of five different designs of DRS was carried out in this study to determine which type of design is able to generate elevated sound and vibration to deter WW freeway entries. A national survey was initiated to collect comments on five DRS designs from transportation professionals. The initial field test was then performed to evaluate the effectiveness of the proposed DRS design patterns. A further verification test was conducted to verify the three recommended patterns from the initial test as well as to develop general guidelines for implementation. The major findings from this research can be summarized as follows.

The national survey suggested that 85% of participants considered that DRS were likely to act as a warning system on off-ramps to mitigate WWD. The designed Pattern B (the raised wedge design of DRS), Pattern A (overlapped removable rumble strips as DRS), Pattern D (triangle-shaped DRS with decreasing length of strips), and Pattern C (DRS with verified number of strips and spacing) were rated as the most feasible conceptual designs.

Based on the initial test results, Pattern C, Pattern D Configuration 3, and Pattern E were recommended for further evaluation based on their attention-getting effects (sound and vibration) and visual attentiveness. All three patterns can generate adequate sound increase in the WW direction to alert drivers (7.2 to 16.6 dBA increases over the ambient condition). Pattern D Configuration 3 and Pattern E produced recognizable vibration changes based on the field test. The statistical test found that Pattern C generated significantly different sound and vibration signals between the RW and WW directions at speeds of 10 to 25 mph. Pattern E showed a statistical vibration difference at 45 mph.

In the verification phase of this study, two new methods (waveform and FFT) were applied to compare the sound and vibration between WW and RW driving. The results from further field testing were found to be consistent with the initial test. The verification testing also found that WWD speed will be different from the RW driving speed depending on the locations where DRS are installed. A pilot speed study was conducted to measure WW and RW driving speed at three different types of ramps. The WW and RW driving speed were estimated to be used to develop general guidelines for implementation of DRS. Considering the specialty of each pattern, specific segments of off-ramps were recommended for installation of DRS. Pattern D Configuration 3 was suggested for installation close to the stop bar at an off-ramp terminal. Pattern C can be implemented on the straight long segment of an off-ramp. It worked similarly to existing TRS for RW drivers to remind them to slow down when they are approaching the stop bar or traffic signal. It generated more sound and vibration for WW drivers, who tended to drive at a higher speed because they assumed they were driving on on-ramps. Pattern E was modified to E.1, which has double strips inside the travel lane. Pattern E.1 can also visually inform RW drivers about the sharp curve ahead to slow them down. Further, it can provide WW drivers with a louder sound and more severe vibration. Therefore, Pattern E.1 was recommended to be installed at the tangent segment before the curve of off-ramps.

Field implementation was recommended to evaluate the effectiveness of DRS in deterring WW freeway entries in the future. Three example locations were identified by the research team for implementation. Three-month before-and-after data can be collected to quantify operational and safety effects on both WW and RW traffic. Practical impacts will be further assessed by implementing DRS on off-ramps in the next project.

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APPENDIX A
NATIONAL SURVEY

Directional Rumble Strips Feasibility and Design Survey

This survey is in support of the research project “Directional Rumble Strips for Reducing Wrong-Way Driving Freeway Entries,” a study conducted by Auburn University and Southern Illinois University-Edwardsville and funded by the University Transportation Center (UTC) Region 5 through the University of Minnesota. The purpose is to conduct feasibility studies of different conceptual designs for the directional rumble strips (DRS) and develop a new safety countermeasure for wrong-way driving on exit ramps.

Two examples of Freeway Exit Ramps

(Left: Birmingham; Right: Mobile, Alabama)

The DRS is a variation of transverse rumble strips (TRS, also named in-lane rumble strips). When vehicles roll over the rumble strips from either direction, the conventional TRS provides motorists with the same levels of sound and vibration. The DRS is designed to generate elevated sound and vibration to warn wrong-way drivers and normal sound and vibration to slow down the traffic for the right-way direction when they are approaching exit ramp terminals.

The survey will take between 5 and 10 minutes to complete, and it is intended to gather information about your thoughts on DRS.

Please write down the Name of your Agency:

____

Type of Agency:

a. State DOT
b. Equipment Vendor
c. Service Provider
d. Other (please describe)____

1. Do you think the DRS can help reduce the wrong-way driving incidents and accidents on freeways?

a. Not at all likely

b. Slightly likely

c. Moderately likely

d. Very likely

e. Completely likely

2. The following are some possible patterns and ideas for DRS. Please rate the appropriateness of models "a" through "e" in their potential to reduce wrong-way driving according to the scale below:

1 - Absolutely Inappropriate

2 - Inappropriate

3 - Slightly Inappropriate

4 - Neutral

5 - Slightly Appropriate

6 - Appropriate

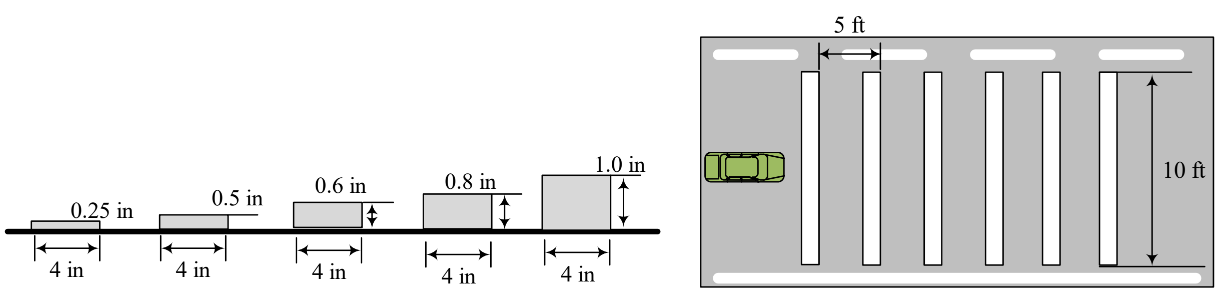
7 - Absolutely Appropriate

(a) _____

[redacted]

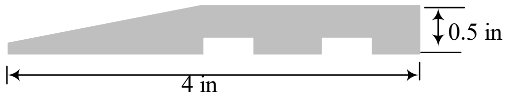
This design constitutes 12 right-angle triangle strips and has 5 ft of spacing between each strip. The left image shows the profile of a single strip. According to the image, if a car travels from left to right, the tire should gradually climb the strip and fall off the back side, making for a smoother ride as compared to traveling from right to left—where the tire will climb much more abruptly, creating dramatic sound and vibration for drivers.

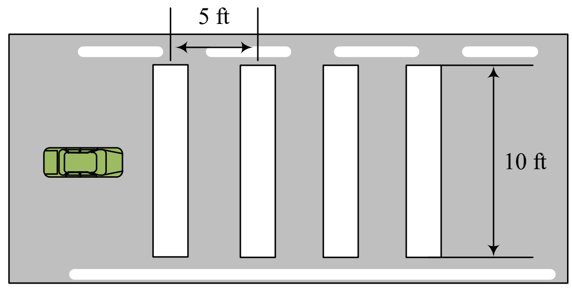
(b) _____



The removable rumble strips may function as the DRS. A 0.25-in. pavement marking strip is placed first and is followed by a 0.5-in. pavement marking strip. The height of the strips gradually increases to 1 in. by combining different thicknesses of tapes. A more aggressive pattern may be made to increase the haptic signals, such as stacking a 0.25-in. pavement marking strip on top of the 1-in. pavement marking strip. The strips in each set are 5 ft apart to generate the best variation in signals.

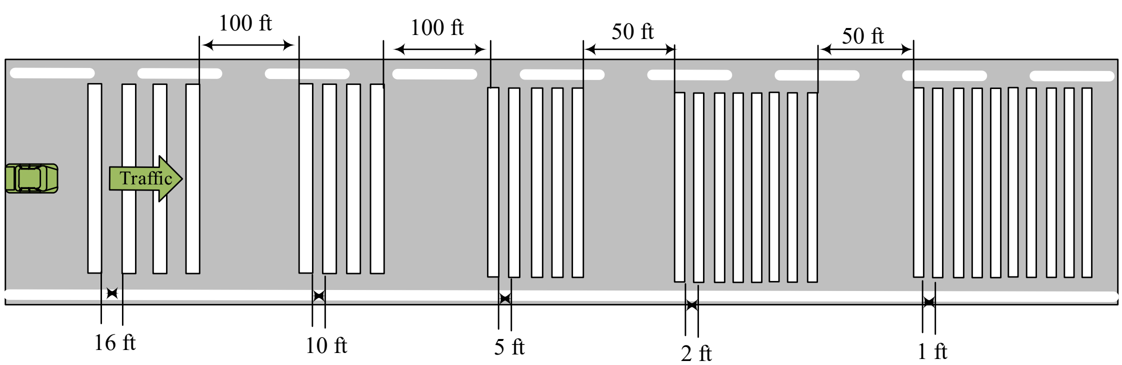
(c) _____





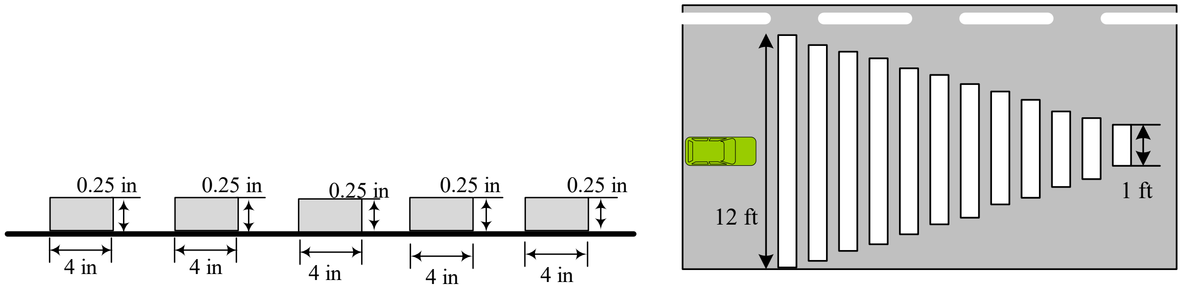
The raided wedge strips may offer audible and tactile signals of DRS. They feature a series of sound steps and a 90-degree drop-off at their trailing edges. The 20-degree angle enables a gradual climb, and the sound steps alert drivers to reduce speed when they travel in the right direction. The 90-degree edge makes it possible to create a more alarming feel for drivers traveling in the wrong direction. There are 4-6 rows of rumble strips across the traffic lanes, and they have 5 ft of spacing in order to make one long strip.

(d) _____



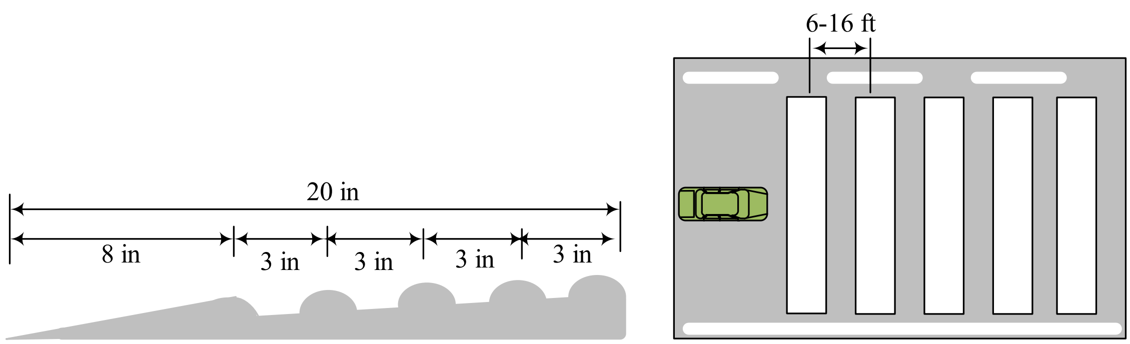
This concept attempts to create different audible and physical warnings by verified number of strips and spacing among them. For a right way driver, the sound and vibration inside the vehicle get gradual increase because of dense strips. While the wrong-way driver will first encounter a noticeable alarming and the warning gradually decrease along the road.

(e) _____



The specifically shaped rumble strip features a set of triangles that also provides visual effects. The length of the strips decreasing from 12 ft to 1 ft, and all strips are spaced at 1 ft. For the right way, the tires of the vehicle roll over the strips with decreasing length, and the directional arrow act as a guide sign. In the opposite direction, the drivers encounter the increasing strip length, and the arrow gives a visual warning to the wrong-way drivers.

(f)



(Reference: Lank C., Steinauer B. (2011). Increasing Road Safety by Influencing Drivers' Speed Choice with Sound and Vibration. Transportation Research Record: Journal of the Transportation Research Board, No. 2248, Transportation Research Board of the National Academies, Washington, D.C., pp. 45–52.)

This design is based on the model of Lank C. and Steinauer B. (2011). It consists of five strips with 6-16 ft of spacing along the driving direction. The width of each strip is 20 in. Two different components are installed on the angled panel. A raised wedge is about 8 in. in length, which provides a smooth transition for vehicles traveling in the right direction. This is followed by the application of four semicircular raised bands with a maximum height of 0.6 in. (or more) above the pavement. For the wrong-way drivers, the height and the suddenness of the raised bands could generate haptic warning signals.

3. Please rank the properties of the DRS based on your expectation of their potential to reduce wrong-way driving.

1 - Low Priority

2 - Low-Medium Priority

3 - Medium Priority

4 - Medium-High Priority

5 - High Priority

___ Optimum dimensions (e.g., length, width, depth, spacing)

___ Visual attentiveness (e.g., retro-reflecting properties and coloring)

___ Minimum level of stimuli (i.e., sound or vibration) necessary to alert inattentive drivers

___ Impact of sound produced by rumble strips on adjacent residents

___ Effect on pavement performance

___ Effect on maintenance activities

___ Accommodation to motorists' demands in adverse weather conditions, such as snow, fog, and rain

___ Others (please specify) ____

4. Does your agency have any product or applications that could work as the DRS for exit ramps?

a. Yes

b. No

5. Do you have any ideas or suggestions about the DRS? If available, please also provide materials you are going to use and the estimated cost.

Thank you for contributing to this important study aimed at developing practical designs of DRS, your time and effort will help to make our highways operate safer and more efficiently. Please contact Ms. Lingling Yang or Dr. Hugo Zhou if you have any questions:

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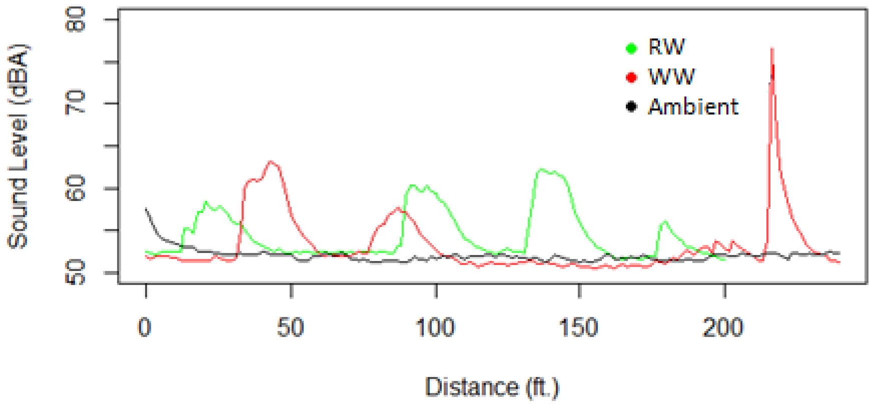
Phone: 408-705-7427

E-Mail: rzb0046@tigermail.auburn.edu

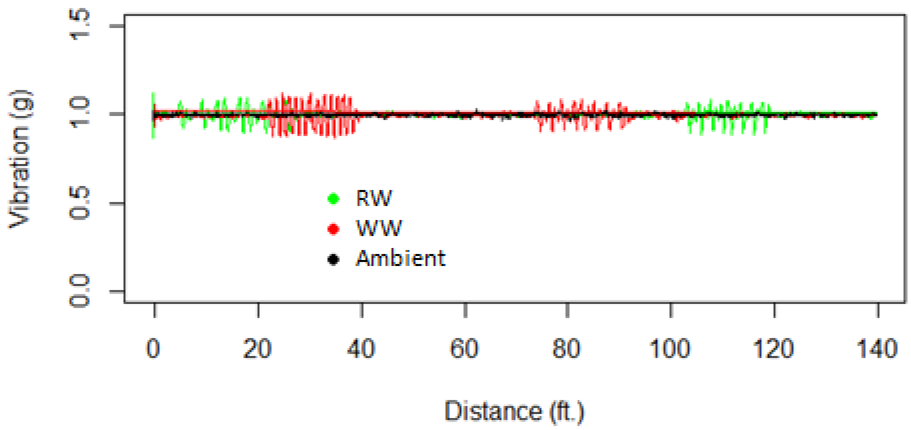
APPENDIX B
SOUND AND VIBRATION TEST RESULTS

Sound and Vibration Profile

Pattern C: Right-way and wrong-way signal profiles

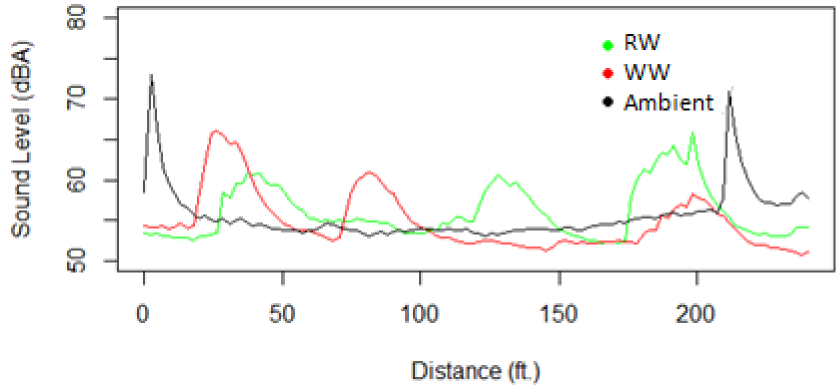


(a)

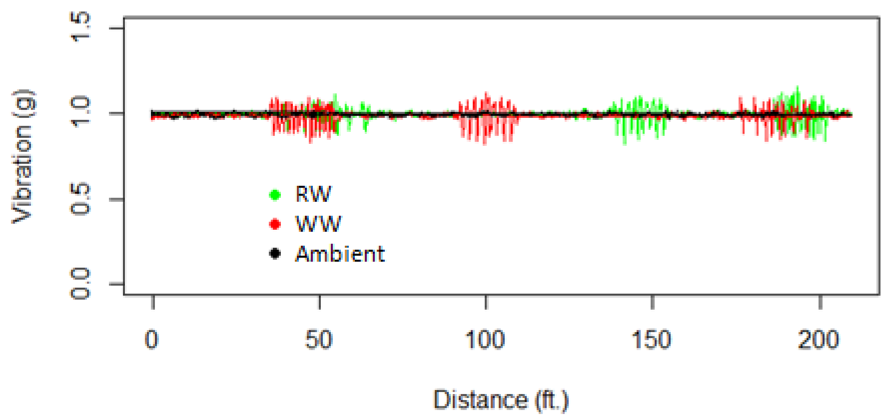


(b)

Figure B.1 Sound and Vibration Curve at 10 mph (a: sound, b: vertical vibration)

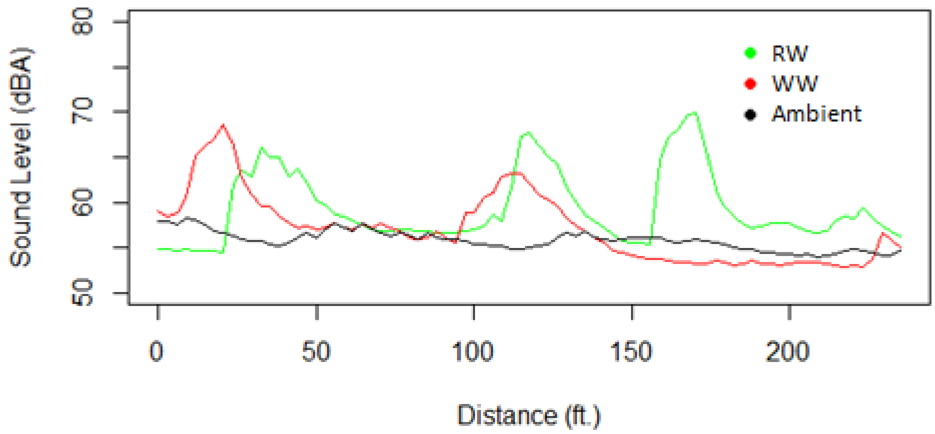


(a)

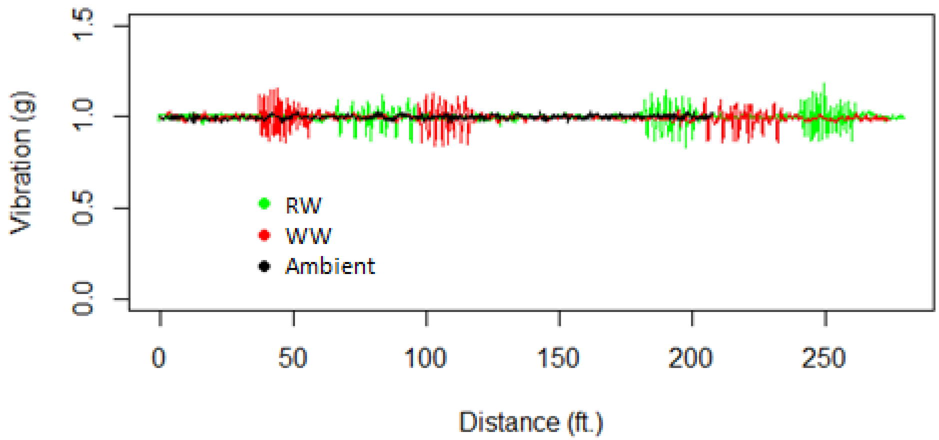


(b)

Figure B.2 Sound and Vibration Curve at 15 mph (a: sound, b: vertical vibration)

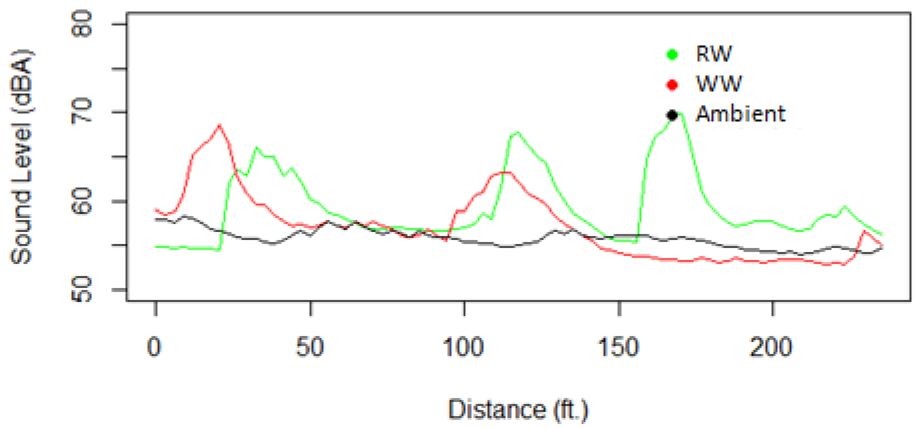


(a)

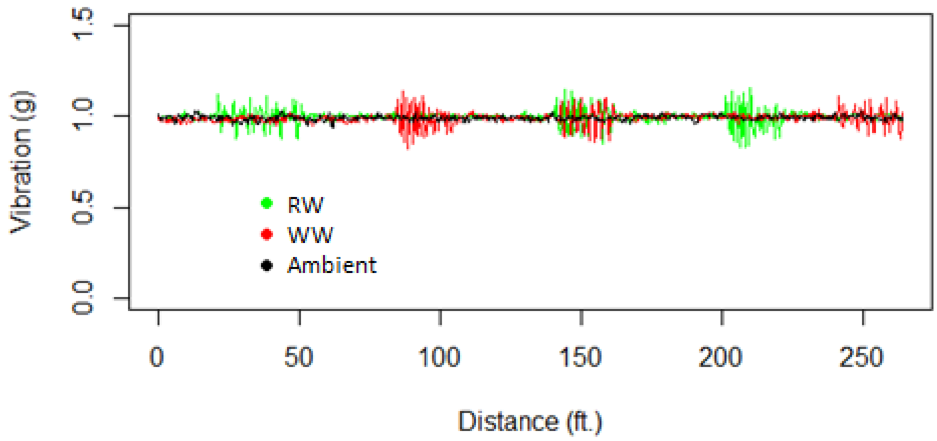


(b)

Figure B.3 Sound and Vibration Curve at 20 mph (a: sound, b: vertical vibration)

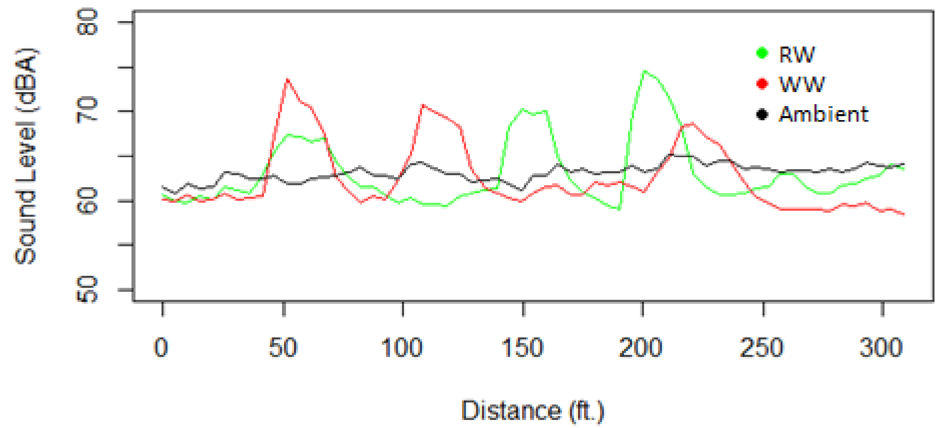


(a)

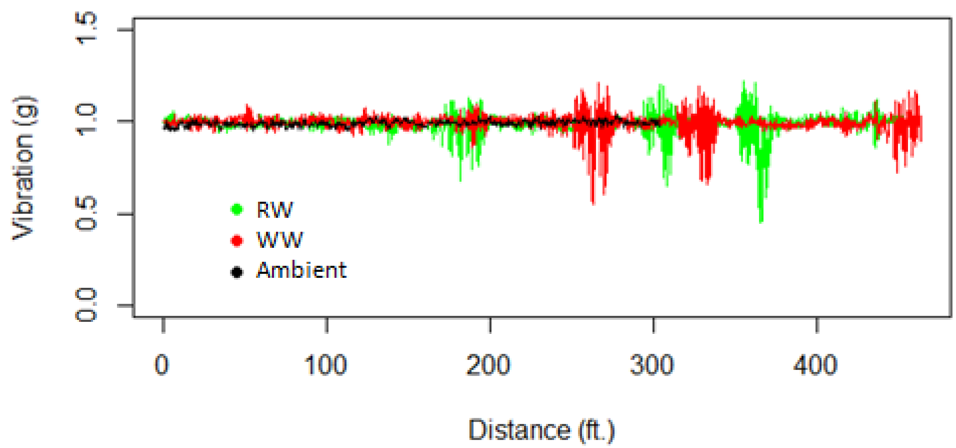


(b)

Figure B.4 Sound and Vibration Curve at 25 mph (a: sound, b: vertical vibration)

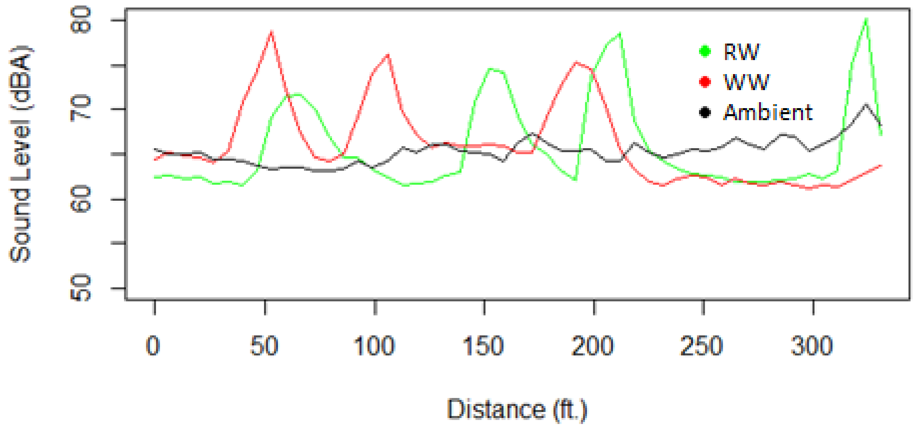


(a)

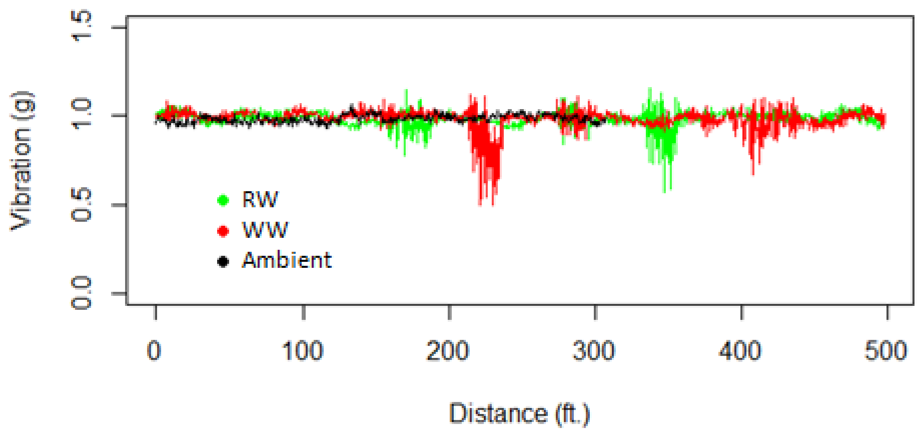


(b)

Figure B.5 Sound and Vibration Curve at 35 mph (a: sound, b: vertical vibration)



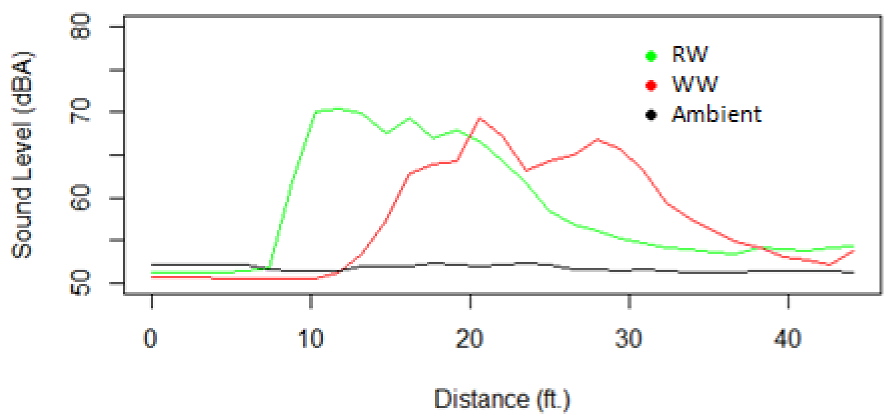
(a)



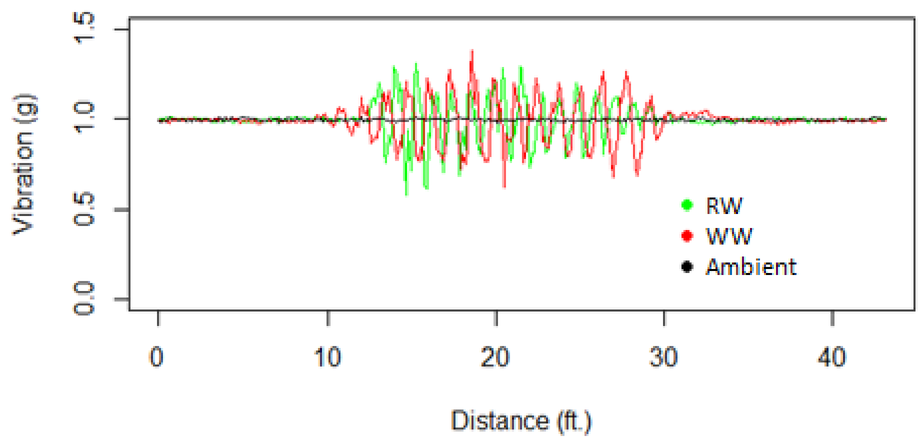
(b)

Figure B.6 Sound and Vibration Curve at 45 mph (a: sound, b: vertical vibration)

Pattern D Configuration 3: Right-way and wrong-way signal profiles

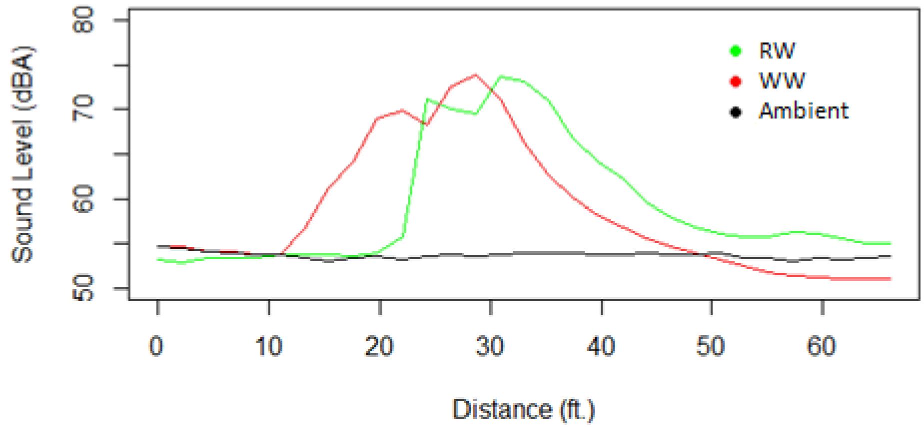


(a)

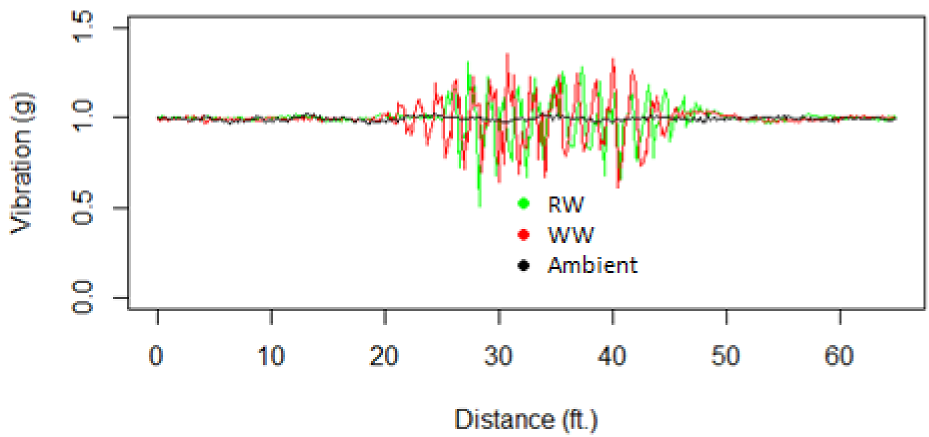


(b)

Figure B.7 Sound and Vibration Curve at 10 mph (a: sound, b: vertical vibration)

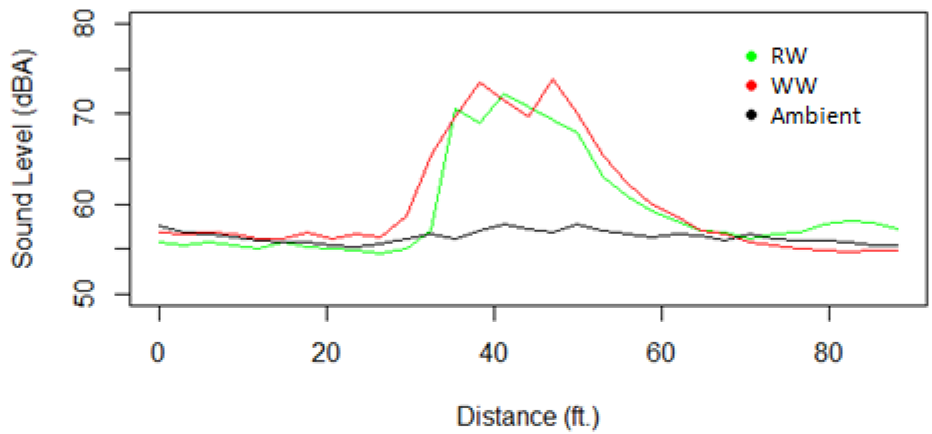


(a)

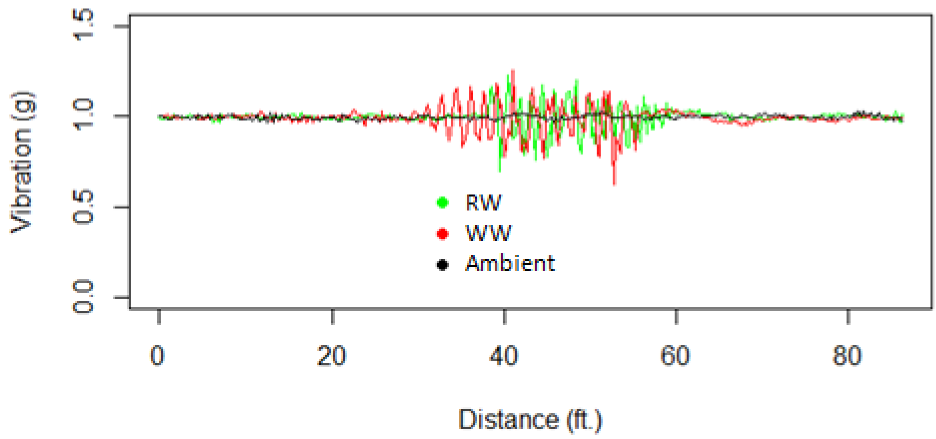


(b)

Figure B.8 Sound and Vibration Curve at 15 mph (a: sound, b: vertical vibration)

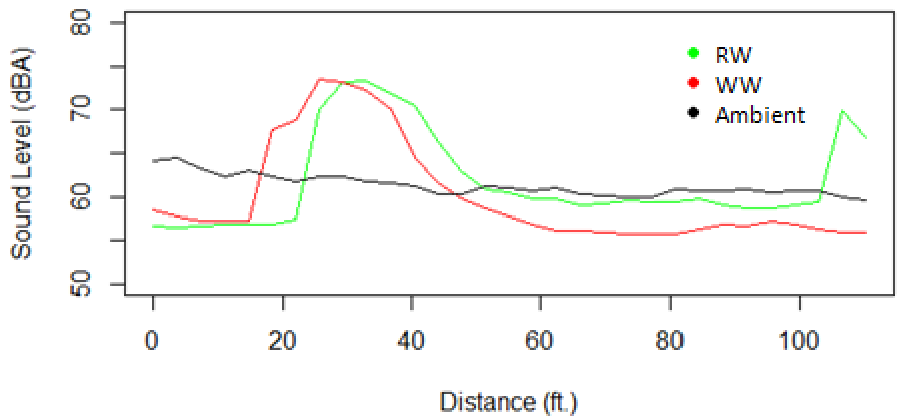


(a)

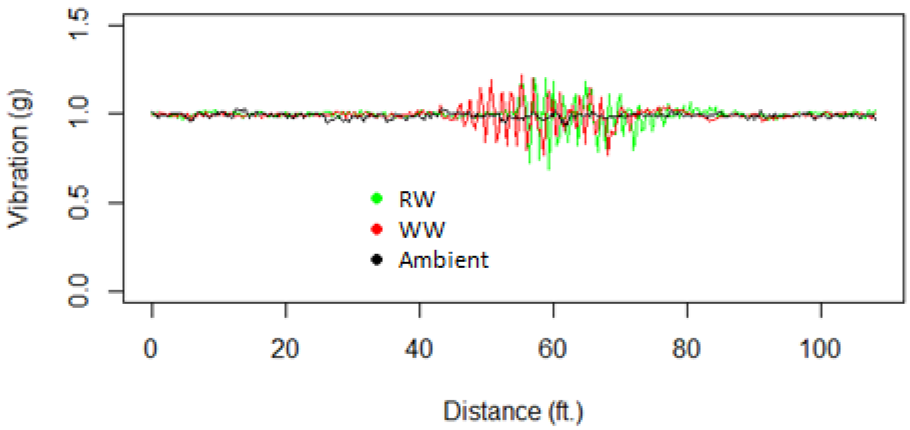


(b)

Figure B.9 Sound and Vibration Curve at 20 mph (a: sound, b: vertical vibration)

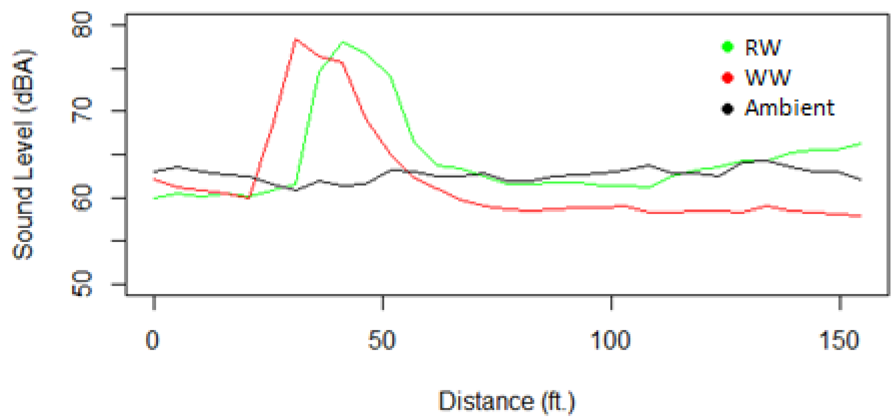


(a)

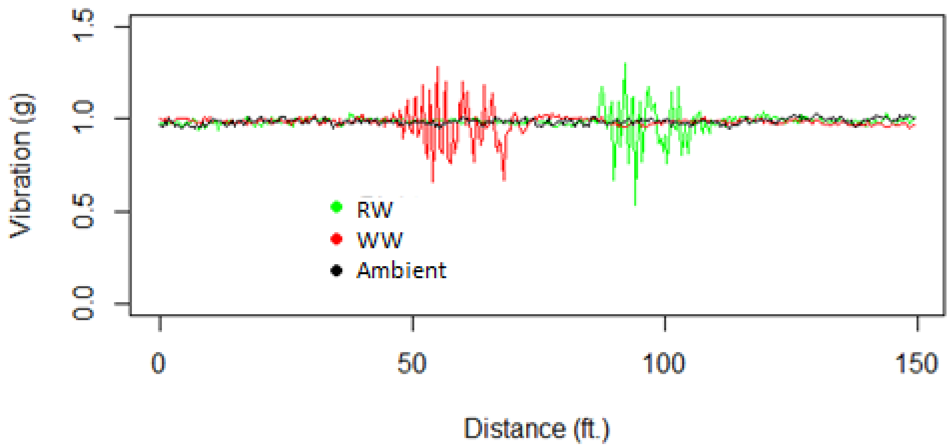


(b)

Figure B.10 Sound and Vibration Curve at 25 mph (a: sound, b: vertical vibration)

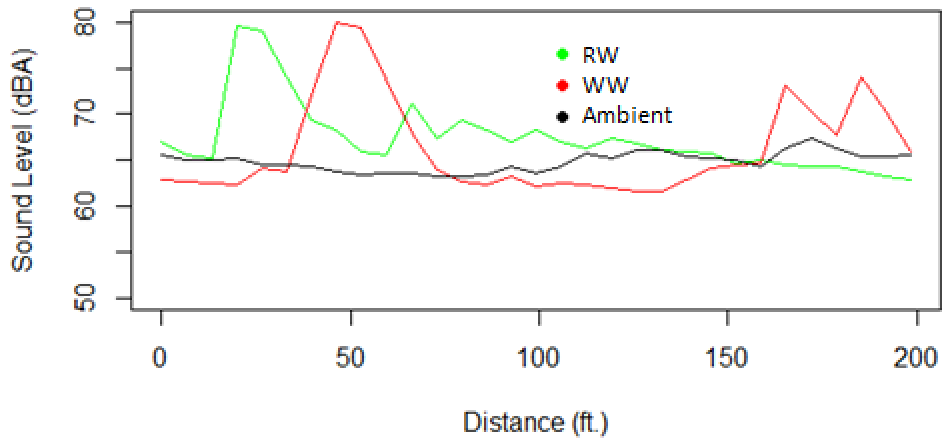


(a)



(b)

Figure B.11 Sound and Vibration Curve at 35 mph (a: sound, b: vertical vibration)



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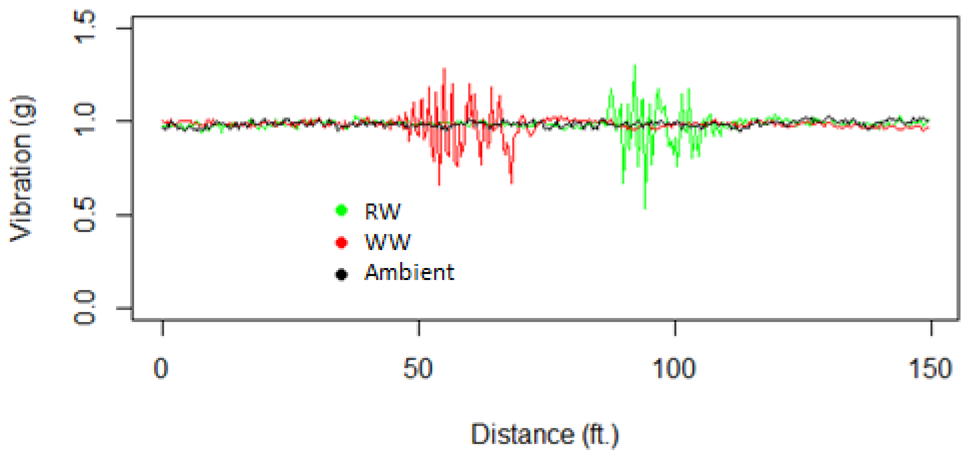
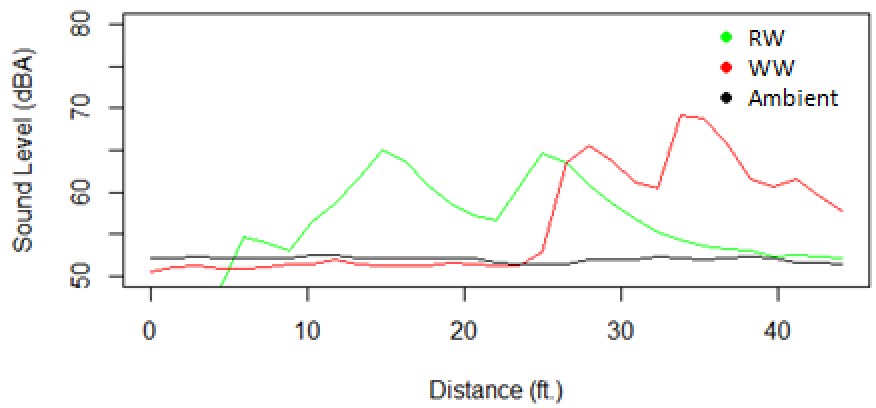


(b)

Figure B.12 Sound and Vibration Curve at 45 mph (a: sound, b: vertical vibration)

Pattern E: Right-way and wrong-way signal profiles



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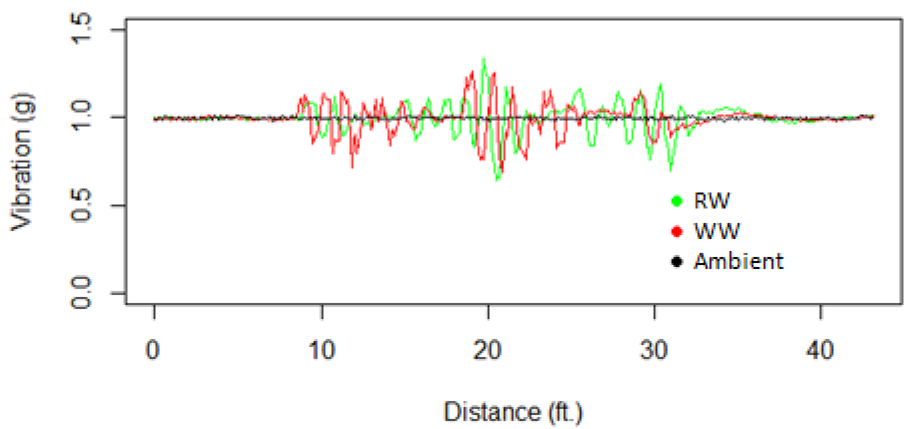
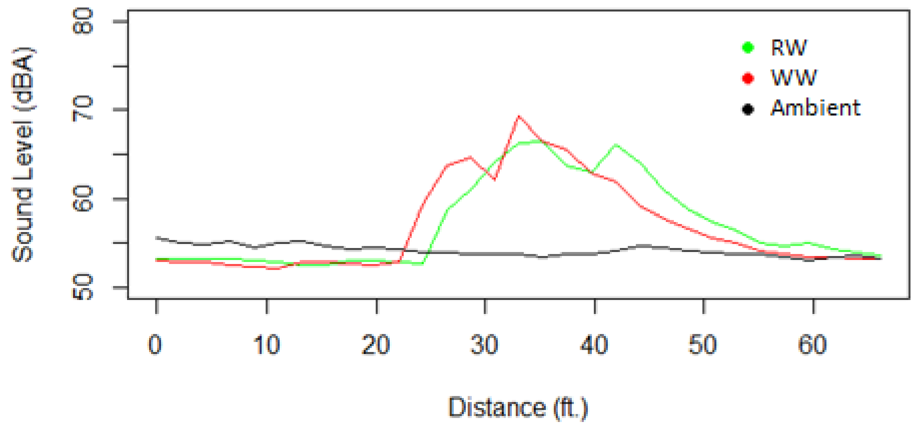


(b)

Figure B.13 Sound and Vibration Curve at 10 mph (a: sound, b: vertical vibration)



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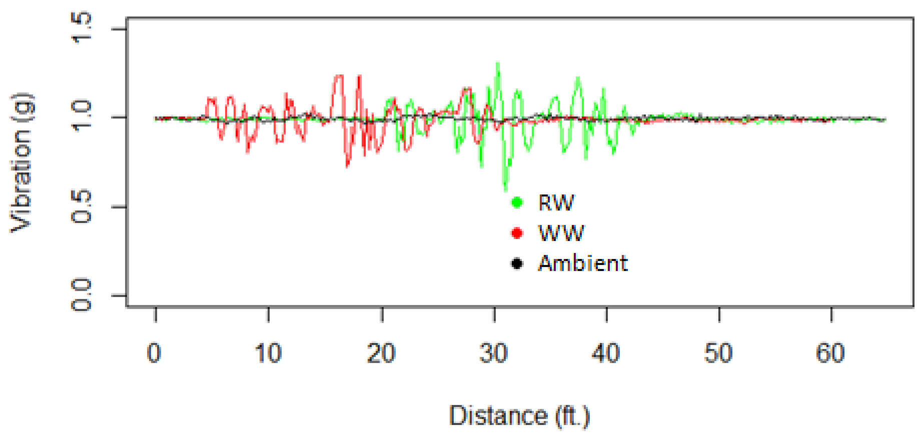
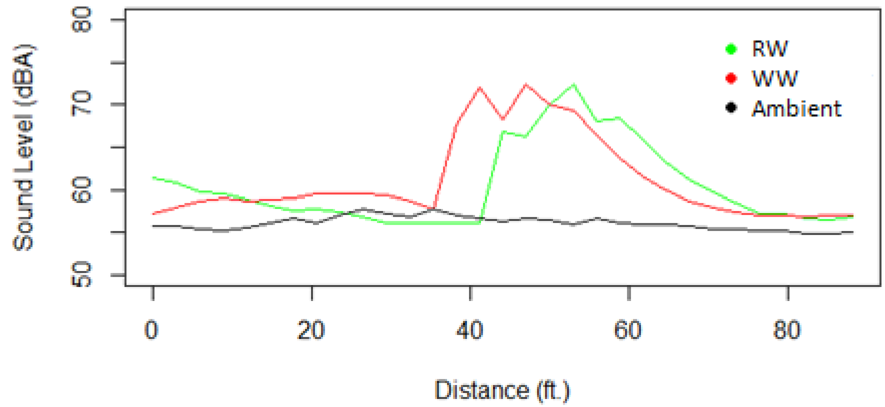
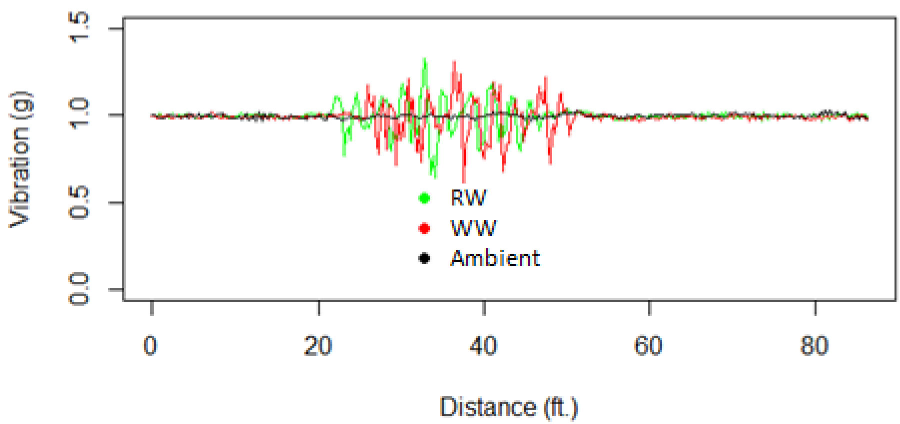


(b)

Figure B.14 Sound and Vibration Curve at 15 mph (a: sound, b: vertical vibration)

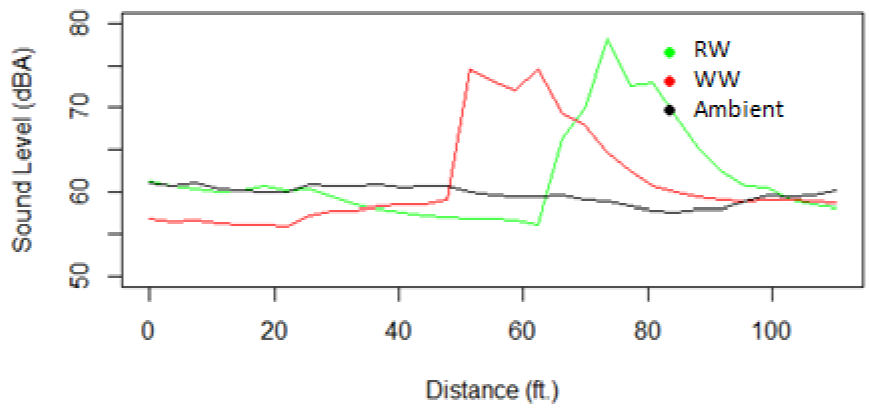


(a)

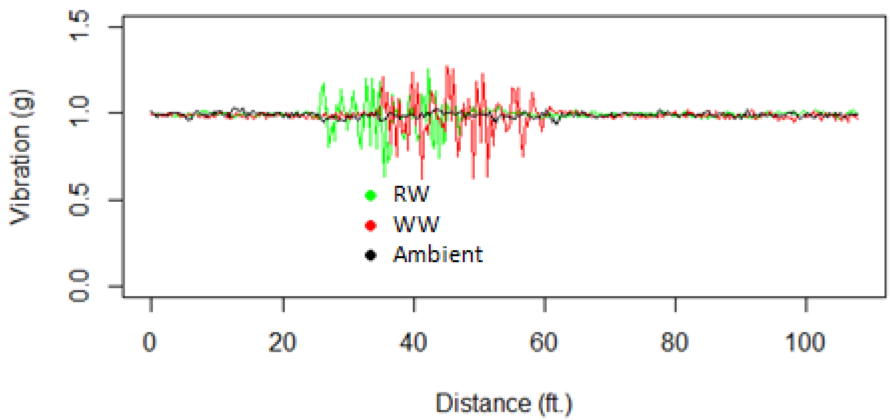


(b)

Figure B.15 Sound and Vibration Curve at 20 mph (a: sound, b: vertical vibration)

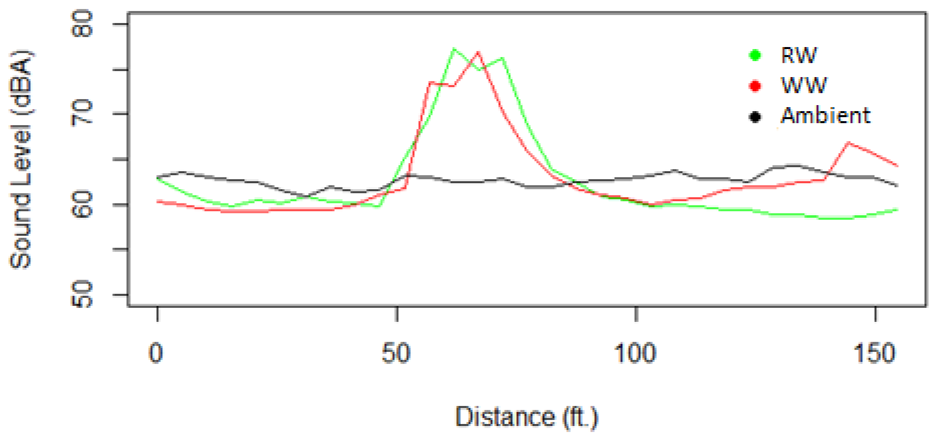


(a)



(b)

Figure B.16 Sound and Vibration Curve at 25 mph (a: sound, b: vertical vibration)



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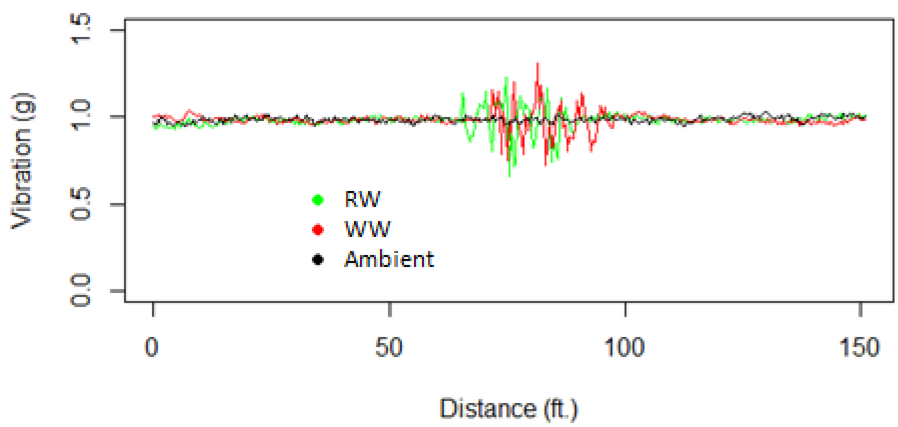
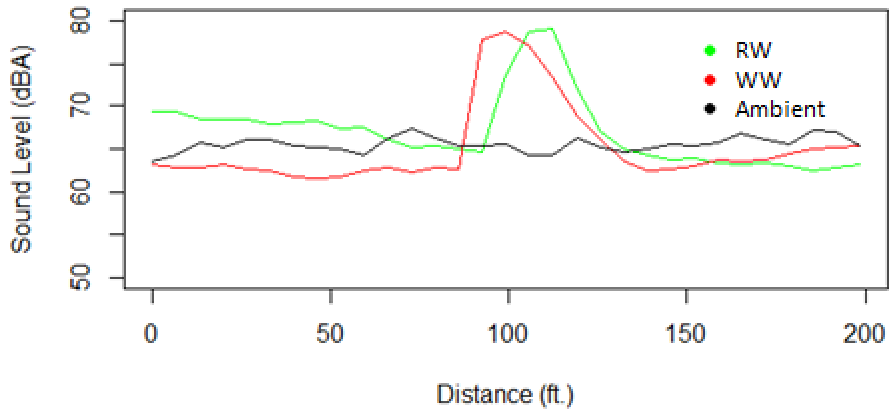
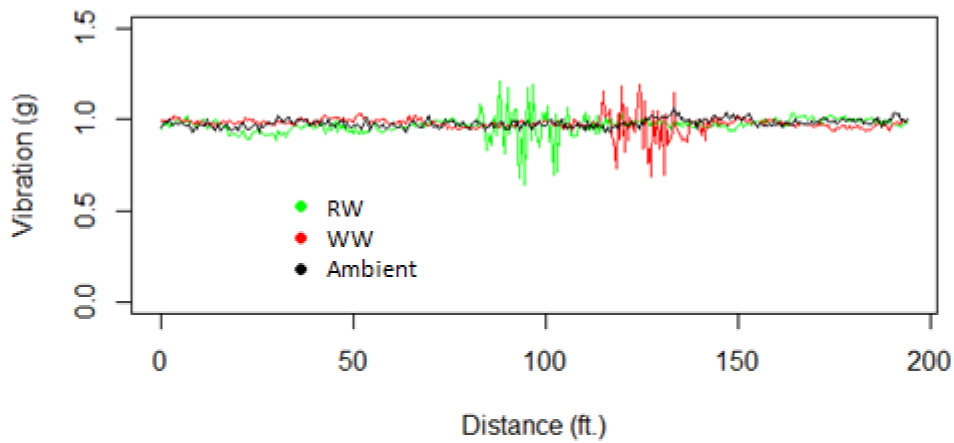


(b)

Figure B.17 Sound and Vibration Curve at 35 mph (a: sound, b: vertical vibration)



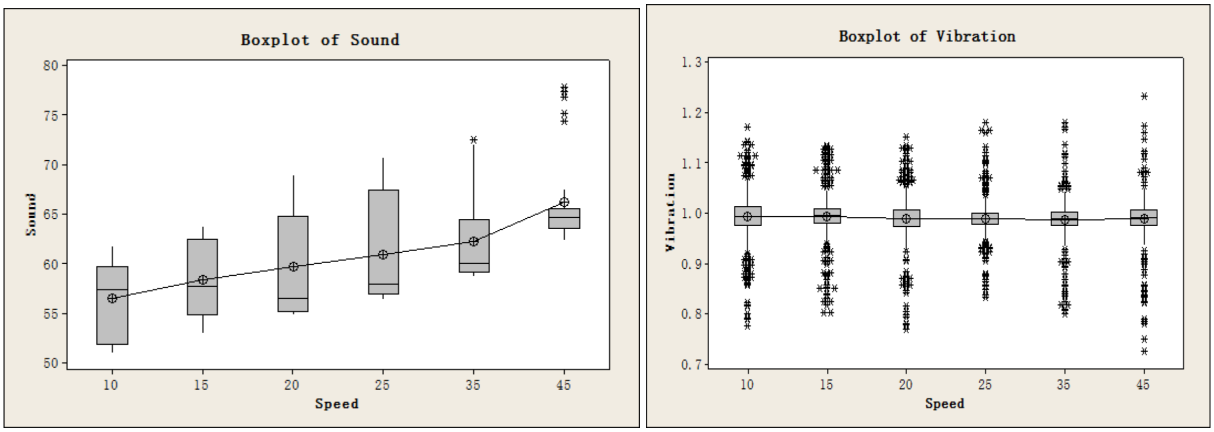
(a)



(b)

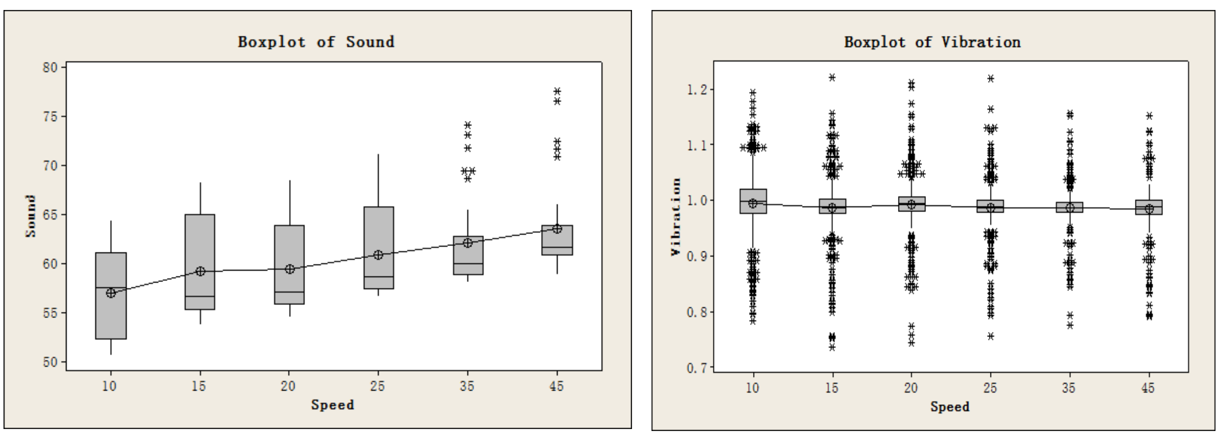
Figure B.18 Sound and Vibration Curve at 45 mph (a: sound, b: vertical vibration)

Speed test using Minitab



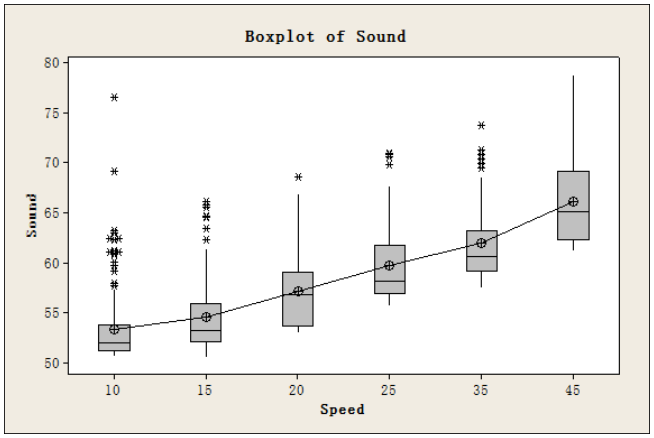
(a) (b)

Figure B.19 Sound level and vibration vs. Speed for Pattern B Configuration 1 (a: sound, b: vibration)

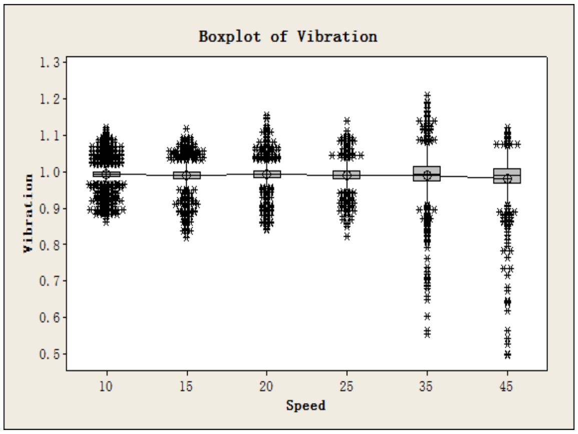


(a) (b)

Figure B.20 Sound level and vibration vs. Speed for Pattern B Configuration 3 (a: sound, b: vibration)

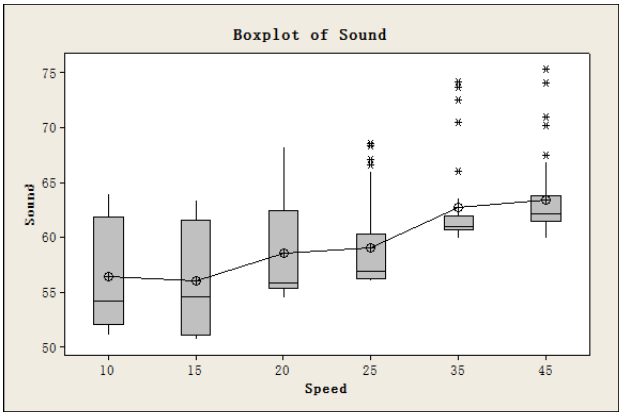


(a)

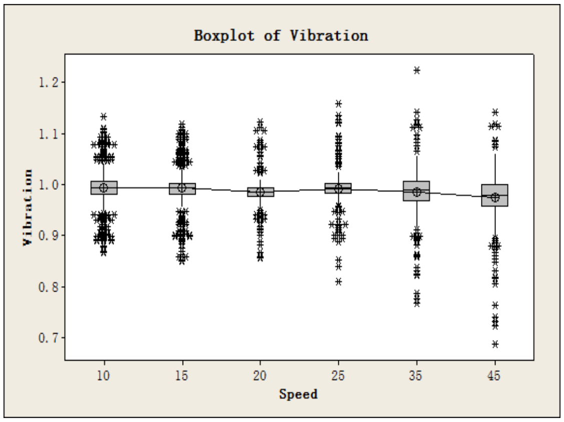


(b)

Figure B.21 Sound level and vibration vs. Speed for Pattern C (a: sound, b: vibration)

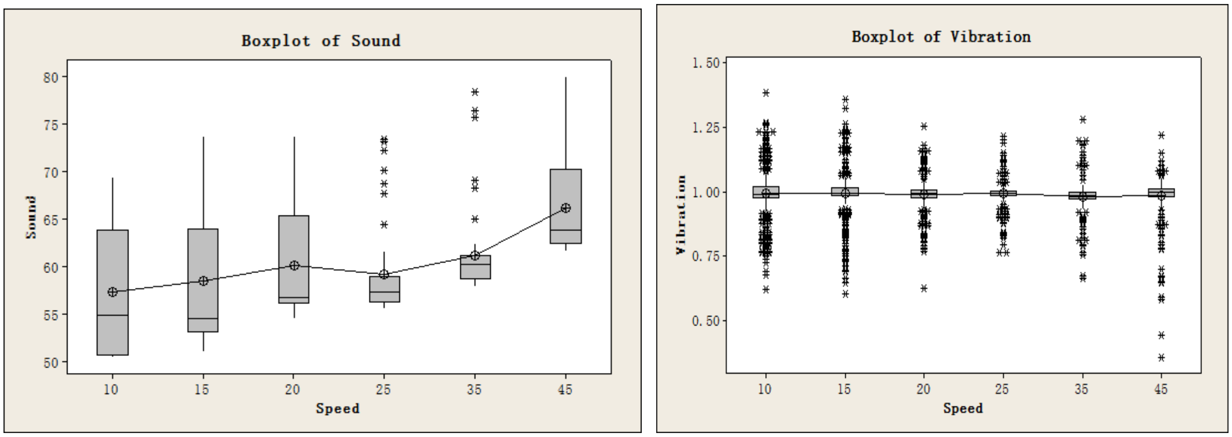


(a)



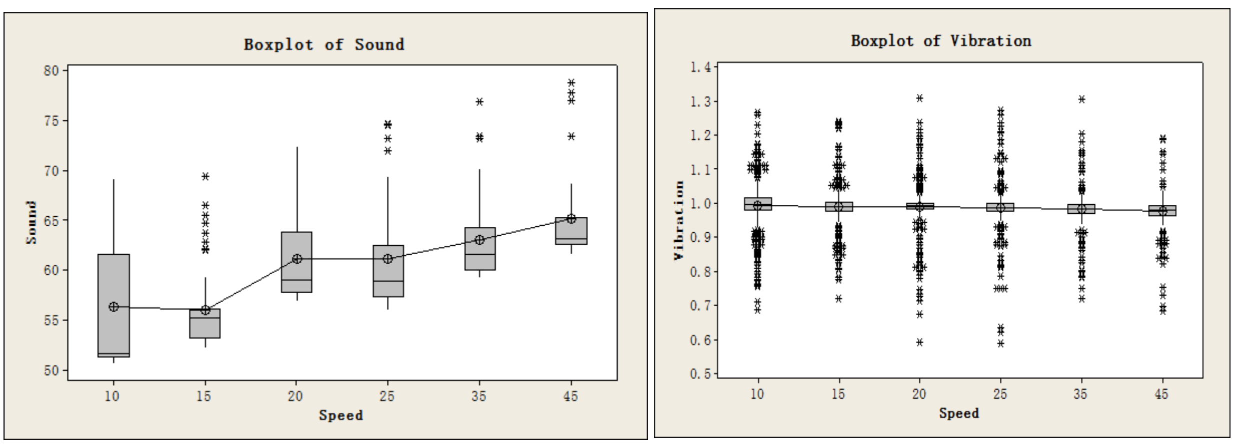
(b)

Figure B.22 Sound level and vibration vs. Speed for Pattern D Configuration 2 (a: sound, b: vibration)



(a) (b)

Figure B.23 Sound level and vibration vs. Speed for Pattern D Configuration 3 (a: sound, b: vibration)



(a) (b)

Figure B.24 Sound level and vibration vs. Speed for Pattern E (a: sound, b: vibration)

APPENDIX C
TYPICAL A-WEIGHTED SOUND LEVEL

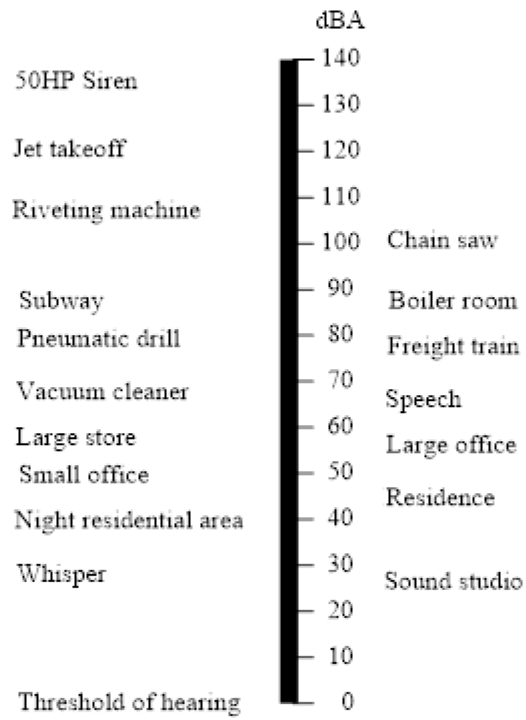


Figure C.1 Typical A-weighted sound level