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

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Final Report



CTS 19-25

Technical Report Documentation Page

1. Report No. CTS 19-25		2.		3. Recipients Accession No.	
4. Title and Subtitle Directional Rumble Strips for Reducing Wrong-Way-Driving Freeway Entries			5. Report Date July 2019		
			6.		
7. Author(s) Albert C.J Luo, Chuan Guo, Siyuan Xing, Yeyin Xu, Siyu Guo and Chuanping Liu			8. Performing Organization Report No.		
9. Performing Organization Name and Address Department of Mechanical and Industrial Engineering 2036 Engineering Building Southern Illinois University Edwardsville Edwardsville, IL 62026-1805			10. Project/Task/Work Unit No. CTS Project 2018071		
			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 evaluation results of directional rumble strips (DRS) designed to deter wrong-way (WW) freeway entries. Mathematical models have been built to identify high-risk locations of WWD. Based on the model, one off-ramp, exit 41 northbound on I-70 was found to have a WW entry probability of 55%. 96 hours of video data were recorded at the chosen off-ramp. Then one pattern of DRS (D3) was implemented on the chosen location with the help of the Illinois Department of Transportation (IDOT). Sound and vibration data were recorded and compared between RW and WW directions for speed ranging from 15 mph to 30 mph. Another 96 hours of video data were recorded after the implementation. The analysis of before and after implementation data showed that the DRS cannot reduce the probability of WWD, but it can warn WW drivers and reduce their speed, which will significantly reduce WWD accidents.					
17. Document Analysis/Descriptors Rumble strips, Sound, Vibration, Wrong way driving, Highway safety, Data analysis			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 33	22. Price

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July 2019

Published by:

Roadway Safety Institute

Center for Transportation Studies

University of Minnesota

200 Transportation and Safety Building

511 Washington Ave. SE

Minneapolis, MN 55455

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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 Jeffrey Abel, the traffic operations engineer at the Illinois Department of transportation (IDOT) Region Five District 8, for arranging the field implementation at northbound off-ramps at Exit 41 on I-70, in Illinois.

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LIST OF ABBREVIATIONS

DOT	Department of Transportation
DRS	Directional Rumble Strips
RW	Right-Way
TRS	Transverse Rumble Strips
WW	Wrong-Way
WWD	Wrong-Way Driving
RWD	Right-Way Driving
AADT	Annual Average Daily Traffic

EXECUTIVE SUMMARY

This report presents evaluation results of directional rumble strips (DRS) designed to deter wrong-way (WW) freeway entries. DRS was proposed based on state DOT design guidelines, current practices, and feedback from a national survey. The DRS is expected to generate elevated sound and vibration for wrong-way driving (WWD) and normal levels of sound and vibration for right-way (RW) traffic on off-ramps.

Mathematical models have been built to identify high-risk locations of WWD. The geometric design features, use of traffic control devices, area type where interchanges are located, and annual average daily traffic (AADT) at exit ramp terminals with or without a history of WWD were used as potential predictors of WW entry. Based on the model, the WWD probability of main highway off-ramps in Illinois were identified. The results show that most off-ramps in Illinois were well designed and had a relatively low probability (less than 20%) of WWD. One off-ramp, Exit 41 northbound on I-70 was found to have a WW entry probability of 55%. The main reason for the high probability was that the exit ramp's annual average daily traffic (AADT) was only 75 while the entrance ramp's AADT was 1450. Also, the nearest entrance of the other roads was too close to the off-ramp, increasing the probability that drivers would choose a wrong way.

After identifying the high-risk location of WWD, a total of 96 hours of video data were recorded on the chosen off-ramp. From the video data, two cases of WWD behavior were observed. The drivers chose the wrong way to enter the highway, but they noticed the situation before the "Wrong Way" sign and turned back. The results matched the previous analysis that showed the chosen off-ramp had a high-risk of WWD because of the complex road condition, but the well-designed traffic signs prevented wrong way drivers from going farther into the ramp.

One pattern of DRS (D3) was implemented on the chosen location with the help of the Illinois Department of Transportation (IDOT). Each strip of Pattern D Configuration 3, which was modified from the advanced warning markings for speed humps, has both an increasing thickness and an increasing length. The D3 DRS was implemented at the stop bar to warn WW drivers with sound and vibration.

Sound and vibration data were recorded and compared between RW and WW directions for speed ranging from 15 mph to 30 mph. The results showed that at 25 mph, WW drivers could create much higher sound and vibration than RW drivers. The difference between sound and vibration for RW and WW drivers decreased with a reduction in speed.

Another 96 hours of video data were recorded after the implementation. There were no significant changes at the ramp terminal after implementing Pattern D3 since the DRS was implemented just at the stop bar, which means drivers would slow down before they passed the DRS. One case of WW behavior was observed in which the driver went in the wrong direction and imminently noticed it when passing the DRS. The analysis of before and after implementation data showed that the DRS cannot reduce the probability of WWD, but it can warn WW drivers and reduce their speed, which will significantly reduce WWD accidents.

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. The further field verification of these three patterns was conducted in 2017 to evaluate the effectiveness of the three recommended DRS patterns. Based on verification results and the study of chosen location, a final DRS design pattern (Pattern D3) was selected for field implementation. This work focused on wrong-way driving in Illinois; previous related work was conducted in Alabama at Auburn University.

1.2 STUDY OBJECTIVES

The objectives of this study were to

- Identify high-risk locations of WWD incidents
- Analyze speed and driver behavior at the chosen location
- Implement the DRS chosen location with the help of the Illinois Department of Transportation (IDOT)
- Develop the general implementation guidelines for the recommended DRS

CHAPTER 2: MATHEMATICAL MODEL STUDY

2.1 MATHEMATICAL MODEL

In 2018, Md Atiquzzaman and Huaguo Zhou built a mathematical model of exit ramp terminals of full diamond interchanges and partial cloverleaf interchanges. The geometric design features, use of traffic control devices, area type where the interchanges located, and annual average daily traffic (AADT) at the exit ramp terminals with or without history of WWD were used as potential predictors of WW entry. Transportation agencies can use these models to assess the risk of WW entries at the exit ramp terminals within their jurisdictions and consider possible countermeasures. They can also be applied during the design phase to determine the combination of geometric design features and traffic control devices that ensures the least possibility of WW entry.

2.2 WRONG-WAY DRIVING PROBABILITY

To identify the wrong-way driving probability of highway off-ramps in Illinois, the research team examined 10 off-ramps of each main highways in Illinois using the mathematical model. The results showed that most highway off-ramps in Illinois were well designed with median, non-traversable channelizing island, “Wrong WAY” arrow and “WRONG WAY” sign. Major highways in Illinois, such as I-55, I-70, I-74, I-72, I-57, I-80, I-39, I-255, I-270 and I-64 have an average probability of WWD less than 20%.

There were still several off-ramps with relative high-risk of WWD. Exit 41 northbound on I-70 was found to have a 55% probability of WWD. Fig. 2.1 shows the off-ramp and crossroad of Exit 41 northbound on I-70. The crossroad, Millersburg Ave, does not have median, which would increase the probability of WWD. The W City Rte 40 is very close to the Exit, so left-turning drivers may choose the wrong way. Furthermore, the AADT of the exit-ramp is only 75 while the entrance-ramp have an AADT of 1450, which means most of the time there are no traffic on exit-ramp.

The above situations cause the Exit 41 northbound on I-70 have a high-risk of WWD than other off-ramps. But the IDOT have noticed it and placed 4 WRONG WAY signs and a DO NOT ENTER sign (as shown in Fig. 2), these efforts will significantly stop WWD drivers from driving further in the wrong direction.

Based on the study of the mathematical model and the situation of the off-ramps, the research team decided to choose Exit 41 northbound on I-70 as the field implementation test location.



Figure 2.1 Interchange terminal of Exit 41 northbound on I-70.



Figure 2.2 Traffic Control Signs at Exit 41 northbound on I-70.

CHAPTER 3: DIRECTIONAL RUMBLE STRIP IMPLEMENTATION

3.1 PRE-TESTING STUDY

Before setting the implementation plan, the research team studied the traffic condition at Exit 41 northbound on I-70 from video data. A COYNTcam2 camera was installed on a traffic sign near the interchange terminal from April 9th to 14th, 2019. According to a total of two hundred random trips, the average RW vehicle speed was 15.4 mph when they were approaching the off-ramp terminal. The average speed on the crossroad when approaching the terminal was 30.45 mph. During the 96 hours recording period, only 2 cases of WWD behavior were observed by the research team, but no WWD accident was observed. The observed WWD behaviors all happened at night when the surrounding was dark. The WW drivers noticed their mistake before the first WRONG WAY sign and turned back.

The video data matched with the analysis in Chapter 2, so the research team decided to choose this off-ramp terminal for the implementation of DRS.



Figure 3.1 Camera Setup at Exit 41 Northbound on I-70.

3.2 IMPLEMENTATION PLAN

Based on the mathematical model study and the actual video data, WWD incident at the off-ramp of Exit 41 northbound on I-70 only happened near the crossroad. WW drivers will notice their WWD behavior before the first WRONG WAY sign and turned back. Then the purpose of the DRS is to remind the drivers. So DRS Pattern D3 was selected to be installed just at the stop bar of the exit-ramp. The Pattern D3 had 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 was equally 0.25 in. The rest strips had the same thickness of 0.5 in. Vehicles passing the DRS will generate sound and vibration, which will remind the drivers that they have gone the wrong direction.

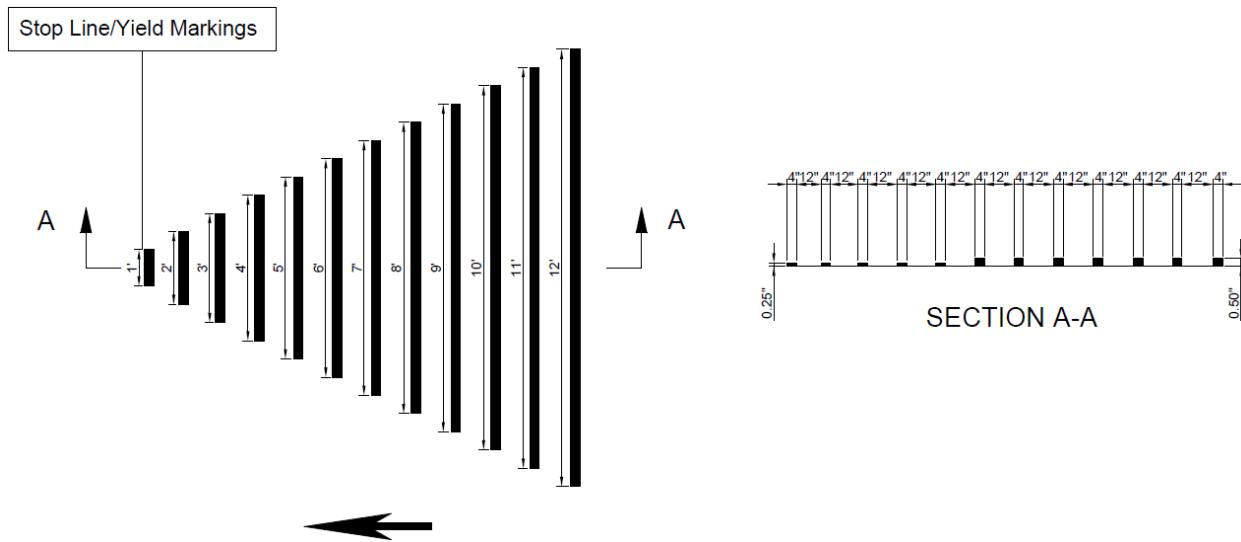


Figure 3.2 DRS Pattern D3 implementation design.

3.3 FIELD IMPLEMENTATION

After confirming the implementation plan, the research team contacted IDOT for traffic control and road construction permit at Exit 41 northbound on I-70. With the help of Engineers from IDOT Region Five District 8, the implementation work started on April 19th, 2019. Two sets of DRS Pattern D3 were implemented immediately after the stop bar at the exit-ramp. 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.



Figure 3.3 Field photos of DRS patterns.

CHAPTER 4: FIELD TEST RESULTS

4.1 EQUIPMENT AND MEASUREMENT

Sound and vibration inside the vehicle were measured by a SUV (Jeep Patriot). The acoustic signature was recorded by an iTestMic with the Audio Tools. The vibration data was recorded using a PCB ICP Sensor, the data then filtered by a PCB ICP SENSOR SIGNAL CONDITIONER to the DAQ. Another 96 hours video was recorded by the COUNTcam2 to observe the traffic behavior after implementation of DRS.

The sound-level meter was located at an average driver’s ear height, and the 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 SigmaPlot 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) iTestMic



(b) PCB ICP Sensor and signal conditioner



(c) DAQ

Figure 4.1 Sound level meter (a), accelerometer (b) and DAQ (c)

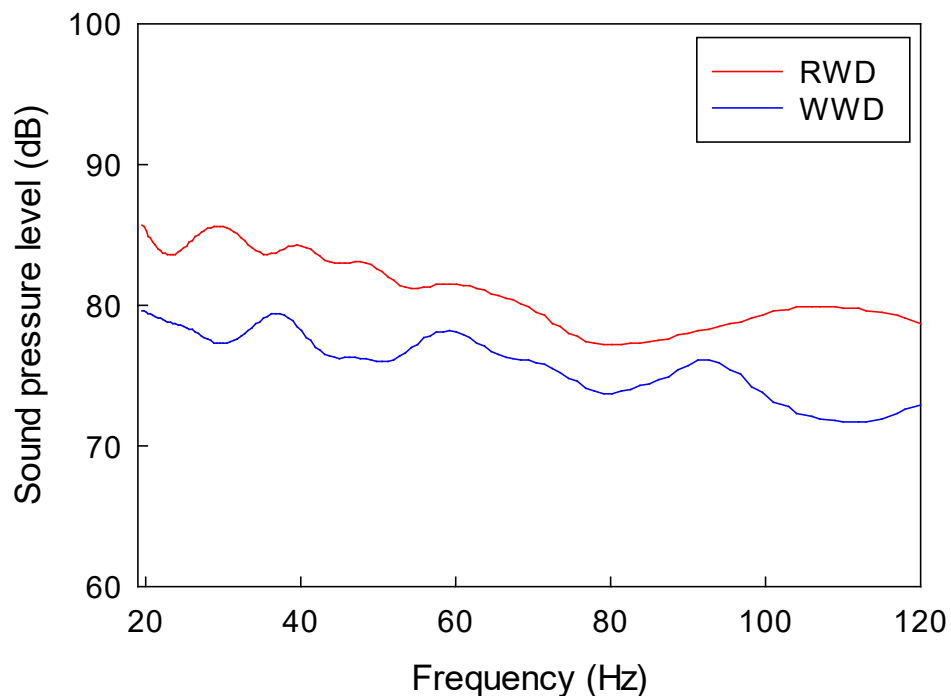
4.2 SOUND TEST RESULTS

The interior sound levels in dB were recorded and compared between RW and WW directions for speed of 15 mph, 20 mph, 25 mph and 30 mph. During the test, the team members in the testing vehicle can hear the noise created by driving through the DRS clearly. The sound test results were collected directly from iTestMic in frequency domain and shown in Fig. 4.2 (a) to (d).

It was found that at 15 mph, the average sound created by RWD and WWD was almost flat in frequency domain with an average of 82 dB for RWD and 76.6 dB for WWD. At 20 mph, the sound for WWD and RWD when driving through the DRS were almost the same, and the average sound level was 78 dB. In addition, the waveform are also similar.

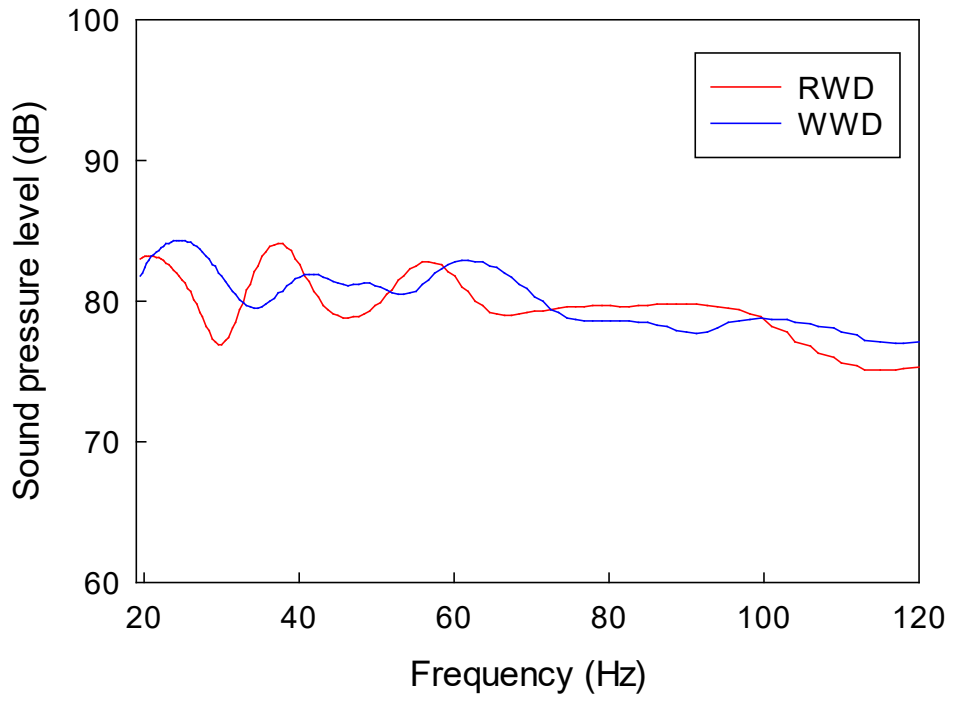
At 25 mph, the average sound pressure level created by WWD, which was 80 dB, was significantly higher than RWD, which was 60 dB. Compared to low-speed cases, the wave was no longer flat, it had a peak at around 26 Hz with the sound level of 90 dB for WWD and 73 dB for RWD.

At 30 mph, the average sound pressure level created by WW vehicles was 80 dB and the average sound pressure level created by RW vehicles was 76 dB. The peak value was also in 26 Hz, same with 25 mph, while the peak values were 87 dB for WWD and 85 dB for WWD.

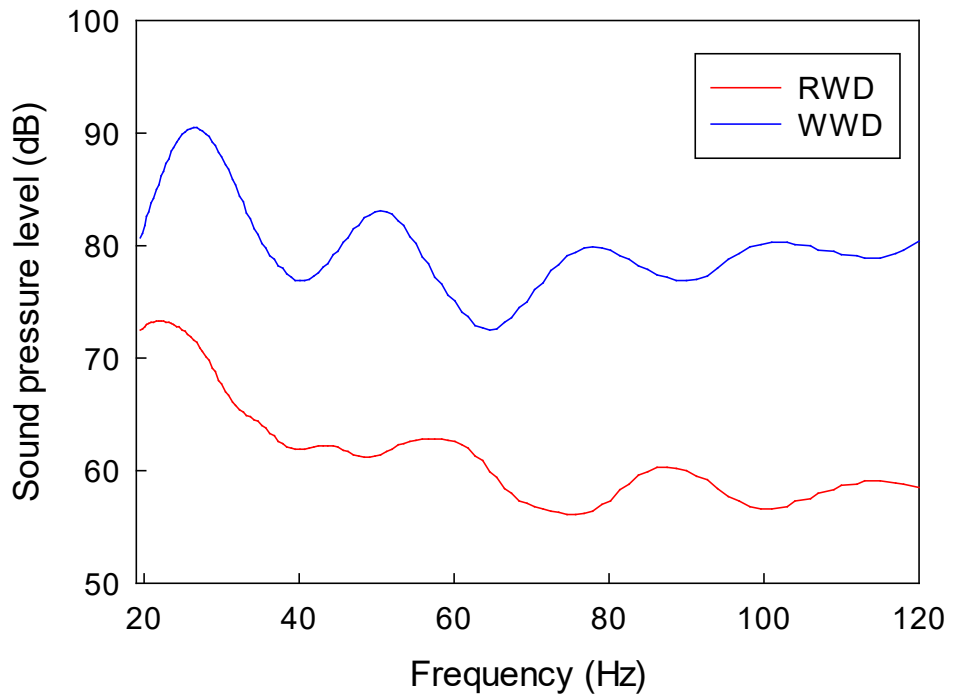


(a)

Figure 4.2 Sound test results: (a) 15 mph, (b) 20 mph, (c) 25 mph and (d) 30mph.

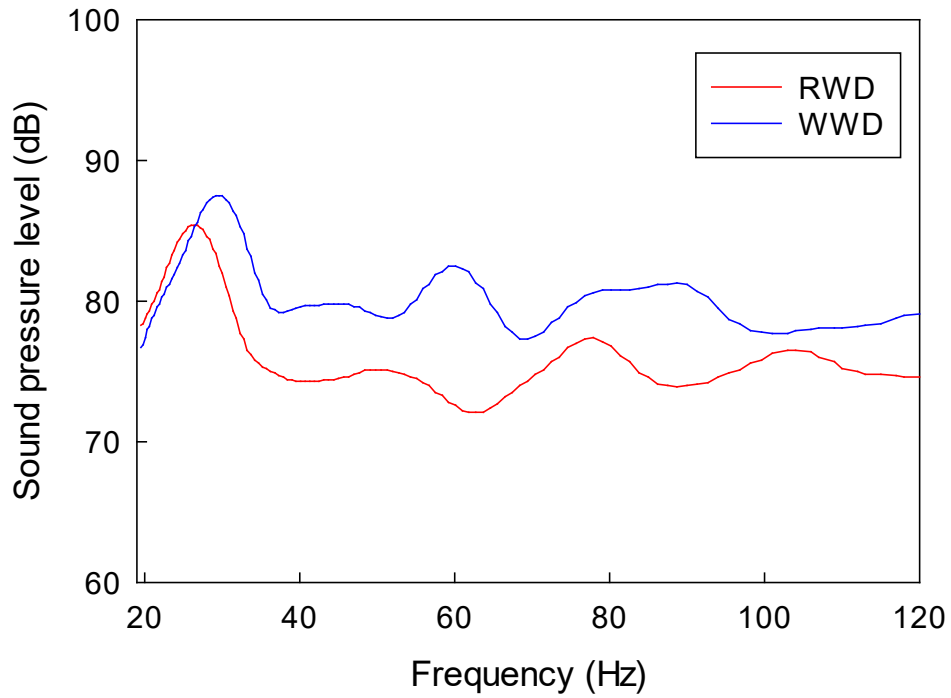


(b)



(c)

Figure 4.2 Continued.

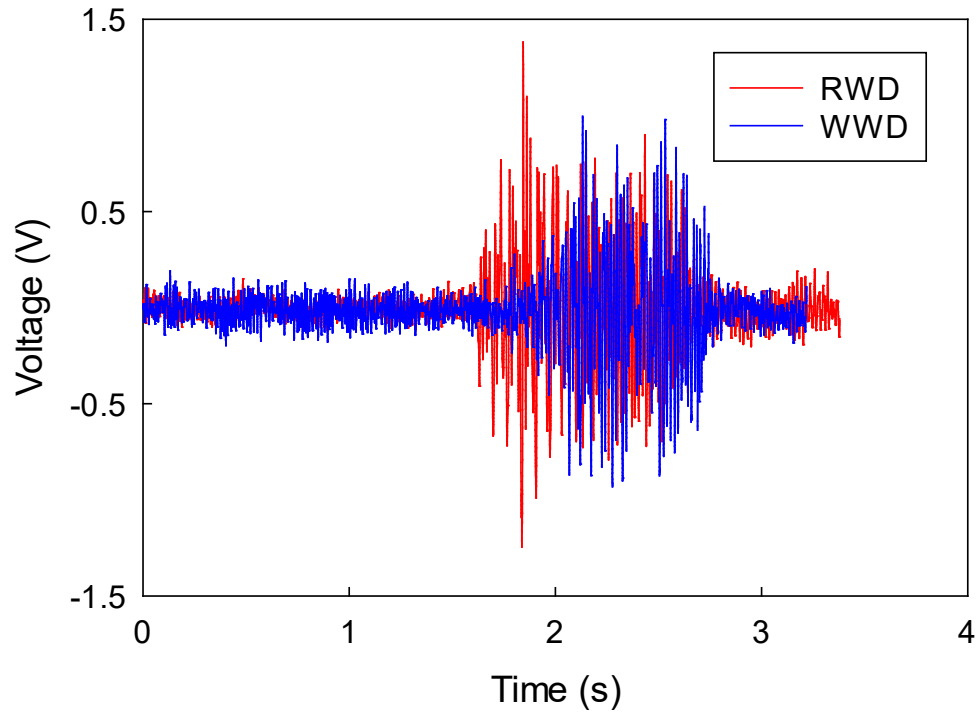


(d)

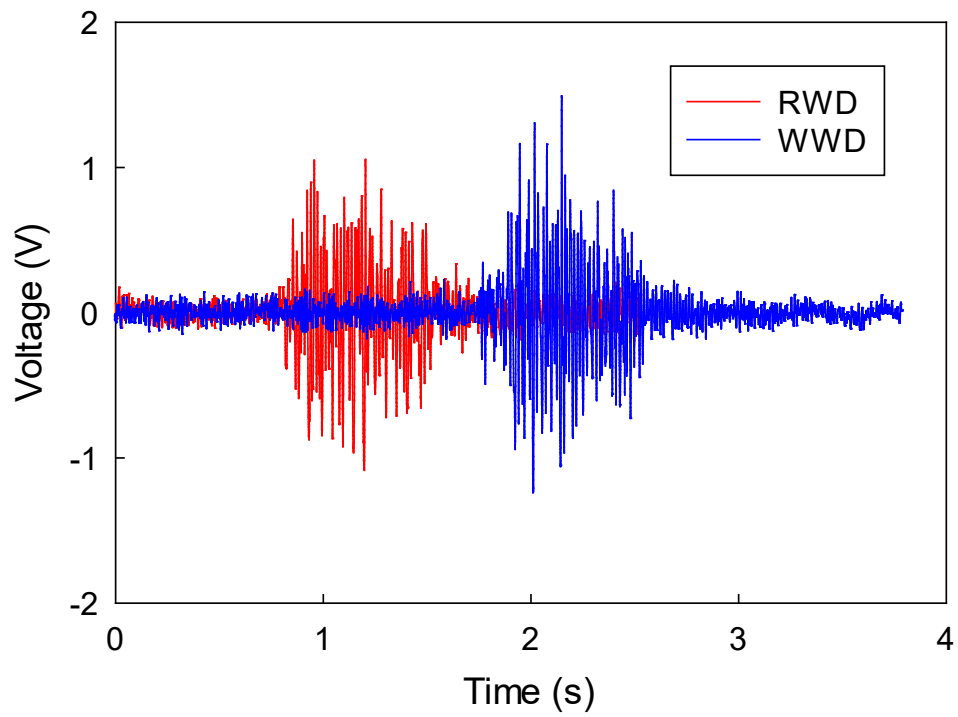
Figure 4.2 Continued.

4.3 VIBRATION TEST RESULTS

The vibration test results were recorded in a PCB ICP sensor. The output voltage was recorded in time domain and shown in Fig 4.3. Unlike sound test results, acceleration sensor can only output voltage value, so we need to transfer the voltage to acceleration and also use a fast Fourier transform (FFT) method to transfer the data from time domain to frequency domain. The detailed FFT processes and data analysis will be discussed in chapter 5.

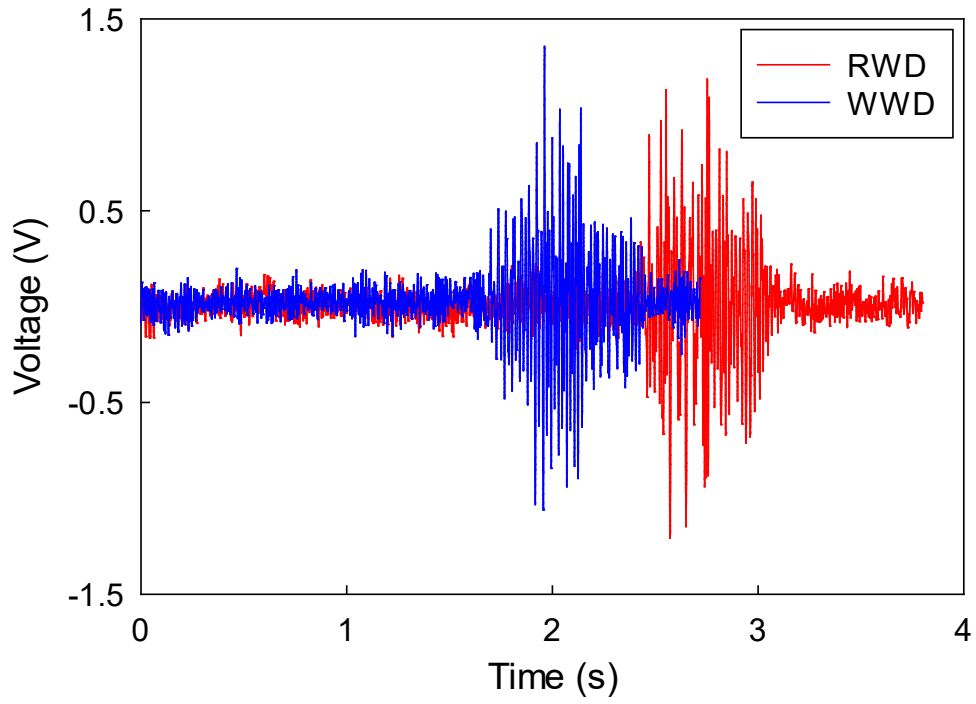


(a)

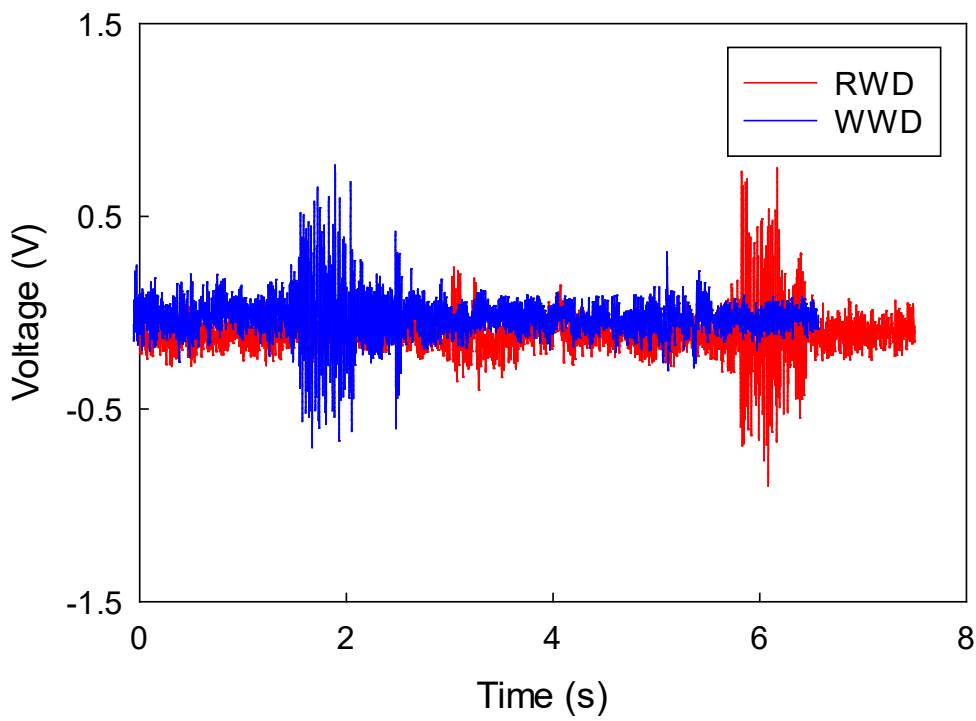


(b)

Figure 4.3 Vibration test results: (a) 15 mph, (b) 20 mph, (c) 25 mph and (d) 30mph.



(c)



(d)

Figure 4.3 Continued.

4.4 VIDEO RECORDING RESULTS

Additional video monitoring was conducted from April 19th to 23th, 2019. Speed data was recorded and 96-hour video data was recorded for both weekday and weekend. There were no significant changes at the ramp terminal after implementing Pattern D3 since the DRS was implemented just at the stop bar. During the recorded 96 hours, only one case of WWD incident was observed. Same with the before-data, the WW driver stopped after driving through the DRS and turned back.

Since the DRS was implemented just before the STOP sign, the average speed of RW vehicles did not change too much after the implementation because drivers need to slow down and stop at the STOP sign. But for WW drivers, they tend to speed up after turning from the terminal, then the DRS can reduce their speed. The average speed when approaching the terminal is 30.45 mph, while the average speed after passed the DRS is only 20.45 mph, 33% reduced.

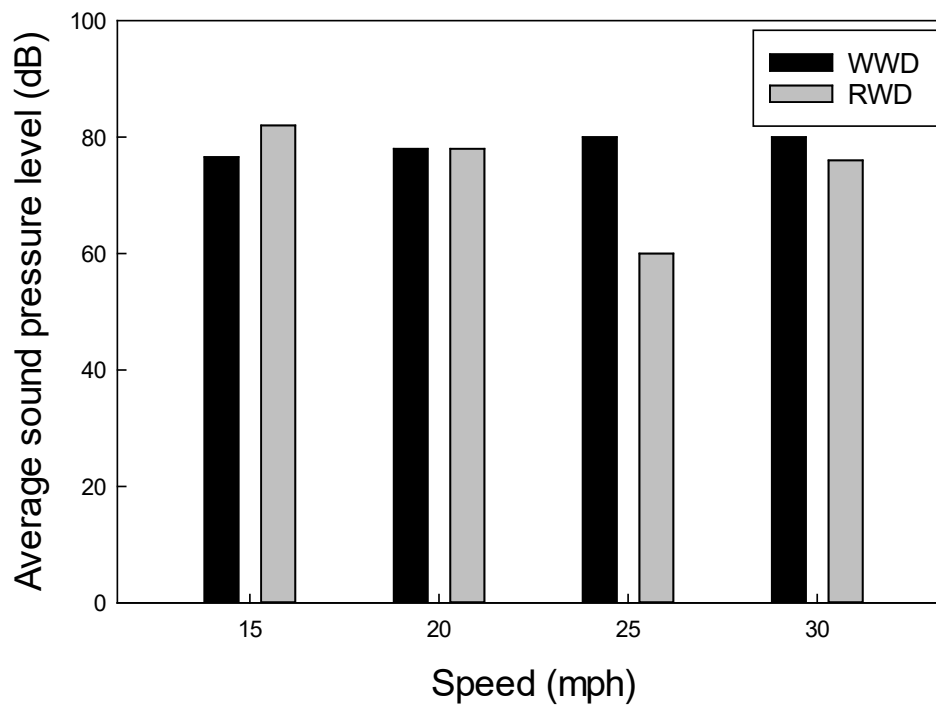
CHAPTER 5: DATA ANALYSIS

5.1 SOUND TEST DATA ANALYSIS

Sound test results are summarized Fig. 5.1. It shows that both RWD and WWD can generate sound more than 60 dB, which is high enough for drivers to notice. At 15 mph, 20 mph and 30 mph, the sound created by WWD and RWD does not have much difference. At 25 mph, WW vehicles make 33% higher sound pressure than RW vehicles.

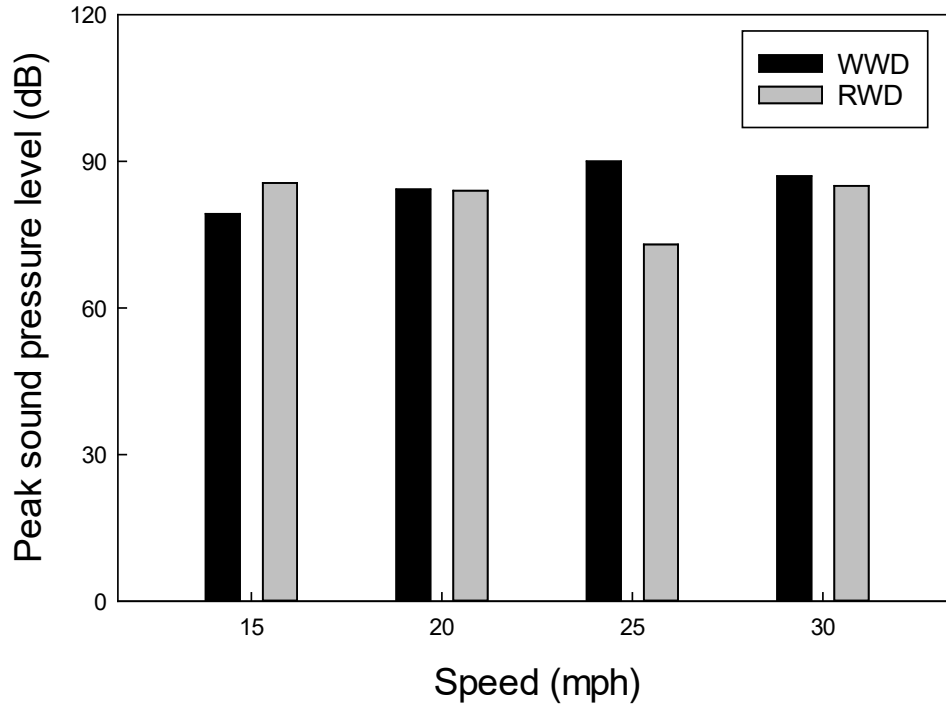
AS mentioned in section 4.4, the DRS was implemented just after the STOP sign, RW vehicles that approaching the STOP sign would not have a high speed, about 15 mph, while WW vehicles driving through the DRS at around 25 mph. So both WW and RW vehicles make around 80 dB noise.

The sound test results show that Pattern D3 is well designed to generate significant noise which will evoke the attention of the WW drivers.



(a)

Figure 5.1 Sound level comparison of different speed: (a) average value, (b) peak value.



(b)

Figure 5.1 Continued.

5.2 VIBRATION TEST DATA ANALYSIS

As shown in section 4.3, the accelerometer recorded was voltage $Vol(n)$ in V. Since the acceleration amplitudes should be $Accel(n)$ in g's, we need the following formula to convert voltage to acceleration

$$Accel(n) = 1000Vol(n)/(S \cdot g) \quad (5.1)$$

where $S = 97.9 mV/(m/s^2)$ is the accelerometer's sensitivity and $g = 9.8m/s^2$.

Assume that the discrete data $Accel(n)$ has N points, in other words, $n = 1, 2, 3, \dots, N$. Then a Hanning window is applied to $Accel(n)$ to avoid energy leakage before doing a FFT. The filtered $Accel_f(n)$ can be obtained by

$$Accel_f(n) = 0.5(1 - \cos \frac{2\pi n}{N}) \cdot Accel(n) \quad (5.2)$$

After a FFT, $Accel_f(n)$ is transferred to a complex sequence, which is denoted by $Accel_{FFT}(n)$

$$Accel_{FFT}(n) = \sum_{k=1}^N Accel_f(k) \cdot e^{\frac{-2\pi i(k-1)(n-1)}{N}} \quad (5.3)$$

The frequency resolution $\Delta\omega$ is obtained by

$$\Delta\omega = \frac{f_s}{N} \quad (5.4)$$

Where $f_s = 5000\text{Hz}$ is the sampling frequency. The acceleration amplitude spectrum $Amp(k\Delta\omega)$ is

$$Amp(k\Delta\omega) = \begin{cases} \left| \frac{1}{N} Accel_{FFT}(k) \right|, & \text{if } k = 1 \\ \left| \frac{2}{N} Accel_{FFT}(k) \right|, & \text{if } k > 1 \end{cases} \quad (5.5)$$

The relationship between $Amp(k\Delta\omega)$ and time domain data $Accel(n)$ is

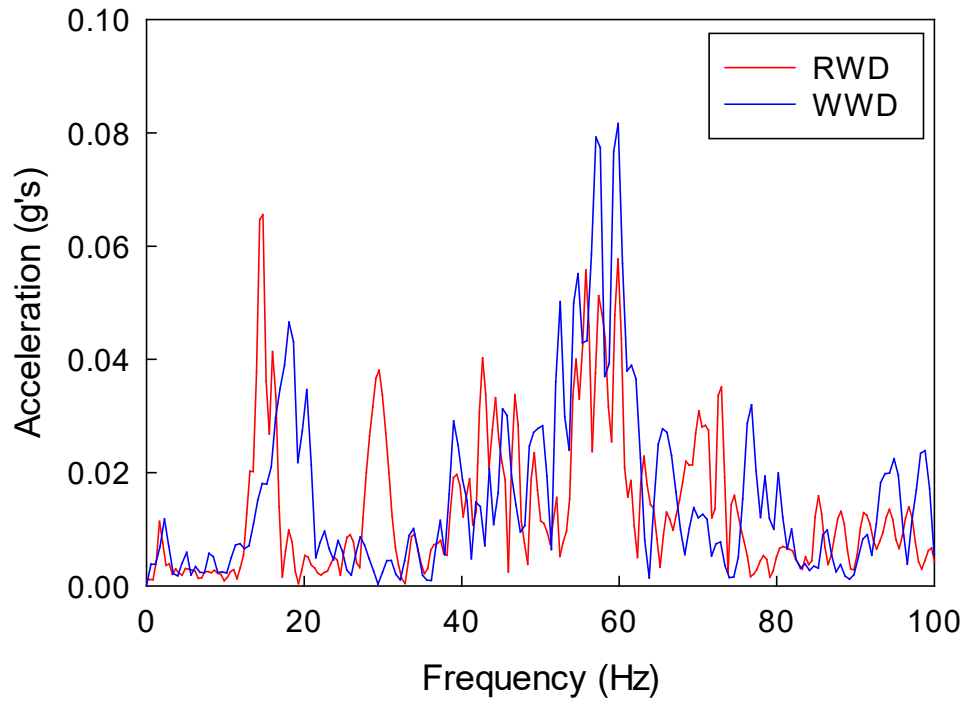
$$Accel(n) \approx Amp(0\Delta\omega) + \sum_{k=1}^N Amp(k\Delta\omega) \sin(k\Delta\omega + \varphi_k) \quad (5.6)$$

where

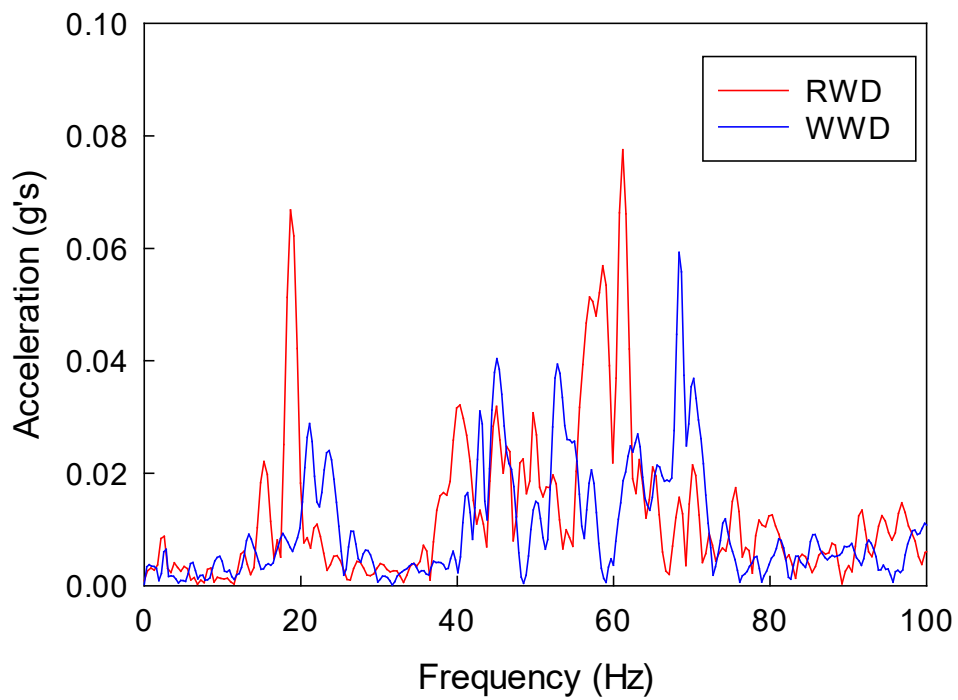
$$\tan \varphi_k = \frac{\text{Re}[Accel_{FFT}(k)]}{-\text{Im}[Accel_{FFT}(k)]} \quad (5.7)$$

and φ_k is the phase shift.

After the data processing above, the recorded voltage data was transformed into the vertical acceleration in frequency domain shown in Fig. 5.2.

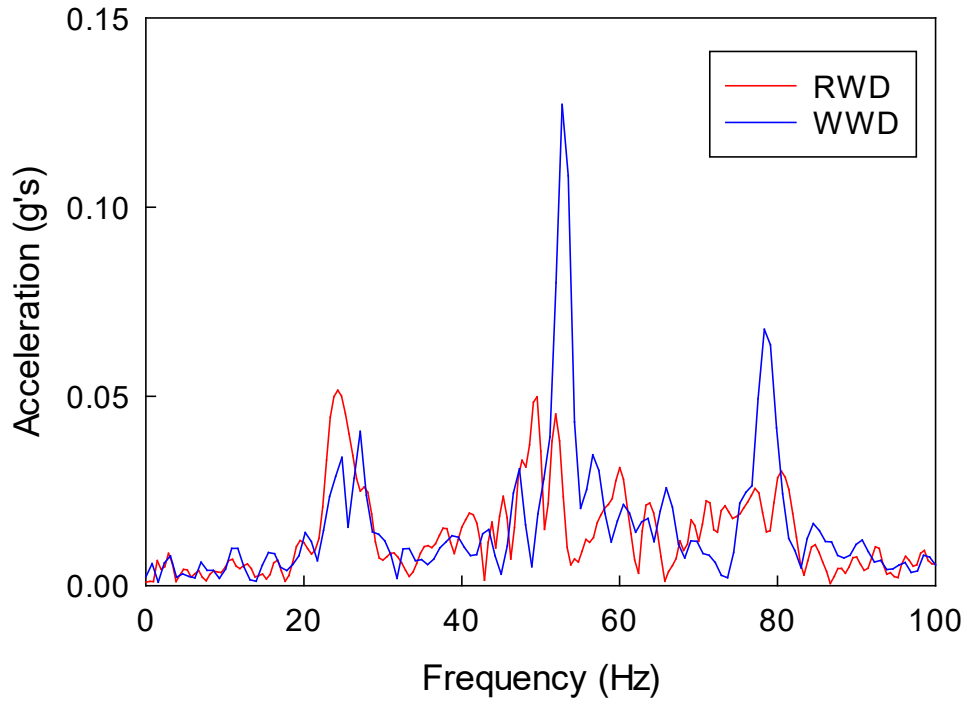


(a)

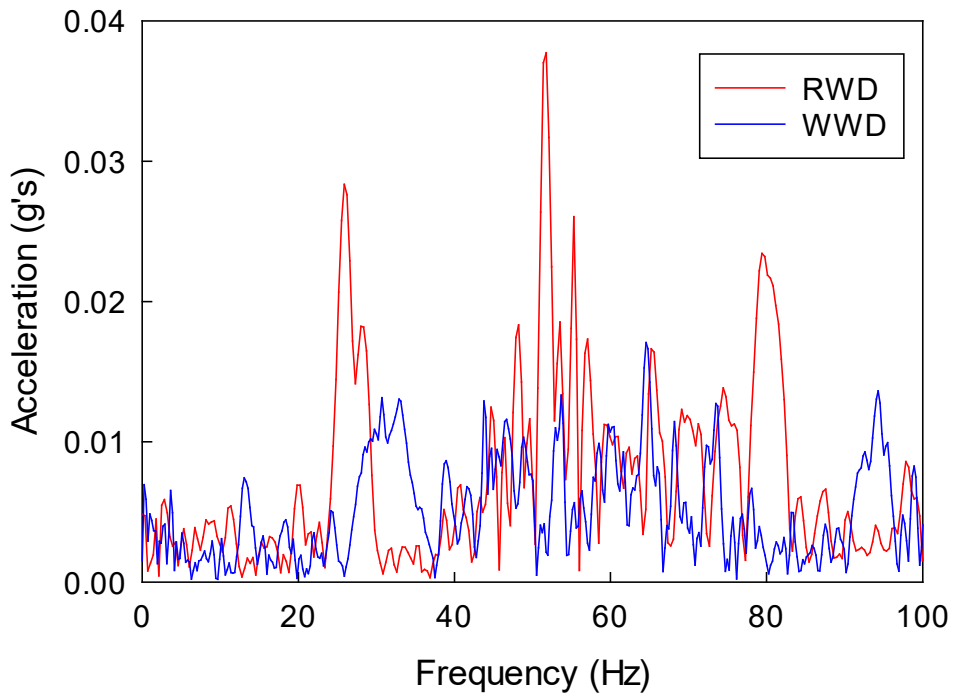


(b)

Figure 5.2 Vibration spectrum at (a) 15 mph, (b) 20 mph, (c) 25 mph, (d) 30 mph.



(c)



(d)

Figure 5.2 Continued.

At 15 mph, the vibration generated by RW drivers has the first peak at 14.4 Hz with 0.065 g's, while the WW drivers have the first peak at 18 Hz with 0.047 g's. The highest vibration occurs at a frequency of 60 Hz with 0.082 g's for WWD and 0.058 g's for RWD.

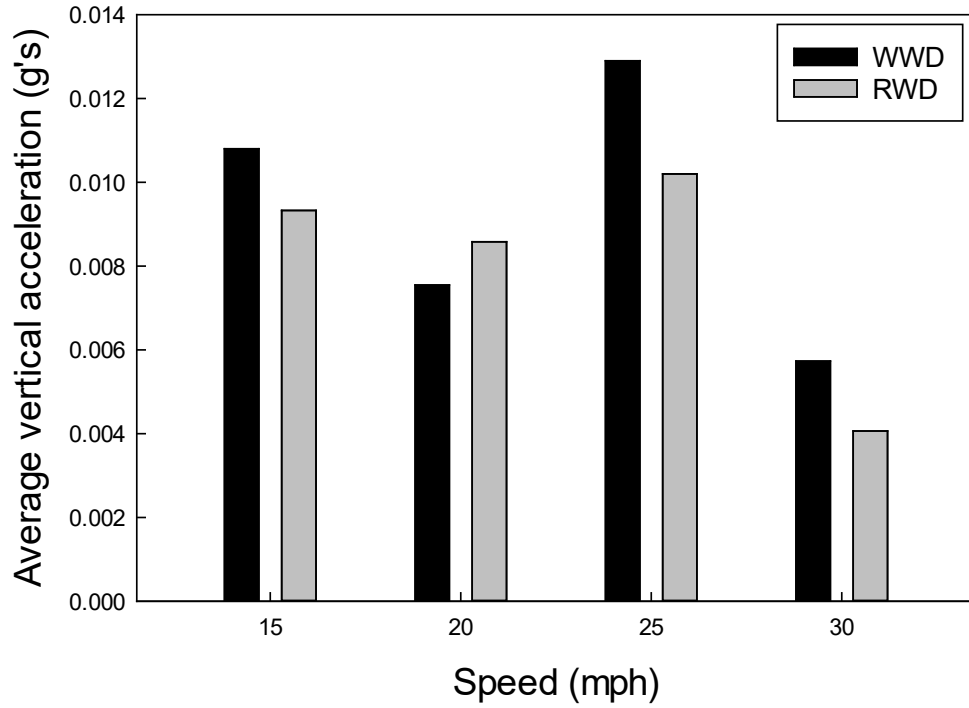
At 20 mph, the RW vehicles have their first peak at 18.69 Hz with 0.067 g's, and the highest value occurs at 61.2 Hz with 0.078 g's. While the vibration generated by WWD have its first peak at 21 Hz with only 0.03 g's. The highest acceleration value for WWD is 0.06 g's occurs at 68.4 Hz.

At 25 mph, RW vehicles have their first peak at 24 Hz with 0.05 g's, and this is also the highest value. WWD generated only 0.04 g's for first peak at 27 Hz, but the highest value is much larger, which is 0.13 g's at 53 Hz.

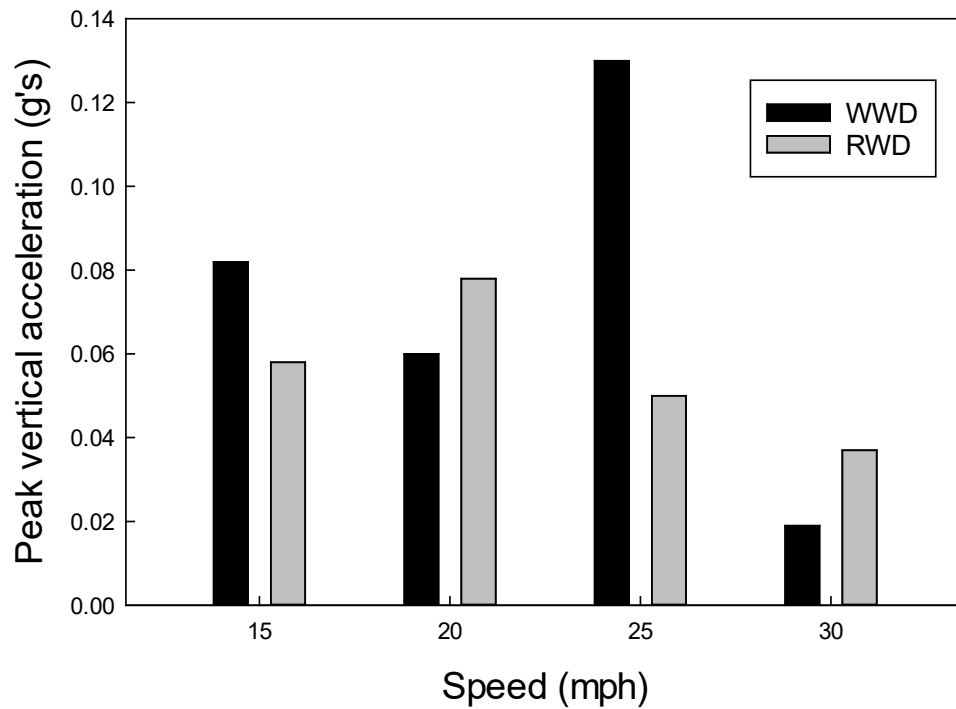
At 30 mph, both WW and RW vehicles generate low vibration. The peak value for RWD is 0.037 g's at 52 Hz, and the peak value for WWD is 0.019 g's at 65 Hz.

The comparison of acceleration at different speed was shown in Fig. 5.3. It shows that besides 20 mph, WWD have higher vertical acceleration than RWD. Similar to sound results, at 25 mph, WWD have the largest average and peak vertical acceleration.

Then based on the speed, sound and vibration test results, WW vehicles passing the DRS at around 25 mph and that speed can generate highest sound and vibration in the 15-30 mph speed range. So the field testing shows that Pattern D3 DRS is well-designed, WW vehicles passing the rumble strips will be alerted by the large noise and strong vibration, then they will notice that they are in the wrong way.



(a)



(b)

Figure 5.3 Acceleration spectrum comparison of different speed: (a) average value, (b) peak value.

CHAPTER 6: CONCLUSIONS

Off-ramps on major highways in Illinois were examined by a mathematical model to identify the probability of WWD. The results showed that most off-ramps in Illinois were well designed and had a relatively low probability (less than 20%) of WWD. One off-ramp, Exit 41 northbound on I-70, was found to have a WW entry probability of 55%.

A total of 96 hours of video data (before-data) were recorded at the chosen interchange terminal. The speed and traffic behavior matched the analytical results. Two cases of WWD incidents were observed. Exit 41 northbound on I-70 was then chosen as the location for the field implementation test.

One DRS pattern (D3) was implemented on the chosen location with the help of IDOT. The DRS was implemented at the stop bar to warn WW drivers with sound and vibration. Sound and vibration data were recorded and compared between RW and WW directions for speed ranging from 15 mph to 30 mph. Another 96 hours of video data (after-data) were recorded after implementation.

The implementation test results showed that vehicles driving through the DRS could generate evident sound and vibration, drawing the attention of the drivers to reduce their speed. Because the DRS was installed after the stop bar, it cannot reduce the probability of WWD, but it can reduce the possibility of accidents caused by WWD.

According to U.S. climate data, the average temperature in Illinois is below 10° C for 6 months and below 0° C for 4 months, which also brings lots of snow. The chosen in-lane rumble strips need to be installed at temperatures above 10° C, and in-lane rumble strips may impede the cleaning of snow. Thus, in Illinois and states with similar climates, we do not suggest using the DRS to reduce WWD. But in states with warmer climates, the DRS would be an effective way to reduce the probability of WW accidents.

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