Evaluation of Mobile Work Zone Alarm Systems

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16. Abstract

Maintenance of highways often involves mobile work zones for various types of low speed moving operations such as striping and sweeping. The speed differential between the moving operation and traffic, and the increasing problem of distracted driving can lead to potential collisions between approaching vehicles and the truck-mounted attenuator (TMA) protecting the mobile work zone. One potential solution to this problem involves the use of a mobile work zone alarm system. This report describes the field evaluation of two types of mobile work zone alarm devices: an Alarm Device and a Directional Audio System (DAS). Three modes of operation were tested: continuous, manual, and actuated. The components of the evaluation included sound level testing, analysis of merging distances and speeds, and observations of driving behavior. The sound level results indicated that the sound levels from both systems fall within national noise standards. All of the tested configurations increased the merging distance of vehicles except for the Alarm Actuated setup. The DAS Continuous setup also reduced vehicle merging speeds and the standard deviation of merging distance. In some instances, undesirable driving behaviors were observed for some of these configurations, but it is unclear whether these driving behaviors were due to the presence of the mobile work zone alarm device. Analysis of alarm activations indicated that factors such as horizontal curves and movement of the TMA vehicle created false alarms and false negatives. The research demonstrated that mobile work zone alarms have the potential to be an effective tool in improving safety by providing audible warnings. Further refinements to the systems, such as modifications to the alarm sound and warning message, could improve system effectiveness.

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Table of Contents

Acknowledgments vi

Disclaimer vii

Executive Summary viii

1 Introduction 1

2 Literature Review 8
- 2.1 Sound Level Standards 8
  - 2.1.1 NIOSH Standards 8
  - 2.1.2 OSHA Standards 9
- 2.2 Other Research 10
  - 2.2.1 Emergency Vehicle Auditory Warning Signals: Physical and Psychoacoustic Considerations 10
  - 2.2.2 Effectiveness of Audible Warning Devices on Emergency Vehicles 11
  - 2.2.3 Directional Sound for Long Distance Auditory Warnings from a Highway Construction Work Zone 11
  - 2.2.4 Crash Avoidance Warning Systems 12
  - 2.2.5 Review of Emergency Vehicle Warning Systems 12
  - 2.2.6 Effectiveness of Warning Signals in Capturing a Driver's Attention 12

3 Methodology Overview 13

4 Sound Testing 16
- 4.1 Methodology for Sound Level Testing 16
- 4.2 Results from Sound Level Testing 18
- 4.3 Spectral Analysis 28
- 4.4 Luminance Testing 32

5 Evaluation of Driver Behavior 34
- 5.1 Methodology for Evaluating Driver Behavior 34
- 5.2 Results for Merging Distances and Speeds 40
- 5.3 Anecdotal Observations of Driver Behavior 44

6 Alarm Activations 47
- 6.1 Methodology for Evaluating Alarm Activations 47
- 6.2 Results from Evaluation of Alarm Activations 47

7 Evaluation of Trade-offs 52

8 Conclusions 54

References 56

List of Figures

Figure 1.1 Figure from MUTCD Showing Layout of Mobile Work Zone (FHWA, 2009) 2
Figure 1.2 Missouri TMA Incident Statistics (MoDOT) 3
Figure 1.3 Aftermath of TMA Collision 4
Figure 1.4 TMA with Alarm Device 5
Figure 1.5 DAS Unit 7
Figure 3.1 Aerial imagery of test area in northern Kansas City, Missouri on I-435 (Google 2014) 15
Figure 4.1 OSHA and NIOSH sound level standards with respect to duration of exposure 16
Figure 4.2 Reading decibel level of DAS while walking outside of vehicle 17
Figure 4.3 Field of view from inside test vehicle 18
Figure 4.4 Sound level results with 5% error bars from parking lot tests 23
Figure 4.5 Sound level results with 5% error bars for DAS and Alarm Device at 10 ft while walking 24
Figure 4.6 Sound level results with 5% error bars for DAS and Alarm Device at 3 ft while walking 25
Figure 4.7 Sound level results with 5% error bars for DAS and Alarm Device from inside TMA vehicle with windows up 26
Figure 4.8 Sound level results with 5% error bars for DAS and Alarm Device from within TMA vehicle with windows down 27
Figure 4.9 Sound level results from highway vehicle testing 28
Figure 4.10 Spectrogram for Alarm Device without background noise 29
Figure 4.11 Spectrogram for DAS without background noise 30
Figure 4.12 Spectrogram for Alarm Device on highway 31
Figure 4.13 Spectrogram for DAS on highway 32
Figure 4.14 Example of a typical warning light setup on TMA truck 33
Figure 5.1 Stopping Sight Distance and Vehicle Speed (AASHTO, 2011) 35
Figure 5.2 Example of video data to be assessed from Alarm Manual setup. 36
Figure 5.3 Curve of video image regression for TMA with Alarm Device 37
Figure 5.4 Example drawing to be overlaid onto video files for TMA with Alarm Device 38
Figure 5.5 Resulting image to be used in vehicle merging analysis for TMA with Alarm Device 39
Figure 5.6 Distribution of merges in 200' segments by setup 44
Figure 5.7 Example of vehicle passing TMA on shoulder 45
Figure 5.8 Sudden breaking by silver car caused dump truck to have to quickly and forcefully apply the brakes 46

List of Tables

Table ES.1 Trade-offs of Warning Setups xi
Table 2.1 NIOSH Sound Level Standards (NIOSH, 1998) 9
Table 2.2 OSHA Sound Level Standards (OSHA, 1983) 10
Table 4.1 Sound Level Analysis for DAS while in Vehicle 19
Table 4.2 Sound Level Analysis for DAS while Walking 20
Table 4.3 Sound Level Analysis for Alarm Device while in Vehicle 21
Table 4.4 Sound Level Analysis for Alarm Device while Walking 22
Table 5.1 Total Number of Merges and Total Time of Observations by Setup 40
Table 5.2 Average Volume and Percentage of Trucks by Setup 41
Table 5.3 Properties of Total Merges by Alarm Setup 42
Table 5.4 Results for Merging Distances and Speeds 43
Table 6.1 False Alarm Analysis with Horizontal Curves by Setup 48
Table 6.2 False Alarm Analysis without Horizontal Curves by Setup 49
Table 6.3 False Negative Analysis with Horizontal Curves by Setup 50
Table 6.4 False Negative Analysis without Horizontal Curves by Setup 51
Table 7.1 Design Trade-Offs by Alarm Setup 52

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Disclaimer

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the information presented herein.

Executive Summary

Mobile work zones are used for many road maintenance operations such as roadway striping, sweeping, and minor pot-hole repair. These types of work zones are slow moving with respect to normal traffic and can surprise an inattentive traveler. With the increasing use of cell phones and other devices that are distracting drivers, there is a growing need for an additional method to alert travelers approaching slow moving mobile work zone operations. One possible counter-measure is a mobile work zone alarm system. This report describes the first field test of mobile work zone alarms in the United States.

This project analyzes two types of devices: an Alarm Device and a Directional Audio System (DAS). Examples of a DAS include parametric speaker arrays and the Long Range Acoustic Device (LRAD) (LRAD, 2014). The LRAD was the DAS used for testing in this research project. Each device is attached to a Truck-Mounted Attenuator (TMA). Five different setups were tested in the field based on various operating modes: Control setup with no alarm system, Alarm Manual, Alarm Actuated, DAS Continuous, and DAS Actuated. In the manual operating mode, the TMA driver manually activates the alarm while the actuated mode uses an actuation system to trigger the alarm based on the speed and merging distance of an approaching vehicle. The evaluation included sound level testing, spectral analysis to investigate the distinctiveness of the alarm sounds, analysis of merging distances and speeds, anecdotal observations of driving behavior, and investigation of the alarm actuations. These investigations provided insight into the effectiveness of the alarm systems and led to recommendations for improvements to the systems.

Sound level tests were performed for both systems in a parking lot at various distances from both inside and outside of a vehicle. Additional sound level tests were performed in the field in instrumented vehicles. Sound levels were also measured from inside the TMA vehicle to analyze worker sound exposure. The results from the tests indicated that the sound levels were in accordance with standards established by the Occupational Safety and Health Administration (OSHA) and National Institute for Occupational Safety and Health (NIOSH) except for the extreme case of standing three feet directly behind the unit for an extended period of time. This situation is all but impossible to occur in a moving work zone. In addition to the sound level tests, the alarm sounds were evaluated for distinctiveness through the use of spectral analysis. The results of the spectral analysis indicated that the DAS produced a more distinctive sound that was better able to overcome background road noise than the Alarm Device. The luminance levels of the lights on both alarm systems were also measured and found to be comparable thus ensuring that they did not affect driver behavior and bias the results.

Driving behavior was the main measure of warning system effectiveness in increasing mobile work zone safety. Factors such as average merging distance, standard deviation of merging distance, average speed, and other observed driving behaviors were analyzed. The Safe Stopping Sight Distance (SSD) from the AASHTO Green Book (AASHTO, 2011) was used as the definition for desirable driving behavior. SSD represents the smallest distance a vehicle could stop safely assuming a conservative deceleration rate and perception/reaction time. SSD was calculated as 600 ft from the TMA vehicle for a 60 mph speed differential. Therefore, desirable driving behavior was defined as merges that occurred at distances greater than 600 ft from the TMA vehicle. Using the 600 ft threshold, each vehicle's merge distance was measured, and vehicle merges that occurred within 600 ft were further analyzed for average vehicle speeds and driving behavior observations.

The first five rows of Table ES.1 show warning setup performance measures. In comparing average merging distances by setup, all setups were observed to result in an increase in merging distance except for the Alarm Actuated setup. The standard deviation of merge distance and average speed were observed to decrease only in the DAS Continuous setup, indicating that DAS Continuous setup may be the most effective setup for improving mobile work zone safety. However, some undesirable driver behaviors were observed with the DAS setups. Instances in which some drivers had sudden reactions, such as braking or swerving, were observed with the DAS Actuated setup. It is unclear whether these behaviors were due to the actuation of the mobile work zone alarm. While the DAS Continuous setup was in operation, some drivers were observed passing the TMA on the shoulder, giving the TMA an additional amount of space while passing. MoDOT personnel have indicated that drivers sometimes pass the TMA on the shoulder during routine operations, so this behavior may not be due to the presence of the mobile work zone alarm.

Table ES.1 Trade-offs of Warning Setups

Factor	DAS Continuous	DAS Actuated	Alarm Manual	Alarm Actuated	Desirable
Merge Distance (ft)	+122	+53	+16	-35	+
Standard Deviation of Merge Distance (ft)	-20	+37	+37	+15	-
Approach Speed (mph)	-3.0	+0.5	+4.3	+3.3	-
False Positive (Including Horizontal Curves)	N/A[+]	62%	53%	69%	0%
False Negative (Including Horizontal Curves)	N/A[+]	26%	13%	54%	0%
Observed Driver Behavior	Drive on Shoulder	Sudden Maneuvers	None Observed	None Observed	None Observed
Sound Safety 50' In Veh. (dB)	86	86	77	77	< 115[++] < 100[+++]
Sound Distinctiveness	****	****	**	**	****
Cost	$$$$	$$$$$	$	$$	$
Convenience	Automatic	Calibration	Manual	Calibration	Automatic
Energy Consumption	*****	****	*	***	*

[+]DAS Continuous did not have actuation system properly collecting data in background
[+] OSHA, 0.25 h
[+++] NIOSH, 0.25 h

False alarm and false negative statistics are an important part of investigating activation systems used in alarm setups. By using the audio data with merging speeds and distances, each vehicle merge was evaluated as either a successful alarm activation, successful negative, false positive, or false negative. Some general causes of false alarms and false negatives were horizontal and vertical curves in the roadway as well as movement of the TMA vehicle.

The research demonstrated that mobile work zone alarms have the potential to be an effective tool in improving safety by warning drivers. In determining which system to use, agencies should consider a variety of factors such as performance, cost, and maintenance requirements as shown in Table ES.1. Since this project was an initial test to investigate the feasibility of mobile work zone alarms, further refinements to the systems, such as modifications to the alarm sound or warning message, could improve system effectiveness.

1 Introduction

Mobile work zones for various types of moving operations such as striping, sweeping, and pothole filling are an important component of maintaining highways. The Manual on Uniform Traffic Control Devices (MUTCD) (FHWA, 2009) provides guidance for the layout for mobile work zones as shown in Figure 1.1. Shadow vehicles, arrow boards, and signs are used to warn drivers that they are approaching a mobile work zone. In addition, a Truck-Mounted Attenuator (TMA) attached to a construction vehicle helps to mitigate the impact of a collision from a highway vehicle.

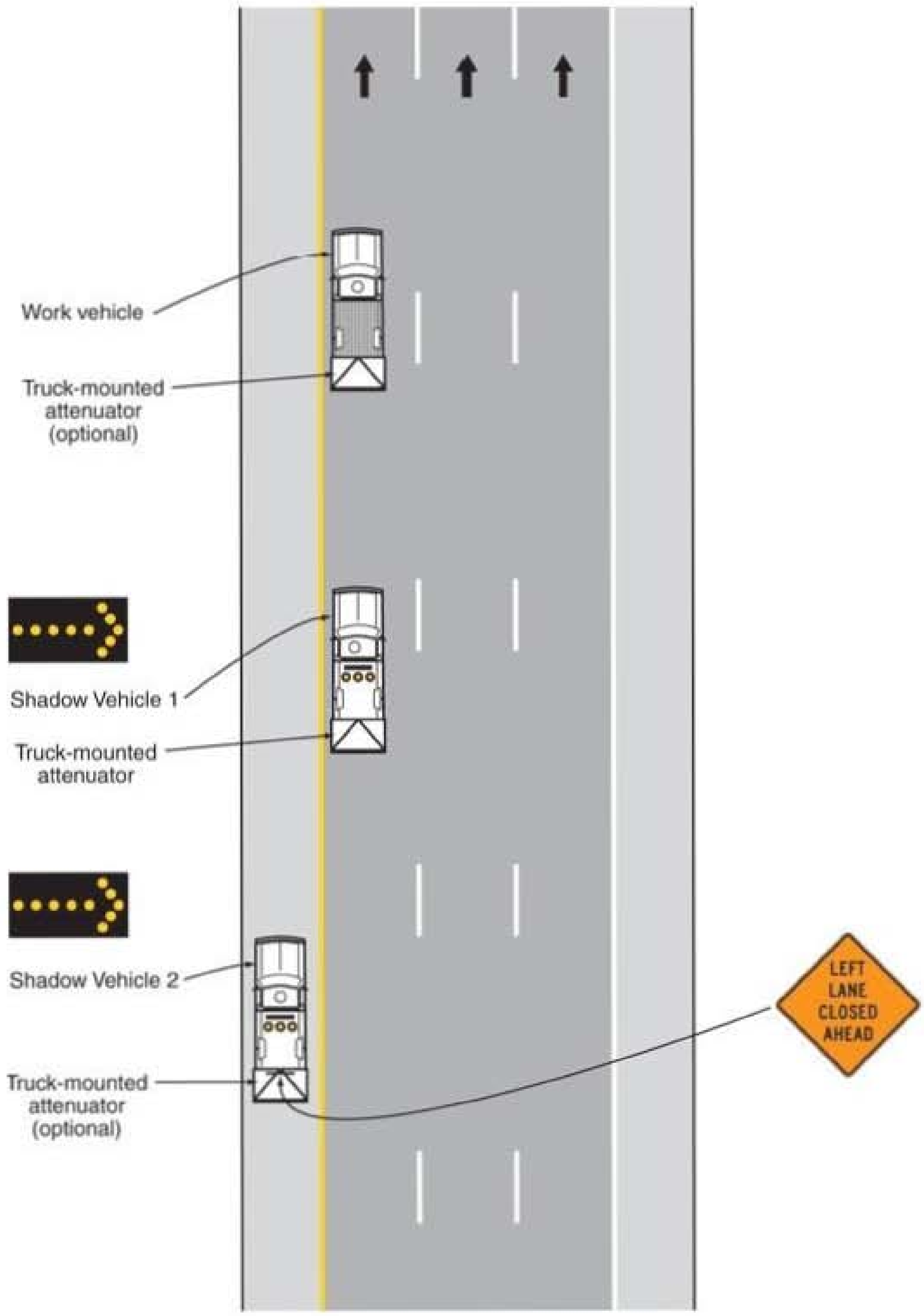

Figure 1.1 Figure from MUTCD Showing Layout of Mobile Work Zone (FHWA, 2009)

Despite these precautions, some drivers do not respond to warnings and collide with the TMA. This problem has been exacerbated by an increase in distracted driving due to factors such as cell phone use and texting while driving. In Missouri, the number of TMA incidents is tracked as a performance measure by the Missouri Department of Transportation (MoDOT). There were 51 TMA incidents in 2012 and 2013 as shown in Figure 1.2 (MoDOT). The majority of these incidents involved third party action. The aftermath of vehicle collision with a TMA is shown in Figure 1.3.

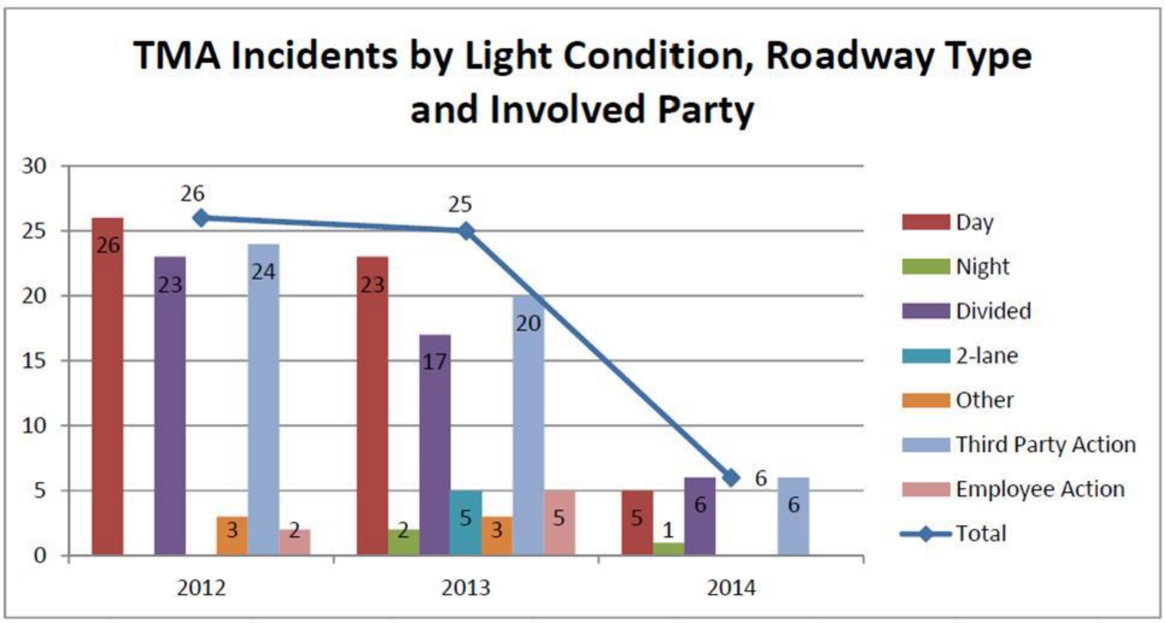

Figure 1.2 Missouri TMA Incident Statistics (MoDOT)

Figure 1.3 Aftermath of TMA Collision

One tool that could help to reduce the number of collisions between highway vehicles and TMAs is a mobile work zone alarm system that sounds an audible warning when drivers are approaching a mobile work zone. Research on mobile work zone alarm systems is very limited, and there have not been any known implementations of them until recently when MoDOT started using an Alarm Device in the Saint Louis District. In addition, MoDOT is also interested in investigating the use of a Directional Audible System (DAS) as a possible work zone alarm.

The Alarm Device, as implemented by the Saint Louis District (Figure 1.4), is a manual system that includes a dual stage warning with lights followed by sound. The TMA driver visually estimates the distance to trailing vehicles by using the number of skips on the lane striping as a reference. The distance from the beginning of one skip to the beginning of the next skip is 40 ft. The driver first triggers the lights when there is a vehicle within a distance of 1040 ft in the TMA lane. If the highway vehicle continues to approach the TMA vehicle without showing any signs of merging, the TMA driver will trigger the alarm sound when the vehicle is within 520 ft of the TMA vehicle.

Figure 1.4 TMA with Alarm Device

DAS is a device that transmits high-intensity and directional warning sounds. Figure 1.5 shows the DAS unit tested in this research project. The DAS produces sounds that are able to overcome background noise such as road noise. A previous study suggested that a DAS could be used in a highway construction work zone (Phanomchoeng et al., 2008). However, there is no known application of the DAS in a mobile work zone. The volume of the DAS is adjustable and can be limited via device software. The message and alarm sound are customizable. The DAS could potentially be used in a wide range of applications that require the use of a long range and directional public address system. There are several versions of the DAS, including ones producing lower sound levels that are more appropriate for public use. These smaller units are also more affordable. In addition, the DAS unit can be programmed from the factory at a preset maximum sound level to avoid accidental or malicious increase of volume.

Figure 1.5 DAS Unit

The objective of this research project was to perform a field evaluation of both the DAS and Alarm Device to evaluate their potential for use as a mobile work zone alarm. The Alarm Device was tested in both manual and actuated modes while the DAS was tested in continuous and actuated modes. The evaluation included sound level testing, spectral analysis to investigate the distinctiveness of the alarm sounds, analysis of merging distances and speeds, and anecdotal observations of driving behavior. Through this evaluation, the effectiveness of the alarm systems was determined and recommendations were made for improvements to the systems. Successful implementation of mobile work zone alarms could help to improve highway safety in mobile work zones and protect both highway workers and the general public.

2 Literature Review

This Chapter gives an overview of Mobile Work Zone Alarm sound level standards and work zone alarm applications through a review of existing literature.

2.1 Sound Level Standards

From the Occupational Safety and Health Act of 1970 two agencies were established to help protect people from various dangers in the work place: the Occupational Safety and Health Administration (OHSA) and National Institute for Occupational Safety (Niquette, 2014). One responsibility of each agency is the establishment of national standards for sound levels. The OSHA standards are enforceable by law while the NIOSH standards serve as guidelines that are not legally enforceable.

2.1.1 NIOSH Standards

NIOSH sound level standards (NIOSH, 1998) are established by Equation 2.1 with factors duration (T) and exposure level (L).

$$T(\text{min}) = \frac{480}{2^{\frac{(L-85)}{3}}} \qquad \text{Equation 2.1}$$

Duration is a daily exposure limit instead of a block type exposure limit and must not equal or exceed 100 by Equation 2.2.

$$D = \left[{}^{C_1}/_{T_1} + {}^{C_2}/_{T_2} + \cdots + {}^{C_n}/_{T_n}\right] x\ 100 \qquad \text{Equation 2.2}$$

Where:

C_n = exposure time at a specific noise level, and

T_n = point at which exposure time for given sound level become harmful.

Table 2.1 shows the NIOSH standard sound levels per duration in hours.

Table 2.1 NIOSH Sound Level Standards (NIOSH, 1998)

Duration (Hours)	Sound Level (dBA)
0.25	100
0.5	97
1	94
2	91
4	88
8	85
16	82

NIOSH standards, however, are not enforceable by law and serve more as guidelines than requirements.

2.1.2 OSHA Standards

OSHA (OSHA, 1983) allows for a base sound level intensity of 85 dBA and for every 5 decibel increase in sound level, the allowed exposure time is halved. Table 2.2 shows the OSHA standards for sound levels by exposure time. Similar to NIOSH, each duration value is a daily limit of hours exposed to decibel level with the same requirements as Equation 2.2. OSHA standards are less stringent than that of NIOSH standards; however, OSHA standards are enforceable by law and must be complied with.

Table 2.2 OSHA Sound Level Standards (OSHA, 1983)

Duration (Hours)	Sound Level (dBA)
0.25	115
0.5	110
1	105
2	100
4	95
8	90
16	85

2.2 Other Research

2.2.1 Emergency Vehicle Auditory Warning Signals: Physical and Psychoacoustic Considerations

Maddern et. al. (Maddern et al., 2011) completed research pertaining to auditory warning signals and studied factors such as perceived urgency, localization, and masking of emergency sirens. The factor of perceived urgency is the importance inertly placed on a sound by the driver. The largest effect on increasing urgency was found to be a fast repetition of sound with rapid repetition of sounds being perceived as more urgent. Another aspect that can have an effect on perceived urgency is attenuation. An attenuated sound is said to be taken as more urgent of an area than that of a non-attenuated sound.

Localization is the aspect of a traveler being able to quickly determine what direction a sound is coming from. This behavior is desirable because it allows travelers to know where the vehicle with the siren is located. Localization can be improved by widening the range of frequencies emitted. However, frequencies above 3000Hz are not advised because hearing-impaired people may not be able to distinguish such frequencies.

Masking is the tendency of a sound to be covered up by background noise. Sounds that consist of low frequencies or that cannot penetrate surfaces are said to have a greater tendency to be masked by background noise.

2.2.2 Effectiveness of Audible Warning Devices on Emergency Vehicles

The United States Department of Transportation Office of the Secretary (Potter et al. 1977) found that for an alarm to be distinct it must be greater than background noise by at least 10 decibels. This would ensure a level of distinctiveness between the alarm warning and usual noise of the roadway.

2.2.3 Directional Sound for Long Distance Auditory Warnings from a Highway Construction Work Zone

A previous research study concentrated on the use of audible warning systems for work zone applications (Phanomchoeng et al. 2008). While the DAS was mentioned, only Loud Speakers and Loud Speaker Arrays were tested in this research. It was found that any one loudspeaker would be inadequate for long distance auditory warnings while an ultrasound based parametric array may have the ability to generate a highly directional sound. However, this sort of setup is difficult for work zone applications due to need of vacuum pump and other special devices. A parametric array with inexpensive components was found to not be adequate for long distance warning applications. The device recommended was an array of multiple ordinary loudspeakers arrayed in a specific pattern that would be suitable for long distance auditory warnings. This setup was said to be portable, inexpensive, and easy to maintain while having good performance for long distance auditory warnings. The DAS was discussed but determined to be too expensive compared to the loudspeaker setups and therefore not tested.

2.2.4 Crash Avoidance Warning Systems

This research study investigated auditory warnings that could be used in crash avoidance applications (Tan and Lerner, 1995). The experimental study investigated 26 acoustic signals and identified four signals that were preferred for this application. The study also evaluated verbal warnings but did not find a verbal warning that performed significantly better than the others.

2.2.5 Review of Emergency Vehicle Warning Systems

Another study consisted of a review of existing literature on emergency vehicle warning systems (De Lorenzo and Eilers, 1991). This synthesis found that several research studies had concluded that emergency vehicle sirens had significant limitations as a warning device especially since their effectiveness is limited to low distances and speeds.

2.2.6 Effectiveness of Warning Signals in Capturing a Driver's Attention

This study investigated possible benefits of spatial auditory cues to capture a driver's attention through the use of 5 experiments (Ho and Spence, 2005). The study found that the use of auditory cues that helped give the driver a spatial reference for the sound were beneficial to getting the attention of drivers. The study suggested that verbal warnings were not as effective as non-verbal cues because they require additional processing by the driver of the vehicle.

3 Methodology Overview

The methodology for evaluating the effectiveness of mobile work zone alarm systems is described in this chapter. This includes measuring the alarm sound level for each device, observing driver behavior, estimating merge distances, and computing false alarm and false negative occurrences for the actuated and manual methods of alarm activation. The data used for these tests include sound levels collected in a parking lot and on roadways, video data from the TMA during deployment, and video data from inside a test vehicle that passed through the mobile work zones. Further details regarding these tests are provided in subsequent chapters of this report.

Three separate field tests were conducted. The first field test was in the Columbia, Missouri, area on Route DD on November 1, 2013. The purpose of this test was to perform preliminary tests on the DAS Actuated and Alarm Manual setups. During this test, Route DD was closed to traffic while a research truck made a number of passes by the TMA truck to trigger the alarm and to test noise levels and actuation. Adjustments were made to the various systems, and sound levels were measured in the test vehicle before and after the alarm sounded.

The second test occurred on the same day as the first field test on I-70 from mile marker 107 to mile marker 117. The test segment consisted of 10 miles of 4-lane interstate with an AADT of 31,571 vpd (2012) and 25% trucks. The data collected at this site was intended to be used for analysis, but the test experienced suboptimal conditions and therefore the results were excluded from the final data set. Some of the issues that arose during this data collection included equipment issues such as an arrow board being burned out and the failure of a portable generator, a queue build-up on I-70 in the afternoon, and a lack of sufficient number of merges because most vehicles moved to the open lane on the two-lane section after seeing the shadow warning truck a mile upstream. Even with these issues, the test was productive because it allowed for more time for calibration of the actuation system, and lessons were learned such as the need for the tests to be conducted on 3-lane sections where the TMA occupied the left lane to produce more vehicle merges away from the TMA. Another insight gleaned from these tests was that within the 2-lane segments the TMA should remain in the inside lane with the shadow vehicle on the shoulder on the outside lane. This modified setup allowed for a greater number of merges because vehicles tended to merge to the inside lane in order to give the shadow vehicle space and then needed to merge to the outside lane to avoid the TMA vehicle.

The final field test occurred in the Kansas City area on I-435 from mile marker 40 to mile marker 51 on November 19 and 20, 2013 as shown in Figure 3.1. The conditions of this segment included 5.5 miles of 6-lane interstate and 7 miles of 4-lane interstate for a total of 12.5 mile stretch. The approximate AADT for this roadway was 21,534 vpd (2012) with 14% trucks.

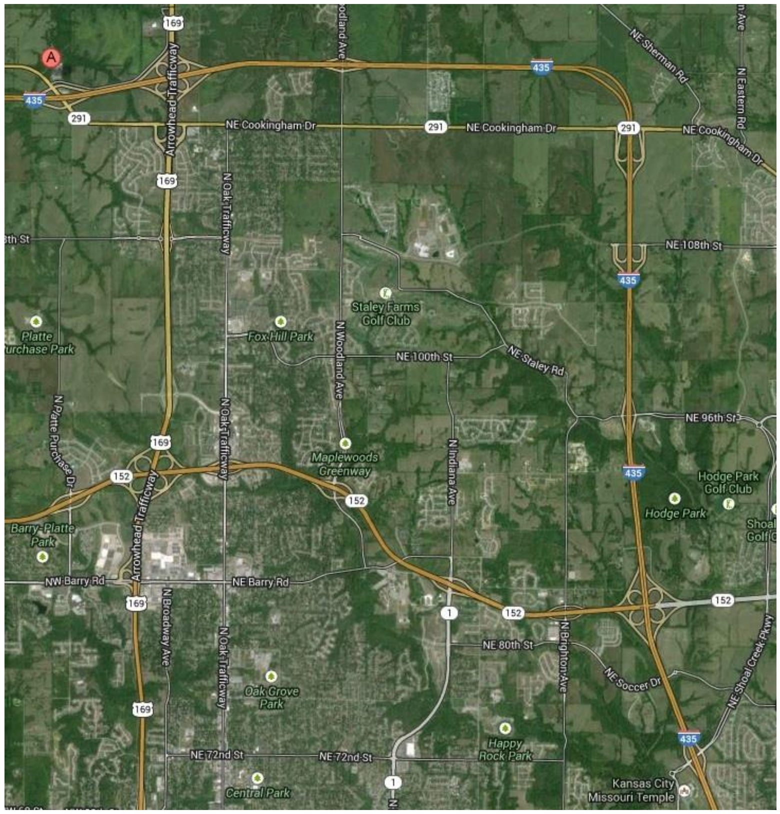

Figure 3.1 Aerial imagery of test area in northern Kansas City, Missouri on I-435 (Google 2014)

Data for five different setups were collected: the Alarm Manual setup, the Alarm Actuated setup, the DAS Continuous setup; the actuated DAS setup, and the Control setup with no alarm warning system. Each setup was individually analyzed and then compared to determine its safety and effectiveness.

4 Sound Testing

4.1 Methodology for Sound Level Testing

The sound level testing examined the exposure of approaching motorists and also drivers and crews of TMA trucks. As mentioned in the literature review, OSHA and NIOSH have sound level standards with respect to exposure duration. NIOSH standards are more stringent than that of OSHA, but OSHA standards are the only enforceable standards. NIOSH standards serve as guidelines but are not enforceable by law. Figure 4.1 shows a chart of both the OSHA and NIOSH sound level standards with respect to exposure time.

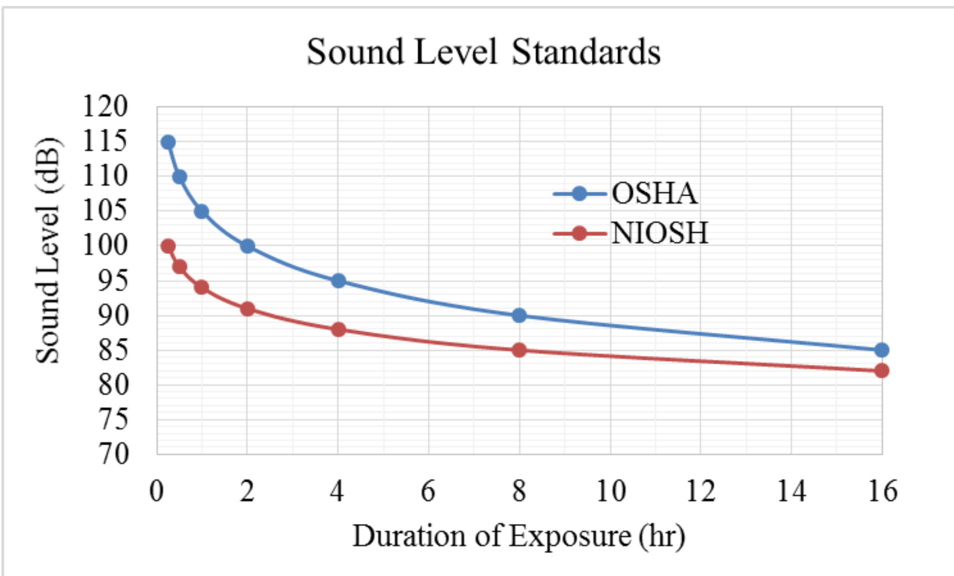

Figure 4.1 OSHA and NIOSH sound level standards with respect to duration of exposure

In order to test all possible scenarios, a series of tests in a parking lot was devised to determine whether or not each warning alarm setup complied with OSHA and NIOSH standards. These tests included measuring decibel levels while inside a stationary vehicle with the windows up and engine off, while outside of a vehicle walking, and while inside the TMA truck cab. Each test was performed at a parking lot, a controlled area at which tests were conducted at specified distances. Decibel levels from inside a parked vehicle were taken at distances of 10 ft, 50 ft, and at increments of 50 ft until 600 ft was reached for both the DAS and Alarm Device warning systems. Decibel readings were also taken while walking outside of a vehicle behind the TMA. Decibel level readings were taken at distances of 3 ft, 10 ft, 50 ft, and increments of 50 ft until 600 ft was reached for both the DAS and Alarm Device warning systems. Due to fluctuations in the sound level readings, ten consecutive sound level measurements were recorded at each location, and the average and standard deviation for these measurements were computed. The average sound level for each location was then compared to the sound level standards in order to determine if any distances experienced a sound level that fell outside of OSHA or NIOSH compliance. Figure 4.2 shows a picture of the sound meter that was used to measure the decibel level while walking outside of a vehicle.

Figure 4.2 Reading decibel level of DAS while walking outside of vehicle

For the in-cab test, the duration of exposure was an important factor, because with a longer duration of exposure, a lower decibel level is considered acceptable. These readings were taken while the alarm system was sounding for each device and were then compared to OSHA and NIOSH standards.

In addition to the sound level parking lot tests, sound levels were also recorded in a test vehicle to evaluate them for compliance with OSHA and NIOSH standards and to investigate the effects of road noise on the sound levels. This was done by having a video camera that recorded the field of view and sound levels inside the test vehicle while passing through the site as shown in Figure 4.3. As the test vehicle approached the TMA vehicle, sound levels were recorded both before and after the alarm sounded.

Figure 4.3 Field of view from inside test vehicle

4.2 Results from Sound Level Testing

Through measuring the sound levels at varying distances from 10 to 600 ft, it was determined whether or not each Alarm Device was in compliance with OSHA and NIOSH standards. At each distance increment 10 consecutive sound level readings were taken. The average, minimum, maximum, and standard deviation sound readings for use of DAS while inside a vehicle with the windows up and engine off are shown in Table 4.1.

Table 4.1 Sound Level Analysis for DAS while in Vehicle

Distance (ft)	Average Sound Reading (dB)	Min. Sound Reading (dB)	Max. Sound Reading (dB)	Std. Dev. Sound Reading (dB)
10	91.9	79.5	115.7	11.3
50	85.7	67.1	110.2	11.6
100	79.4	69.2	100.6	10.1
150	77.1	69.1	88	7
200	73.9	64.6	88.5	7.9
250	72.4	64.7	83.2	6.2
300	69.7	64	78.8	4.8
350	67.3	58.6	79.7	5.4
400	66.1	59	70.5	3.4
450	65.8	58.3	72.1	4
500	64.8	59.5	76.3	4.8
550	63.1	57.6	71.9	4.1
600	60.6	53.5	65.4	3.6

The same procedure was used for DAS while walking, and the findings are shown in Table 4.2. A reading was also taken from three feet behind the DAS to simulate being directly behind it for a worst-case scenario although this scenario is virtually impossible in a moving work zone.

Table 4.2 Sound Level Analysis for DAS while Walking

Distance (ft)	Average Sound Reading (dB)	Min. Sound Reading (dB)	Max. Sound Reading (dB)	Std. Dev. Sound Reading (dB)
3	116.4	81.5	129.2	14.9
10	99.9	79.5	118.3	10.7
50	97.4	72.5	119.6	16.2
100	96.8	73.5	113.9	12.5
150	93.2	74.7	113.9	11.8
200	89.1	68.4	108.5	13.1
250	87	69.3	114.6	12.7
300	85.5	72.1	103	9.6
350	83.3	73.1	101.8	8.6
400	82.1	73.4	101	7.5
450	81.2	70.7	95	6.8
500	79.9	68.4	98	7.2
550	78.6	68.5	91.6	6.7
600	77.1	68.4	89.1	5.5

The sound levels for the Alarm Device were also tested at varying distances from 10 to 600 feet. The results from the Alarm Device while within a vehicle with the windows up and engine off are shown in Table 4.3.

Table 4.3 Sound Level Analysis for Alarm Device while in Vehicle

Distance (ft)	Average Sound Reading (dB)	Min. Sound Reading (dB)	Max. Sound Reading (dB)	Std. Dev. Sound Reading (dB)
10	83.6	82	85.1	1
50	77.1	75.6	78.8	1.1
100	71.9	69.6	74.8	1.5
150	70.7	66.8	73	1.9
200	68.3	65.7	70.8	1.7
250	66.1	62.6	68	1.6
300	66.1	64.1	68	1.5
350	64.1	60.4	69.8	2.9
400	63.3	61	65.7	1.5
450	62.6	59.8	66.8	2.1
500	61.3	57.2	63.9	2.2
550	60.8	57.2	67.6	2.8
600	58.8	56.8	61.5	1.6

The sound levels for the Alarm Device were also tested while walking, and results are shown in Table 4.4. A reading for distance equal to three feet was also included to simulate being directly behind the Alarm Device while being outside of a vehicle as a worst-case scenario.

Table 4.4 Sound Level Analysis for Alarm Device while Walking

Distance (ft)	Average Sound Reading (dB)	Min. Sound Reading (dB)	Max. Sound Reading (dB)	Std. Dev. Sound Reading (dB)
3	120.9	118.8	123.6	1.4
10	106.3	103.8	108.8	1.5
50	102	100.3	103.2	1
100	96.5	95.2	98	0.8
150	92.8	90.7	95.3	1.4
200	92.7	90.7	95.3	1.4
250	88.2	86.2	91.1	1.4
300	85	82.9	86.8	1.1
350	84.4	79.7	89	2.7
400	84.2	81.6	86.4	1.4
450	82.1	79.2	85.3	2
500	80.2	75.9	84.8	2.6
550	79.2	76.3	82	1.6
600	76.6	72.4	79.7	2.4

In comparing the average sound levels at each distance increment, differences can be seen between the warning devices. Figure 4.4 shows the sound level experienced at each distance increment for each noise test with 5 percent error bars. OSHA and NIOSH standards for 0.25 hours of exposure are also plotted to easily show whether or not each device follows these standards at each distance increment.

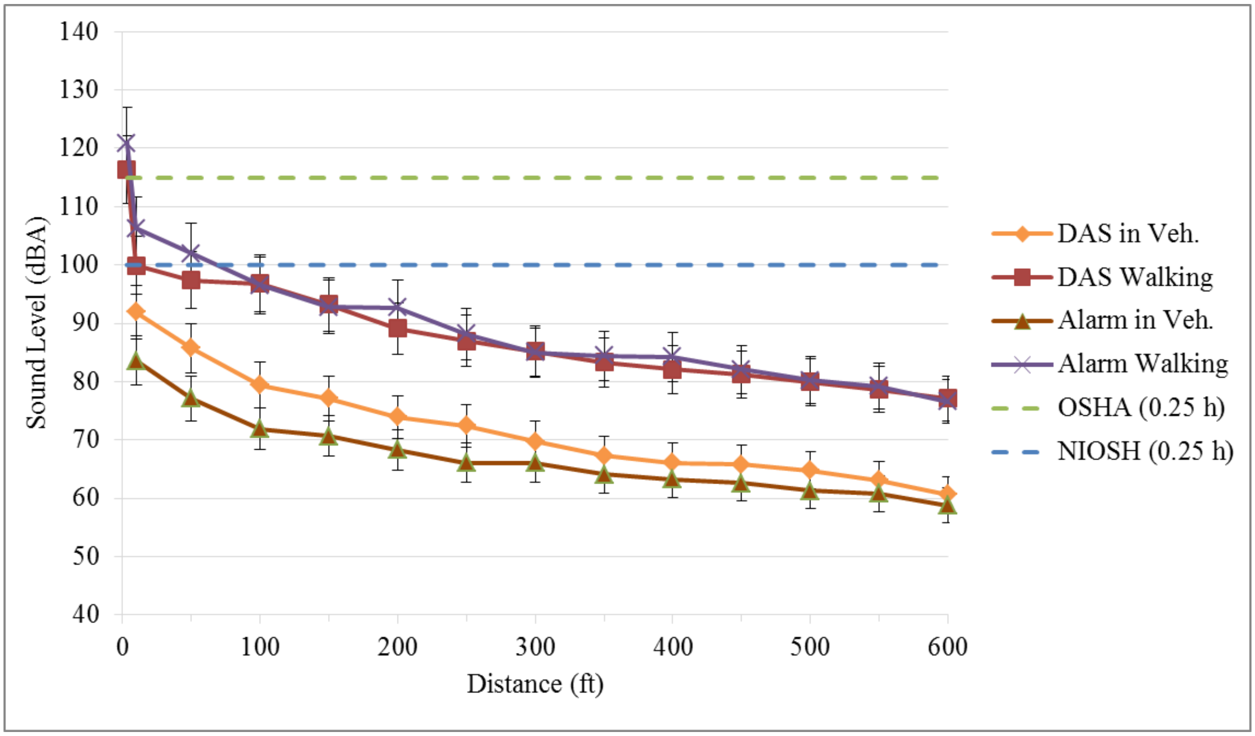

Figure 4.4 Sound level results with 5% error bars from parking lot tests

As can be seen in Figure 4.4, noise levels for both the DAS and the Alarm Device fall within OSHA and NIOSH standards at 0.25 hours of exposure with the exception of the Alarm Device within 50’ while being outside of a vehicle and the DAS within 3’ while being outside of a vehicle. However, the results showing noncompliance at locations close to the devices may not be significant because the OSHA and NIOSH noise levels are based on a 15 minute exposure time and it may be assumed that one would not stay within 50’ of the devices for longer than 15 minutes while they are sounding. In a typical mobile work zone application, the exposure time would typically be less than one second at near normal or normal highway speeds. In comparing the DAS and Alarm Device, the DAS constantly operates at a higher decibel level than that of the Alarm Device while in a vehicle. This result indicates that the sounds produced by the DAS penetrate through objects better than that of the Alarm Device. In comparing the Alarm Device walking and the DAS walking, the devices have similar decibel levels for each distance with a similar regression in sound. While both the Alarm Device and DAS have lower levels of sound while in vehicle than while walking, the DAS has a smaller difference between the two which indicates that the sound from the DAS is able to penetrate through the car windows.

For the sound results of walking at 10 ft shown in Figure 4.5, it was observed that the DAS operated at 99.9 dBA while the Alarm Device operated at 106.3 dBA. Both of these devices fall outside of the NIOSH standards for these conditions. The DAS falls outside of OSHA compliance at approximately 2 hours exposure time per day while the Alarm Device falls outside of OSHA compliance at approximately 0.75 hours exposure time per day.

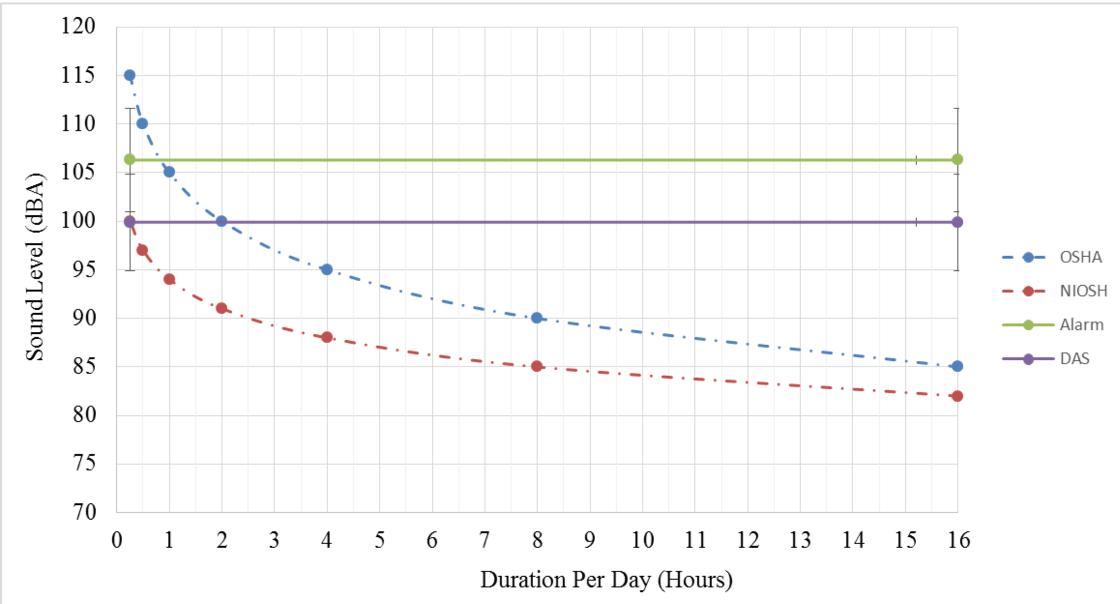

Figure 4.5 Sound level results with 5% error bars for DAS and Alarm Device at 10 ft while walking

While at 3 ft from each device, sound levels were seen to be at 116.4 dBA for the DAS and 120.9 dBA for the Alarm Device. Both of the devices at a distance of 3 ft fall outside of NIOSH and OSHA standards and therefore would require care or ceasing of the alarms in areas of possible pedestrian traffic. Figure 4.6 shows the sound level results for both the DAS and Alarm Device compared to NIOSH and OSHA standards.

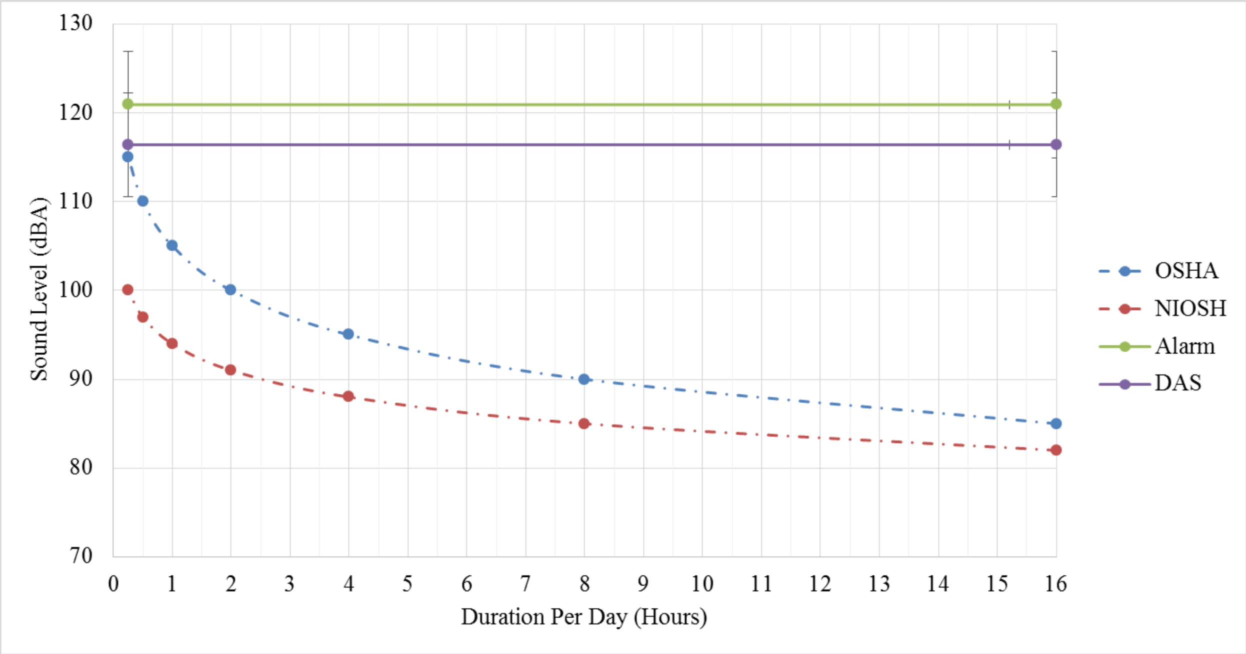

Figure 4.6 Sound level results with 5% error bars for DAS and Alarm Device at 3 ft while walking

In order to evaluate the safety of the sound levels for the workers inside the TMA vehicle, sound level measurements were taken inside the TMA vehicle to determine whether or not the prolonged exposure to each alarm sound operating continuously met national standards. The DAS was found to operate at a sound level of 80.5 dBA while within the TMA vehicle with the windows up. For this instance the Alarm Device produced a sound level of 76.7 dBA. In comparing each result with national sound standards, it can be seen in Figure 4.7 that both devices are within OSHA and NIOSH standards past 16 hours of exposure time per day.

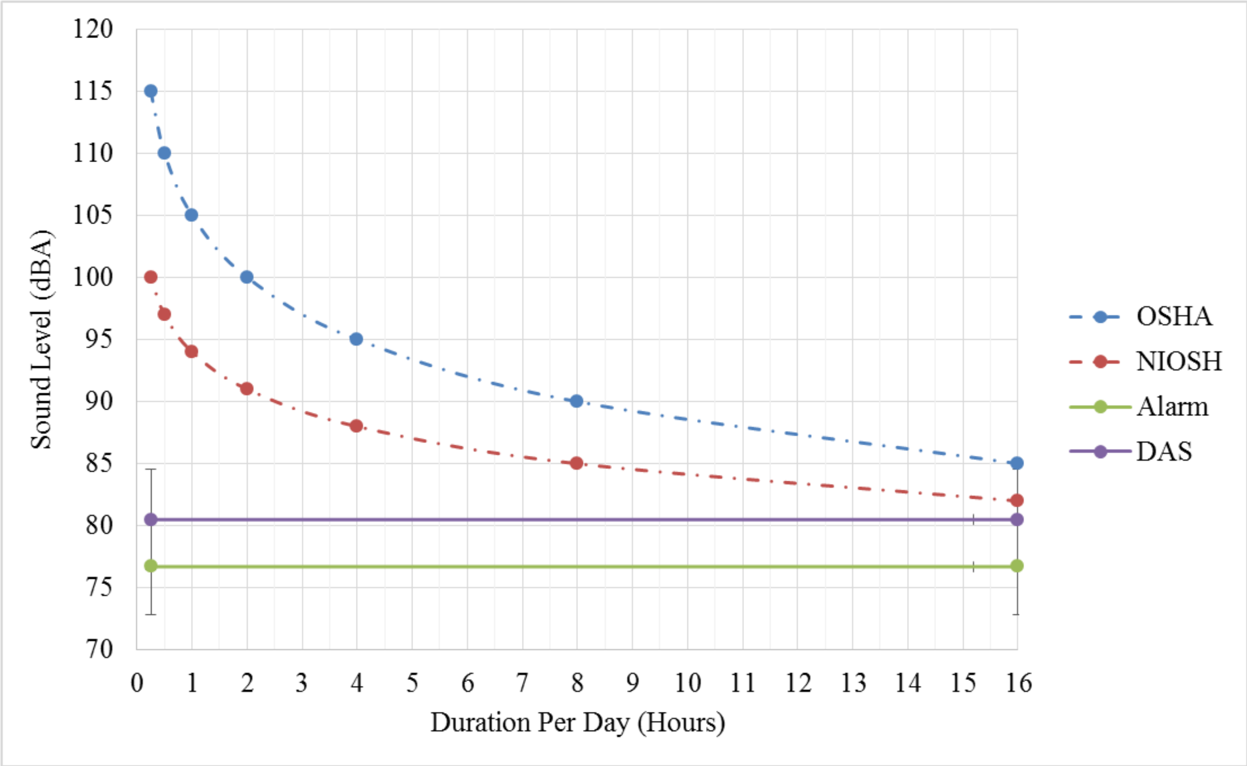

Figure 4.7 Sound level results with 5% error bars for DAS and Alarm Device from inside TMA vehicle with windows up

Sound levels inside the TMA vehicle with the windows down were also measured. The DAS was observed to have a sound level of 80.2 dBA while the Alarm Device had a sound level of 90.3 dBA from within the TMA vehicle with the windows down. Figure 4.8 shows a comparison of each device to national sound standards for this instance. The sound levels from the DAS were in compliance with both NIOSH and OSHA standards for a 16 hour exposure time per day. The sound levels for the Alarm Device fell out of NIOSH guidelines at approximately 2.25 hours exposure time per day and fell out of OSHA standards at approximately 8 hours exposure time per day. This result indicates that for use of the Alarm Device windows of the TMA vehicle should not be lowered for more than 8 hours per day of alarm operations if the alarm sound is continuous.

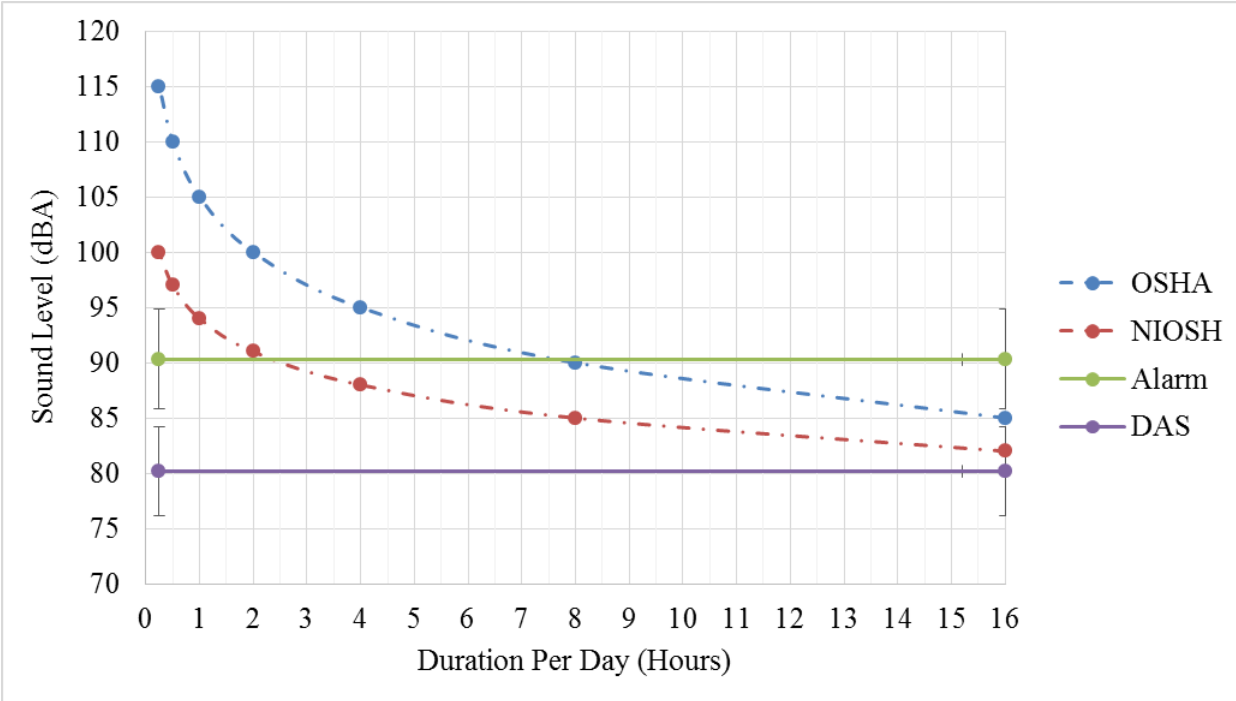

Figure 4.8 Sound level results with 5% error bars for DAS and Alarm Device from within TMA vehicle with windows down

Figure 4.9 shows the results from the highway test vehicle sound tests. In comparing average alarm sound level to average base sound level from inside the highway test vehicle, the severity of effects from background noise was determined. The base sound levels of each alarm system were found by measuring the average sound level from inside the vehicle before the alarm sounded, and these sound levels were compared with the average sound level measured after the alarm sounded. The 45 degree line in Figure 4.9 indicates the case where the sound levels before the alarm sounded are the same as the sound levels after the alarm sounded. The results from this plot show that the sound levels inside the vehicle did not increase significantly when the alarm sounded. This result reinforces the importance of looking at the distinctiveness of the sounds in addition to the sound levels.

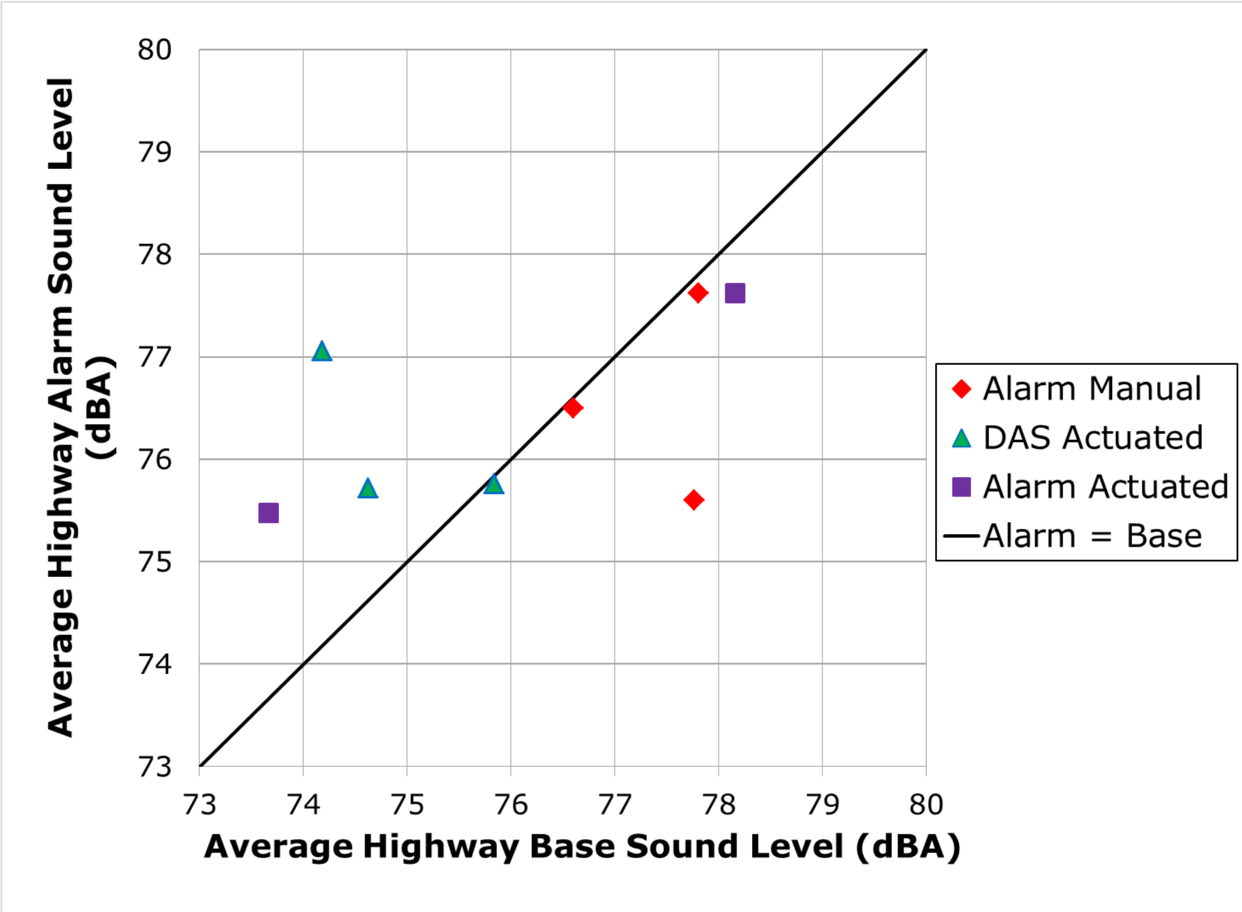

Figure 4.9 Sound level results from highway vehicle testing

4.3 Spectral Analysis

In addition to the sound level, it is also important to evaluate the distinctiveness of each alarm sound. One way of measuring the distinctiveness of alarm sounds is through the use of spectral analysis. Spectral analysis is the examination of frequencies through the creation of a spectrogram. A spectrogram is a plot of frequency versus time which shows the amplitude of the frequencies through variations in color intensity. High concentrations (or energies) of frequencies are shown on a spectrogram with red in a red-green scale. A spectral analysis was performed on both the Alarm Device and DAS sounds for cases with and without the presence of highway background noise. For the DAS alarm sound, the spectral analysis without highway noise was performed using the digital sound file that the DAS broadcasts. For the Alarm Device sound, the spectral analysis without highway noise was performed using an audio clip from the parking lot tests while outside of the vehicle. For both alarm sounds, the spectral analysis with highway noise was performed using audio clips from the highway vehicle tests. This analysis helped to evaluate the alarm sounds for their distinctiveness and for their effectiveness in cutting through other noises and not blending in with background noises.

Figure 4.10 shows the spectrogram of the Alarm Device sound without background noise. This image shows the Alarm Device to send a wide range of frequencies with little concentration.

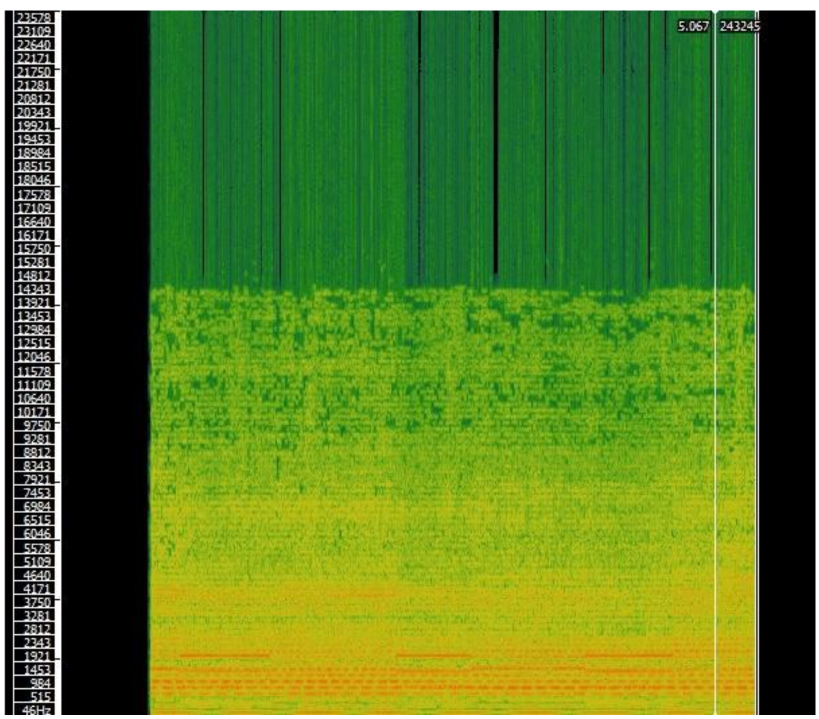

Figure 4.10 Spectrogram for Alarm Device without background noise

Figure 4.11 shows the spectrogram of the DAS without background noise. The alarm sound from the DAS unit consisted of short bursts of noise followed by an audible message that said, “Slow vehicles ahead”. This analysis shows the DAS to send a concentrated burst of frequencies for the first section of the alarm and then a wider range of frequencies for the audible message portion of the alarm.

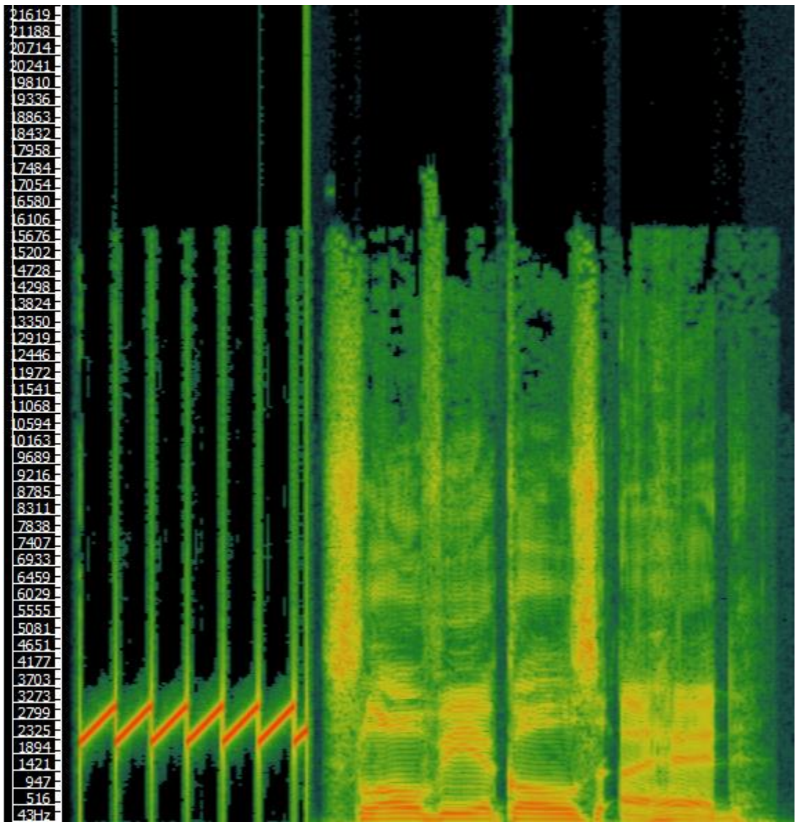

Figure 4.11 Spectrogram for DAS without background noise

In order to better understand how these devices would perform in use, a spectral analysis was performed for both the Alarm Device and DAS sounds on the highway. Figure 4.12 shows the spectrogram for the Alarm Device on the highway. The background noise is shown as the green lines with the alarm activation being boxed in red.

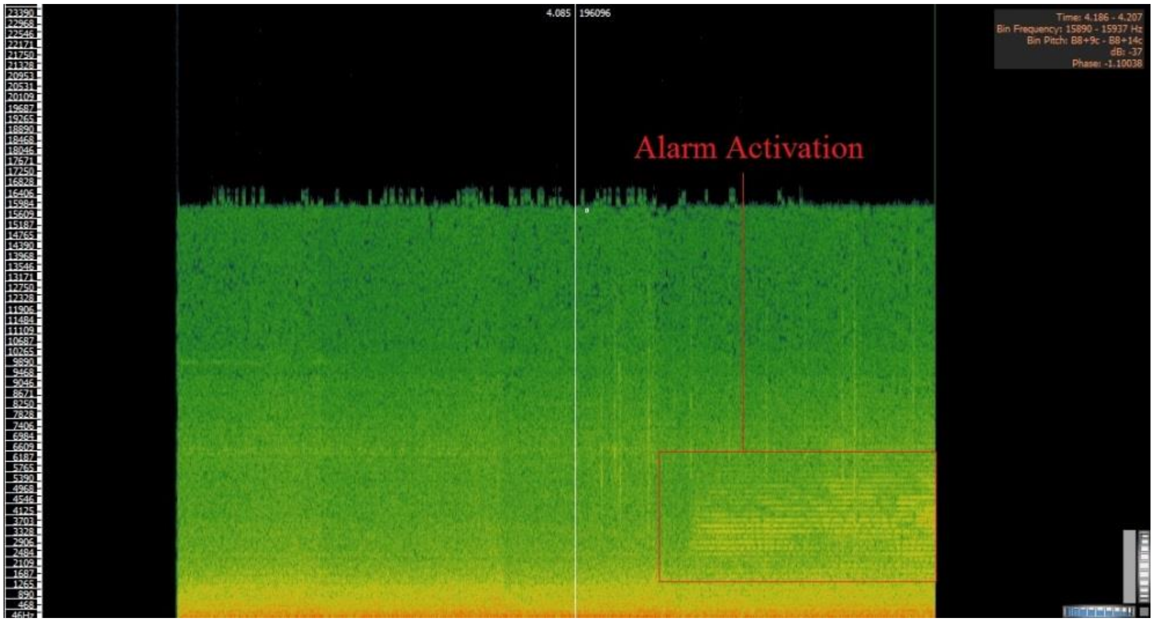

Figure 4.12 Spectrogram for Alarm Device on highway

In looking closely at Figure 4.12, it can be seen that whenever the alarm sounded, several thin, yellow lines appeared over a range of frequencies in the y-axis. This result indicates that the Alarm Device sound produced a wide spectrum of frequencies, but the road noise appeared to mask out the Alarm Device sound.

Figure 4.13 shows the spectrogram for the DAS warning system on the highway. The green lines show the background noise of the highway while the alarm instance is boxed in red.

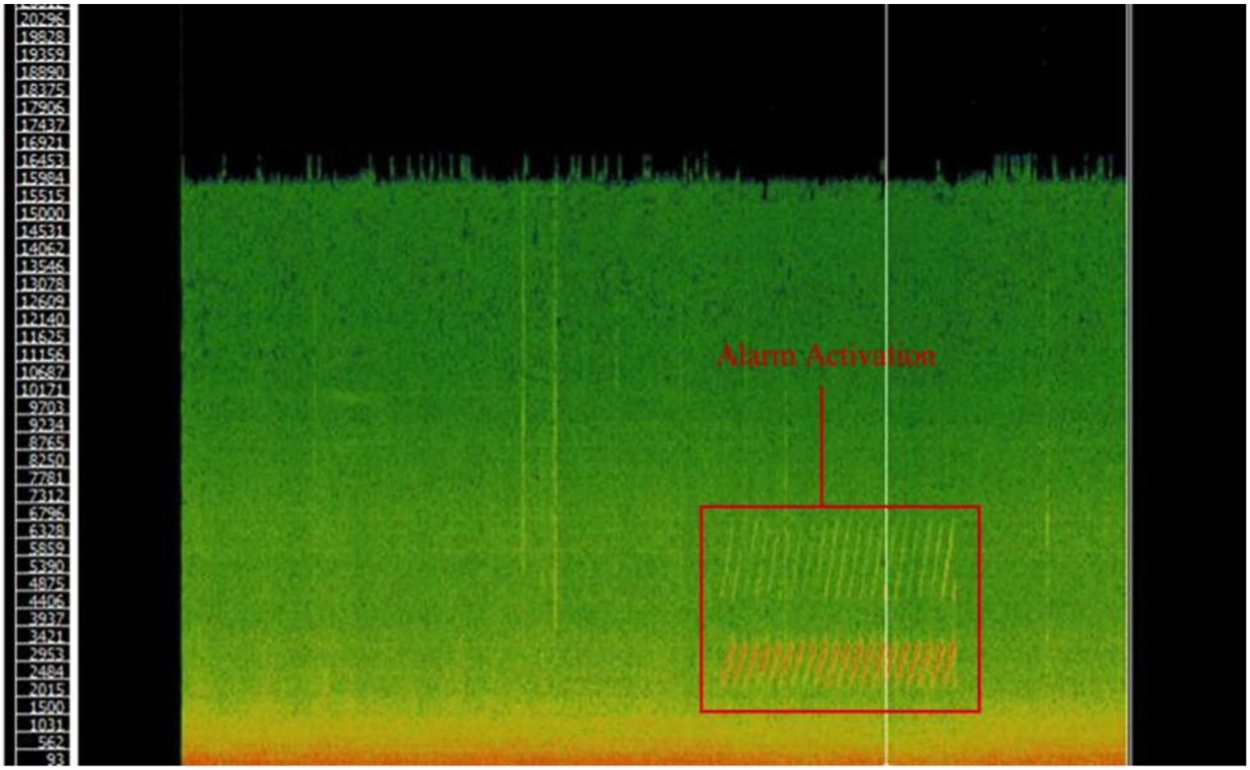

Figure 4.13 Spectrogram for DAS on highway

The spectrogram for the DAS sound produced distinct, red lines in a small range of frequencies while also producing simultaneous lighter yellow line at a higher frequency. The DAS sound did not appear to be masked out by the road noise. In comparing the analyses for the Alarm Device and DAS sounds, it can be seen that the DAS produced a much more distinct sound than the Alarm Device even with background noise of a highway.

4.4 Luminance Testing

Luminance is a measure of light intensity in units of $\frac{cd}{m^2}$ or NITS and was determined for each warning set up. This testing was done to ensure each truck was emitting similar luminance levels to avoid a bias due to a light intensity difference. The luminance levels of the two TMA trucks were found to be comparable. Figure 4.14 shows a typical warning light setup on TMA trucks.

Figure 4.14 Example of a typical warning light setup on TMA truck

5 Evaluation of Driver Behavior

5.1 Methodology for Evaluating Driver Behavior

A variety of factors were analyzed for investigating driver behavior, including merging distances, average vehicle speeds, and undesirable driving behaviors. Undesirable driving behaviors must first be defined. The AASHTO Green Book (AASHTO, 2011) was referenced for safe stopping sight distance (SSD). SSD is the distance at which a vehicle may safely come to a halt from a given velocity and reaction time. The SSD is given by

$$\boldsymbol{SSD = 1.47Vt + 1.075\frac{V^2}{a}} \qquad \text{Equation 5.1}$$

where:

SSD = stopping sight distance, ft

V = vehicle speed, mph

t = brake reaction time (s)

a = deceleration rate (ft/s^2).

The standard values recommended by AASHTO are 2.5 s for brake reaction time and 11.2 ft/s^2 for the deceleration rate. Figure 5.1 shows a graph of SSD with respect to vehicle speed based on these values. For the purposes of this research, the values recommended by AASHTO were used except for some of the preliminary tests in Columbia, Missouri in which a value of 4.5 s for brake reaction time was used.

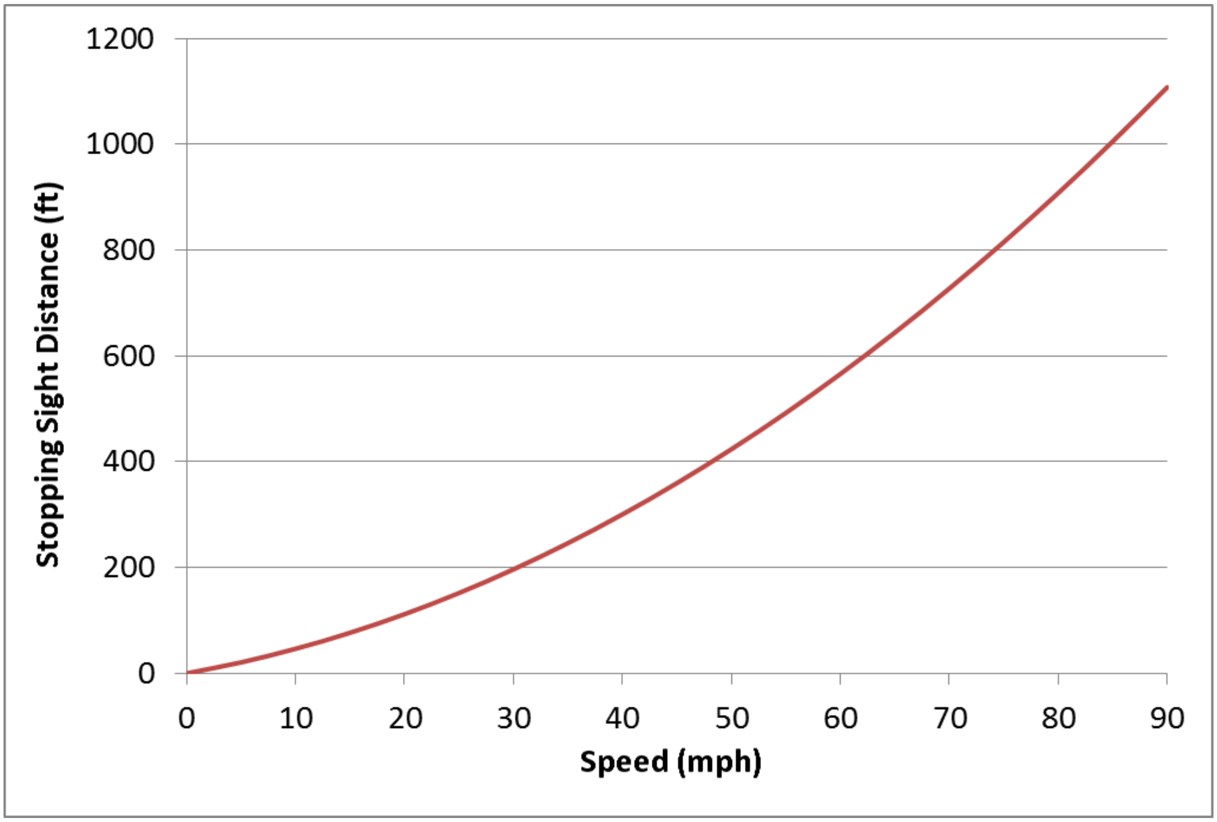

Figure 5.1 Stopping Sight Distance and Vehicle Speed (AASHTO, 2011)

In referring to Figure 5.1, it can be seen that for a speed differential of 60 mph, corresponding to the test conditions of 70 mph prevailing speeds and 10 mph TMA speed, a proper SSD was approximately 600 ft. Therefore, any merges at a distance of greater than 600 ft from the TMA vehicle were considered a desirable behavior, and merges within 600 ft were considered undesirable.

In order to determine whether or not a merge happened within 600 ft, the distance from the TMA to the vehicle was measured from video data for each warning setup using photogrammetry. Photogrammetry is the use of an image to measure distances. Figure 5.2 shows an example image from the TMA video data from the Alarm Manual setup. Photogrammetry using manual processing of video data was selected over other methods such as active infrared for several reasons. First, the video data processing facilitated the collection of additional data besides merging distances which allowed for analysis of audio data and led to a false alarm and false negative analysis. Manual video data processing also allowed for the collection of vehicle types and roadway geometrics aided in understanding the analysis. As previously mentioned, the photogrammetry is accurate up to distances of approximately 600 ft while active infrared can reach distances of up to 2400 ft depending on the target reflectivity. However, horizontal and vertical curves in the roadway could become an issue in dealing with large distances. Another reason for using photogrammetry was the flexibility of post-processing of videos. The processing of video data allowed for easy replay and analyzing of data to be sure that data was accurate and also facilitated the investigation of undesirable driver maneuvers.

Figure 5.2 Example of video data to be assessed from Alarm Manual setup.

To estimate the distances using photogrammetry, the centerline striping was used as a reference. MoDOT uses a standard of 40 ft distance from the beginning of one white stripe (skip) to the beginning of the next. Using this standard, 15 skips are equivalent to 600 ft, and therefore each merge within 15 skips needed to be analyzed further and merges greater than 15 skips were considered the most desirable. However, in looking at Figure 5.2 it is difficult to determine the number of skips greater than 5 skips and therefore there is a need to make it easier to differentiate the farther skips. A calibration process was used to determine the relationship between physical distance and distance on the image. Separate calibrations were performed for the TMA with the Alarm Device and the TMA with the DAS. Each calibration was accomplished by overlaying an image onto the video that had distinct lines at each skip distance. The first step of overlaying was to determine the relationships between actual physical distance and measured distance on the image. This step was done by measuring the skips that were easily differentiated. These points were then plotted and a power trend line for each TMA was applied in order to generate an equation that estimated the image distances of the farther skips. Figure 5.3 shows the regression function for the TMA with the Alarm Device.

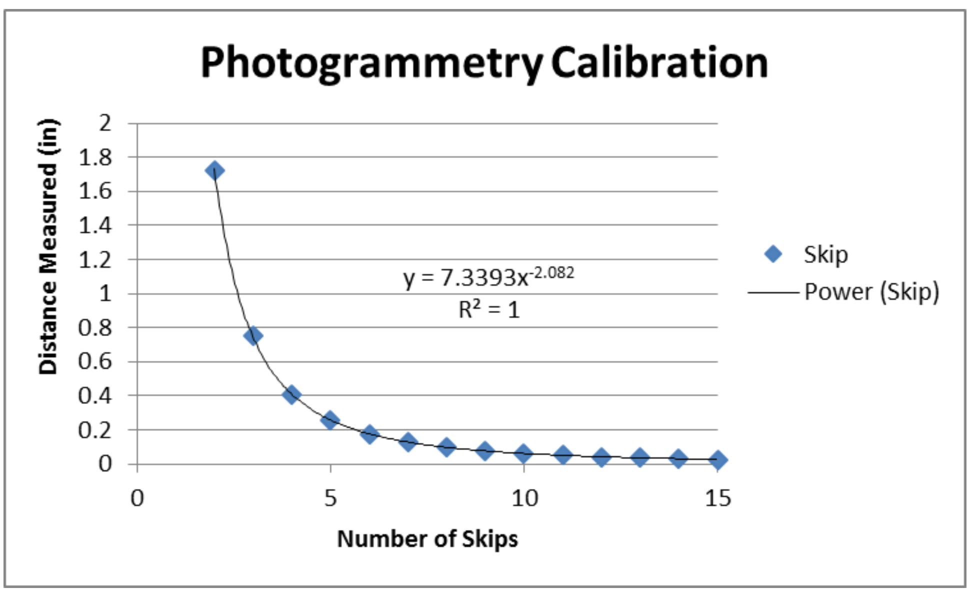

Figure 5.3 Curve of video image regression for TMA with Alarm Device

Using the equation generated by the curve of regression, a drawing was constructed and overlaid onto the video files. This drawing showed a more clear differentiation of farther skips. The drawing for the TMA with the Alarm Device is shown in Figure 5.4.

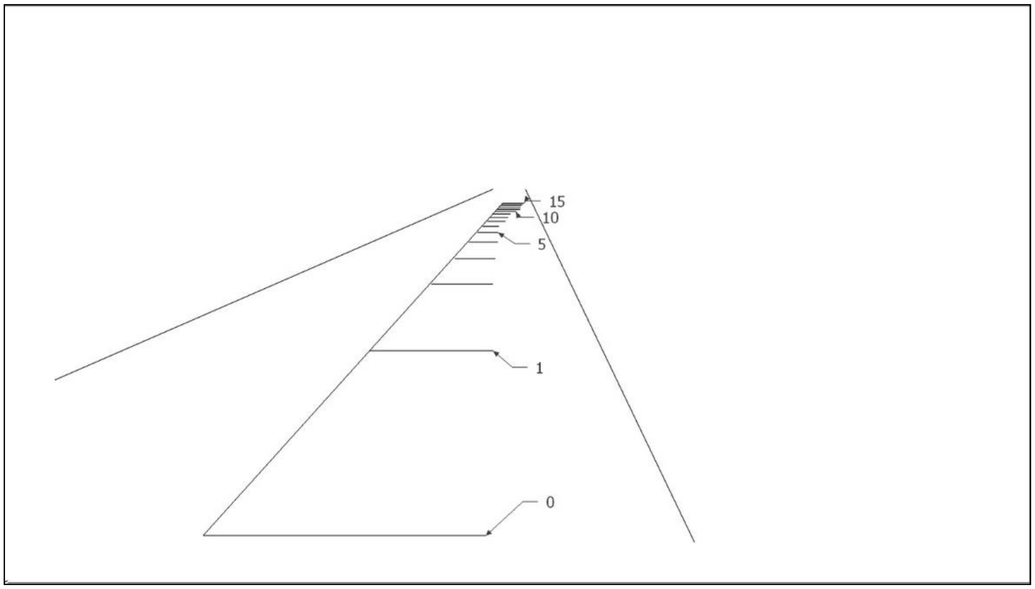

Figure 5.4 Example drawing to be overlaid onto video files for TMA with Alarm Device

By overlaying the drawings with the video file, each skip was easily identified. An example of this combined image for the TMA with the Alarm Device is shown in Figure 5.5. This resulting image allowed for the determination of vehicle merging distances.

Figure 5.5 Resulting image to be used in vehicle merging analysis for TMA with Alarm Device

In addition to merging distances, merging speeds were also calculated by measuring the distance and time traveled by a merging vehicle. The time calculation was performed by using the frame rate of the video player which was 30 frames/sec. Therefore, the number of frames it took for a vehicle to travel a set distance was counted to determine its speed.

In order to determine statistical significance, ANOVA tests were performed for the merge distances within 600 ft and merging vehicle speeds within 600 ft for each warning setup. ANOVA is an analysis of variance between entries and outputs a p-value that is used to determine statistical significance. The statistical confidence is determined by subtracting the p-value from 1.00.

5.2 Results for Merging Distances and Speeds

In analyzing the number of total merges by test site it was determined that the DAS Actuated setup experienced the highest number of merges while the Alarm Manual setup experienced the fewest number of merges. The total time of observations was also determined by removing segments during which data was not being collected such as in periods of changing roadways or during worker breaks at which the cameras were still recording footage. This data is shown in Table 5.1.

Table 5.1 Total Number of Merges and Total Time of Observations by Setup

Setup	Total Number of Merges	Total Time of Observations
Control	884	2:24
Alarm Manual	711	2:02
Alarm Actuated	807	2:53
DAS Continuous	816	2:28
DAS Actuated	894	3:02
Total	**3312**	**12:49**

The total number of merges for the Alarm Manual, DAS Continuous, and DAS Actuated setups changed slightly from the mid-project presentation due to additional data checking and clean-up. The Alarm Manual setup was discovered to have more merges than previously thought while both DAS setups had a decrease in merges. The DAS setups had a decrease in number of total merges because the original count included all merges in all lanes throughout the 3-lane segments. This process caused several vehicles to be double counted through the 3-lane segments which lead to the higher original count for total number of merges.

A 15-minute volume count was collected for each test site and then converted to vehicles per hour which gave a good estimate to the average volume experienced at each location. The percentage of trucks was also taken during this volume count. The average volume and percentage of trucks for each test setup are in Table 5.2. The traffic conditions for all five setups were similar being light and with approximately the same percentage of trucks. Compare the volumes over all lanes listed in Table 5.2 with freeway lane capacities which are typically higher than 2000 vehicles per hour per lane. Light traffic conditions are important in order to keep vehicle interaction effects from polluting the data. The objective of the study is to measure driver reaction to the mobile alarm systems unencumbered by the presence of other vehicles.

Table 5.2 Average Volume and Percentage of Trucks by Setup

Setup	Average Volume (vph)	% Trucks
Control	676	27%
Alarm Manual	577	25%
Alarm Actuated	488	24%
DAS Continuous	857	29%
DAS Actuated	739	24%

From the total number of merges, more detailed information such as percentage of merges within 600 ft, percentage of merges involving commercial vehicles, percentage of merges on horizontal curves, and percentage of merges on 3-lane segments was determined. A majority of the merges were observed to be on tangent 2-lane segments. On average, 15% of the merges were seen to occur on horizontal curves and 8% of the merges were observed on 3-lane roadway segments. The majority of the merges were also observed to involve private vehicles with 19% of the merges involving commercial vehicles. Percentages of merges within 600 ft, merges involving commercial vehicles, merges on curve, and merges on 3-lane segments for each setup along with the total number of merges observed are shown in Table 5.3.

Table 5.3 Properties of Total Merges by Alarm Setup

Setup	Total Number of Merges	Percent Merges within 600'	Percent of Merges Involving Commercial Veh.	Percent of Merges on Curve	Percent of Merges on 3-Lane Segment
Control	884	11%	20%	11%	5%
Alarm Manual	711	15%	18%	26%	14%
Alarm Actuated	807	7%	21%	5%	8%
DAS Continuous	816	21%	20%	17%	7%
DAS Actuated	894	18%	18%	16%	4%

Through analyzing the merges within 600 ft, values for average merging distance, standard deviation of the average merging distance, average speed, and standard deviation of the vehicle speeds were determined and are shown in Table 5.4. Table 5.4 shows that the DAS setups had the longest average merge distances being 122 ft and 53 ft longer than the Control. This result equates to drivers having an additional 1.2 and 0.52 seconds of reaction time at 70 mph. DAS Continuous also had the smallest standard deviation of merging distance among all setups which means traffic behaved more uniformly with the DAS Continuous setup. Furthermore, DAS Continuous decreased the average speeds by 3 mph while all other setups resulted in similar or higher speeds compared to Control. The similar or higher speeds could be due to travelers getting startled by actuation and wanting to pass the TMA, or not feeling a need to decrease speed due to Alarm Device sound being less distinctive. The decrease in speed for the DAS Continuous setup could be due to the distinctiveness of the DAS sound and the positive effects of continuous operation of the alarm which could cause all travelers to hear the warning and lessen the sudden actuation effect that may tend to startle some travelers. Even though the standard deviation of speed for DAS Continuous was higher than the other alarm setups, it was still smaller than the Control.

Table 5.4 Results for Merging Distances and Speeds

Setup	Number of Merges within 600'	Average Merge Distance (ft)*	Std. Dev. Merge Distance (ft)	Average Speed (mph)**	Std. Dev. Speed (mph)
Control	95	392	146	58.4	9.6
Alarm Manual	108	408	183	62.7	7.3
Alarm Actuated	57	357	161	61.7	7.9
DAS Continuous	171	514	126	55.4	9.2
DAS Actuated	157	445	183	58.9	8.4

* and ** separate Anova tests – each statistically significant 99.99% confidence interval

To analyze the statistical significance of average merging distances within 600 ft and average speeds of vehicles merging within 600 ft, separate ANOVA tests were performed. Both measures were statistically significant at a 99.99% confidence interval, thus none of the results were due to randomness.

In looking at the merges within 600’ for each warning type, divisions were made for every 200’ in order to find the percentage of merges from 0-200’, 201-400’, and 401-600’ (Figure 5.6). Three subdivisions were chosen to better break up the data in order to provide a distribution of merging distances within each alarm setup. If too many divisions were chosen then the data would be too divided while too few would not be descriptive enough. As can be seen in Figure 5.6, each warning setup had the greatest percentages of merges in the 401-600 ft distance. However, the comparison between warning setups shows that the DAS Continuous has a greater ratio of merges within the 401-600’ group than any other setup.

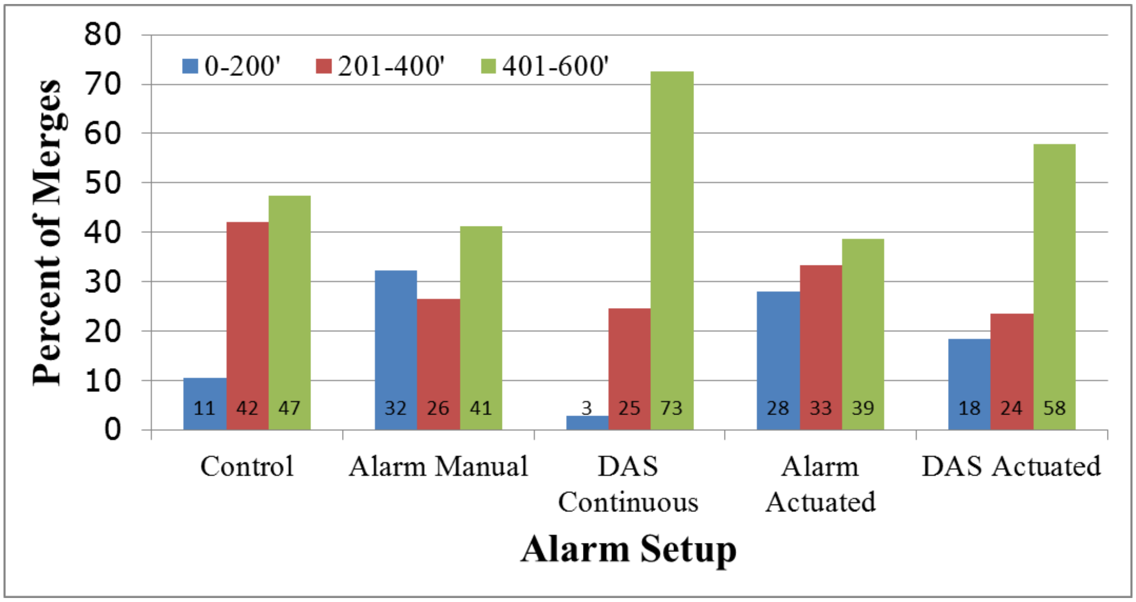

Figure 5.6 Distribution of merges in 200' segments by setup

The average merging distance for each alarm setup was observed to increase for every alarm setup except for the Alarm Actuated when compared to the control with the DAS Continuous having the most dramatic effect on merging distance. The increased merging distance for the Alarm Manual setup could be due to the fact that this was the only setup with a two stage alarm system where the TMA driver first triggered the lights and then triggered the sound alarm when the vehicle got closer. For the actuated setups, the lights and sound were activated simultaneously.

5.3 Anecdotal Observations of Driver Behavior

Some undesirable driving behaviors were observed with the DAS setups. While the DAS Continuous setup was in operation, some drivers were observed passing the TMA on the shoulder, giving the TMA an additional amount of space while passing. An example of this behavior is shown in Figure 5.7. This behavior could be due to drivers reacting to the presence of a mobile work zone and/or to the alarm and the “Slow Vehicles Ahead” audio message. Some vehicles dramatically decreased their speed as they moved over to the shoulder to match the speed of the work vehicles. MoDOT personnel indicated that this type of driving behavior has been observed during routine striping operations, so the behavior may not be due to the presence of the mobile work zone alarm.

Figure 5.7 Example of vehicle passing TMA on shoulder

When the DAS Actuated setup was in effect, some drivers were seen to perform emergency driving maneuvers such as quick merges or swerving, perhaps because drivers were startled by the actuation and reacted to the unexpected DAS sound. Sudden merges or swerving are undesirable from both traffic operations and traffic safety perspectives. An instance in which a driver in a silver car was startled and suddenly applied brakes was seen with the DAS Actuated. What made this example undesirable was the fact that a dump truck was closely behind the silver car that was startled, making the dump truck driver have to suddenly apply the brakes as well. However, the traffic situation in front of the silver car could not be determined from the video so it is possible that this vehicle was reacting to another event. Therefore, it is unclear whether this undesirable driving maneuver was due to the presence of the DAS Actuated mobile alarm. An image of this event is shown in Figure 5.8.

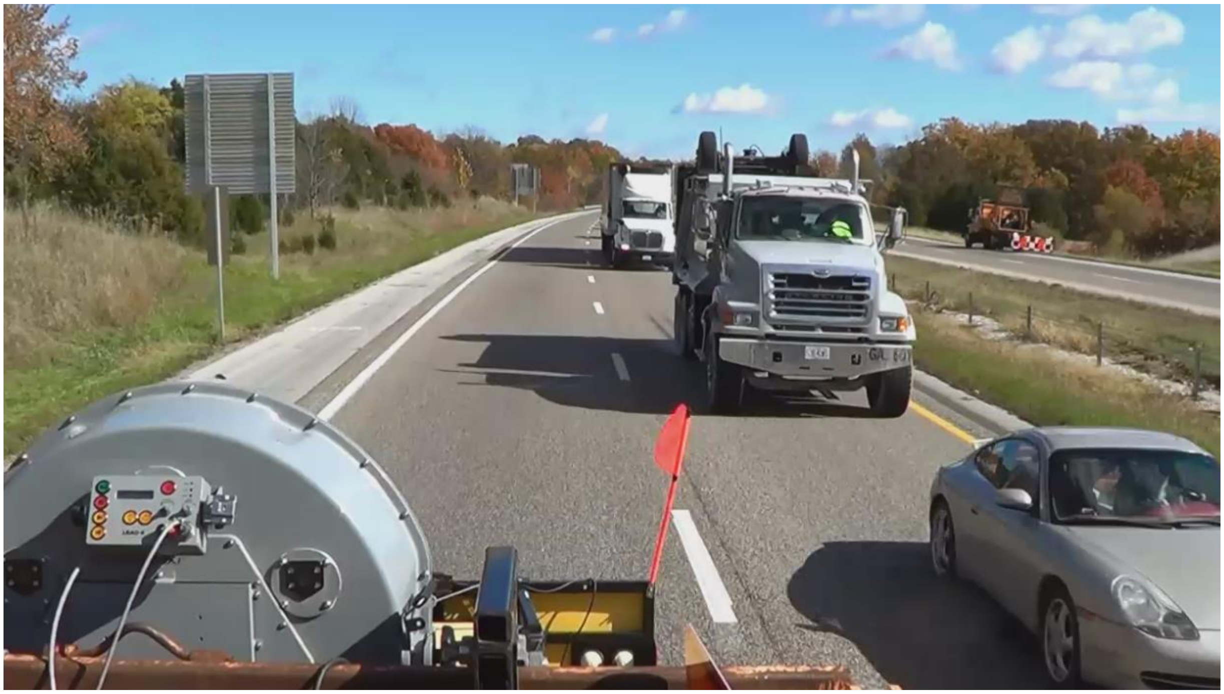

Figure 5.8 Sudden breaking by silver car caused dump truck to have to quickly and forcefully apply the brakes

6 Alarm Activations

6.1 Methodology for Evaluating Alarm Activations

In addition to evaluating driver behavior, another important component of the research involved evaluating both the manual and actuated alarm activation modes for false negatives and false alarms. For the manual and actuated modes, the alarm was intended to sound if a vehicle had reached or passed the threshold distance from the TMA truck. A false negative occurred when the vehicle reached the threshold distance behind the TMA truck but the alarm did not sound. Conversely, if the alarm did sound but the vehicle did not yet reach the threshold distance, it was considered a false alarm.

For the actuated mode, the threshold distance was the SSD as described in the previous chapter. The SSD for each vehicle that merged within 600 ft was determined based on the vehicle speed. For the manual mode, the threshold distance was based on the instructions that were given to the driver for activating the alarm. For the manual mode, the driver was instructed to first turn on the lights when the vehicle was at a distance of 26 skips (1,056 ft) and then to sound the alarm when the vehicle was at a distance of 13 skips (528 ft). To account for the uncertainties of estimating the number of skips, a threshold distance of 11 skips (440 ft) to 15 skips (600 ft) was used for the evaluation of false negatives and false alarms for the manual mode.

6.2 Results from Evaluation of Alarm Activations

Major contributing factors to false alarms were the presence of horizontal curves in which the actuation system was directed at an adjacent lane and lateral movements by the TMA vehicle that caused the alarm to sound on a vehicle in an adjacent lane. The total number of false alarms, number of activation events, and false alarm rate by test setup is shown in Table 6.1. The results found in Table 6.1 differ from the results provided in the mid-project presentation after further data checking and correction. Each false alarm rate was determined by dividing the number of false alarms by the total number of activation events for the Control, Alarm Manual, Alarm Actuated, and DAS Actuated setups. The Control setup was able to measure false alarms because it had the actuation system running in the background and therefore recorded data that was used to complete a false alarm analysis. The DAS Continuous setup also had the actuation system running the background, but the actuation system was not running properly to collect any data.

Table 6.1 False Alarm Analysis with Horizontal Curves by Setup

Setup	No. False Alarms	No. Activation Events	False Alarm Rate
Control*	19	61	31%
Alarm Manual**	51	97	53%
Alarm Actuated	27	39	69%
DAS Continuous***	N/A	N/A	N/A
DAS Actuated	90	145	62%

* had actuation program running in background
** based on 440-600 ft acceptable manual actuation threshold
*** actuation system was not properly collecting any data

In order to isolate additional causes for false alarms, false alarms due to horizontal curves in the roadway were filtered out. Since the systems tested were prototype systems, different technologies such as a curve tracking system could be employed in the future to account for changes in horizontal alignment. The analysis of the false alarms with the horizontal curve segments eliminated is shown in Table 6.2. Other causes of false alarms included slight swerving of the TMA vehicle which angled the actuation system towards the adjacent lane and vehicles in the adjacent lane driving close to or on the center stripe. False alarms were also observed to be high for the Alarm Manual setup due to the driver being cautious and sounding the alarm earlier than intended.

Table 6.2 False Alarm Analysis without Horizontal Curves by Setup

Setup	No. False Alarms	No. Activation Events	False Alarm Rate
Control*	18	60	30%
Alarm Manual**	42	97	43%
Alarm Actuated	17	39	44%
DAS Continuous***	N/A	N/A	N/A
DAS Actuated	25	145	17%

* had actuation program running in background
** based on 440-600 ft acceptable manual actuation threshold
*** actuation system was not properly collecting any data

In addition to false alarms, false negatives were also analyzed. False negatives are instances in which the alarm should have been activated given the circumstances but did not activate. The threshold distance for determining whether or not the alarm should have sounded was the stopping sight distance for the actuated mode and 600' for the manual mode. False negatives occurred on both horizontal and vertical curves. The total number of false negatives and the false negative rates are shown in Table 6.3.

Table 6.3 False Negative Analysis with Horizontal Curves by Setup

Setup	No. False Negatives	No. of Merges < Threshold Distance	False Negative Rate
Control*	42	74	57%
Alarm Manual**	6	48	13%
Alarm Actuated	26	48	54%
DAS Continuous***	N/A	N/A	N/A
DAS Actuated	25	97	26%

* had actuation system running in background
** based on 440-600 ft acceptable manual actuation threshold
*** actuation system was not properly functioning in background

The number of merges that occurred when the distance from the vehicle to the TMA was less than the stopping sight distance (actuated mode) or 600’ (manual mode) indicated the number of instances in which the alarm should have been triggered. Therefore the false negative rate was calculated as the number of false negatives divided by the number of merges that occurred within the threshold distance. The Control setup produced false negatives because the actuation system was running in the background but not sounding any alarms. The results found in Table 6.3 also differ from the results given in the mid-project presentation due additional data checking and correction.

Like the false alarm analysis, horizontal curve segments were excluded to isolate causes for false negatives. The false negative analysis excluding horizontal curve segments is shown in Table 6.4. Another cause of false negatives involved instances in which the TMA vehicle was on either a vertical sag or crest curve. In some cases, vertical curves caused the actuation system to aim below or above the approaching vehicle.

Table 6.4 False Negative Analysis without Horizontal Curves by Setup

Setup	No. False Negatives	No. of Merges < Threshold Distance	False Negative Rate
Control*	28	74	38%
Alarm Manual**	4	48	8%
Alarm Actuated	20	48	42%
DAS Continuous***	N/A	N/A	N/A
DAS Actuated	6	97	6%

* had actuation system running in background
** based on 440-600 ft acceptable manual actuation threshold
*** actuation system was not properly functioning in background

7 Evaluation of Trade-offs

The decision regarding which system to use involves trade-offs between performance, cost, and other factors such as maintenance requirements. Some of these trade-offs are summarized in Table 7.1.

Table 7.1 Design Trade-Offs by Alarm Setup

Factor	DAS Continuous	DAS Actuated	Alarm Manual	Alarm Actuated	Desirable
Merge Distance (ft)	+122	+53	+16	-35	+
Standard Deviation of Merge Distance (ft)	-20	+37	+37	+15	-
Approach Speed (mph)	-3.0	+0.5	+4.3	+3.3	-
False Positive (Including Horizontal Curves)	N/A^{+}	62%	53%	69%	0%
False Negative (Including Horizontal Curves)	N/A^{+}	26%	13%	54%	0%
Observed Driver Behavior	Drive on Shoulder	Sudden Maneuvers	None Observed	None Observed	None Observed
Sound Safety 50' In Veh. (dB)	86	86	77	77	< 115^{++} < 100^{+++}
Sound Distinctiveness	****	****	**	**	****
Cost	$$$$	$$$$$	$	$$	$
Convenience	Automatic	Calibration	Manual	Calibration	Automatic
Energy Consumption	*****	****	*	***	*

$^{+}$ DAS Continuous did not have actuation system properly collecting data in background
$^{++}$ OSHA, 0.25 h
$^{+++}$ NIOSH, 0.25 h

As described previously in this report, all of the setups resulted in an increase in the merging distance except for the Alarm Actuated setup. The DAS Continuous setup was the only setup that led to a reduction in approach speed and standard deviation of merging distance. With regard to alarm activations, both the manual and actuated modes experienced some false alarm and false negative events. The DAS Continuous setup led to situations where vehicles drove partially on the shoulder while some sudden vehicle maneuvers were observed with the DAS Actuated setup.

The performance of these systems could be evaluated in conjunction with other factors such as cost and maintenance requirements when deciding which system to implement. In evaluating estimated costs between each setup, the DAS Actuated is the most expensive due to the costs of the DAS unit and actuation device followed by the DAS Continuous setup, then Alarm Actuated, and Alarm Manual. The DAS Continuous setup requires the greatest energy consumption. The Alarm Device setups require less energy to operate. The actuated system requires calibration, while the manual system creates additional tasks for the driver of the TMA.

8 Conclusions

Both the Alarm Device and DAS were found to be in compliance with national standards using sound level testing. In comparing the two alarm sounds, the DAS sound was much more distinctive. The Alarm Device sound had a tendency to blend in with background noise as shown in the spectral analysis.

The most significant finding from this project was the results from the analysis of average merging distances, standard deviation of merging distances, and average vehicle speeds. Merging distances and speeds are surrogate safety measures for mobile work zones in that a longer average merging distance and a lower average vehicle speed represent a lower likelihood for crashes. Crash analysis was not possible, since the brevity of test deployments meant statistically insignificant sample sizes. The Alarm Actuated setup decreased the average merging distance while other warning setups caused an increase. The DAS Continuous setup caused the greatest increase in average merging distance and was the only setup that led to a decrease in the average vehicle speed and standard deviation of the merging distance. A lower standard deviation of merging distance indicates that vehicles are merging in a more uniform manner. Other important findings relate to driving behavior. Some undesirable driving behaviors were observed with the DAS warning setups, specifically with sudden maneuvers while using DAS Actuated setup and with vehicles travelling partially on the shoulder while using the DAS Continuous setup. However, it is unclear whether these driving behaviors were caused by the presence of the mobile work zone alarm or the presence of the mobile work zone.

In examining the results as a whole, the DAS Continuous setup had the most significant impact on average merging distances and average merging speed while a main drawback was the tendency of some drivers to use part of the shoulder while passing the TMA vehicle. Perhaps, some drivers were reacting to the alarm sound by looking for slow vehicles and behaved accordingly. One recommendation for the DAS therefore is to use continuous operation but to explore different types of alarm sounds since this project was an initial test to demonstrate the concept of mobile work zone alarms and further refinements to the alarm sounds would likely improve the results. For the Alarm Device warning systems, recommendations include the use of continuous operation, more directional and distinctive sound, shortened repetition period of sound, and a mounted loud speaker replacing the Alarm Device. In exploring alternative sounds for both systems, various factors such as localization, masking, urgency, and attenuation could be taken into account.

Some recommendations for the actuated system include reducing false alarms and false negatives by narrowing the band of actuation and performing horizontal and vertical curve tracking. Road segments containing horizontal and vertical curves were the most problematic for the actuated system.

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