Evaluation of Mobile Work Zone Alarm Systems

by

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ABSTRACT

Highway maintenance often involves the use of 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 moving work zone. One novel tool for mitigating this problem is a mobile work zone alarm system. This paper 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 levels for the tested configurations 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. Some undesirable driver behaviors were occasionally observed, but it is unclear whether these driver behaviors were due to the presence of the mobile work zone alarm device. Factors such as horizontal and vertical curves and movement of the TMA vehicle caused false alarms and false negatives. The research demonstrated that mobile work zone alarms have the potential to be an effective tool in improving safety. Further refinements to the systems could improve system effectiveness.

Key Words: Highway Safety, Work Zones, Distracted Driving
INTRODUCTION

Mobile work zones are used for road maintenance operations such as roadway striping, sweeping, and minor pothole repair. Guidance for the layout for mobile work zones is provided in the Manual on Uniform Traffic Control Devices (MUTCD) (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.

Mobile 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 countermeasure is a mobile work zone alarm system. 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. This paper describes the first field test of mobile work zone alarms in the United States.

This project analyzed two types of devices shown in Figure 1: an Alarm Device and a Directional Audio System (DAS). Each alarm device is attached to the construction vehicle with the TMA, and a shadow vehicle trails the construction vehicle on the shoulder. Examples of a DAS include parametric speaker arrays and the Long Range Acoustic Device (LRAD) (2). The LRAD was the DAS used for testing in this research project. The Alarm Device, as implemented by the Missouri Department of Transportation (MoDOT), is a manual system that includes a dual stage warning with lights followed by sound if the vehicle continues to approach the TMA without changing lanes. The TMA driver visually estimates the distance to trailing vehicles by using the number of skips on the lane striping as a reference. The DAS is a device that transmits directional warning sounds and produces sounds that are able to overcome background noise such as road noise. Because the volume of the DAS is adjustable and software-limited, and the message and alarm sound are customizable, this system could potentially be used in a wide range of applications that require the use of a long range and directional public address system. For the field tests, the DAS broadcasted a series of three alarms followed by the message, “slow vehicles ahead”.
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.

LITERATURE REVIEW

One previous research study concentrated on the use of audible warning systems for work zone applications (3). While the DAS was mentioned, only Loud Speakers and Loud Speaker Arrays were tested in a laboratory setting in this research. An array of multiple ordinary loudspeakers suitable for long distance auditory warnings was recommended due to its portability, low cost, low maintenance, and 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.

Although previous studies regarding the use of mobile work zone alarms are limited, some studies have looked at the effects of auditory warnings in the context of emergency vehicles. Maddern et al. completed research pertaining to auditory warning signals and studied factors such as perceived urgency, localization, and masking of emergency sirens (4). 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. Sound levels attenuate as the distance from the source increases. Localization is
the ability of a traveler to quickly determine the direction a sound and can be improved by widening the range of frequencies emitted. 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.

In a study that investigated the effectiveness of audible warning devices on emergency vehicles, the United States Department of Transportation found that for an alarm to be distinct it must be greater than background noise by at least 10 decibels in order to ensure a level of distinctiveness between the alarm warning and usual noise of the roadway (5). According to a synthesis of emergency vehicle warning systems, emergency vehicle sirens had significant limitations as a warning device especially since their effectiveness is limited to low distances and speeds (6). Another research study investigated auditory warnings that could be used in crash avoidance applications and identified four preferred signals (7). A study that investigated possible benefits of spatial auditory cues to capture a driver’s attention through the use of five experiments 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 (8).

GENERAL METHODOLOGY

The methodology for evaluation of the effectiveness of mobile work zone alarm systems included measuring the alarm sound level for each device, observing driver behavior, measuring 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. Details regarding these tests are provided in subsequent sections of this paper.

Three separate field tests were conducted. The first field test was near Columbia, Missouri, on Route DD without traffic. The purpose of this test was to perform preliminary tests on the DAS Actuated and Alarm Manual setups and make adjustments to the various systems. The second test occurred on the same day as the first field test on a 10-mile section of I-70 near Columbia, Missouri. The data collected at this site was ultimately excluded from the analysis because the test experienced suboptimal conditions such as equipment issues and traffic queuing. One insight gleaned from these tests was that within the two-lane segments, the TMA should remain in the inside lane with the shadow vehicle on the outside shoulder to allow for a greater number of merges. The final field test occurred in the Kansas City area on an urbanized section with flexible pavement on I-435 from Cookingham Drive to Shoal Creek Parkway as shown in Figure 2. This segment included 5.5 miles (8.9 km) of 6-lane interstate and 7 miles (11.3 km) of 4-lane interstate for a total section length of 12.5 mile (20.1 km). The approximate AADT for this roadway was 21,534 vpd (2012) with 14% trucks.
Data for five different setups were collected: the Alarm Manual setup, the Alarm Actuated setup, the DAS Continuous setup; the DAS Actuated setup, and the Control setup with no alarm warning system. Each setup was individually analyzed and then compared to determine its safety and effectiveness.

SOUND TESTING

An important component of the evaluation of the mobile work zone alarm systems included testing sound levels and comparing them with sound level standards. Sound level standards have been developed by two organizations that 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 and Health (NIOSH) (10)(11)(12). The OSHA standards are enforceable by law while the NIOSH
standards serve as guidelines that are not legally enforceable. Both the OSHA and NIOSH standards define maximum sound levels for different durations of exposure as shown in Figure 3.

![Sound Level Standards]

**FIGURE 3  OSHA and NIOSH sound level standards.**

**Methodology for Sound Level Testing**

A series of tests in a parking lot with flexible pavement was devised to determine whether or not each warning alarm setup complied with OSHA and NIOSH sound level standards. These tests included measuring sound 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 with windows up and windows down. Sound level measurements were taken at distances of 10 ft (3 m) and from 50 ft (15 m) to 600 ft (183 m) in increments of 50 ft (15 m) for both the DAS and Alarm Device warning systems. A reading for a distance equal to 3 ft (1 m) while walking was also included to simulate being directly behind each device as a worst-case scenario.

In addition to the sound level parking lot tests, sound levels were also recorded while driving a test vehicle which was a pickup truck through the I-435 site to investigate the effects of road noise on the sound levels. This was performed by having a video camera record the field of view and sound levels inside the test vehicle while passing through by the work zone. As the test vehicle approached the TMA vehicle, sound levels were recorded both before and after the alarm had sounded.

**Results from Sound Level Testing**

Figure 4 shows the results for the sound level readings that were recorded from within a parked test vehicle with the windows up and engine off and from outside of the vehicle at various distances from the TMA along with the OSHA and NIOSH standards for 0.25 hours of exposure. Noise levels from the parking lot tests 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 ft (15 m) while walking and the DAS within 3 ft (1 m) while walking. However, the results at locations close to the devices are not of
practical concern to drivers on highways, because they were taken while walking and the
OSHA and NIOSH noise levels are based on a 15 minute exposure time; highway
vehicles do not stay within 3 ft (1m) or 50 ft (15 m) of the devices for longer than 15
minutes while they are sounding. In most typical situations, a work zone worker will not
be exposed to the alarm sound at close range for 15 minutes. However, earplugs could be
considered if a work zone worker is expected to be exposed more than the acceptable
duration in order to adequately lower the sound level for the worker to meet OSHA
requirements. In a typical mobile work zone application, the exposure time would be less
than one second at near normal or normal highway speeds. In comparing the DAS and
Alarm Device while in a vehicle, the DAS consistently operates at a higher decibel level
than that of the Alarm Device. 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 attenuation in sound. While both the Alarm Device and DAS have
lower levels of sound while inside a vehicle with the windows up than while walking, the
DAS has a smaller difference between the two which indicates that the sound from the
DAS may be more effective at penetrating through car windows than the Alarm device.

FIGURE 4 Sound level versus distance with 5% error bars from parking lot tests
while parked inside test vehicle and while walking.
(NOTE: 1 ft = 0.3048 m)

The results from the sound level tests while inside the cab of the construction
vehicle with the TMA indicate that the sound levels inside the cab are below the NIOSH
and OSHA standards for typical operations. From inside the cab with the windows up, the
DAS was found to operate at a sound level of 80.5 dBA while the Alarm Device
produced a sound level of 76.7 dBA. In this instance, both devices are within OSHA and
NIOSH standards past 16 hours of exposure time per day. 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. 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. It is also interesting to note that the difference between the sound levels measured from inside the parked vehicle and while walking is less for the DAS than the Alarm Device. This difference was found to be approximately 15dBA for the DAS and 21dBA for the Alarm Device. This result suggests that the windows may have masked out more of the Alarm Device sound than the DAS sound. However, it should be noted that sound reduction caused by windshields is a function of frequency and sound.

Figure 5 shows the results from sound level tests inside the vehicle while driving through the I-435 site. 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 5 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. It should also be noted that the sound level differences observed before and after the alarm sounded are less than the 10 dBA threshold suggested by the United States Department of Transportation for emergency vehicles (5).
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 by 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. The sound files for the spectral analysis were obtained from the following sources: Alarm Device without highway noise from walking during the parking lot tests, DAS without highway noise from the digital audio file provided by the manufacturer, and both Alarm Device and DAS from inside the test vehicle from the highway tests on I-435.

Figure 6 shows the spectrograms for both alarm systems with and without highway noise. The spectrograms of the Alarm Device and DAS without background noise show that the DAS utilizes a smaller distribution of frequencies than the Alarm Device. In looking closely at the spectrograms for the Alarm Device and DAS with highway background noise, it can be seen that the DAS produced a much more distinct sound than the Alarm Device even with highway background noise. The y-axis represents audible frequency, while the x-axis represents time. When the Alarm Device sounded, several thin, yellow lines appeared over a range of frequencies. 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. Conversely, the spectrogram for the DAS sound showed distinct, red lines in a small range of frequencies while also showing simultaneous lighter yellow line at a higher frequency. Therefore, the DAS sound did not appear to be masked out by the road noise.
FIGURE 6 Spectrograms for (a) Alarm Device without highway background noise, (b) DAS without highway background noise, (c) Alarm Device with highway background noise and (d) DAS with highway background noise.
EVALUATION OF DRIVER BEHAVIOR

A variety of factors were analyzed to investigate driver behavior, including merging distances, average vehicle speeds, and undesirable driving behaviors. Undesirable driving behaviors are first defined. According to the AASHTO Green Book (13), a proper SSD is approximately 600 ft (183 m) for a speed differential of 60 mph (97 km/hr) which corresponds to the test conditions of 70 mph (113 km/hr) prevailing speeds and 10 mph (16 km/hr) TMA speed. Therefore, any merges at a distance of greater than 600 ft (183 m) from the TMA vehicle were considered desirable, and merges within 600 ft (183 m) were considered undesirable.

In order to determine the merge distance, the distance from the TMA to the trailing vehicle was measured from video data for each warning setup using photogrammetry. An example image from the construction vehicle with the TMA video data is shown in Figure 7. To estimate the distances using photogrammetry, the centerline striping was used as a reference for calibrating images. MoDOT uses a standard distance of 40 ft (12 m) from the beginning of one white stripe (skip) to the beginning of the next. Once calibrated, merging distances were calculated by determining the number of skips between the TMA and the trailing vehicle at the time when the trailing vehicle began to merge into the adjacent lane to avoid the TMA. 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 time code of video frames at a resolution of approximately 1/30 second.

The results for merging distances and speeds are shown in Table 1. All setups were observed to result in an increase in merging distance over the Control setup 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. To analyze the statistical significance of average merging distances and speeds within 600 ft of the TMA, separate ANOVA tests were performed. Both measures were statistically significant at a 0.01 significance level.

**TABLE 1 Results for merging distances and speeds**

<table>
<thead>
<tr>
<th>Setup</th>
<th>Total Number of Merges</th>
<th>Number of Merges within 600 ft</th>
<th>Average Merge Distance, ft*</th>
<th>Std. Dev. Merge Distance, ft</th>
<th>Average Speed, mph**</th>
<th>Std. Dev. Speed, mph</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>885</td>
<td>95</td>
<td>392</td>
<td>146</td>
<td>58.4</td>
<td>9.6</td>
</tr>
<tr>
<td>Alarm Manual</td>
<td>570</td>
<td>108</td>
<td>408</td>
<td>183</td>
<td>62.7</td>
<td>7.3</td>
</tr>
<tr>
<td>Alarm Actuated</td>
<td>808</td>
<td>57</td>
<td>357</td>
<td>161</td>
<td>61.7</td>
<td>7.9</td>
</tr>
<tr>
<td>DAS Continuous</td>
<td>939</td>
<td>171</td>
<td>514</td>
<td>126</td>
<td>55.4</td>
<td>9.2</td>
</tr>
<tr>
<td>DAS Actuated</td>
<td>1027</td>
<td>157</td>
<td>445</td>
<td>183</td>
<td>58.9</td>
<td>8.4</td>
</tr>
</tbody>
</table>

* and ** separate ANOVA tests – each statistically significant at 0.01 significance level

(NOTE: 1 ft = 0.3048 m; 1 mph = 1.609344 km/hr)

In addition to the quantitative results, some anecdotal observations of driver behavior were noted. Some undesirable driver behaviors were occasionally observed with the DAS setups. Instances in which some drivers had sudden reactions, such as braking or swerving, were noted 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.

**EVALUATION OF 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 which was determined based on the vehicle speed for each vehicle that merged within 600 ft (183 m). 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 or 1,056 ft (322 m)
then to sound the alarm when the vehicle was at a distance of 13 skips or 528 ft (161 m). To account for the uncertainties of estimating the number of skips, a threshold distance of 11 skips or 440 ft (134 m) to 15 skips or 600 ft (183 m) was used for the evaluation of false negatives and false alarms for the manual mode.

The false alarm and false negative rates for each setup are shown in Table 2. Each false alarm rate was determined by dividing the number of false alarms by the total number of activation events. The false negative rate was calculated as the number of missed alarm activations divided by the number of merges that occurred within the threshold distance. Major contributing factors to false alarms for the actuated setups were the presence of horizontal curves in which the actuation system was directed at an adjacent lane and lateral movements by the TMA vehicle or vehicles in the adjacent lane that caused the alarm to sound on a vehicle in an adjacent lane. 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. Horizontal and vertical curves were the main contributing factors for false negatives with the actuated system. Measurement of false alarms and false negatives was possible with the Control setup because the actuation system was running in the background and therefore recorded data regarding alarm activations.

**TABLE 2 False alarm and false negative rates by setup**

<table>
<thead>
<tr>
<th>Setup</th>
<th>False Alarm Rate (%)</th>
<th>False Alarms Due to Horizontal Curves (%)</th>
<th>False Negative Rate (%)</th>
<th>False Negatives Due to Horizontal Curves (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control*</td>
<td>31</td>
<td>5</td>
<td>57</td>
<td>38</td>
</tr>
<tr>
<td>Alarm Manual**</td>
<td>53</td>
<td>18</td>
<td>13</td>
<td>8</td>
</tr>
<tr>
<td>Alarm Actuated</td>
<td>69</td>
<td>37</td>
<td>54</td>
<td>42</td>
</tr>
<tr>
<td>DAS Actuated</td>
<td>62</td>
<td>72</td>
<td>26</td>
<td>6</td>
</tr>
</tbody>
</table>

* had actuation program running in background
** based on 440-600 ft (134-183 m) acceptable manual actuation threshold

**SUMMARY OF TRADE-OFFS**
The decision regarding which system to use involves trade-offs between performance, cost, and other factors such as maintenance requirements and ease of operation. Some of these trade-offs are summarized in Table 3. The performance measures are those discussed previously, including merge distance, standard deviation of merge distance, approach speed, false positives/negatives, other undesirable driving behavior, sound levels, and sound distinctiveness.
### TABLE 3  Design trade-offs by alarm setup

<table>
<thead>
<tr>
<th>Factor</th>
<th>DAS Continuous</th>
<th>DAS Actuated</th>
<th>Alarm Manual</th>
<th>Alarm Actuated</th>
<th>Desirable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Merge Distance, ft</td>
<td>+122</td>
<td>+53</td>
<td>+16</td>
<td>-35</td>
<td>+</td>
</tr>
<tr>
<td>Standard Deviation of Merge Distance, ft</td>
<td>-20</td>
<td>+37</td>
<td>+37</td>
<td>+15</td>
<td>-</td>
</tr>
<tr>
<td>Average Approach Speed, mph</td>
<td>-3.0</td>
<td>+0.5</td>
<td>+4.3</td>
<td>+3.3</td>
<td>-</td>
</tr>
<tr>
<td>False Positive (Including Horizontal Curves) (%)</td>
<td>N/A&lt;sup&gt;+&lt;/sup&gt;</td>
<td>62</td>
<td>53</td>
<td>69</td>
<td>0</td>
</tr>
<tr>
<td>False Negative (Including Horizontal Curves) (%)</td>
<td>N/A&lt;sup&gt;+&lt;/sup&gt;</td>
<td>26</td>
<td>13</td>
<td>54</td>
<td>0</td>
</tr>
<tr>
<td>Observed Driving Behavior</td>
<td>Drive on Shoulder</td>
<td>Sudden Maneuvers</td>
<td>None Observed</td>
<td>None Observed</td>
<td>None Observed</td>
</tr>
<tr>
<td>Sound Safety 50 ft in Veh. (dB)</td>
<td>86</td>
<td>86</td>
<td>77</td>
<td>77</td>
<td>&lt;115+++&lt;100+++</td>
</tr>
<tr>
<td>Sound Distinctiveness</td>
<td>****</td>
<td>****</td>
<td>**</td>
<td>**</td>
<td>****</td>
</tr>
<tr>
<td>Cost</td>
<td>$$$</td>
<td>$$$$</td>
<td>$</td>
<td>$</td>
<td>$</td>
</tr>
<tr>
<td>Convenience</td>
<td>Automatic</td>
<td>Calibration</td>
<td>Manual</td>
<td>Calibration</td>
<td>Automatic</td>
</tr>
<tr>
<td>Energy Consumption</td>
<td>*****</td>
<td>****</td>
<td>*</td>
<td>***</td>
<td>*</td>
</tr>
</tbody>
</table>

<sup>†</sup> DAS Continuous did not have actuation system properly collecting data in background

OSHA, 0.25 h

NIOSH, 0.25 h

(NOTE: 1 ft = 0.3048 m; 1 mph = 1.609344 km/hr)

The performance of these systems as discussed previously in this paper 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. 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.
CONCLUSIONS
Both the Alarm Device and DAS were found to be in compliance with national standards using sound level testing. The inside the cab sound levels of 80.5 dBA for DAS and 76.7 dBA for Alarm Device were under OSHA and NIOSH standards for 16 hours of exposure. In comparing the two alarm sounds with spectral analysis, the DAS sound was much more distinctive. The Alarm Device sound had a tendency to blend in with background noise.

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 since 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 results for all of the warning setups except for the Alarm Actuated setup showed an increase in the average merging distance. The DAS Continuous setup resulted in the greatest increase in average merging distance of 122 ft and was the only setup that led to a decrease in the average vehicle speed of 3 mph and standard deviation of the merging distance of 20 ft.

Other important findings relate to driver 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.

Based on the results of these tests, recommendations are made for improvements to both the DAS and Alarm Device. Since this project was an initial test to demonstrate the concept of mobile work zone alarms, further refinements to the alarm sounds would likely improve the results. One recommendation for the DAS is to use continuous operation but to explore different types of alarm sounds and messages. 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 should 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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