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Development and Testing of a Tag-based Backup Warning System for Construction Equipment

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ABSTRACT

Incidents in which a piece of construction equipment backed into a worker resulted in an average of 17 deaths per year at road construction sites and 15 deaths per year at building construction sites from 1997 through 2001. This trend continues and researchers at the National Institute for Occupational Safety and Health are evaluating methods to decrease these incidents. A new technology based on the detection of electronic identification tags worn by workers has been developed and evaluated at a road construction site. The tag-based proximity warning system consists of a magnetic field generator and communications system that mounts on the back of a piece of construction equipment such as a dump truck, road grader, or loader. Workers at a construction site wear a small tag that detects the magnetic marker field. If the electronic tag is within 15 ft (4.6 m) of a reversing piece of equipment, an audible alarm is sent to the equipment operator, and an audible and vibrating alarm is generated by the worker's tag. Preliminary tests show that this cooperative two-way warning system is effective in detecting workers near reversing equipment and may have potential to decrease backing incidents in certain work environments. The system's limitations are identified and recommendations for future improvements are discussed.

INTRODUCTION

From 1995 through 2002, 844 workers were killed at road construction sites in the United States. Of those, 509 (60%) were struck by a vehicle or piece of equipment within the construction work zone. Workers were more likely to be struck by construction equipment (158 or 31%) than by a passing vehicle (28%). The most common piece of equipment involved in these incidents was dump trucks (36%) (Pegula, 2004). Researchers at the National Institute for Occupational Safety and Health (NIOSH) further analyzed these incidents by concentrating on those that occurred from 1997 through 2001 and involved a reversing piece of construction equipment. This analysis showed a total of 87 fatalities at road construction sites (17 per year) and a total of 75 fatalities at other types of construction sites (15 per year) that were at least partially attributed to the lack of visibility to the rear of construction equipment (BLS, 1997-2001).

In the United States, mobile construction equipment with an obstructed view to the rear must either have someone signal the operator that it is safe to move in reverse, or an audible backup alarm must be installed that is automatically activated when the equipment is in reverse gear. Audible backup alarms are very popular; however, backing incidents still occur and the effectiveness of the alarms when used alone has been questioned (Laroche, 2006; Purswell & Purswell, 2001). Other devices are available that increase situational awareness for the machine operator. Collision or proximity warning sensors based on sonar, radar, and infrared sensing technology detect any obstacle near the equipment and provide an alarm to the operator. Cameras mounted on the exterior of a machine can provide a view of blind areas on a video monitor in the cab. Studies have been conducted on cameras and proximity warning systems on road construction and mining equipment (Johnson et al., 1986; Ruff, 2004; Ruff, 2006) and their limitations prompted NIOSH researchers to study alternatives.

One drawback to using passive, sensor-based systems for obstacle detection is that they produce numerous false and nuisance alarms, especially in the congested work areas that are typical of construction sites. False alarms occur when the sensor detects objects that do not warrant an alarm, such as rocks, curbs, foliage, or objects well out of harm's way. Nuisance alarms occur when the sensor correctly detects a nearby obstacle, but the object or person is not in danger of being hit. Examples of nuisance alarms include situations where the equipment operator must reverse near barriers, equipment, or workers that are not in the direct path of the equipment. Video cameras can supplement the operator's view of areas near the machine, but they do not provide alarming functions and a potential collision can go unnoticed.

Another possible drawback of existing sensor-based systems is the nature of the alarming functions. Typically, an alarm is provided to the operator only. This is understandable, because the operator is ultimately responsible for the safe operation of the equipment. However, benefits may be realized if a meaningful alarm was also provided to workers in the path of the moving equipment. Currently, backup alarms are meant to accomplish this; however, worker habituation to these alarms and their ambiguity in congested work zones may decrease their effectiveness (Purswell & Purswell, 2001). Thus, a new device was desired that would provide increased discrimination between high-risk obstacles (workers) and lower-risk obstacles while warning both the operator and the worker (two-way alarming). Furthermore, because of the "cry wolf" effect that can result from numerous false alarms (Breznitz, 1984), a more positive alarm methodology was sought.

One approach to increasing alarm reliability is to only detect those obstacles that are deemed high priority or high risk. This requires a method for discriminating between obstacles. Tag-based proximity warning systems accomplish this by attaching electronic transmitters or tags to high priority obstacles, e.g., workers (Figure 1). Other obstacles, such as utility poles and mobile or stationary equipment, could also be tagged. Tag detectors are mounted on mobile equipment that have significant blind areas. These detectors generate a marker field (usually magnetic or radio frequency) around the equipment that defines a warning zone. When a tag enters the marker field, an alarm is generated at the tag and in the cab of the equipment.

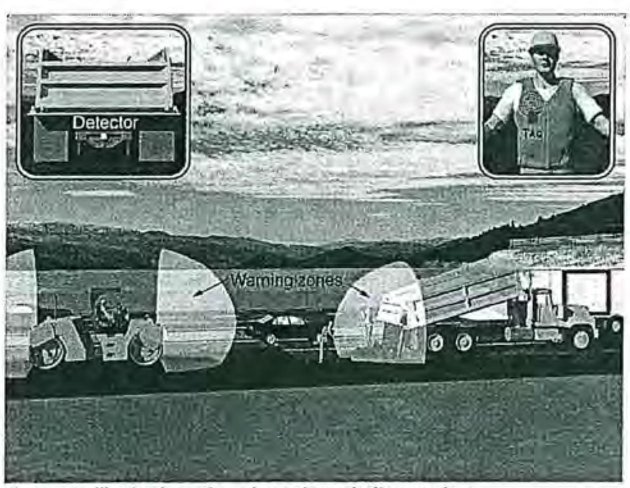

Figure 1. Illustration of tag-based proximity warning.

Several tag-based proximity warning systems were available for surface mining equipment at the start of this study (Foose, 2004). However, most were developed by foreign manufacturers and operated at frequencies not approved by the Federal Communications Commission. Also, the existing systems were too expensive for most construction companies. Recently, a tag-based system originally developed by NIOSH researchers for coal mining equipment (Schiffbauer, 2005) was commercialized by two sister companies. Geosteering Mining Systems, LLC, (GMS)[1] developed a system called TramGuard™ for underground mining applications and Frederick Mining Controls, LLC, (FMC) developed a similar system, called HazardAvert™, for other applications above ground. With modifications, HazardAvert™ showed potential for the construction application.

To the authors' knowledge, tag-based proximity warning systems have not been tested at construction sites in the United States. One goal of this research project was to test the system at a road construction site and obtain feedback from workers and equipment operators about the system's operation. Quantitative data were also desired to determine the number of true, false, and nuisance alarms that would be generated. The following sections describe the development and testing of the HazardAvert™ tag-based system.

SYSTEM DESCRIPTION

Pinning and crushing of personnel is a major concern for the mining and construction industries, equipment manufacturers, and for associated governmental agencies. GMS was encouraged by mine operators to develop a suitable safety system that would protect miners from this hazard. Through a collaborative effort between industry and government, GMS developed and demonstrated the TramGuard™ Proximity Protection System, utilizing the active tag-based concept developed by NIOSH. The Mine Safety and Health Administration (MSHA) certified the TramGuard™ system for use in explosive underground coal mining applications and approved its intrinsically safe Personal Alarm Device, the tag carried by the person to be protected. The HazardAvert™ system is based on TramGuard™ technology and was developed to meet the needs of the surface mining and construction industries.

The HazardAvert™ proximity warning system includes a low frequency magnetic field generator and tags that sense and respond to the marker field. System components are shown in Figure 2. All pieces of mobile equipment within a work area are equipped with a generator so that any worker on the ground who is

[1] Mention of a company name or product does not constitute endorsement by the National Institute for Occupational Safety and Health.

wearing a tag will be warned if they are within a defined area near the equipment. In addition to warning the worker, the tag sends a message to the operator of the equipment to warn that a person is near their machine.

The magnetic field generator consists of a ferrite bar wound with a coil through which a special signal generator sends current. The current flowing around the ferrite bar produces the field. The generator also contains a radio frequency (RF) receiver to obtain alarm information from tags. The generator is mounted on the equipment and positioned such that the marker field covers the area to be monitored. The rear blind area near the machine is generally the greatest concern; as such, the generator is mounted on the rear bumper or grill. An operator's alarm display, which generates both audible and visual warnings, is mounted in the equipment cab. Vehicle power, reverse signal wires, and the generator cable are connected to the back of the alarm display. The tag, also called a Personal Alarm Device (PAD) (Figure 3), contains sensors that measure the magnetic marker field strength and an RF transmitter to send alarm signals back to the generator.

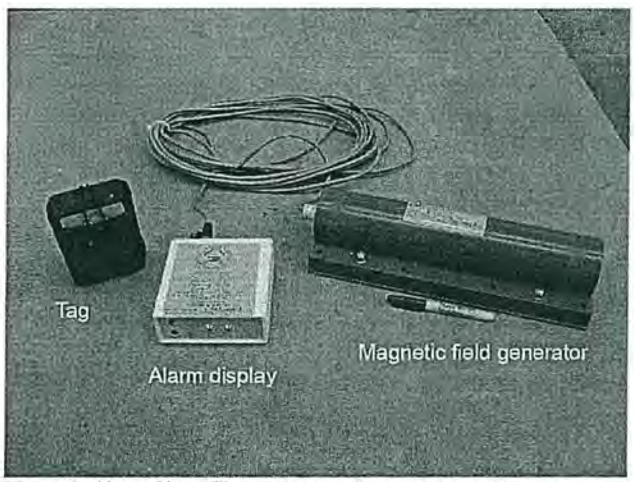

Figure 2. HazardAvert™ prototype system components.


Figure 3. HazardAvert™ tag or PAD worn on belt.

For this version of the system, the tag produces an audible alarm that changes pulse rate depending on its distance from the generator. If a machine is in reverse gear and a tagged worker is within the outer warning zone (approximately 8 to 15 ft (2.4 to 4.6 m) from the rear of the machine), a pulsed tone of 2900 Hz is generated every second at the tag and at the operator's alarm display. If the distance continues to decrease and the worker enters the zone from 0 to 8 ft (2.4 m) from the rear of the machine, the audible alarm changes to a series of three pulses every 0.5 seconds. In addition, a vibrating tactile alarm is integrated into the tag which generates a continuous vibrating alarm in the closest zone. These zones and alarm pulse rates are configurable at the factory and could be changed depending on the application and environment.

The tag is typically worn on the worker's belt or in a vest pocket. Other versions of the tag are available that allow a wired remote alarm sounder to be worn at a different location than the tag, such as a lapel or hat brim. The battery in the tag will last in excess of 12 hours (depending on the number of alarms) and should be recharged at the end of each day. Tag power is indicated by a small light which flashes if battery power is low.

Another important feature of this system is each generator has one tag designated as the operator's tag. Thus, the equipment operator can wear this dedicated tag and not generate false alarms while operating their machine. This is especially important for pieces of equipment wherein the operator's seat is near the generator. In such scenarios, the marker field wraps around the equipment and may encompass the operator's seat. If an operator exits the equipment, their dedicated tag is detected by the other generators, offering the operator protection if he/she is on foot.

The audible alarms at the operator's display sound similar to the alarms of the tag. A lockable sound level adjustment is provided on the back of the display to adjust sound intensity based on background noise for a particular piece of equipment. Visual alarms are also provided using yellow and red flashing lights for the warning and danger zones, respectively.

The system is installed by mechanically mounting the field generator on the exterior of the mobile equipment, routing a cable to the operator's cab to connect the display, and connecting 12Vdc vehicle power. If it is desired that the system only operate when the equipment is in reverse, then the reverse signal from the vehicle must be connected to the alarm display also.

TEST DESCRIPTION AND SETUP

To evaluate this system in a construction environment, a partnership was established with Inland Asphalt Co., Spokane, Washington. A road grading crew that consisted of 5 to 6 workers and various pieces of equipment was selected to test the system during 10 consecutive work days. Job sites consisted of sub-grading and spreading crushed rock at driveways, parking lots, residential streets, and major arterials in preparation for asphalt paving (Figure 4). This type of work crew was selected because jobs typically require workers to be near moving equipment in congested work zones. Also, several pieces of equipment were dedicated to the selected crew, so the research team was assured that the equipment they outfitted would be used at the site where the crew was working.

Figure 4. Typical work scene during the study.

Four pieces of equipment were outfitted with generators: a motor grader, a dump truck, and two water trucks. Equipment was selected based on potential worker exposure to blind areas at the rear of the equipment and the extent of the blind areas. Test results for the grader, one water truck, and five crew members are discussed here. One water truck was removed from the study when it was assigned to a different crew. The dump truck was not used extensively during the tests and the limited results will be discussed in a future report.

All five crew members and one traffic-control worker (flagger) agreed to participate in the study. The first crew member primarily operated the grader and directed work at the site. This crew member operated other machinery when needed. The second crew member operated the water truck, a front-end loader, and occasionally a roller. The third crew member primarily operated a small finish grader and worked on the ground. The fourth crew member generally worked on the ground, directed trucks when dumping crushed rock, and occasionally operated the roller. The fifth crew member worked on the ground surveying and placing grade stakes and markers. The flagger was not assigned to this crew's work sites during the test period.

To obtain feedback from the crew members, a NIOSH researcher recorded comments regarding their opinions about the number of alarms, the effectiveness of the system, and any other comments or suggestions. This was done when tags were collected at the end of the day. The researcher also rode in the water truck for short periods to watch the driver's response to alarms.

To obtain quantitative data, three cameras and a video recorder were mounted on each machine to provide video footage of the sides and rear of the equipment. One camera was mounted on each side mirror and one was mounted on the rear of the equipment. The field of view for the cameras was such that the marker field or tag detection area of the generator was contained within the camera views. A video processor allowed all three camera views to be displayed on one screen. Figure 5 shows a screen shot of the recorded video with an example of a tagged worker being detected by the system.

An alarm signal, provided by the alarm display, was also connected to the video recorder. This 12V signal was activated whenever the alarm display generated any alarm (warning or danger zone) and triggered an icon that was recorded on the video footage (W just above the time stamp in Figure 5). The camera views were only recorded, they were not shown on any type of display in the cab. At the end of the study, NIOSH researchers reviewed the video footage, recorded the number of alarms, and classified the alarms based on observations of the video.

Figure 5. Video screenshot of three camera views, time stamp, and alarm icon (W) for detected worker (bottom left).

A generator was mounted on a Caterpillar 140G motor grader at the top of the back grill at a height of approximately 6 ft (1.8 m) (Figure 6). The generator for the water truck was mounted on the rear of the water tank at a height of approximately 5 ft (1.5 m) (Figure 7). For both machines, power was obtained from the 12Vdc converter that supplied power to the radio. The reverse signal was obtained by running wires from the backup alarm on the rear bumper to the alarm display in the cab.

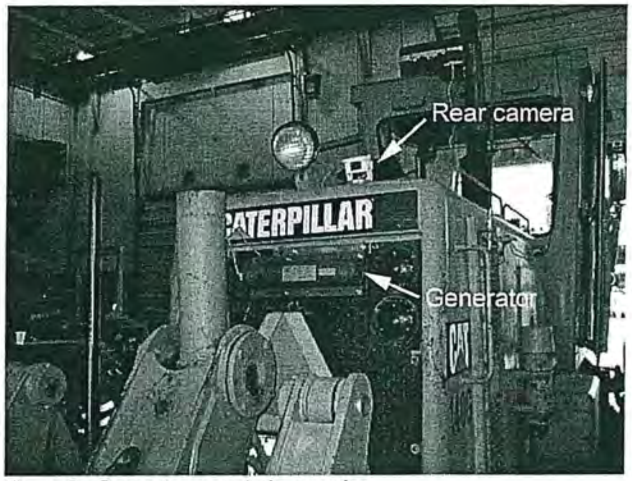

Figure 6. Generator mounted on grader.

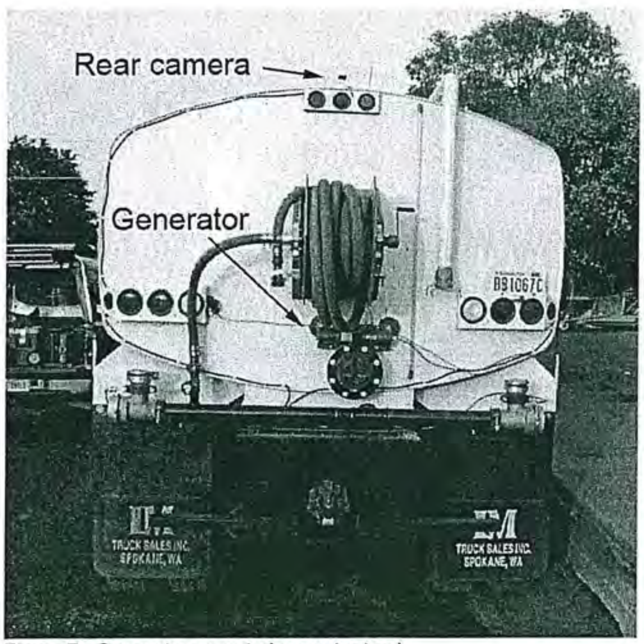

Figure 7. Generator mounted on water truck.

The detection zones for the grader are shown in Figure 8. The marker field is roughly circular when seen from the top with a radius of approximately 12 to 15 ft (3.7 to 4.6 m), centered at the generator. The detection zones for the water truck are similar and are shown in Figure 9.

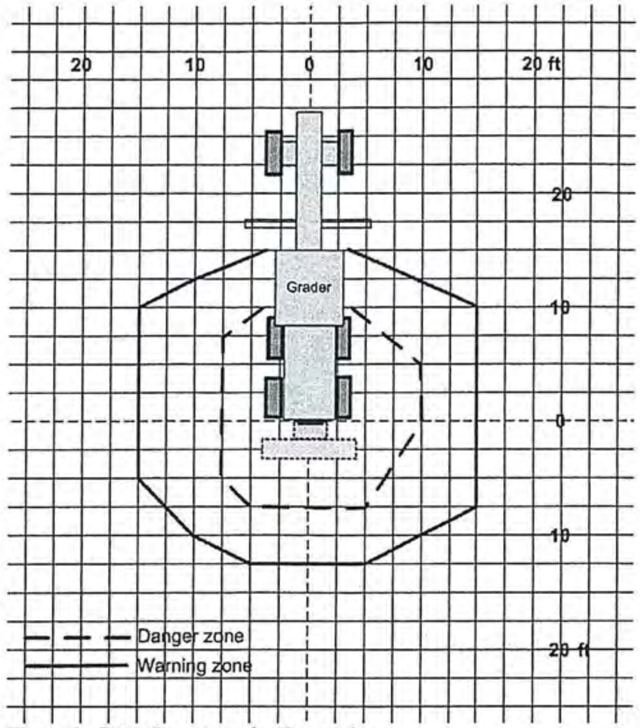

Figure 8. Detection zones for the grader.

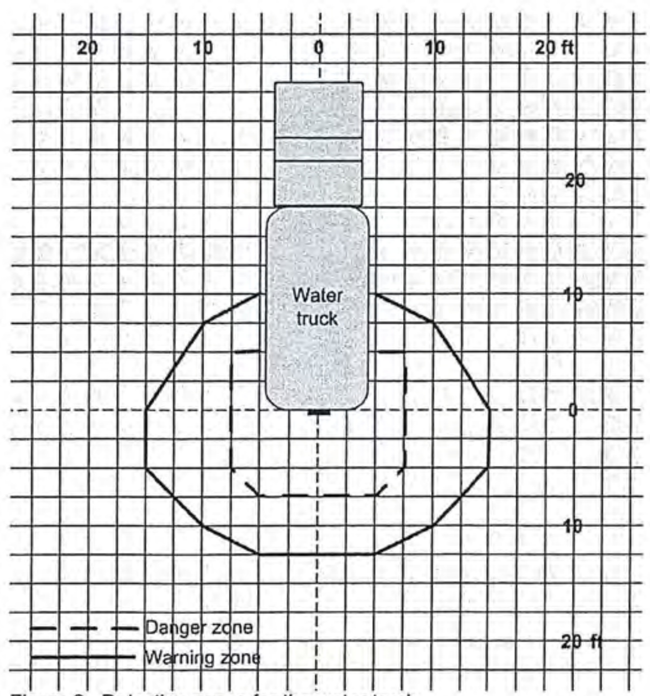

Figure 9. Detection zones for the water truck.

TEST RESULTS

Researchers conducted tests at various paving sites and obtained the most meaningful data at sites involving major arterial street construction. Small parking lot and driveway jobs did not always require the equipment outfitted by the research team. For this reason, data was collected on 6 out of the 10 planned test days. Approximately 30 hours of video footage was collected from the grader, and 10 hours from the water truck.

Video analysis allowed the number and types of alarms to be quantified. True alarms were defined as alarms generated by a tagged worker who was in the potential path of the reversing equipment (either directly behind the equipment or behind and slightly off to the side). Nuisance alarms were defined as alarms generated from tagged workers that were not in a hazardous location, i.e. not in the potential path of the reversing equipment. Missed detection occurred when a tagged worker was clearly within the marker field, but no alarm was generated. False alarms occurred when an alarm was generated with no tagged worker within the equipment's exterior marker field. (All false alarms observed in these tests were generated from an operator's tag while sitting in the cab). Table 1 summarizes the number and types of alarms recorded along with the number of missed detections.

Table 1. Alarm information.

	Grader (30 hours of operation)		Water truck (10 hours of operation)	
Event	Quantity	Alarms per hour	Quantity	Alarms per hour
True alarms	55	1.8	6	0.6
False alarms	3	0.1	0	0
Nuisance alarms	54	1.8	6	0.6
Total alarms	112	3.7	12	1.2
Missed detection	2	-	0	-

GRADER ALARMS

For the grader, 112 total alarms were generated at the alarm display and corresponding worker tags. On average, almost 4 alarms were generated per hour. The number of true alarms signifying that a nearby worker was in the path of the equipment was almost equal to the number of nuisance alarms. The video footage demonstrated that all nuisance alarms were initiated by a worker located to the side of the equipment. This may indicate a need to redesign the generator to limit the lateral extent of the marker field. However, it can be argued that some side detection is needed to protect workers near tires or to give adequate warning if the machine suddenly turns.

The three false alarms were all generated when a worker with an undedicated tag operated machinery that they do not normally operate. Consequently, the system detected their tag while they were sitting in the cab. The two missed detections are unexplainable. A tagged worker was clearly in the marker zone and his tag was not detected. This happened twice to the same worker in a short period at the end of one day. When the tag was collected the power switch was on and there was no indication of malfunction. The tag functioned properly the next day.

Midway through the tests, the tag dedicated to the grader operator started to generate an occasional and random alarm (single beep) when the operator was seated in the machine. The alarm was only generated at the tag so no indication was seen on video. The grader operator indicated that this was a distraction and the tag was removed from service. When tests were completed, the generator and tag were sent to the manufacturer to determine the cause of the malfunction; however, the analysis was not available at the time of this report. No other dedicated tag and generator combination exhibited this problem.

The main comments received from the grader operator had to do with concerns that the detection zone was too small to the rear of the grader and did not give enough advanced warning to protect workers (a consistent concern for all of the crew members). The detection zone was considered too large at the sides of the machine, but the operator did not indicate that the resultant nuisance alarms were annoying. Also, tag size and weight were a concern and the operator had a difficult time finding a comfortable location for the tag. Alarm sound levels in the cab were adequate and there were no complaints regarding the number of in-cab alarms.

WATER TRUCK ALARMS

Only 10 hours of data were collected for the water truck due to its late inclusion in the study and the occurrence of a temporary malfunction in its data collection system. Twelve alarms were recorded with the number of true alarms equal to the number of nuisance alarms. On average, around one alarm was generated per hour. No false alarms were seen and no missed detections occurred. Even though the water truck was frequently operated in reverse, the risk associated with this equipment was lower than that of the grader based on observation. Workers did not need to perform tasks near the water truck very often. In addition, if the water spray was on at the rear of the truck, there was incentive to keep a safe distance from the rear to avoid getting wet.

True alarms were generated by the tags of workers either directly behind the truck or near the rear corner when it was backing. Nuisance alarms were generated when the truck was reversing beside another piece of equipment with a tagged operator. Several nuisance alarms were also generated by the tags of workers standing on the sidewalk, off to the side of the truck.

Comments from the driver of the water truck included the need for a smaller, more comfortable tag, and a larger detection zone directly behind the truck. He also noted that he could hear the display alarms in the cab. Furthermore, the driver was assigned a tag that was dedicated to the generator on that truck, but he frequently operated other equipment. This arrangement could potentially give rise to false alarms as discussed earlier.

TAG ALARMS

On the first day of testing, workers were outfitted with tags as shown in Figure 3 with the alarm speaker at the bottom of the belt pouch. This decreased the intensity of the alarm such that some workers, when wearing earplugs, had a hard time hearing the tag alarms above equipment noise and backup alarms. This concern requires more study as it is vitally important that alarms be heard, but at the same time not annoying or damaging to the worker's hearing. On subsequent days, the tag was placed in the pouch with the alarm speaker exposed at the top. Workers on the ground indicated that they could hear the alarm better, but this made the tag vulnerable to water damage. For the one or two workers that wore earplugs and operated machinery, the tag alarms were still not always audible.

The optional vibrating tag alarm that was activated in combination with the audible alarm in the danger zone was turned on for all of these tests. However, workers that wore the tag in the belt pouch indicated that the vibration could not be felt. A better arrangement would have been to mount a clip on the tag housing so that it could be directly attached to the belt. This may have alleviated both the sound and vibration isolation problems associated with the pouch. Workers that wore the tag in a vest pocket indicated that the vibration could be felt some of the time, depending on how close the tag was to their body. Alarm presentation is an area needing further study. One proposed change made by the manufacturer involved a remote vibrating alarm that could be worn closer to the body. The alarm would be attached by thin wires to the existing tag.

With the exception of the grader tag malfunction, no false alarms were generated at the tags while on the work site. Interestingly, one worker noticed a short false alarm while in a grocery store at break time. This also occurred with a NIOSH researcher's tag when in the same grocery store. The cause was not determined.

Workers on the ground commented that there was not enough advanced warning when a piece of equipment was backing toward them, indicating a need to lengthen the detection zone to the rear of the machine. All workers felt the alarms would be more meaningful if this improvement could be made. Most of the workers commented that the detection zones to the sides of the machines were too large, resulting in nuisance alarms.

In general, the workers on the ground felt that the system could be effective, especially for new employees, inspectors, or other contractors that were not as familiar with the road construction process or work zone traffic. But, because this crew was very familiar with work practices and procedures, they perceived themselves as being at a low risk for involvement in a backing incident.

CONCLUSIONS

The evaluation of this tag-based warning system at multiple road construction sites demonstrated that the system has potential to protect workers on foot from being struck by equipment within the work zone. However, there are certain situations and work environments that are better suited to this intervention than others. While tests of this system were limited, researchers were able to draw some conclusions and make recommendations regarding the implementation of this and other tag-based systems. The following discussion summarizes the findings and possible directions for moving toward expanded tests and implementation.

- In general, the advantages of a tag-based approach for protecting workers center on the positive detection and alarming features that are unique to a methodology that uses cooperative obstacles. For an operator, an alarm means a detected tag, and thus a high-risk obstacle, is nearby. For workers, when their tag generates an alarm, it is personal and more meaningful because it is only generated when a reversing piece of equipment is nearby.
- Conversely, this approach only protects workers that are wearing tags (although stationary objects could have a tag attached to them, but this wasn't tested in this study). While this may lead to a decreased number of nuisance and false alarms for operators when compared to passive sensing systems such as radar or sonar, it introduces concerns regarding property damage and injuries resulting from collisions with a non-tagged object, worker, or pedestrian. For this reason, tag-based systems may be better suited to work sites that have controlled access.
- A related concern involves work sites that have multiple contractors using mobile equipment in the work zone. Not all the equipment may have the tag detection system implemented, which could cause confusion and an unsafe work environment if a

secondary warning system is not used. For this reason, and to protect untagged workers or the public, audible backup alarms cannot be replaced by tag-based warning systems, but they could be used in combination.

- All nuisance alarms observed during this study were generated by tagged workers standing or operating equipment to the side of the test machine. These alarms would dramatically decrease if the detection zones on the sides of the equipment were reduced in size. Some side detection is beneficial for situations involving workers near the tires or when a piece of equipment is turned while reversing; however, for the current system, the side detection was too pronounced. Equipment operators did not indicate that side detection was annoying - it only occurred an average of two times per hour for the grader. However, reducing nuisance alarms would further enhance reliability.
- False alarms were rare and only occurred when a worker was driving a piece of outfitted equipment they did not normally operate, i.e. their tag was not dedicated and thus not ignored by the generator on the equipment they were temporarily operating. A new procedure has been devised to allow workers to operate multiple pieces of equipment. It involves a simple key press on the tag when a worker operates a new piece of equipment, which temporarily assigns or dedicates the tag to that piece of equipment. Once the operator leaves the equipment and associated marker field, the system resets allowing the operator to be reassigned to another piece of equipment.
- The low number of false alarms with this system is a major benefit. False alarms are a major consideration for any type of proximity warning system as they can render a system useless. If an operator or worker perceives that alarms do not usually indicate danger, the alarms will eventually be ignored (Breznitz, 1984).
- The most serious and common complaint was that the detection zone directly to the rear of the equipment was not large enough to give workers sufficient time to react when standing behind a piece of equipment moving at moderate speeds (greater than approximately 4 mph (6.4 kph)). The detection zone shape should be modified before this system goes to a larger field trial. At a minimum, the zone should extend 20 to 30 ft (6.1 to 9.1 m) to the rear and only 5 to 10 ft (1.5 to 3 m) to the sides. Ideally the length of the detection zone would vary according to vehicle speed. The SAE vehicle standard J1741 provides a formula for calculating sensing distance that takes into consideration vehicle speed, width, and worker reaction times (SAE, 1999). However, nuisance alarms will increase if long detection zones are in effect while equipment moves slowly, so this tradeoff must be considered.
- System reliability was of some concern during these limited tests, but not more than what was expected for a prototype system. There were two instances in which a worker's tag was not detected by the system. These occurred near the end of the day for the same worker and could have been due to a low tag battery or accidental shut off. The current system has a low-battery indicator on each tag, but this may need to be made more obvious. It is recommended that a procedure be established to verify that the tags are operating correctly at the beginning of each day. Also, the tag that was dedicated to the grader operator began to generate false alarms midway through the tests when it started to detect the magnetic field that it was supposed to ignore. That tag was removed from service. A longer field trial is necessary to draw further conclusions about reliability and robustness of the system.
- Workers in this study commented that, in most situations, the audible alarms could be heard both at the tag and in the cab. However, the method of alarm presentation to both equipment operators and workers on foot should be studied further. At present, the most effective alarming method is not known. Audible alarms are the standard practice, but their effectiveness may be diminished in noisy environments, especially when earplugs are worn. Vibrating alarms may be more effective for workers if sufficient contact with the body can be made without being invasive. Visual indicators such as flashing lights are not always effective, especially for equipment operators who have other visual demands while driving.
- Finally, if tag-based systems are to be accepted by workers and operators, the size and weight of the tag must be decreased. Many comments were made regarding difficulties with finding a comfortable location to wear the tag. Most crew members wore the tag on their belt, but had a hard time adjusting its location when sitting in equipment. Some crew members chose to place the tag in their safety vest pocket, but its weight pulled the vest downward, making it uncomfortable. Given alarm and power requirements, engineers were confident that the tag could be decreased in volume by 50% in the future.

Note: The findings and conclusions in this report have not been formally disseminated by the National Institute for Occupational Safety and Health and should not be construed to represent any agency determination or policy.

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