Safety 360: Surround-View Sensing to Comply with Changes to the ISO 5006 Earth-Moving Machinery - Operator's Field of View - Test Method and Performance Criteria

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ABSTRACT

Despite recent efforts towards protecting construction personnel from equipment which operates in too close proximity, most of the existing and more advanced accident prevention techniques focus on approaches using sensing technologies. These can alert workers-on-foot or personnel operating the equipment in real-time. The drawbacks that some of these technologies have, however, limits their use in practice as the applications in construction are diverse and the environment is harsh. This article first presents significant safety statistics related to visibility-related construction equipment accidents. It introduces a brief but critical review of the existing ISO 5006:2006 standard for earth-moving machinery – operator's field of view – test method and performance criteria. Further, this article comments on a significant change that will soon be implemented in the standard and how equipment manufacturers expect to comply with the modification. Novel equipment design and sensing to provide equipment operators with a surround-view, called here "Safety 360", is introduced and tested to verify that solutions for responding to the expected change in the International Standard – although they are technically challenging – exist. An outlook presents matters that need to be addressed in the future should equipment operation ever become safe.

Keywords - Equipment design and manufacturing, infrared, International Standard, laser, magnetic fields, prevention through design, operator visibility, pro-active, proximity detection and alert technology, RADAR, radio frequency, real-time, sonar, vision camera.

1 Introduction

The construction industry annually experiences one of the highest fatality rates among the industrial sectors in the world. The factors that contribute to this reputation include the nature of the work, human behavior, the tools and equipment involved, and also the compact work zones.

Construction workers perform tasks daily in often-crowded and sometimes hazardous settings to accomplish their job objectives. These dangers include, but are not limited to falls, electrocutions, contact with faulty or improperly-operated power tools, and working in close proximity to large equipment such as trucks, excavators, small mobile vehicles, and cranes. Construction workers consistently sustain a disproportionately high number of fatalities and injuries when compared to workers in other industries. Because of the constantly changing work environment, construction workers are often faced with new hazards that may go unnoticed. In some cases the hazards are not seen by the workers [1].

Industrial fatalities in the United States and Germany are investigated by the Occupational Safety and Health Administration (OSHA) and the Berufsgenossenschaft Bau (BG Bau), respectively. While OSHA groups the causes of fatalities into a few general categories, too little information is gleaned in most other countries to effectively target specific problem areas.

To improve the safety performance in the construction industry, it is necessary to understand the underlying causes of accidents. This article first investigates the details with respect to 659 isolated fatalities in which vision or lack of good visibility was the principle factor or contributing cause [1]. The objective of examining the details surrounding these fatalities is to uncover the contributing factors and to identify the agents that compromised visibility.

This article presents the test method and selected performance criteria of the ISO 5006:2006 standard to measure the operator's field-of-view (FOV) [2]. Due to an overhaul of the standard, changes will occur in the near future that especially equipment manufacturers are required to comply with. The impact of and a proposed solution to one particular change in the standard, as it relates to detecting workers-on-foot in very close range to equipment, is investigated. Examples that provide equipment operators with technical aids to enlarge their visibility around equipment demonstrate the techniques are available to comply with the changes in the upcoming regulation.

2 Visibility-related Fatalities Occurring in Construction Equipment Operation

The U.S. construction industry accounts for approximately 7% of the total workforce, but construction worker deaths account for about 20% of all industrial fatalities [3]. This death rate of 15.2 of every 100,000 workers makes construction the third most dangerous industry behind mining and agriculture [4]. Every working day approximately five construction workers die in the US [5].

One fourth of the construction worker deaths are the result of collisions, rollovers, struck-by accidents, and a variety of other equipment-related incidents. When equipment is brought onto the job site, the general contractor, subcontractor or the equipment rental companies have the responsibility to make sure it is in proper operating condition. The equipment must be deemed safe after inspection for its intended use [5].

2.1 Work Site Conditions and Safety Data

On a typical construction site it is very common for workers, (mobile) equipment, and other objects to be in close proximity in often restricted spaces [6]. According to OSHA data from 1985 to 1989, "struck-by" accidents comprised 22% of all construction fatalities [7]. Of these cases the most common cause is related to the lack of visibility or a worker being present in the blind spot of equipment [8]. Decreasing vigilance is the result of workers that are engaged in specific tasks while ignoring distracting noises. When a truck or piece of machinery is reversing, a worker can be easily distracted by focusing on the work task alone. In general, workers are probably more vigilant at the beginning of the project when they pay more attention to alarm signals. Alarms can easily become routine to the workers, and the noise is processed more as an annoyance and it tends to be ignored. Equipment that deviates from their usual paths of operation increases the likelihood of accidents [9].

The data for this research were obtained from OSHA personnel and included incidents that occurred from 1990 to 2007 [1]. OSHA collects information on injuries and fatalities that occur on U.S. construction jobsites. The information of interest for this study was contained in the construction fatality investigation abstracts that resulted from visibility-related impairments. The purpose of the research conducted by Hinze and Teizer [1] was to examine construction fatalities investigated by OSHA with the intent of identifying and quantifying the root causes of visibility-related fatalities. Results of this study should be helpful in developing the proposed preventative measures to create a safer work environment. Vision search terms included: backed, black, blind, blur, bright, could not see, dark, did not see, didn't see, dim, dull, failed to see, gloomy, illuminate, illumination, light, lit, obscure, obstruct, plastic sheet, ran over, reverse, seeing, shine, view, visibility, and vision. The search for the various visibility-related terms yielded 659 individual cases. These specific cases formed a working database for this investigative research study on visibility-related fatalities.

2.2 Categorizing Equipment Fatalities

The study of Hinze and Teizer [1] identified 659 fatality accidents from a data pool of 13,511 OSHA-investigated cases. It was discovered that blind spots, obstructions and lighting conditions were the most common factors contributing to vision-related fatalities. This research also analyzed the specific conditions associated with particular pieces of construction equipment.

Personnel of occupational safety and health administration typically investigate most construction worker fatalities and their underlying causes. Fatalities, for example, are grouped into five major categories: falls, struck-by, electrocutions, caught-in-between, and other. While these categories are informative, they do not provide sufficient detail by which an effective accident prevention program or technology could be developed. Additional causal details are needed.

OSHA, for example, investigates and records job-related injuries that occur throughout the United States. In addition to legally demanding that each employer abide by its guidelines, it also provides a valuable database that allows firms to benchmark their safety practices. The OSHA log data provides a wealth of accident information and the contents found within it allow for a single point of information for identifying exactly what it is that should be addressed in order to reduce injury frequencies. Other equally developed countries have similar accident recording databases, but are either not as detailed or restricted to access.

2.3 Investigating Struck-By Incidents

Of the 659 cases, 594 involved equipment and 521 were incidents in which workers were struck by traveling equipment. The equipment related visibility-related fatalities are summarized below in Figure 1. In addition to being struck by moving equipment, workers were hit by the buckets of equipment, material being dropped or lowered by the equipment, electrocutions when equipment contacted power lines, rollovers when equipment was operated on slopes that were too steep, and drowning when equipment rolled into ponds or some type of deep water. A total of 65 cases that did not involve equipment related to falling from roofs, through stairwell/floor openings and through skylights. While these 65 cases were attributed to visibility/awareness issues, further analysis was focused solely on those cases involving equipment.

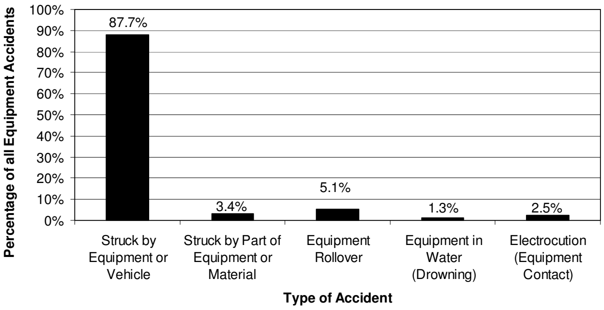

Figure 1. Distribution of construction fatality cases attributed to visibility/awareness issues (N=594) [1]

The frequency of the involvement of specific pieces of equipment in all investigated fatality cases (N=594, percent of total) was: dump trucks (173, 29%), not specified trucks (73, 12%), excavators (50, 8%), private vehicles (42, 7%), dozer (38, 6%), grader (37, 6%), front end loader (31,5 %), forklift (30, 5%), compactor (18, 3%), scraper (15, 3%), skid steer loader (15, 3%), water truck (13, 2%), paver (8, 1%), and other equipment (27, 5%).

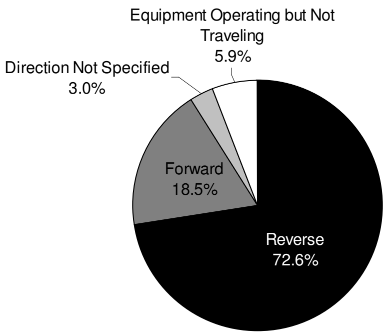

Figure 2. Nature of construction equipment movement at the time of accident occurrence (N=594) [1]

The direction of travel of the equipment was of particular interest in this study [1]. Figure 2 shows that more than half of all visibility-related fatalities occurred when equipment was backing up. Note that when only equipment-related cases are considered (N=594), in about 73% of the instances the equipment was traveling in reverse. In the equipment-related incidents, in about 19% of the instances the equipment was traveling forward. The percentile that was labeled "direction not specified" refers to cases where the accident report did not clearly state the direction of travel of the vehicle at the time of the incident and no inference could be made. The "operating but not traveling" percentile refers to cases where the equipment was stationary, for example, when an excavator crushed a worker while trenching or a crane hit a worker while lifting material.

The data were examined to evaluate the percentage of instances that specific pieces of equipment were traveling in reverse [1]. Skid steer loaders (14 fatal cases, representing 92.9% of all fatalities that involved skid-steer loaders), water truck (12, 91.7%), graders (37, 91.9%), and dump trucks (173, 91.9%) were traveling in reverse in more than 90% of the accidents where these pieces of equipment were involved. In more than 50% of the cases, dozers (34 cases, 82.4%), compactors (14, 82.4%), scrapers (15, 80%), tractor trailers (22, 54.5%), and excavators (45, 53.3%) were involved in fatal accidents when traveling in reverse. Note that private vehicles were generally traveling forward. The private vehicles (33 cases, 28.6%) were generally driven through work zones, with several involving alcohol consumption by the drivers. Front-end loaders (29 cases, 72.4%) and forklifts (28, 57.1%) were noted to be involved in some accidents when driving forward but where visibility was limited due to loads being carried, buckets raised to the point where visibility was obscured, or forks raised to the point where vision was impaired.

Overall results presented in the study performed by Hinze and Teizer [1] show that 431 visibility-related fatalities occurred when vehicles or equipment were traveling in reverse, nearly four times the number of vehicles or equipment that were traveling forward (110). This statistic indicates the magnitude of the potential hazards that exist when vehicles travel in reverse [10].

3 Exiting Safety Equipment to Prevent Workers-on-Foot Struck By Equipment

Equipment, machines and tools can be broken into general categories that include transporters such as trucks, forklifts, conveyors, pipelines, railways, roadways, and aircraft [3]. Trucks, forklifts, and earthmoving equipment (skid steer loaders, scrapers, backhoes, front-end loaders, bull dozers, and compactors) are often involved in visibility-related injuries [1]. Several types of personal protective equipment (PPE) for workers-on-foot or alert techniques for equipment exist that are reviewed in the context of blind spots.

3.1 Blind Spots

Although not all accident investigation reports described the ambient environment when an accident occurred, 82 of the fatal cases reported poor or limited visibility as cause of the accident (see Figure 3). The most frequently cited cause of vision-related fatalities for all types of construction equipment was the presence of blind spots, followed by obstructions. Blind spots and obstructions accounted for 56.1% and 23.2%, respectively. When combined, they accounted of more than 75% of all fatal accidents. Too dark or too bright lighting conditions were the cause of 7.3% of all fatal cases that described the nature of visibility in equipment accidents in greater detail (N=82).

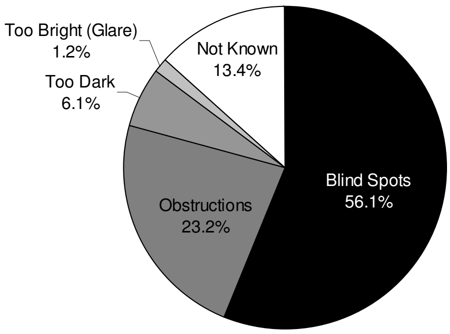

Figure 3. Poor visibility/awareness as the cause of fatal accidents related to construction equipment (N=82) [1]

It is common for equipment to have blind spots located in various areas surrounding the equipment. The most commonly known blind spots are to the rear [8]. The back-up alarm is a safety measure intended to warn anyone in the vicinity of blind spots (or within close proximity of equipment parts).

In particular, alerts should be used for all construction vehicles that include large blind spots. Blind spots are a frequent cause of visibility-related fatalities and several techniques exist to measure these precisely [8,11-17].

3.2 Defining General Requirements for Back-Up Alarms and Other Protective Gear

It is important motor vehicles be equipped with restraint devices such as seatbelts, which decrease the severity of injury in the event of an accident. In addition, equipment must be equipped with other operational safety equipment such as horns, head lights, brake lights, directional signals, mirrors, and others [3].

The main purpose of wearing protective apparel is to protect the workers from dangers in the work environment. The conditions often associated with workers not wearing appropriate safety equipment deal with garment wearability, comfort, fit and style. These factors lead to workers not complying with safety regulations and end in unsafe operating procedures [27].

Drivers of trucks that are backing up do not see when they are steering into danger, resulting in running off the road or in striking workers-on-foot. Although a spotter should always be used when backing up vehicles, audible backup alarms should also be operational. The US regulations (CFR 1926.601 and 29 CFR 1926.602) state that all trucks and mobile construction equipment must be equipped with an operable back-up alarm. These alarms must be loud enough to be audible over the surrounding noises and should be activated whenever equipment is put into reverse.

OSHA, like many agencies in other countries, has specific regulations regarding the use of machinery when engaged in reverse. OSHA regulations, specifically Title 29 CFR 1926.601(b)(4), state:

"*No employer shall use any motor vehicle equipment having an obstructed view to the rear unless:*

(i) The vehicle has a reverse signal alarm audible above the surrounding noise level or:
(ii) The vehicle is backed up only when an observer signals that it is safe to do so."

The research by Hinze and Teizer [1] investigated 69 specific cases of reversing vehicles that had or did not have (audible) alarms. In 21 of these cases, equipment was operated in reverse in close proximity to others but did not utilize any alert mechanism. It was specifically noted that from the vehicles and equipment that were involved in visibility-related fatalities, in 56 out of the 69 cases the back-up alarm was not functioning. Note that the other cases did not specifically mention back-up alarms.

4 ISO 5006:2006 Standard, Modification and Measurement Practice

The first edition of the International Standard ISO 5006, published in 2006 [2], addresses "operator's visibility in such a manner that the operator can see around the machine to enable proper, effective and safe operation that can be quantified in objective engineering terms." As such, the standard includes a test method that measures blind spots along a boundary line (1 m) away from the smallest rectangle encompassing the machine and the visibility on a test circle (12 m) with the operator being in the origin of the circle [2]. The standard applies to earth-moving machines for operation on works sites and for travelling on public roads.

The test method in the standard further describes the masking, measuring a "shadow on the 12m visibility test circle or the vertical test object at the rectangular 1 m boundary created because parts of the base machine and/or its equipment block the light rays from both of the light bulb filaments" positioned at the operator's eye [2]. Parts that can cause shadows are, for example, cabin elements such as rollover protective structures, window and door frames, exhaust or emission control pipes, engine hood and equipment or attachment, such as bucket or boom [2].

Direct visibility is defined as the visibility by direct line-of-sight (LOS) of the operator to an object, indirect LOS is defined as the visibility only through aids, such as mirrors or closed circuit television (CCTV) cameras.

The International Standard [2] specifies a 300 mm masking dimension for the rectangular 1 m boundary line that represents roughly the chest depth of personnel working in the near field of earth-moving machinery. It also specifies the following three reference dimensions for the measurement on a flat, compacted ground surface with a gradient less than 3% in any direction:

a) 1 m, the distance used in conjunction with the rectangular 1 m boundary line around the earth-moving machinery to describe the near field (closest distance) around earth-moving machinery.
b) 1.5 m, the maximum height above the ground reference plane on which a visibility observation in the near field is made. **This height has been previously based on the height of 5% of the earth-moving machinery operators, but changes in the next release of the International Standard to 1.0 m**. The vertical test object (VTO) has a suitable width of 150 mm to evaluate the masking on the rectangular 1 m boundary.
c) 12 m, the radius of the visibility test circle on a horizontal surface measured from the filament position center-point.

To determine the maskings on the visibility test circle or the rectangular 1 m boundary, a hand held mirror can be used to detect the LOS between the light source and the ground reference plane or VTO. Other apparatus giving equivalent results is permitted as demonstrated by, for example, Teizer et al. [8] and Bostelman et al. [17].

5 Technological Approaches to Alert Workers-on-Foot Nearby Equipment

Aside from using human flaggers that themselves are put at risk when warning operators backing up equipment, a variety of techniques exist to prevent workers-on-foot of getting too close to equipment in operation. Several of these technologies have been extensively discussed or experimentally tested by various research groups investigating construction vehicle-worker interactions. A relative large body of research work has been produced to enlarge the industry's knowledge in this domain [5,8,11,15,18-26,28-30].

Technological approaches are preferred over conventional techniques, such as, installing mirrors that do not function well when the height of engine compartments increases (partially due to new emission regulations) or the mirror mount vibrates while the equipment is in operation (see Figure 4). Legislation or leaders within companies, for example in the United Kingdom and Germany, have therefore demanded the installation of CCTV cameras in addition or as a replacement for using mirrors (see Figure 5).

Figure 4. Ineffective use of mirrors in life-threatening proximity areas surrounding construction equipment (image courtesy [31])

Figure 5. Large equipment manufacturers and contractors start installing and using vision-based monitoring technology on entire equipment fleets

A central monitor mounted inside a vehicle which is connected to front, side and/or rear-mounted CCTV cameras allows the operator to get a real-time image of what is happening directly surrounding the vehicle. Cameras, of which rear and side view cameras have become standard applications on many pieces in equipment fleets within many companies, come usually at the cost of a few hundred dollars. This investment is often co-subsidized by insurance companies or federal/state-driven safety programs in many countries.

Emerging vision-camera solutions implement multiple cameras (4) and combine these to a so-called 360º views as shown in Figure 6. These allow an operator to view any nearby object projected in bird's-eye view on an in-cabin monitor (mounted typically on the dash board near the steering wheel). However, these systems require the operator to constantly monitor the screen, potentially distracting her/him from manually screening the surrounding spaces of the vehicle for workers-on-foot or other hazardous objects. As operators report frequently, these camera systems become useful in cases where the operator briefly checks the space a vehicle heads next.

Figure 6. Surround-view (360º) providing equipment operator (here: a maintenance truck driver) with an on board bird's-eye-view of the areas around the vehicle

A one-technology-solves-the-problem solution, however, is difficult to find since even modern technologies rather quickly reach the boundaries of modern physics. For example, the ability to accurately apply and control the signal of RADAR or SONAR (radio and sound detection and ranging, respectively) technologies is limited to a few meters (ranging from 2 to at most 20 m). Subsequently, engineers have fused signals from multiple object detection technologies, for example, cameras with RADAR or SONAR, to bypass the limitations of each other technology.

Adding such active alerting techniques allows the operator to concentrate on the work task until an alert appears in form of an acoustic, visual, or vibration signal. Figure 7 illustrates such a solution for a large mining vehicle, where the investment in safety easily pays for the installation, operation, and maintenance of multiple systems of technological detection and warning devices.

In addition, one of the main issues that requires modification to such systems is a change in the upcoming ISO 5006 standard. Lowering the height of the VTO from 1.5 to 1.0 m demands explicit change to these existing technological systems. These are in case of a dump relatively simple to implement. For example, wide FOV cameras may replace ones to accommodate for the extra space that needs to be covered. However, the illustration shown in Figure 8 shows that the change in the International Standard will impact smaller vehicles much more. Shown are the new blind spots that are created through lowering the VTO's height.

Two practical opportunities were identified that allow compliance with the upcoming changes in the International Standard (ISO 5006):

a) Modify equipment design to ensure the operator can see the top of the VTO at the 1 m rectangular boundary, and/or
b) Deploy new or modify existing alert technology that provides visibility where equipment design does not allow the operator to detect the VTO.

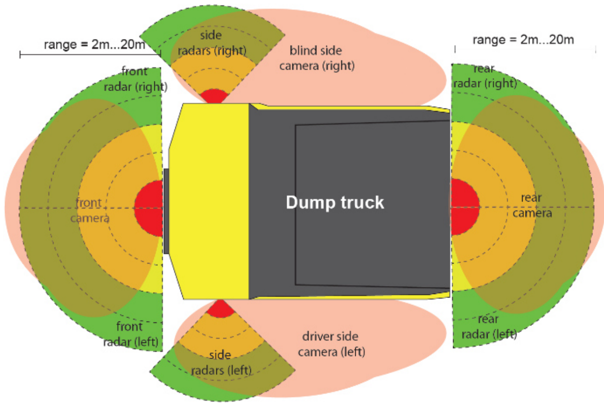

Figure 7. Integrated system consisting of commercially-available camera and RADAR solutions (plan view) (image courtesy [28])

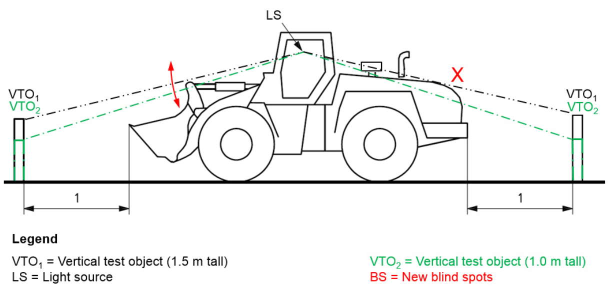

Figure 8. Expected changes to the existing ISO 5006 standard cause new blind spots and require solutions for novel equipment design or advanced sensing systems to detect the VTO

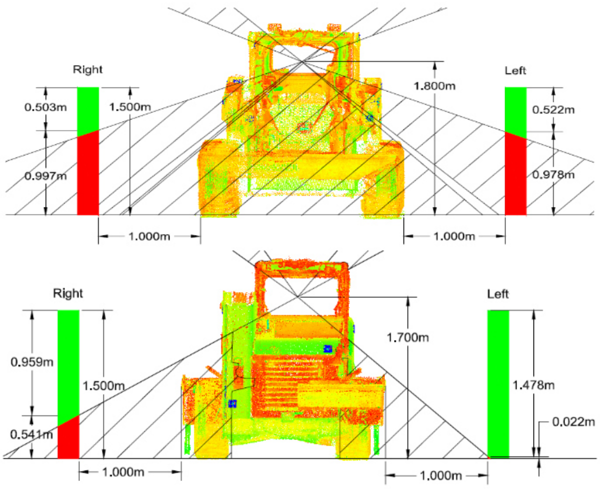

Figure 9. Example of a novel solution to enhance an equipment operator's visibility through modified equipment design: skid steer loader with only one lift arm reduces blind spots (according to ISO 5006:2006 standard, measurement using laser scanning sensor) [14]

As shown in Figure 9, changes to equipment design is possible, but can result in high cost for re-designing potentially large parts of the equipment (incl. engine, emission control), receiving new permits and other compliance tests to satisfy stricter regulations. An alternative is to weigh advantages and limitations of the redesign of equipment versus making minor modifications or additions to the existing proximity warning or alert technology already in place.

Shown in Figure 8 already, additional blind spaces are created by lowering the height of the VTO. Replacing the rear and side view cameras with wide-FOV cameras and adding a new camera, mounted at the front axle of the vehicle looking forward, may also resolve the problem equipment manufacturers will face once the new International Standard becomes effective.

Figure 10 shows the position of the new front camera that monitors the space below the bucket the operator of a wheel loader cannot see. Driving the equipment in the carry-position (bucket is raised) increases the size of the blind spots and prevents direct LOS of the operator to larger parts in the front field. Although the best alternative would be to drive the equipment in reverse – like many forklift operators are required – this is often not practiced in reality.

Alternatively, two bright light sources (see Figure 11) are proposed to provide enough illumination for the potentially darker spaces that are being covered by the bucket or any other attachment or load. See Figure 12 where the operator recognizes workers-on-foot through monitoring the screen that is provided inside the cabin.

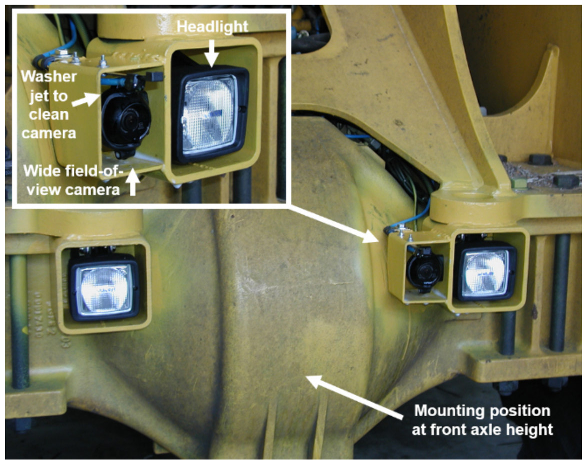

Figure 10. Implementation of camera-based sensing at the front axle on a wheel loader to comply with changes in the revised ISO 5006

Figure 11. Lights brighten the space beneath the bucket (example: 13 m^3 bucket for light material) of a wheel loader that is in a carry position

Figure 12. Operator field-of view to the front of a wheel loader as headlights illuminate the ground

6 Conclusions and Future Work

The focus on worker safety continues to grow in importance throughout the construction industry. Safety is a major priority that has been and will likely continue to be emphasized by public opinion, policy makers, and construction managers. Fatalities on construction jobsites are no longer considered a part of doing business. As construction research continues to identify areas for safety improvement, there are reasons to suggest that fatality numbers will continue to decline.

This research targeted visibility-related fatalities in the construction industry with the aim of discovering relevant patterns of unsafe practices, such as the frequency of incidents related to poor operator visibility.

This research determined that visibility-related construction fatalities accounted for nearly 5 percent of all construction fatalities from 1990 to 2007. Research into visibility-related fatality cases showed that specific safety practices, including technology, could be implemented to reduce the number of these fatalities. Relatively minor modification to existing vision-based camera sensing technology come at low investment, but allow to resolve potential threats to construction personnel and equipment design through the upcoming change in the International Standard (ISO 5006).

It can be argued, however, if the changes to the International Standard will significantly increase safety in the operation of equipment. Arguments against an increase in safety were made, because the International Standard focuses on a very close range (rectangular 1 m boundary) to the equipment. Even non-safety experts will confirm that a worker-on-foot being 1 m away from a piece of equipment has already put herself/himself into a hazardous, highly risky, and life-threatening spot.

An argument for an increase in safety is the additional implementation of safety equipment. In fact, most vehicle owners will drive the adaption towards using closed circuit television (CCTV) in combination with other technology (e.g., RADAR, SONAR, active-tag-based approaches), because changing the design of equipment is very costly and unlikely when legislative requirements demand the installation of new, potentially bulky emission control systems on the rear end of machines. Research has shown such systems enlarge the space near the engine compartment causing additional blind spots to appear which limit the operator visibility.

As such, one could expect at some point soon a true disruptive technological breakthrough, like it seems to occur these days in the car manufacturing industry. However, the traditionally conservative construction market has trailed for some time being an innovative leader. Revisions to International Standards, like the important ISO 5006, are one way to drive innovation. This happens only if the most advanced measurement and test methods are selected.

7 Acknowledgments

The author gratefully acknowledges the support from the following corporations: Brigade Electronics PLC, J.C. Bamford Excavators Ltd., and Volvo Construction Equipment. Any opinions, findings, or conclusions included in this article are those of the author and do not necessarily reflect the views of the sponsors.

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