www.itcon.org - Journal of Information Technology in Construction - ISSN 1874-4753

EVALUATION OF SENSING TECHNOLOGY FOR THE PREVENTION OF BACKOVER ACCIDENTS IN CONSTRUCTION WORK ZONES

SUBMITTED: August 2013
REVISED: December 2013
PUBLISHED: January 2014 at http://itcon.org/2014/1
EDITOR: Ghang Lee

Sooyoung Choe, PhD Student,
Department of Civil, Architectural and Environmental Engineering, The University of Texas at Austin,
email: sooyoung.choe@utexas.edu

Fernanda Leite, Assistant Professor,
Department of Civil, Architectural and Environmental Engineering, The University of Texas at Austin,
email: fernanda.leite@austin.utexas.edu

Dan Seedah, Research Associate,
Center for Transportation Research, The University of Texas at Austin,
email: dseedah@mail.utexas.edu

Carlos Caldas, Associate Professor,
Department of Civil, Architectural and Environmental Engineering, The University of Texas at Austin,
email: caldas@mail.utexas.edu

SUMMARY: *Various sensing technologies, such as video cameras, ultrasonic, radars and tag-based systems, have been developed and tested to prevent collisions within blind areas of construction equipment. However, the performance of sensing technologies varies in different environments, such as dynamic vehicle conditions or characteristics of sensing technologies. Also, there are little standardized testing protocols to evaluate sensor systems performance in an objective manner. Therefore, this paper focuses on evaluating sensing systems performance based on a test design developed specifically for construction back-over safety practices. The presented testbed designs include sensor installation, static test, dynamic test, and dirty sensor test. Each test presents a generalized sensor evaluation factors that should be considered and results are shown in tabular and graphical formats. Contents of this study are expected to help researchers evaluate new technologies objectively and provide users with a better understanding of the implementation of sensing technologies in construction work zones to improve safety.*

KEYWORDS: *Construction Safety, Back-over accidents, Sensing technology, Sensor evaluation factor, Testbed design*

REFERENCE: *Sooyoung Choe, Fernanda Leite, Dan Seedah, Carlos Caldas (2014). Evaluation of sensing technology for the prevention of backover accidents in construction work zones. Journal of Information Technology in Construction (ITcon), Vol. 19, pg. 1-19, http://www.itcon.org/2014/1*

1 INTRODUCTION

Construction work zones are hazardous environments especially due to the dangerous combinations of pedestrian workers and heavy construction vehicles, such as dump trucks, dozers, and rollers. According to the Census of Fatal Occupational Injuries data (CFOI, 2012), the construction industry was responsible for 18.3% of all work related fatalities in 2009, which were 834 out of 4551. 834 fatalities indicate that fatal occupational injury rate equals to approximately 9.7 per 100,000 construction workers, while the total 2009 annual fatal occupational injury rate was 3.5 for all industries. Among the 834 construction industry fatalities, machinery and vehicle related fatalities accounted for 34.3%, or 284 of 834. Table 1 compares the total and construction industry's fatalities from 2003 to 2009 as well as machinery and vehicle related fatalities within the construction industry. Also, CFOI data indicates dump trucks and pickup trucks as the main causes, about 25%, among all construction equipment types.

TABLE 1: Fatalities data from 2003 to 2009 (CFOI, 2003 - 2009)

	Number of Fatalities						
	2003	2004	2005	2006	2007	2008	2009
All Industries	5575	5764	5734	5840	5657	5214	4551
Construction	1131	1234	1192	1239	1204	975	834
Machinery or Vehicle	397	407	416	422	386	336	286
Pickup trucks	67	64	71	74	65	37	59
Dump trucks	29	47	37	48	32	14	27

Construction vehicle related deaths were responsible for more than half of 844 road construction workers deaths in the United States from 1995 to 2002 and dump trucks accounted for 41% of "worker on foot" related deaths, with 52% of these involving dump trucks backing up (Washington, 2009). The American Road & Transportation Builders Association (ARTBA) named back-overs as one of the leading causes of death among roadway construction workers, with over half occurring when workers were struck by construction vehicles or equipment in work zones (Zeyher, 2007). According to the Occupational Safety and Health Administration (OSHA), about 360 industrial workers were killed from back-over accidents from 2005 to 2010 in the United States (OSHA 2012).

To minimize backing fatalities, many object detection technologies, such as radar, ultrasonic, and radio-frequency identification based systems, have been tested and applied within the automotive, construction and mining industries. These sensor-based object detection technologies provide hazard warnings to either operators or workers to prevent collisions within blind areas of construction equipment. However, it is common practice that every construction equipment type has limited possible sensor installation locations. Also, due to the lack of an appropriate sensor performance measurement framework, developed specifically for construction safety practices, there is a need to develop a construction industry-specific testing and reporting protocol to evaluate sensor system performance. The main objectives of this study are: (1) to conduct a comprehensive sensing technology detection performance set of experiments that is practical and relevant to the construction industry; and (2) to present different sensor detection performance in different scenarios to improve construction vehicle related back-over safety practices.

2 BACKGROUND RESEARCH

Blind areas differ by equipment types and enable the understanding of visibility limitations around construction equipment. It is therefore important to study blind areas of various construction equipment types to implement sensor systems for each equipment type. Within OSHA fatality cases from 1990 to 2007, blind area was found to be the leading cause of construction equipment related back-over fatalities (Hinze and Teizer, 2011). In addition, understanding blind areas of equipment help select and implement technology-based devices to minimize the risk to workers (Hefner and Breen, 2003; Ruff, 2007). In order to help understand blind areas of various construction equipment types, the National Institute for Occupational Safety and Health provides blind area diagrams for 13 types of equipment and 41 models (NIOSH, 2012). Also, expanding on NIOSH's blind area diagrams, researchers have developed an automated blind spot detection tool using a laser scanner (Allread and Teizer, 2010).

Many studies have evaluated various sensing technologies to minimized equipment related accidents caused by blind areas near vehicles. A sensing system typically consists of a type of sensor that detects the presence of an object, an interface that provides an audible and/or visual alarm to the equipment operator, and wiring between the two. Potential sensing technologies include video cameras, ultrasonic, radar, radio-frequency identification (RFID), and global positioning systems. Video camera is the most widely used device to cover blind areas of a vehicle and provide the exact location of hazards (Wierwille, 2008). However, operators must observe the monitor to identify the nature of the hazard (Mazzae and Garrott, 2007), thus it is recommended as a supplemental device with other sensing technologies, which enable the automatic generation of alarms (Ruff, 2000; Ruff 2001). Ultrasonic-based sensing systems are popular to aid with parking for light vehicles, but have relatively limited detection ranges (i.e., both distance and width) to be implemented for heavy construction equipment (Ruff, 2007). Radar-based systems enable the generation of longer and wider detection zones as compared to ultrasonic-based sensing systems. This system detects people and metal object such as other vehicles effectively, but showed limitations to detect plastics and wood (ISO, 2010). Another limitation in using radar-based sensing systems is false alarms which might eventually make the drivers ignore warnings from the systems, but this problem can be minimized by integrating sensor-based with video camera systems (Ruff, 2007). In recent years, tag-based RFID systems have been actively studied for real-time monitoring and tracking in construction work zones because of its capability to collect data (Maalek and Sadeghpour, 2013; Marks and Teizer, 2012; Naticchia et al., 2013). Also, these systems cover relatively long detection ranges. However, tag-based RFID systems are relatively expensive as compared to ultrasonic and radar-based systems and have the potential of collisions with workers who are not outfitted with a tag (NIOSH, 2011). In busy and dynamic construction work zones, especially in open job sites, relying on all possible hazards, including workers and fixed objects (e.g., other vehicles and materials), wear a tag will be challenging. Global positing system (GPS) has been used to prevent vehicle related collisions in work zones (Oloufa, 2002). This system enables covering wide areas using satellite signals in open areas, but has limitations related to accurately estimating locations near high-rise structures, as they typically interfere with satellite signals (Sacks et al., 2003).

Testing sensing systems in realistic environment is a key process for the successful technology implementation. In order to evaluate the reliability of technology, testbeds should be developed before the technology deployment in jobsites (Saidi et al., 2011). The National Highway Traffic Safety Administration (NHTSA) developed ten testbeds based on three scenarios, which are vehicle to vehicle, vehicle to pedestrian, and vehicle to fixed object crash scenarios to evaluate sensor systems in the automotive industry (Perez et al., 2011). Static and dynamic tests are the most widely used testbed types to determine a detection zone of a sensor system (Ruff, 2000; Ruff, 2007; Mazzae and Garrott, 2007). However, there is no clear evidence of why these two types of tests are important and lead to contradictory results. In addition, due to the lack of testbeds designed to evaluate sensor systems for construction safety practices, there is a need to develop construction industry-specific testbeds.

3 RESEARCH METHODOLOGY

3.1 Tested sensor systems and vehicles

In order to select sensor systems for the test, a sensor selection criteria was developed based on literature review (Ruff, 2000, 2001, 2007; Oloufa, 2002; Mazzae and Garrott, 2007; ISO, 2010; NIOSH, 2011). The criteria included technology types, maximum range of rear detection zone, system response time, false alarm rate in clear field, and cost. Based on the system selection criteria, specific data for ten commercially available systems were collected among five technologies examined in the background research and reviewed by six safety experts who have worked in Texas Department of Transportation (TxDOT) as upper level decision makers for TxDOT's safety implementation. As a result, two sensing technologies, ultrasonic and radar-based technologies, were selected mainly due to implementation constraints in road maintenance vehicles. Within two technologies, four commercially available sensor systems were selected for the tests. The selected sensor systems include an ultrasonic system (U1) and three pulsed radar systems (R1, R2, and R3). Key features of each sensor system were provided by vendors and are summarized in Table 2.

TABLE 2: Key features of four sensor systems

System Type	Technology	Number of Sensors	Max. Detection Range (meters)	Response Time (ms)	Detection Shape	Frequency	Cost*
U1	Ultrasonic	2	2.7	250	U	40 kHz	Under $500
R1	Pulsed radar	1	3.0	500	U	5.8 GHz	$500 - $1,000
R2	Pulsed radar	1	6.0	500	V	6.3 GHz	$500 - $1,000

R3	Pulsed radar	1	6.0	500	U+V	5.8 GHz	$1,500 - $2,000

* Cost surveyed in Feb. 2012

System U1 is an ultrasonic-based sensor system and uses 40 kHz low frequency sound waves to detect the objects within the detection zone. Two sonar sensors detect objects behind the vehicle and both visual and audible warnings are generated on the monitor in the cap. This system has a ‘U’ shaped detection zones and 2.7 meters (9 feet) maximum detection range. The other three systems (R1, R2, and R3) are pulsed radar-based systems between 5.8 and 6.3 GHz super high frequency signals. These radar-based systems have a single sensor and both visual and audible warnings are generated in the same way as system U1. System R1 has a ‘U’ shaped detection zones and 3.0 meters (10 feet) maximum detection range. System R2 and R3 have 6.0 meters (20 feet) maximum detection range with a ‘V’ and the combination of ‘U’ and ‘V’ shaped detection ranges, respectively. According to vendors, sensor systems with ‘U’ shaped detection ranges have a better capability of detecting close proximity area but have a limited detection range and width. On the other hand, sensor systems with ‘V’ shaped detection range enable the detection of longer and wider distance objects but have a limitation to cover close proximity area. To leverage strengths of both detection shapes, the combination of ‘U’ and ‘V’ shaped detection ranges have recently been developed, which has better detection ranges as well as enhanced capability to detect close proximity area. Figure 1 illustrates three different detection shapes of sensor systems and the authors verified them during the tests.

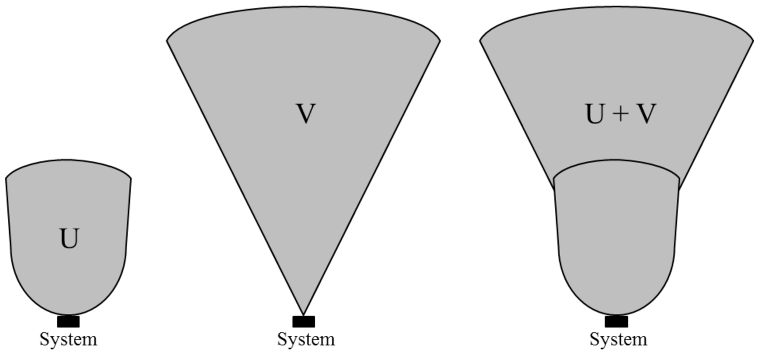


FIG. 1: U, V and U+V detection shapes

In addition, two types of construction vehicles, a dump truck and a pickup truck, were selected for the tests because these two vehicle types are the most widely used in construction work zones and recognized as the leading causes of backing accidents in the United States (CFOI, 2012; Washington, 2009; Zeyher, 2007; OSHA, 2012).

3.2 Experimental setup

In order to evaluate sensor systems in an objective manner, testing sensor systems in different conditions is an essential process in terms of the reliability of sensor systems. In this study, one experiment was conducted to evaluate proper sensor installation positions on the vehicles and three experiments were developed to assess the performance of sensor systems in different scenarios, which can commonly occur in construction work zones.

3.2.1 Sensor installation

It is common practice that every construction equipment type has limited possible sensor installation locations and, as identified by previous studies (Ruff, 2007), sensor installation height and angle are influential factors in detection performance of sensor systems. Therefore, it is important to identify proper sensor mounting positions and limitations for installation with typical construction equipment types. According to the Texas Department of Transportation (TxDOT) maintenance officers, three different capacity dump trucks and two models of pickup trucks are most widely used in TxDOT work zones (Table 3). Therefore, three dump trucks and two pickup trucks were measured to evaluate proper installation locations for four sensor systems at the TxDOT Central Maintenance Office, in Austin, Texas. Because sensor systems were designed to aid low speed backing maneuvers, the rear of each vehicle was checked for possible sensor mounting positions, which were finally determined from the evaluation with the maintenance manager and vendors. Figure 2 illustrates samples of sensor installation review with a dump truck and a pickup truck.

2-a *2-b*

FIG. 2: Sensor installation survey. Installation survey with dump truck (2-a) and Installation survey pickup truck (2-b)

According to sensor installation review with three types of dump trucks, system U1 can be installed to the steel plate just outside the brake lights or to the bottom of the bed with brackets. Three radar-based systems (R1, R2, and R3) should be attached to the bottom of the bed in the middle. Because three single sensors have a socket at the back of the sensors, they need a bracket to be hung on. For dump trucks, U1 system which consists of double sensors is more flexible for installation because pre-installed devices in the middle of the rear such as a license plate and a trailer connecting device limit installation space for single sensor systems which should be installed in the middle. From the installation assessment with three dump trucks, installation heights and widths of system U1 range from 0.86 meters (34 inches) to 1.12 meters (44 inches) and from 1.01 meters (40 inches) to 1.12 meters (44 inches), respectively. Installation heights of three radar-based sensor systems range from 0.97 meters (38 inches) to 1.12 meters (44 inches) in the center. On the other hand, the sensor installation review with two types of pickup trucks shows that there is no ideal location for single sensor systems (R1, R2, and R3) for both pickup trucks because of the tailgate and license plates. According to the Texas Transportation Code - Section 502.404, Operation of Vehicle without License Plate or Registration Insignia (Texas, 2007), operators need to display two license plates, at both front and rear of the vehicle. Therefore, single radar-based sensor systems cannot cover the license plate. In case of system U1, two sensors can be attached to the rear bumper with relatively flexible width. Also, system U1's two sensors might be installed at the bottom of the bumper (0.36 meters high) to avoid possible contact with bumpers from other vehicles. Even though single sensor systems (R1, R2, and R3) do not seem to have proper areas for sensor installation, the authors assumed that sensors could be installed on the step plate immediately behind the license plate (see Figure 2-b) for the purpose of the field tests because the license plate might be moved Table 3 summarizes installation review of four sensor systems for five different vehicles. The measurement results will be used to design the static test.

TABLE 3: Summary of sensor installation survey with five construction vehicles

No.	Vehicle type		U1		R1		R2		R3	
			Height (meter)	Width (meter)	Height (meter)	Width (meter)	Height (meter)	Width (meter)	Height (meter)	Width (meter)
1	Dump truck	6 yards	0.86	1.01	0.97	Center	0.97	Center	0.97	Center
2		10 yards	1.12	1.12	1.12	Center	1.12	Center	1.12	Center
3		F-450	1.01	1.01	0.97	Center	0.97	Center	0.97	Center
4	Pickup truck	Chevrolet-1500	0.61	1.32	0.56	Center	0.56	Center	0.56	Center
5		RAM-1500	0.36	1.32	0.56	Center	0.56	Center	0.56	Center

3.2.2 Static test

The static test represents the scenario in which both vehicle and detectable objects are stationary. In this scenario, it is expected that a sensor system enables the maximum detection performance regardless of sensor response time and vehicle speed. The detection area measured in the static test will serve as a benchmark for the dynamic test and the dirty sensor test. All tests were performed at the J.J. Pickle Research Campus in Austin, Texas. A wooden frame was built and used to install four sensor systems (see Figure 3) in different heights and widths instead of actual vehicles, and a DC 12 voltage car battery was used as a power source. In order to record an accurate detection range, a 5.5 meters by 9.1 meters (18 feet by 30 feet) measurement grid was set up using nylon strings with each cell at 0.3 meters by 0.3 meters (1 foot by 1 foot).

FIG. 3: Frame and measurement grid setup for static tests

In order to compare the impact of different sensor installations on sensor detection performance, sensors were tested in different heights and widths. Since sensor installation heights and widths may be modified due to specific conditions such as a size of hanger and a height of bumper, the authors believe that tests with representative heights and widths are more important for future users rather than specific dimensions. Therefore, seven different heights measured from the sensor installation survey were rounded to three representative heights, 0.61 meters (24 inches), 0.91 meters (36 inches), and 1.22 meters (48 inches). For system U1, 0.30 meters (12 inches) installation height was also tested and additional tests were conducted at three different widths, 1.02 meters (40 inch), 1.32 meters (52 inch), and 1.63 meters (64 inch) because this sensor system consists of two sensors. A total of 15 tests were performed and a human male participated as the object to be detected by the sensor systems.

The static test process was designed based on two previous testbed designs (Ruff, 2007; Mazzae and Garrott, 2007). The detection area was determined by having a person walk towards the stationary sensor system installed in the wooden frame and Figure 4 describes the basic scenario of the static test. After installing a sensor system at the specific installation position, the person moved toward the sensor in a line parallel to the longitudinal centerline of the sensor. When the alarm was triggered the first time, the cell was recorded on the data collection sheet. Similarly, when the alarm stopped, the cell just passed was recorded as the other end point of detection range in the straight line. To minimize response time impact of each sensor system, the subject stayed at least one second in each cell to implement the static test. In this scenario, cells between two end points were assumed within the detection range. By repeating the same scenario along with the other lines, the detection range of the sensor system was obtained. This process was repeated ten times for each test.

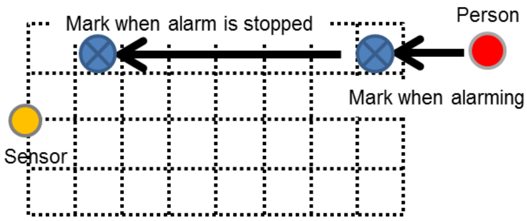


FIG. 4: Basic procedure of static test

During the test, manual results were recorded on the data collection sheet whether or not an alarm is activated in the cells and then converted into cumulative (Figure 5). In the cumulative result, cells with 10 indicate that the areas were detected ten times out of ten trials and cells with 4 indicate that the areas were detected four times out of ten trials. From the cumulative result, reliable detection area (90% accuracy or above) and sporadic detection area (less than 90% accuracy) were also determined.

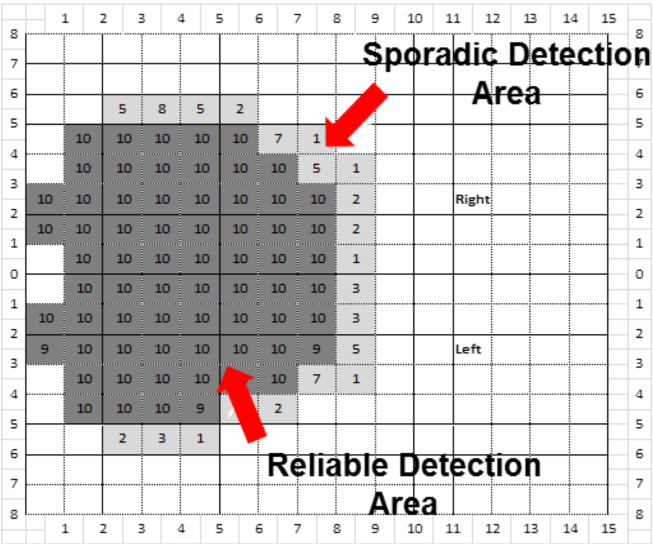
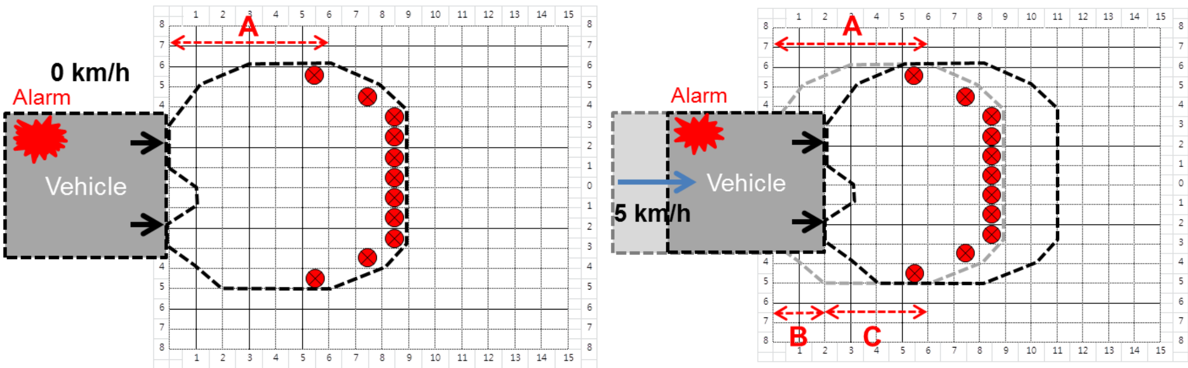


FIG. 5: A sample of the static test data collection. The size of each cell is 0.3 by 0.3 meter (1 by 1 foot).

3.2.3 Dynamic test

The dynamic test was performed to evaluate maximum detection range changes due to dynamic conditions of vehicles and different sensor response times. The basic scenario of the dynamic test is that a vehicle is moving and an object is stationary. A dynamic test design was developed based on the theoretical detection range models in static and dynamic conditions, shown in Figure 6.



6-a *6-b*

FIG. 6: Detection range model. Static test model (6-a) and dynamic test model (6-b). Distance A: Maximum detection range of the sensor in the static condition, Distance B: Detection range reduction due to the dynamic condition, and Distance C: Dynamic detection range of the sensor in the dynamic condition. The size of each cell is 0.3 by 0.3 meter (1 by 1 foot).

As illustrated in Figure 6-a, the static test model reflects a scenario that both a vehicle and an object are stationary. In this scenario, we were able to obtain a maximum detection range, 'A' of a system regardless of sensor's response time and vehicle's backing speed. In the dynamic test, a vehicle is moving and a detectable object is stationary, and the dynamic test model reflects simple physics, $D = V \times T$, where 'D' is distance, 'V' is velocity, and 'T' is time. As can be seen Figure 6-b, maximum detection ranges reductions were expected because there is a lapse until a signal is reflected from the object and triggers an alarm. The range reduction (‘*D*’) will be dependent on sensor’s response time (‘*T*’) and vehicle’s backing speed (‘*V*’).

The dynamic tests were conducted in the TxDOT Central Maintenance Office. Dimensioned floor grids were composed of 0.3 meters (one foot) squares which were painted on a level and asphalt-paved parking lot to place a test object on the same distance, ‘A’, as tested in the static test and to measure the range reduction, ‘B’, in dynamic conditions. The total size of the outdoor grid was 6 by 6 meters (20 by 20 feet) and additional area for the vehicle was provided to reach the 4.8 kilometers per hour (3mph) backing speed. In order to minimize the impact of different vehicle speeds, the driver participated in the test was asked to back both pickup and dump trucks at 4.8 kilometers per hour (3mph) and a researcher measured the changed distance ‘B’ when an audible alarm was triggered from the cab. Also, a sensor specialist from a vendor participated to assist with sensor installations.

Based on the dynamic detection range model in Figure 6, the dynamic test was designed to measure detection range reductions in dynamic conditions of vehicles. After installing a sensor system on a vehicle which was surveyed for vehicle measurement, equipment reversed at 4.8 kilometers per hour (3 mph) toward the stationary obstacle, a mannequin which is positioned at the far edge of the detection range defined in the static test. When an alarm was triggered, a researcher recorded range reductions ‘B’ as illustrated in Figure 7. Each test was performed five times during the dynamic test.

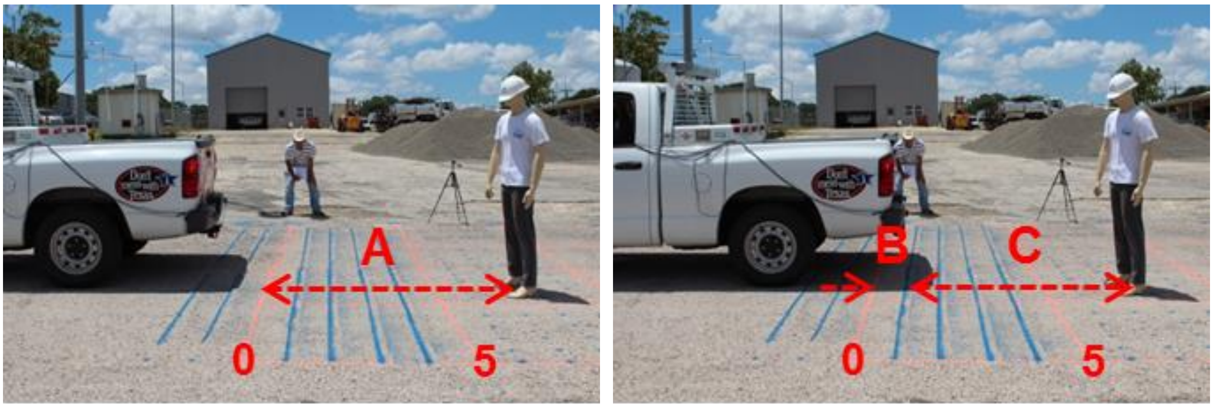


FIG. 7: Basic procedure of the dynamic test. Distance A: Maximum detection range of the sensor in the static condition, Distance, B: Range reductions due to the dynamic condition, and Distance C: Dynamic detection range of the sensor in the dynamic condition. The size of each cell is 0.3 by 0.3 meter (1 by 1 foot).

During the field test, detection range reduction ‘B’ (See Figure 7) was recorded on the data collection sheet and then the dynamic detection range ‘C’ was calculated from ‘A’ and ‘B’ in the cumulative results (Figure 8). In Figure 8, red colored cells indicate maximum detection range ‘A’ obtained from the static test and numbered cells in grey and red indicate dynamic detection range ‘C’ measured from the dynamic test. For example, boxed cells (3, 1, 1) indicate that ‘A’ is 6 feet in the static test and out of 5 trials ‘C’ is measured three times at 1.22 meters (4 feet), one time at 1.52 meters (5 feet), and another one time at 1.83 meters (6 feet).

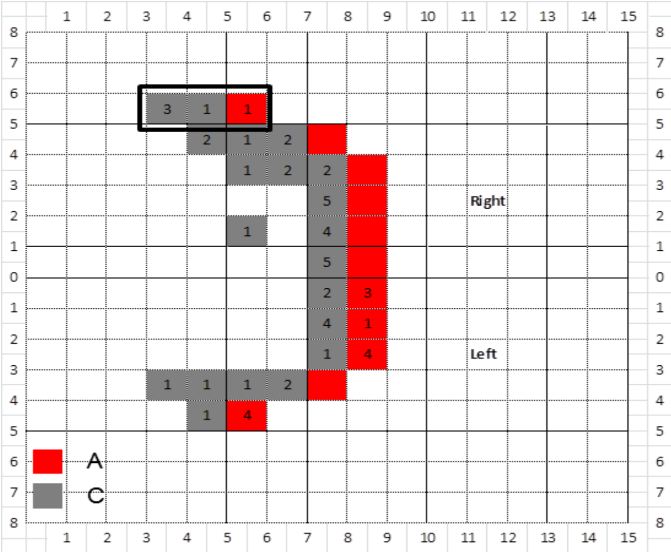


FIG. 8: A sample of the dynamic test data collection. The size of each cell is 0.3 by 0.3 meter (1 by 1 foot).

3.2.4 Dirty sensor test

Due to the nature of construction work zones, sensor systems are likely to be covered in dirt, mud, or other materials at some point in the construction process. Since ultrasonic and radar-based sensor systems use signals to detect objects, any materials covering sensors might impact the detection performance of the sensor systems by interrupting the process of emitting and receiving signals. The dirty sensor test was designed to evaluate the impact of dirt on sensor systems related to their detection performance. Two sensor systems, U1 and R3, were tested to examine the change of detection performance with cleaned sensors and U1 and R3 represent ultrasonic and radar systems, respectively. The dirty sensor test was conducted in the at the J.J. Pickle Research Campus in Austin, Texas. The same grid line and procedure of detection zone measurement were used as the static test. For the dirty sensor test, two sensor systems were only tested at 0.91 meters (36 inches) height, which is the recommended installation height from the vendors. The following diagram (Figure 9) details the process undertaken for the dirty sensor test.

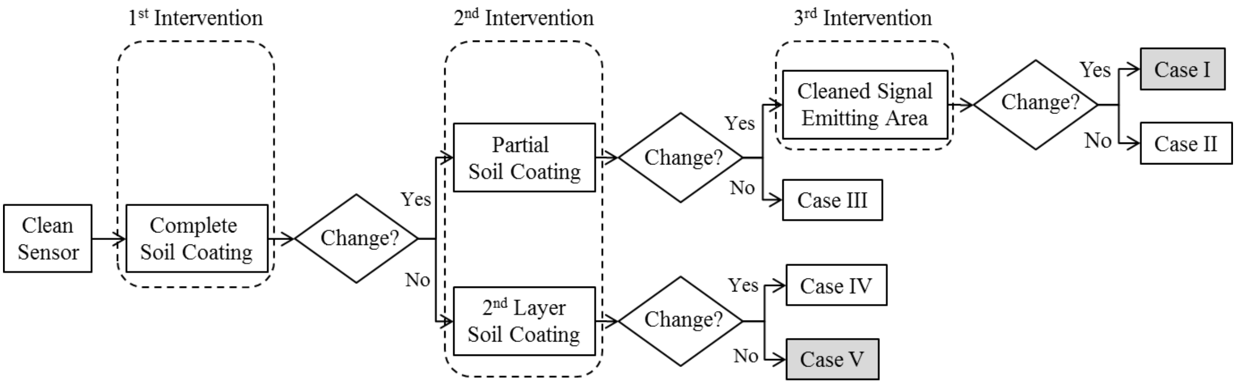


FIG. 9: Process diagram of dirty sensor test

To measure the detection performance difference between the clean and the dirty sensor, the clean sensor was coated with soil in a first intervention (Figure 10). Based on measured sensor detection performance changes, a second intervention was conducted either by removing soil partially when the sensor detection performance was changed or by adding a second layer of soil when there was no detected difference after the first intervention. The third intervention was only performed when the sensor performance was influenced by partially removed soil. In the third intervention, the signal emitting areas on sensors were cleaned clearly, and the detection performance was compared with the static test result of the clean sensor. Among possible five cases, Case I indicates a sensor system is influenced by soil on the sensor detection performance and Case V represents a sensor system is not affected by soil. For the other three cases, it is difficult to explain the relationship between the detection performance and soil on the sensor.

FIG. 10: Dirty sensor test with system R3 - before (left) and after coating (right).

3.3 Scope and limitations

The following are scope and limitations of this research.

- Even though Tag-based systems (e.g. RFID) or GPS are also commercially available and have been studied actively in the construction area, only two types of sensing technologies, ultrasonic and radar, were evaluated in the study based on recommendations from TxDOT maintenance supervisors.
- Only two types of construction vehicles, pickup and dump trucks, were tested during the dynamic test. Even though these two types are leading causes of vehicle-related accidents in the work zones, involvement of additional types of construction equipment types might be needed to generalize application of sensor systems in terms of sensor installation review.
- Since the focus of this study is to prevent backing accidents between construction vehicles and pedestrian workers, only a human male and an equivalent size of mannequin were used as objects. However, it would be useful to perform tests with other objects, such as typical construction materials or other vehicles, in future research.
- Sensor response time data were obtained from vendors. Since their response time data were tested in controlled indoor conditions, these data can differ from active jobsite conditions.
- During the dynamic test, the driver was asked to maintain backing speed at 4.8 kilometers per hour (3mph) and a researcher was on the cap to observe the speed, but the actual backing speed might have been slightly different for each trial.
- Dynamic tests performed in this study do not include the scenario in which a vehicle is backing and an object is moving due to the safety issue to a moving object (human). However, the dynamic detection range of sensor systems in this scenario can be estimated from the formula, $D = (V_v + V_o) x T$, where 'D' is distance, 'V_v' is a velocity of a vehicle, 'V_o' is a velocity of a moving object, and 'T' is a response time of a sensor system.

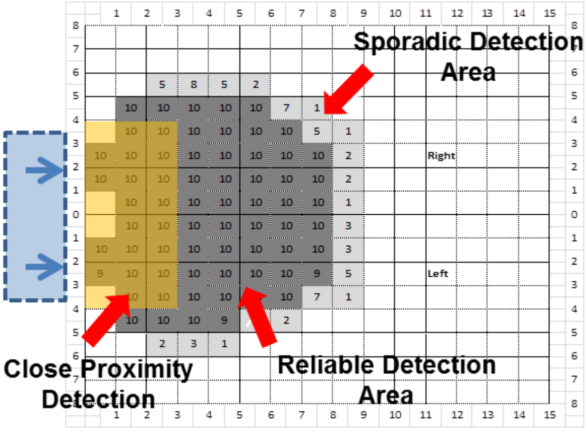
4 RESULTS

4.1 Static test results

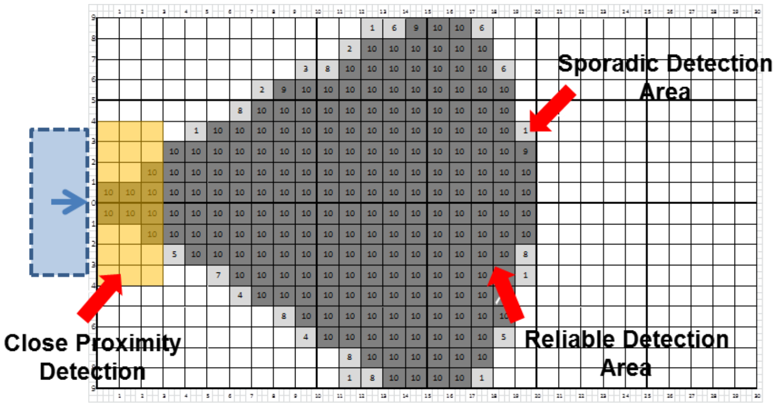
To assess the detection performance of four sensor systems in the static scenario (i.e. both vehicle and object are stationary), the following performance evaluation factors were observed:

- Total coverage: To evaluate the overall detection zone, the total number of cells detected by a sensor system was measured, which is the summation of reliable and sporadic detection areas.
- Reliable detection area: To evaluate reliability of detection zone, the number of cells detected more than nine times out of ten trials was measured and the reliable detection area percentage indicates a ratio of total coverage and reliable area. This area will be used to determine the size of the detection zone.
- Sporadic detection area: To indicate unreliable detection zone from the total coverage, the number of cells detected less than nine times out of ten trials was measured and sporadic area percentage indicates a ratio of total coverage and sporadic detection area.
- Close proximity detection area: To evaluate the capability of detection in close proximity areas, the number of cells detected by a sensor within 0.91 meters (3 feet) of an 2.44 meters (8 feet) wide vehicle was measured.

Figure 11 shows two sample detection area diagrams of system U1 at 0.91 meters (36 inches) heights with 1.32 meters (52 inches) width and systems R2 at 0.91 meters (36 inches) in the middle.



11-a



11-b

FIG. 11: Samples of static detection zone diagrams. System U1 - Test 03, H: 0.91m and W: 1.32m (10-a) and System R2 - Test 11, H: 0.91m and Middle (10-b).The size of each cell is 0.3 by 0.3 meter (1 by 1 foot)).

A dashed blue box and arrows in each figure indicate approximate width of pickup truck and installation position of sensors, respectively. In addition, the close proximity area, which is colored in yellow, was defined to evaluate the capacity to detect within 0.91 meters (3 feet) long and 2.44 meters (8 feet) zone. A total of 15 sets of static tests were conducted and Table 4 summarizes static test results with maximum detection distance, total coverage, reliable detection area, sporadic detection area, and close proximity detection area.

TABLE 4: Static Test Results

Test No.	Sensor Type	Height (meter)	Width (meter)	Max. Detection Distance (meter)	Total Coverage (count)	Reliable Detection		Sporadic Detection		Close Proximity Detection	
						count	%	count	%	count	%
S1	U1	0.30	1.32	Detect the ground frequently							
S2		0.61	1.32	2.74	99	80	80.8%	19	19.2%	19	79.2%
S3		0.91	1.32	2.44	88	67	76.1%	21	23.9%	20	83.3%
S4		1.22	1.32	2.74	92	77	83.7%	15	16.3%	20	83.3%
S5		0.91	1.02	2.74	81	67	82.7%	14	17.3%	17	70.8%
S6		0.91	1.63	2.74	106	96	90.6%	10	9.4%	19	79.2%
S7	R1	0.61	Center	3.01	88	75	85.3%	13	14.8%	13	54.2%
S8		0.91	Center	3.01	92	98	76.5%	16	17.4%	10	41.7%
S9		1.22	Center	3.01	100	108	83.7%	8	8.0%	15	62.5%
S10	R2	0.61	Center	6.10	225	202	89.8%	23	10.2%	6	25.0%
S11		0.91	Center	6.10	237	214	90.3%	23	9.7%	8	33.3%
S12		1.22	Center	6.10	247	228	93.3%	19	7.7%	6	25.0%
S13	R3	0.61	Center	6.10	264	238	90.2%	26	9.8%	13	54.2%
S14		0.91	Center	6.10	272	246	90.4%	26	9.6%	13	54.2%
S15		1.22	Center	6.10	294	262	89.1%	32	10.9%	19	79.2%

When two ultrasonic sensors (U1) were installed at 0.30 meters (12 inches) height, the ground was detected frequently by sensors, so Test S1 could not be continued. Except for Test S1, there were no false alarms through the rest of the tests. Total coverage described in Table 4 is used to calculate the percentages of reliable and sporadic detection areas. The percentage of reliable detection area indicates consistency of system detection performance. Higher percentage of reliable detection area represents higher detection performance of a system in terms of consistency. To determine a detection zone of a system in a static condition, it is recommended to use reliable detection zone instead of total coverage. In terms of detection capability of close proximity area, system U1 which consists of two sensors, detected more than 70% of the cells within close proximity areas and followed by systems R1 and R3. However, system R2 showed very limited capabilities to detect close proximity areas, at most 33.3% during the tests.

In order to see detection range variances by installation heights, each three sets of tests were used to compare detection range variances of four sensor systems. Each sample is ten individual tests conducted at three different heights with four different systems. A one-way Analysis of Variance was performed. The ANOVA results (see Table 5) showed that, at $p<0.05$, there was a significance difference between means, thus the null hypothesis stating that the means of different installation heights are equal at 95% confidence level can be rejected. Therefore, in accordance with a previous study (Ruff, 2007), we verified that sensor installation heights do impact sensor detection performance.

TABLE 5: Results of the one-way ANOVA test for three different installation heights

System	H: 0.61 meters			H: 0.91 meters			H: 1.22 meters			F value	p-value
	Sample size	Mean	Standard Deviation	Sample size	Mean	Standard Deviation	Sample size	Mean	Standard Deviation		
U1	10	86.30	5.29	10	73.80	2.97	10	83.70	6.70	27.202	0.000
R1	10	80.90	2.51	10	81.70	3.59	10	95.20	1.48	90.509	0.000
R2	10	209.60	2.63	10	224.00	2.58	10	236.00	2.91	237.774	0.000
R3	10	250.40	4.53	10	257.70	3.50	10	273.70	3.68	92.050	0.000

4.2 Dynamic test results

During the dynamic test, the dynamic detection ranges of sensor systems were studied by placing sensor systems on moving equipment (i.e. a vehicle is backing and an obstacle is stationary). To access the performance of sensor systems in dynamic conditions, the following performance evaluation factors were considered:

- Detection range reduction (‘B’): This factor evaluates changed detection range of sensor systems due to the dynamic conditions of the vehicle. Individual results of each trial are presented in the detection zone diagram and averaged 'B' is recorded in the dynamic test results. This changed detection ranges should be compared to maximum detection ranges in the static condition to see differences.

- Non-detection: This evaluation factor is designed to measure the detection consistency for sensor systems comparing to the static test results and percentage indicates a ratio of the number of total trials and the number of no detection.
- False alarm: False alarms are alarms generated in the clear field because the sensor might detect the ground or parts of vehicles such as tires during backing operations. Percentages of false alarms indicate a ratio of the number of total trials and the number of false alarms.

Figure 8 shows the dynamic detection area diagram of system U1 with the 4.8 kilometers per hour (3mph) backing pickup truck installed at 0.61 meters (24 inches) heights with 1.32 meters (52 inches) width. Another possible installation position of system U1 with a pickup truck, which is under the bumper at 0.30 meters (12 inches) high, was not tested because the static test result showed that sensor installation at 0.3 meters (12 inches) height generate frequent false alarms due to the detection of the ground. Figure 12 is the diagram of systems R2 with 4.8 kilometers per hour (3mph) backing dump truck installed at 0.91 meters (36 inches) in the middle.

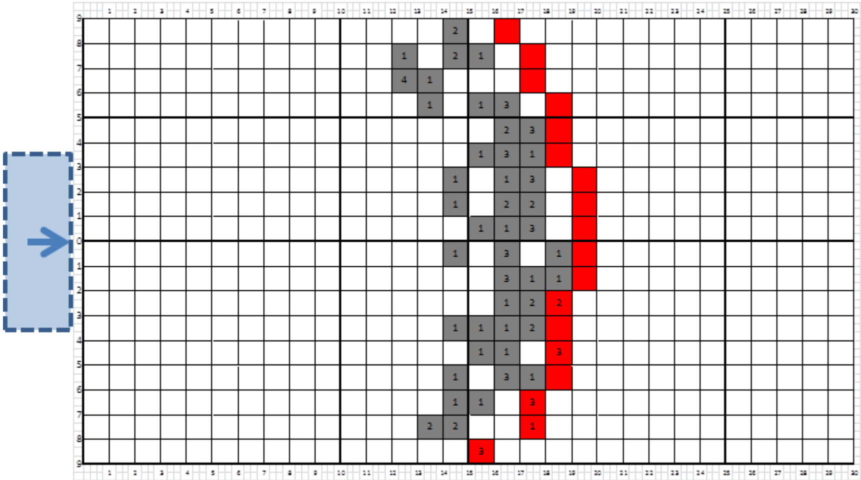


FIG. 12: Dynamic detection zone diagram of system R2 with a pickup truck (Test D3). The size of each cell is 0.3 by 0.3 meter (1 by 1 foot).

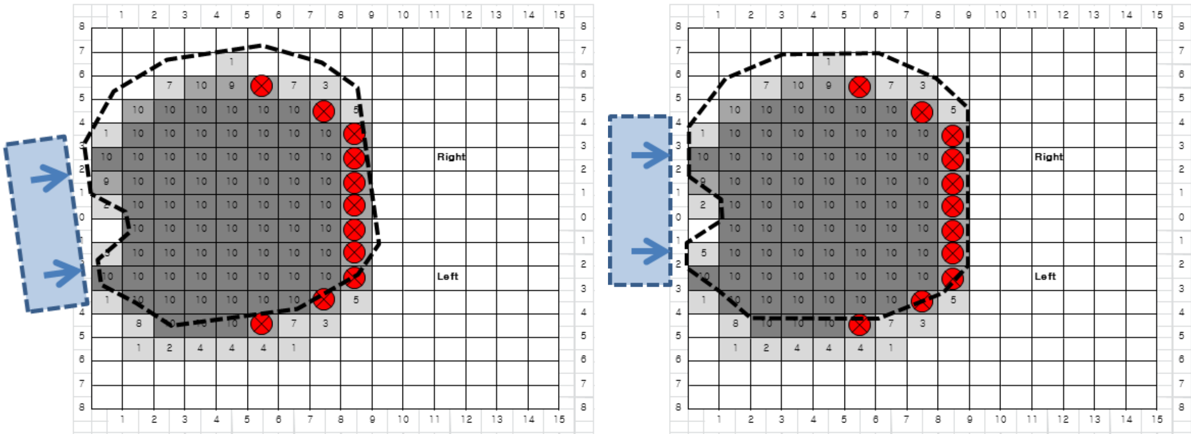
TABLE 6: Dynamic test results

Test No.	System Type	Vehicle Type	Height (meter)	Width (meter)	Average 'B_a' (meter)	'B_c' (meter)	Non Detections		False Alarms		Trials
							Count	Percentage	Count	Percentage	
D1	U1	Pickup Truck	0.61	1.32	-0.34	-0.34	0	0.0%	3	5.5%	55
D2	R1	Pickup Truck	0.61	Center	-1.21	-0.67	16	32.0%	0	0.0%	55
D3	R2	Pickup Truck	0.61	Center	-0.61	-0.67	6	6.7%	0	0.0%	90
D4		Dump Truck	0.91	Center	-0.92	-0.67	12	13.3%	0	0.0%	90
D5	R3	Pickup Truck	0.61	Center	-1.11	-0.67	12	13.3%	0	0.0%	90
D6		Dump Truck	0.91	Center	-1.34	-0.67	27	30.0%	0	0.0%	90

In Table 6, 'B_a' indicates the reduced maximum detection range measured from the dynamic test and 'B_c' represents the reduced maximum detection range calculated based on the vehicle's backing speed (4.8 kilometers per hour) and sensors' response times (250 ms for U1 and 500 ms for R1, R2, and R3 within their detection zones). As can be seen Table 6, Test D1 (system U1 with a pickup truck) and Test D3 (system R2 with a dump truck) showed almost same reduced maximum detection range measured and calculated. However, the other four tests indicated that there is a disparity between values of 'B_a' and 'B_c' ranged from 0.25 meters to 0.67 meters. These differences represent additional reduction in the sensor's detection capability from 37.3% to 100.0% comparing to calculated detection range reductions. These differences can be from measurement errors such as different backing speed and recording errors, but the following factors resulted in detection range reduction differences between measured and calculated.

- Response time: Response time data of four sensor systems were collected from the vendor, which tested the sensors in a controlled indoor environment. Therefore, it is possible that response times in an outdoor field test might be different due to extraneous factors such as dirt or weather conditions.
- Vehicle operation conditions: Vehicle's dynamic conditions such as vibration can affect the sensor's detection performance. When the same sensor systems were compared in terms of values of 'B_a' measured from pickup and dump trucks were compared (Test D3 vs. D4 and Test D5 vs. D6), detection range reductions ('B_a') measured with the dump truck showed more gaps compared to 'B_c' than 'B_a' tested with the pickup truck.

Overall, system U1 showed the shortest average range reductions while the test of system R3 with dump truck presented average -1.34 meters detection distance reduction comparing to the static test results. Also, Test D6, system R3 with dump truck, showed 27 times non-detections, which is 30% of total test trials. Non-detections might be obtained as the same reasons as differences between 'B_a' and 'B_c'. However, since most non-detections occurred in both sides of detection zones, vehicle direction can be more influential factor. As described in Figure 13, vehicle's backing angle or backing location could be off when the vehicle arrived at the zero distance point in the measurement grid and led to non-detections in both sides of detection zones.



13-a *13-b*

FIG. 13: Example of possible vehicle angle (13- a) and vehicle location (13- b) at zero distance point. The size of each cell is 0.3 by 0.3 meter (1 by 1 foot).

In terms of false alarms, three radar systems (R1, R2, and R3) presented no false alarms and system U1 presented three false alarms during the dynamic test.

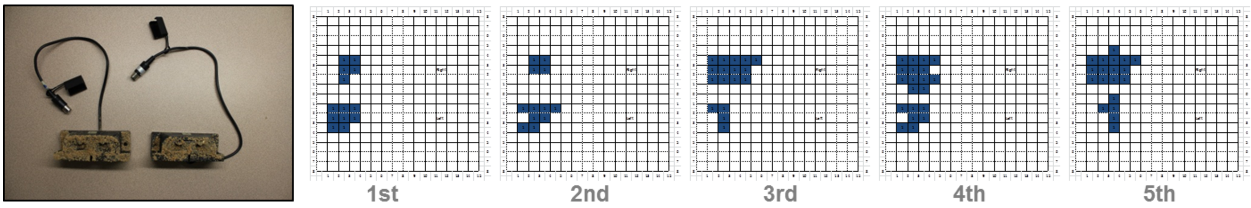
4.3 Dirty sensor test

Two sensor systems, U1 (0.91 meters height and 1.32 meters width) and R3 (0.91 meters height in the middle), which represent ultrasonic and radar-based systems, respectively, were tested to access the performance of dirty sensors. Two other radar systems, R1 and R2, were tested once given that both R1 and R2 systems are from the same vendor as R3 system and initial results of both systems showed similar performance of the system, R3, so further tests were not continued for these systems. During the dirty sensor test the following performance evaluation factors were checked:

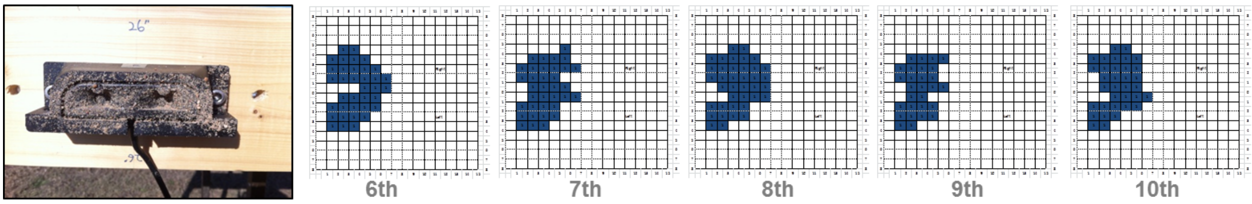
- Average total coverage: Total number of cells detected by clear sensors from the static test at 0.91 meters height.
- Coverage (1st intervention): Number of cells detected by dirty sensors. To measure this coverage, sensors were coated with soil (Figure 10 and 14). This number was calculated from the average of five trials.

- Coverage (2nd intervention): Number of cells detected by less or more covered sensors based on process diagram of the dirty sensor test, shown in Figure 9. This number was calculated from the average of five trials.
- Coverage (3rd intervention): Number of cells detected by sensor that signal emitting areas were cleaned.

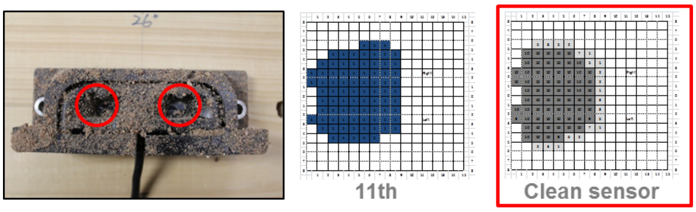
Dirty sensor test with system U1 was Case I in Figure 9 and the test with system R3 was Case V. As described in Figure 14 and Table 7, when first five test trials were conducted with 1st intervention for system U1, the detection capability of this system dropped dramatically from 82 to 16 cells detected, approximately 80% decrease. The second five trials were performed with sensors with less soil coverage; we partially removed the soil from the two sensors. After the 2nd intervention, the detection performance had been improved by approximately double. From the comparisons among coverage of cleaned sensor and after the 1st and 2nd interventions, we concluded that the detection performance of the two ultrasonic sensors were impacted by soil coverage. The 3rd intervention was cleaning the red circled area in Figure 14-c. The test results after 3rd intervention showed that the detection performance returned to the performance with the clean sensors.



14-a



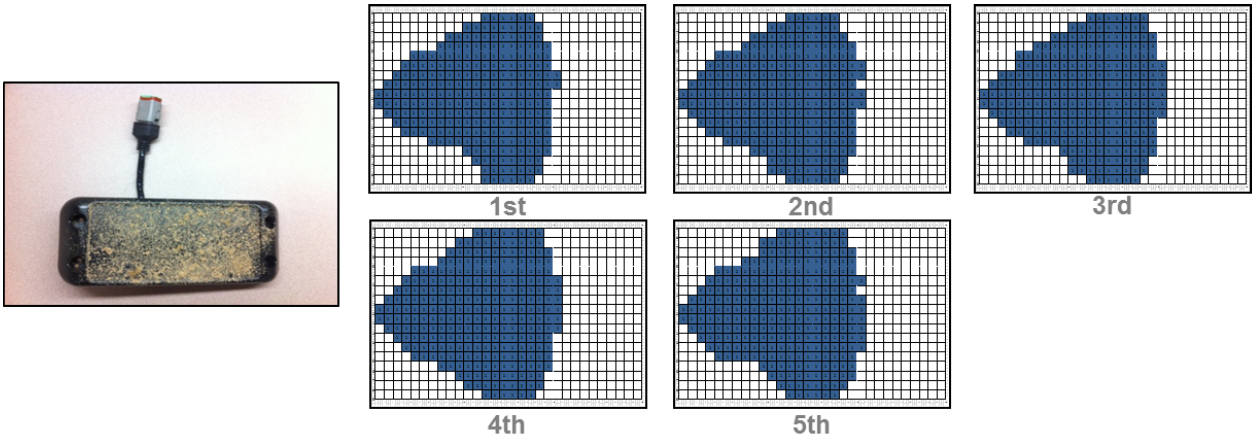
14-b



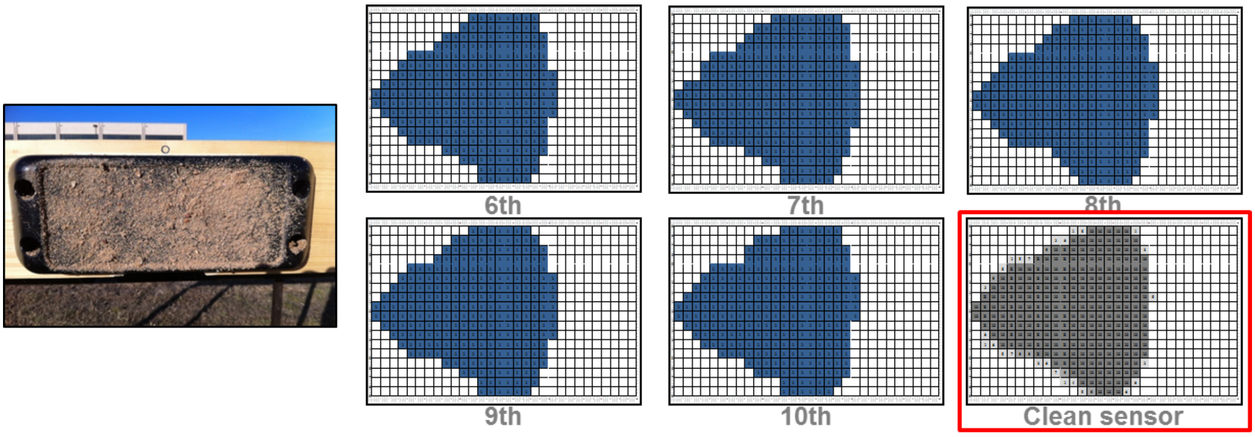
14-c

FIG. 14: Dirty sensor test I - Detection zone diagrams of system U1. 1st intervention, complete soil coating (13-a), 2nd intervention, partial soil coating (13-b), and 3rd intervention, signal emitting areas cleaned (13-c). The size of each cell is 0.3 by 0.3 meter (1 by 1 foot).

As shown in Figure 15 and Table 7, when the first five test trials for system R3 were conducted with 1st intervention (1st layer of soil), there was no detection performance difference from the previous static test with clean sensor. The second five trials were performed with the 2nd intervention (2nd layer of soil) and there was also no detection performance difference. From the comparisons among coverage of clean sensor and after the 1st and 2nd interventions, we concluded that the detection performance of the sensor was not affected by soils covered.



15-a



15-b

FIG. 15: Dirty sensor test II - Detection zone diagrams of system R3. 1st intervention, complete soil coating (14-a) and 2nd intervention, 2nd layer of soil (14-b). The size of each cell is 0.3 by 0.3 meter (1 by 1 foot).

Table 7 summarizes the dirty sensor test results of both systems, U1 and R3.

TABLE 7: Dirty sensor test results

System Type	Height (meter)	Width (meter)	Average Total Coverage(count)	1st Intervention (count)	2nd Intervention (count)	3rd Intervention (count)
U1	0.61	1.32	82	16	34	82
R3	0.61	Center	258	260	262	NA

From the dirty sensor test, the authors found that system U1, which uses ultrasonic signals and has small signal emitting area, is significantly affected by soil coverage. However, system R3, which uses pulsed radar signals and has large emitting area, is not affected by soil coverage. Influential factors causing the performance difference between two sensor types include size of emitting area, signal type, or a frequency. It is recommended to perform tests with different types of ultrasonic and radar sensors to obtain generalizable results.

4.4 Summary of results

Table 8 summarizes the findings with performance evaluation factors from the four experiments conducted.

TABLE 8: Summary of four experiments

		U1	R1	R2	R3
Technology		Ultrasonic	Pulsed Radar		
Sensor Installation	Pickup truck	Yes	No	No	No
	Dump truck	Yes	Yes	Yes	Yes
Static Test	Max. Detection Range (meter)	2.7	3.0	6.0	6.0
	Close Proximity Detection (out of 24 cells (%))	20 (83.3%)	10 (41.7%)	8 (33.3%)	13 (54.2%)
Dynamic Test (at 4.8km)	Detection range reduction 'B_a' (meter)	0.34	1.21	Pickup 0.69	Pickup 1.11
				Dump 1.11	Dump 1.34
	No-Detection (count)	0	16	Pickup 6	Pickup 12
				Dump 12	Dump 27
	False Alarms (count)	3	0	0	0
Dirty Sensor Test	Impact of soil coverage	Yes	No	No	No

Systems (R1, R2, and R3) that comprise of the single sensor have limitations to be installed at a pickup truck due to the existing devices such as a tailgate and a license plate. System U1 showed the best performance in terms of close proximity detection, detection range reduction, and non-detection. However, this system was the only system generating false alarms during the dynamic test and affected by soil coverage while the other three radar-based systems did not generate false alarm and were not affected by soil coverage. Both the test of system R1 with the pickup truck and the test of system R3 with the dump truck presented limited capabilities in terms of detection range reduction ('B_a'). System R2 showed very limited capability to detect close proximity areas during the static test.

5 CONCLUSION AND FUTURE WORK

A set of experiments were conducted in this study to evaluate the reliability of sensing technologies that can prevent back-over accidents. Four types of experiments conducted were: sensor installation review, static, dynamic, and dirty sensor tests. From the experiments, the authors discussed practical sensor installation issues with typical construction equipment types as well as insights on detection ranges of different scenario-based tests; detection range differences between static and dynamic scenarios and between clean and dirty sensor scenarios. Each experiment was designed with several performance evaluation factors. As a result, the performance of different types of sensor systems were compared and evaluated.

This paper has two primary implications for researchers and practitioners in construction safety. Firstly, the research has described a sensing technology performance testing procedure that is geared for the construction industry. Secondly, this research provides users with a better understanding of the systems, from their installation to performance in realistic construction environments and scenarios. Potential backing accidents can be prevented by adding an extra layer of protection, using sensors to automatically identify objects behind the equipment. However, in order to validate the effectiveness of the benefits of sensor-based object detection systems, future research should be conducted to estimate the quantitative benefits from implementation of proximity warning systems to minimize backing accidents in construction work zones.

6 ACKNOWLEDGEMENTS

This research was funded by grant number 0-6703 from the Texas Department of Transportation (TxDOT). TxDOT's support is gratefully acknowledged. Any opinions, findings, conclusions or recommendations presented in this paper are those of the authors and do not necessarily reflect the view of TxDOT. The authors would also like to acknowledge Roger Chen, Jungyeol Kim, and Jinouk Choi, for their assistance during field tests.

REFERENCES

BLS, Census of Fatal Occupational Injuries. (2003 – 2009). Current and Revised Data, Bureau of Labor Statistics. http://www.bls.gov/iif/oshcfoi1.htm#2007 [Accessed 29 May 2012]

Washington State Department of Labor and Industries. (2009). Road Construction Work Zone Safety – Protecting workers on road and highway construction sites, Presentation developed by the Division of Occupational Safety and Health.

Zeyher A. (2007). Separation is a Positive: Good Planning Can Prevent Run-Over Accidents Technology Can Help Too, *Roads and Bridges*, Vol. 45, Issue 9, http://www.roadsbridges.com/Separation-is-a-positive-article8509 [Accessed 23 June 2012]

OSHA. (2012). OSHA seeks comments on how to prevent worker injuries and deaths from reinforcing concrete activities and vehicle backovers, Occupational Safety & Health Administration. http://www.osha.gov/pls/oshaweb/owadisp.show_document?p_table=NEWS_RELEASES&p_id=22071 [Accessed 10 Dec. 2012]

Hinze J. W. and Teizer J. (2011). Visibility-related fatalities related to construction equipment, *Safety Science*, Vol. 49, Issue 5, 709-718.

Hefner R.E. and Breen P.J. (2003). Construction Vehicle and Equipment Blind Area Diagrams, Caterpillar Inc., Contract # 200-2002-00563.

Ruff T.M. (2007). Recommendations for Evaluating and Implementing Proximity Warning Systems on Surface Mining Equipment, National Institute for Occupational Safety and Health (NIOSH), Publication No. 9672.

Mazzae E. N. and Garrott W. R. (2007). Evaluation of the Performance of Available Backover Prevention Technologies for Light Vehicles, National Highway Traffic Safety Administration (NHTSA).

Wierwille W. W., Shaudt W. A., Gupta S. K., Spaulding J. M. and Hanowski R. J. (2008). Development of a Performance Specification for Camera Video Imaging Systems on Heavy Vehicles: Supporting Research, NHTSA, U.S. Department of Transportation Publication DOT-HS-810-958.

Ruff T. M. (2000). Test Results of Collision Warning Systems on Off-Highway Dump Trucks, National Institute for Occupational Safety and Health (NIOSH).

Ruff T. M. (2001). Test Results of Collision Warning Systems on Off-Highway Dump Trucks: Phase 2, National Institute for Occupational Safety and Health (NIOSH).

National Institute for Occupational Safety and Health (NIOSH) Mining Division. (2011). Engineering Considerations and Selection Criteria for Proximity Warning Systems for Mining Operations. http://www.cdc.gov/niosh/mining/topics/electrical/pwsselection.htm [Accessed 5 Nov. 2011]

ISO (2010). Transport information and control systems – Maneuvering Aids for Low Speed Operation (MALSO) – Performance requirements and test procedures, International Organization for Standardization, ISO 17386.

Maalek R. and Sadeghpour F. (2013). Accuracy assessment of Ultra-Wide Band technology in tracking static resources in indoor construction scenarios, *Automation in Construction*, Vol. 30, March 2013, 170-183.

Marks E. and Teizer J. (2012). Proximity Sensing and Warning Technology for Heavy Construction Equipment Operation. *Proceedings of Construction Research Congress 2012*, West Lafayette, Indiana, 981-990.

Naticchia B. Vaccarini M. and Carbonari A. (2013). A monitoring system for real-time interference control on large construction sites, *Automation in Construction*, Vol. 29, January 2013, 148-160.

National Institute for Occupational Safety and Health. (2011). Highway Work Zone Safety – Construction Equipment Visibility Diagram Lookup. http://www.cdc.gov/niosh/topics/highwayworkzones/BAD/imagelookup.html [Accessed 5 Nov. 2011]

Oloufa A. Ikeda M. and Hiroshi O. (2002). GPS Based Wireless Collision Detection of Construction Equipment, *Proceedings of 19th International Symposium on Automation and Robotics in Construction*, Gaithersburg, Maryland, 1-5. http://fire.nist.gov/bfrlpubs/build02/PDF/b02127.pdf [Accessed 22 Oct. 2012]

Sacks R. Navon R. and Goldschmidt E. (2003). Building Project Model Support for Automated Labor Monitoring, *Journal of Computing in Civil Engineering*, Vol. 17, Issue 1, 19-27.

Saidi K., Cheok G., Franaszek M., Brown C., Swerdlow J., Lipman R., Katz I., Golparvar-Fard M., Goodrum P., Akula M., Dadi G. and Ghadimi B. (2011). Development and Use of the NIST Intelligent and Automated Construction Job Site Testbed. National Institute of Standards and Technology (NIST). NIST Technical Note 1726.

Perez M., Angell L.S., Deering R.K., Llaneras R.E., Green C.A., Neurauter, M.L. and Antin J.F. (2011). Advanced Crash Avoidance Technologies (ACAT) Program – Final Report of the GM-VTTI Backing Crash Countermeasures Project, National Highway Traffic Safety Administration (NHTSA). Report No. DOT HS 811 452.

Texas Transportation Code - Section 502.404. Operation of Vehicle without License Plate or Registration Insignia. http://law.onecle.com/texas/transportation/502.404.00.html [Accessed 20 June 2012]