UNDERSTANDING THE REQUIREMENTS FOR A BLIND-SPOT DETECTION SYSTEM ON AGRICULTURAL MACHINES FROM THE OPERATOR'S PERSPECTIVE

by

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Abstract

The operator of a modern agricultural machine is unable to physically see all around the machine, a factor that contributes to accidental run-overs. There is a need to devise an effective blind-spot detection system for agricultural machines to enable operators to avoid accidental run-overs. The purpose of the study is to identify blind spots around two specific tractors and then to propose a conceptual blind-spot detection system based on the observed locations of blind spots. Grids were constructed around all four sides of the tractors to assess blind spots. The Human Activity Assistive Technology (HAAT) model was used to identify the requirements for a blind-spot detection system from the operator's perspective. Diagrams were created to display blind spots around the two tractors. A camera-based system, which was able to eliminate all blind spots, was proposed as a feasible blind-spot detection system.

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1. INTRODUCTION

Canada is one of the biggest exporters of agricultural products in the world (Statistics Canada, 2016). According to the results of the 2016 census on agriculture, farms are getting larger. Farmers take advantage of new technologies and equipment, which allows them to farm more efficiently.

However, workplace safety in the agricultural area is increasingly critical due to the usage of more complicated, more powerful equipment. The Canadian Agricultural Injury Reporting (CAIR) has collected agriculture-related fatality data from 2003 to 2012 (Canadian Agricultural Injury Reporting Agriculture-Related Fatalities in Canada, 2016). There were 843 agriculture-related fatalities in Canada from 2003 to 2012. Among all these fatalities, machine run-overs were the leading cause, accounting for 18% of fatalities. Of machine run-over fatalities, bystander run-overs account for 21%. As agricultural machines increase in size, the existence of blind-spots has become a main factor in bystander run-overs, which also has been a critical issue in safety performance. For example, when operating an enclosed tractor, the fact that the operator cannot detect all the objects and bystanders nearby may cause accidental run-overs.

Blind spots around all types of vehicles and machines can cause severe damage and injuries. Around 1500 people lose their lives every year because they are not seen by the truck driver (De Lausnay et al., 2011a). When toddlers are behind reversing vehicles, blind spots exist at the rear of vehicles (Byard & Jensen, 2009). Ehlers and Field (2015) concluded that numerous incidents were documented due to the operator not seeing a person in close proximity of the equipment during its operation. Thus, studies about blind spots around agricultural machines are critical.

Without assistive technologies, detecting all blind spots around agricultural machines is not possible during operation. A qualified blind-spot detection system is important for safety purposes. It is believed that identifying the location of blind spots would be the initial task of designing a blind-spot detection system. A method of collection and analysis of rearward visibility data for agricultural machinery was developed recently (Ehlers, Field, & Ess, 2017). Therefore, the first objective of this study is identifying blind spots all around the agricultural machines using this method.

Blind spots can be modeled as a form of “blindness” from the perspective of the operator. This is in line with the newly adopted definition of disability that The World Health Organization’s (WHO’s) International Classification of Functioning, Disability and Impairment (ICF) views, which considers disability in social terms rather than in medical terms. Disability is seen as a socially constructed phenomenon that results from barriers that are present in the environment (Cook & Polgar, 2015). Therefore, the HAAT Model was borrowed from the discipline of occupational therapy. The second objective of this study is to propose a conceptual design for a blind-spot detection system using the HAAT model.

2. LITERATURE REVIEW

2.1. Agriculture-related Accidents

Workplace safety is critical for all kinds of industries. The presence of blind spots causes workplace accidents and injuries in industry. Agriculture-related accidents have been recorded in several databases. Although the data on blind spots is relatively limited, the importance of this issue is still clear according to those data. Canadian Agricultural Injury Reporting (CAIR) provides one of the few resources on national agricultural safety records in Canada. It was set up in 1995 and funded by the Canadian Agricultural Safety Association (CASA). CAIR (2016) reported that in Canada, run-overs accounted for the highest percentage of agriculture-related fatalities from 2003 to 2012, and run-overs mostly affect operators (21%) and bystanders (17%). The aim of CASA is to address problems of agricultural illness, injury, and accidental death. However, in all those reports, small injuries were not included, which means the exact number of related accidents would be higher. The data about damage or injuries and economic loss due to blind spots around agricultural machines are limited. In the United States, Bureau of Labor Statistic (BLS), Occupational Safety and Health Administration (OSHA) and National Institute for Occupational Safety and Health (NIOSH) provide databases for safety and health topics about agricultural operations. However, there were limited data showing injuries or fatalities due to the victim being in a blind spot or due to the operator's limited visibility. Recently, NIOSH conducted case studies about blind-spot related accidents which happened in passenger vehicles and construction equipment (Mazzae & Garrott, 2006; Ruff, 2001). Resources related to construction equipment blind spots are abundant in NIOSH. Agricultural machines and construction equipment share many characteristics. For example, they are both large and have plenty of blind spots around them. There are numerous types of equipment, and it is reasonable to assume that blind spots will occur in different locations for each unique type of machine.

Due to the similarity of these types of machines, studies for addressing blind spots around construction equipment could be adapted to agricultural settings. In conclusion, blind spots in agricultural settings are an important issue for workplace safety and related databases have not paid enough attention to this specific field.

2.2. Standards and Recommendations

Relevant standards and recommendations were checked during the literature review. In the Canadian Occupational Health and Safety Regulations (SOR/86-304), there are no regulations related to agriculture-related blind-spot protection or increasing the operator's visibility. For preventing accidental run-overs, it only mentioned "where an employee is regularly exposed to contact with moving vehicles during his work, he shall wear a high-visibility vest and be protected by a barricade". OSHA has no standards related to injuries occurring on the agricultural field. No guidelines related to acceptable visibility are followed by manufacturers with regard to American society of agricultural and biological engineers (ASABE) standards. The International Organization for Standards (ISO) developed an international standard to evaluate operator's visibility during operation which is referred to as the Earth-moving machinery-operator's field of view (ISO 5006:2017). Basically, this method locates lights on SIP (i.e., seated index point) as the operator's eyes. A circle with 12 m radius, called the visibility circle, was marked on the ground. The equipment is located in the center of the circle. The lights are 360º rotatable. Blind spots are identified as the spots where the lights does not hit. These processes described in ISO 5006 were followed to identify blind spots around several large mining machines (Steele, 2006). The locations of blind spots around mining equipment were documented in a report (Steele, 2006). As mining equipment and agricultural machines (i.e., tractors) are similar from many perspectives, this method could be applied to tractors.

Mining equipment and tractors are both heavy machines. Operators usually operate mining equipment in the enclosed cab, while the operators with a tractor might work in an enclosed cab or open cab. The average size of the mining equipment is bigger than tractors in general. In other words, mining equipment might have more blind spots compared to tractors, so this method should work to identify blind spots around tractors.

However, the work environment of tractors is more complicated than the work environment of mining equipment. Mining equipment usually works in a mine, where children or any other members who are not associated with mining tasks are prohibited. On the contrary, farms and other agricultural sites are not just workplaces, but also places where people of all ages live and participate in recreational activities. It is common for family members, including children, to be present near large agricultural machines. The fact that this standard method (ISO 5006:2017) only considered blind spots at the two heights (ground and 1.5 m above the ground) might not work well for blind-spot study in agricultural machines. Accordingly, as different heights of people are needed to be visible for tractor operators, this method should be modified to include more heights when it is applied to tractors. In this study, four different heights were considered when identifying blind spots on agricultural machines. They were i) kneeling worker height, ii) child height, iii) woman height and iv) man height. Furthermore, this methodology is a light-based technique, and it will be difficult to identify blind spots when using cameras and sensors as blind-spot detection technologies.

2.3. Methods for collecting and analyzing visibility data

In addition to the Earth-Moving Machinery-Operator’s Field of View (ISO 5006:2017), three main approaches for collecting and analyzing visibility data were found: i) original technique proposed by OSHA (OSHA, 2000), ii) the volumetric projection technique for digital evaluation of field of view (Marshall, Summerskill, & Cook, 2013), and iii) Rearward Visibility Testing Methodology for Agricultural Machinery (Ehlers & Field, 2017).

2.3.1. OSHA Technique

OSHA published a handout, suggesting a simple way to locate blind spots around large equipment. The steps of the method are followed by positioning a worker near the equipment, moving the worker to different locations, and changing the distance from the equipment until the other worker who sits in the cab cannot observe the worker standing nearby the equipment. With this technique, the length and width of blind areas can be roughly obtained. Applying to different kinds of equipment and demonstrating how blind spots vary from one to another is suggested. This approach measures driver field of view by identification of visible targets outside of the vehicle. Similar approaches were found in other research. For example, Cheng et al. (2016) investigated nine front blind spot crashes which happened with transport vehicles and the researchers created a colored mat to measure front blind spots from mirrors. This type of testing method is easy to understand and simple to complete. However, it is hard to apply the results from case to case. There are limited control factors for the method, different workers or mat construction can give different results.

2.3.2. The volumetric projection technique

Recently, a software-based volumetric projection tool was developed to provide a three-dimensional field of view (Marshall et al., 2013). This methodology uses a computer-based Digital Human Modelling (DHM) tool, called SAMMIE, containing an existing environment and human model. The core implementation of SAMMIE involves projecting a ray from the driver's eye through all the windows and mirrors of the vehicle and then tracing the ray to identify the field of view. Basically, this methodology includes selecting vehicles, capturing three-dimensional data from selected vehicles, modeling the vehicles and the mirrors using CAD, and analyzing the models to assess the visibility from the vehicles.

This methodology successfully measured the field of view for a passenger vehicle (Marshall et al., 2013). More recently, Summerskill (2016) used this methodology to identify blind spots in a large-goods vehicle and compared the results under various driver eye levels and mirror designs. As a 3D modelling system, SAMMIE has an outstanding advantage compared to two-dimensional approaches. Since it simulates the driver's field of view as a complex three-dimensional model, which is in line with real life situations, it provides a greater understanding of field of view. However, it is hard to assess driver's field of view when assistive technologies other than mirrors (i.e., cameras, sensors) are used. As the 3D modeling system is not compatible with cameras and sensors, it cannot be effectively used for designing a blind-spot detection system in vehicles with cameras or sensors.

2.3.3. Rearward Visibility Testing Methodology for Agricultural Machinery

In recent research, a specific rearward visibility testing methodology for agricultural machines was developed (Ehlers et al., 2017). It was originally modified from the on-highway vehicle method (Mazzae & Garrott, 2006). The grids, made of poles, are set up behind the agricultural machine to evaluate blind spots behind the machine. A camera, situated in the tractor cab, simulates the operator's eyes. The height of the pole that would be visible to the operator can be detected by the camera. However, the method was developed for quantifying rearward visibility for agricultural machines; it did not consider the sides or the front of the machine.

2.4. Studies for eliminating blind spots

After locating blind spots, the next step is to eliminate them. The methods for locating blind spots were introduced in the previous section. In this section, the methods to eliminate blind spots are discussed. There are many studies about eliminating blind spots in certain vehicles. Basically, three main types of solutions are available for addressing blind-spot problems (De Lausnay et al., 2011b). The first type of solution, which is most common, is to make blind spots visible to the driver or to the operator by using assistive technologies, such as the placement of mirrors or cameras. The second solution is to indicate the danger zones for bystanders, while the operator or the driver gets no information of the presence of them. This approach reduces the harm of blind spots by offering warning signs to bystanders, but not by improving the operator's visibility. The limitation of using a warning sign is that it could be only used to indicate blinds spots near the machines and the bystanders need to have the capability to understand the warning. Finally, technologies using sensors inform both the operator and the bystander when there is a dangerous situation.

To sum up, mirrors, cameras and sensors are the most common assistive technologies used to eliminate blind spots. In this section, the applications of these three assistive technologies are discussed, while the advantages and disadvantages of them will be discussed in a later section.

Blind-spot detection mirrors, that are usually located on the sides of the tractors or somewhere in the cab, are provided by almost all manufacturers. Several studies mentioned the fact that using mirrors helped the operator to work safely and effectively (S G Ehlers & Field, 2016; Lee, Kim, & Yi, 2013; Sjoflot, 1980). However, the performance of mirrors in detecting blind spots was not mentioned.

Camera-based detection systems are common for passenger vehicles. For example, the rear-view camera is popular for passenger vehicles, which can automatically switch to camera views depending on the gear selection. Mine Safety and Health Administration released some successful applications of camera-based detection systems on mining equipment (Ruff, 2001). The applications for their use on agricultural equipment are also available. Further studies should be done to determine the application of cameras in the agricultural field.

The application of sensors was found in truck and mining equipment. A Zigbee communication system was set up to inform the truck driver and the cyclist of each other's presence (De Lausnay et al., 2011a). Mahapatra et al. (2008) implemented an ultrasonic sensor-based blind spot accident prevention system for passenger vehicles to increase road safety. Sensors are commonly used as a collision warning system for mining equipment (Ruff, 2001). However, there is minimal data that showed the performance of collision warning systems while mounted on heavy equipment. Evaluation of collision warning systems on the selected mining equipment was done by following “Discriminating Backup Alarm System Standard” (SAE standard J1741) (Ruff, 2001). Results showed that the radar is good at detecting people and small vehicles, but false alarms may occur, causing less confidence for the operator during operation. The combination of cameras and sensors was recommended in the literature (Mazzae & Garrott, 2006; Ruff, 2001).

2.5. Limitations Identified in the Literature

Previous research showed that several approaches were available to test visibility in agricultural machines. The volumetric projection technique was impressive because it took into account the field of view in three dimensions, which is closer to the viewable zone in real life. However, it is hard to apply when the goal is to design a blind-spot detection system. A good blind-spot detection system would not just involve mirrors but other technologies, like cameras or sensors. This technique is not compatible with cameras and sensors as blind-spot detection technologies. The performance of the system is hard to evaluate by a software-based technique and needs to be verified on actual equipment (Ruff, 2001).

The Earth-Moving Machinery-Operator’s Field of View (ISO 5006:2017) is a standard model to identify viewable zones. However, it has the same weakness as the volumetric projection technique. This standard model uses light-based techniques which project a cone of light starting at the driver’s eye. This technique is not suitable for identifying blind spots when using cameras or sensors. Besides, this standard only considered blind spots at the ground and at 1.5 m above ground.

In order to identify blind spots around agricultural machines in real-life situations and to ultimately come up with a better blind-spot detection system, the methodology previously used by Ehlers (2016) was chosen and modified for this study. This methodology was designed to achieve the following:

- To test operator’s visibility in agricultural machines.
- To identify blind spots on the rear, the two sides, and the front.
- To consider the fact that different people are likely to be present in the agricultural field and therefore, blind spots were evaluated on multiple elevations representing the height of a kneeling worker, the standing height of a child, the average standing height of a woman, and the average standing height of a man.
- To test the performance of mirrors in detecting blind spots and to assess the effectiveness of other technologies.

3. MATERIALS AND METHODS

The methodology previously used by Ehlers (2017) was modified for this research to enable blind spots to be identified on all four sides of the selected agricultural machines. Grids composed of cells were set up around selected tractors in order to identify blind spots (Figure 1). At the center of each cell was a pole containing colored tapes at different heights. The different colored tapes indicated the average heights of a Canadian man (red tape), woman (orange tape), child (pink tape), and kneeling worker (grey tape). A camera situated on the tractor seat simulated the operator’s eyes. It was physically rotated through 360 degrees with pictures taken at 45 degree intervals to assess the visibility all around the machine. The corresponding tapes on the poles, that would be visible to the operator, can be detected by the camera. Therefore, the blind spots around the tractor can be quantified.

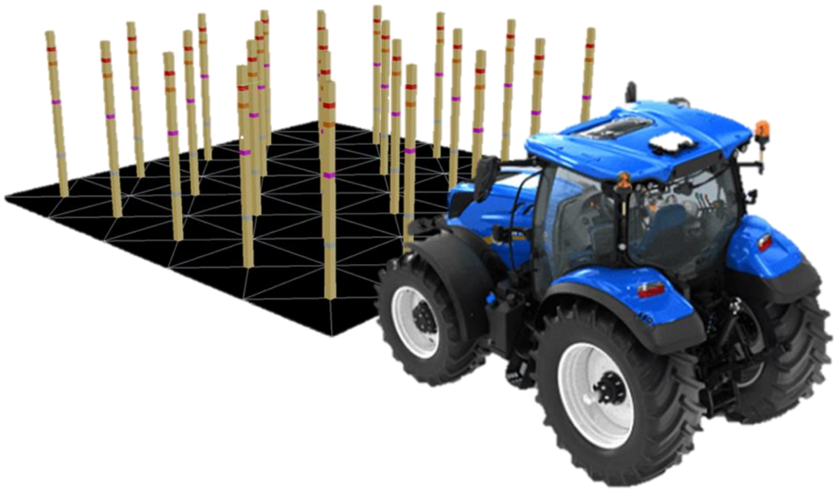


Figure 1 Evaluation grid in front of the tractor.

3.1. Machine selection

Two different agricultural machines (Figure 2) were selected in order to identify and compare blind spots around different types of agricultural machines. Both machines were from the same manufacturer. One machine was a loader tractor (Tractor 1), New Holland T6.175, with a front-end loader attached in the front. Inside the cab of Tractor 1, a passenger seat was provided by the manufacturer. Accordingly, the visibility of the operator with a seated passenger and without a seated passenger were assessed to compare the difference between these two conditions. The other selected agricultural machine was a bi-directional tractor (Tractor 2), New Holland TV6070, without any implement attached during the experiments. They are referred to as T1(Tractor 1) and T2(Tractor 2) in this thesis. Additional details about the tractors are listed in Table 1.

Figure 2 Tractor1(left) and Tractor2(right)

Table 1 The details information of Tractor 1 and Tractor 2.

Agricultural Machine		Tractor 1 (T1)	Tractor 2 (T2)
Type		Shop Loader Tractor	Bi-directional tractor
Manufacturer & Model		New Holland T6.175	New Holland TV6070
Dimensions (mm)	Length	6000	4500
	Width	2300	2500
	Height	3000	3100
Implement		A Loader in the front	None
Other Information		Two extended arm mirrors on two sides; One mirror inside the cab (right front corner)	Two mirrors inside the cab. (One is located in the front right corner, the other locates in the rear left corner.)

3.2. Experimental testing heights

Four different heights were evaluated in order to document the blind spots at different horizontal planes; they were height of kneeling worker, height of standing child, height of standing woman, and height of standing man. These four testing heights represented the average height of certain groups of people in order to evaluate the visibility in different heights. The average height of a kneeling worker is 61 cm (CDC.2012). The average heights, taken from the Canadian health measures survey (2009-2011) are shown in Table 2.

Table 2 Heights chosen for each testing height (Canadian health measures survey)

Categories	Mean Height (cm)	Height Value Selected
Child (both sexes, age 6 to 11)	134.84	135
Female (age 20 to 39)	162.98	163
Male (age 20 to 39)	177.70	178

3.3. Grid construction

Based on the method that Ehlers (2017) developed, grids were constructed in the front, in the rear side, and on both sides of the tested tractors in this study.

3.3.1. Grids in the front and the rear side

The dimensions of grids are 7.62 m (25 feet) wide by 7.62 m long, with each grid composed of 25 cells. As mentioned, at the center of every cell was a pole containing colored tapes at different heights. The different colored tapes indicated the average heights of a Canadian man (red tape), woman (orange tape), child (pink tape), and kneeling worker (grey tape). The top views of grids were shown in Figure 3.

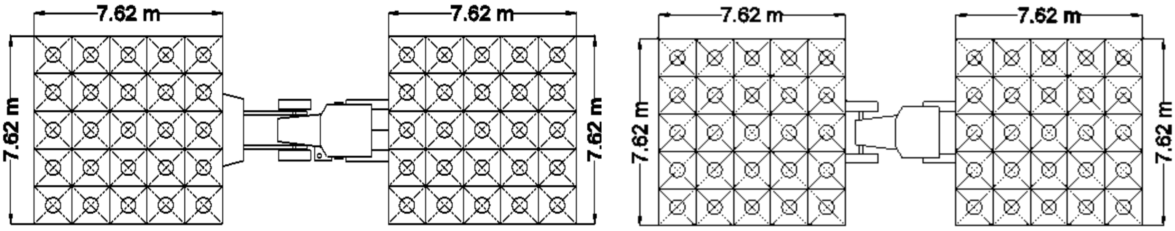


Figure 3 Grids in the front side and rear side for Tractor1(left) and for Tractor2(right)

The poles were wooden stakes with sharpened bottoms, and the tapes were attached at the corresponding heights, indicating the four testing heights. The grid construction was completed based on experimental work conducted by Ehlers (2016). After marking the locations of each pole, surveying equipment was used to ensure that all of the tapes were placed at the appropriate heights.

3.3.2. Grids on the sides of the tractors

Grids on two sides are similar to the grids in the front and the rear (Figure 4).

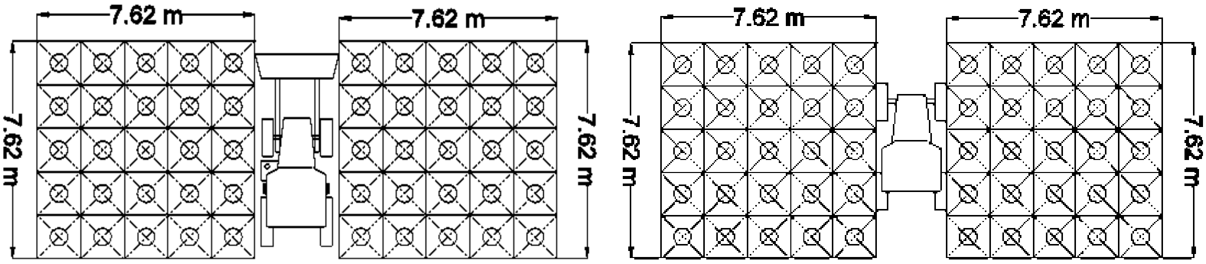


Figure 4 Grid on the two sides in Tractor1 (left) and Tractor2 (right)

3.3.3. Additional grids

There were some special blind spots that the standard square grids could not identify. Therefore, additional grids were set up for Tractor1 to determine those blind spots (Figure 5).

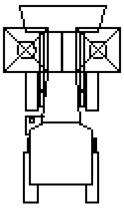


Figure 5 T1_additional grid construction

3.4. Simulating the operator's eye level

Inside the cab, a 12 Mega Pixel camera of IPhone Model A1778, with up to 5X digital zoom, was set up at the level of the operator's eyes. The reference levels proposed were intended to simulate the level of 5th, 50th and 95th percentile male driver's eyes (Behara & Das, 2012). Both straight seated eye level and slumped seated eye level were tested (Table 3) in order to compare the results from two different seating postures.

Table 3 Canadian adult male structural anthropometric measurements (Behara & Das, 2012)

Seating Posture	Seated Eye Level (mm)		
	5th Percentile Male	50th Percentile Male	95th Percentile Male
Straight sitting position	668	730	811
Slumped sitting position	614	706	781

Tools used to determine eye levels included a camera tripod, a measuring tape and a level (Figure 6). Setting up the camera at the appropriate eye level consisted of the following steps: 1) Choosing a reference spot in the center of the operator's seat, with the center pole of the tripod at the reference point, 2) Using the measuring tape and arranging the legs to the desired eye level, 3) Leveling the tripod and making sure the center pole of the tripod was perpendicular to the ground, 4) Placing the camera on the tripod, and rotating the tripod head allowing the camera to rotate 360° horizontally

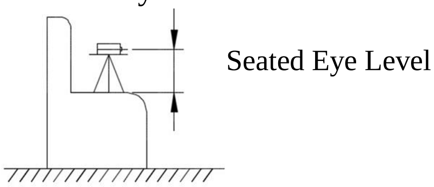


Figure 6 Camera set-up.

In the experiments, the camera was rotated through 360° to simulate the operator's physical turning. It captured images at every 45° of turn. From the images obtained from the camera, the height of the poles that would be visible to the operator was detected by the corresponding tapes visible to the camera. Therefore, the blind spots around the agricultural machines can be quantified. In order to determine whether the blind-spot detection systems are effective in detecting blind spots, the images for mirrors were also captured.

Figure 7 An image captured by the camera

3.5. Procedures

Experiments were conducted to identify the blind spots around the selected tractors. All the experiments in this study were conducted outdoors in a field during the summer months (May, 2017 and June, 2017).

Before the experiments, the two tractors were cleaned with a high-pressure washer in order to ensure windows were clean. A large, level field site was selected at the university's research farm. Before doing the experiments, the tractor was parked at the site and enough space for grid construction was ensured. Poles were set up in order to construct the grids. Surveying equipment was used to obtain elevation differences at the location of each pole so that adjustment could be made to ensure all the tapes were at the same height. The camera was set up inside the cab at one of the intended eye levels. Pictures were captured when rotating the camera. A summer student was asked to sit in the passenger seat in Tractor 1, in order to simulate the situation where a passenger would be seated inside the cab. Accordingly, the visibility of the operator with a seated passenger was measured. All pictures were collected and analyzed to determine the blind spots. After the field experiments, all data were input into MS Excel and blind-spot zone plots were draw using AutoCAD.

4. RESULTS

The first objective of this study was achieved by assessing blind spots around the two tractors. In this section the visibility of the operator under different experimental conditions is presented by grid diagrams. These diagrams show a top view of the test grids with the tractor at the center of the grids. To simplify the presentation of the operator's visibility, four heights were generated separately to describe the locations of blind spots. Different colors are used to indicate blind spots at different testing heights. The colors are consistent with the tape colors (i.e., grey tapes were used at kneeling working height, blind spots at kneeling worker height were indicated using the color grey).

4.1. Blind-spots diagrams for Tractor 1 (slumped sitting positions)

The results of the blind spots around Tractor 1 for slumped seated operators, grouped by testing heights, are shown in Figures 8 – 11. The set of 6 grid diagrams below (Figure 8) indicate the visibility of the kneeling worker height around Tractor 1 for operators of 5^{th}, 50^{th} and 95^{th} percentile slumped sitting levels. The results include situations with the passenger seated beside the operator and without the passenger. Above each individual grid diagram, the specific experimental condition is indicated (i.e., "k, slumped, 5^{th}, without" means the visibility of kneeling worker height around the Tractor for an operator of 5^{th} percentile slumped sitting level, without the passenger seated beside the operator). The same approach was used to present data for Tractor 1 at the other three heights (i.e., child height, woman height, and man height).

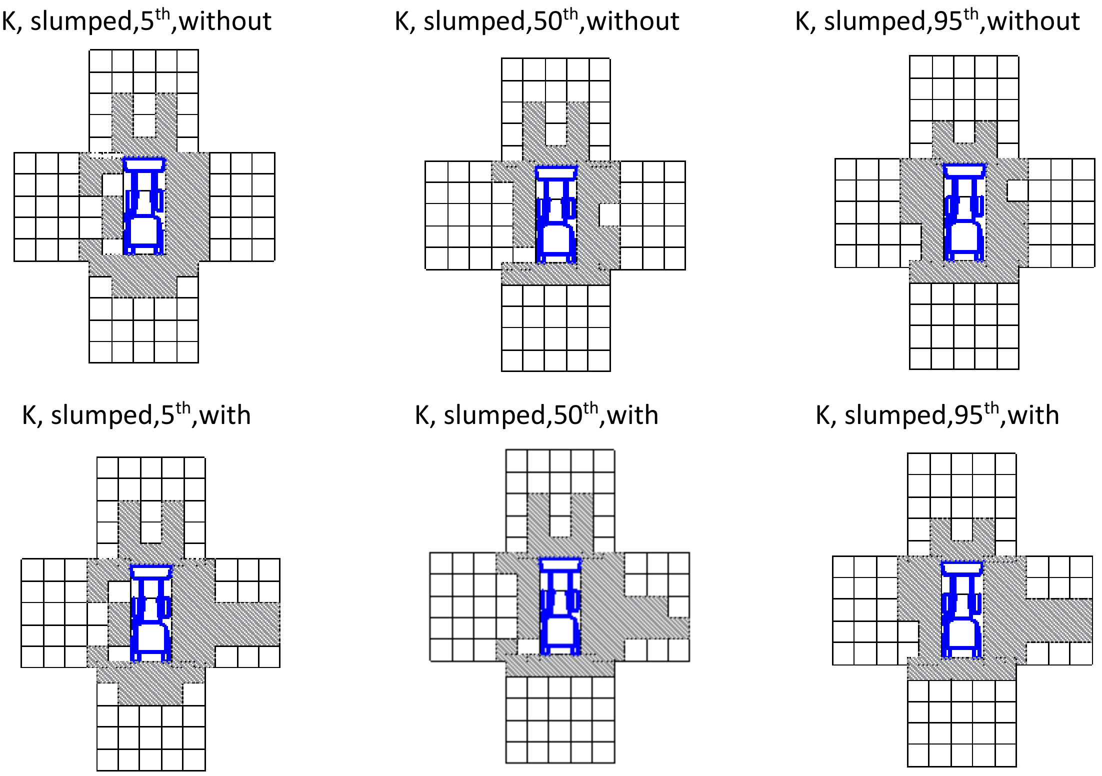


Figure 8 Visibility results for Tractor 1 at the kneeling worker height for a slumped sitting position.

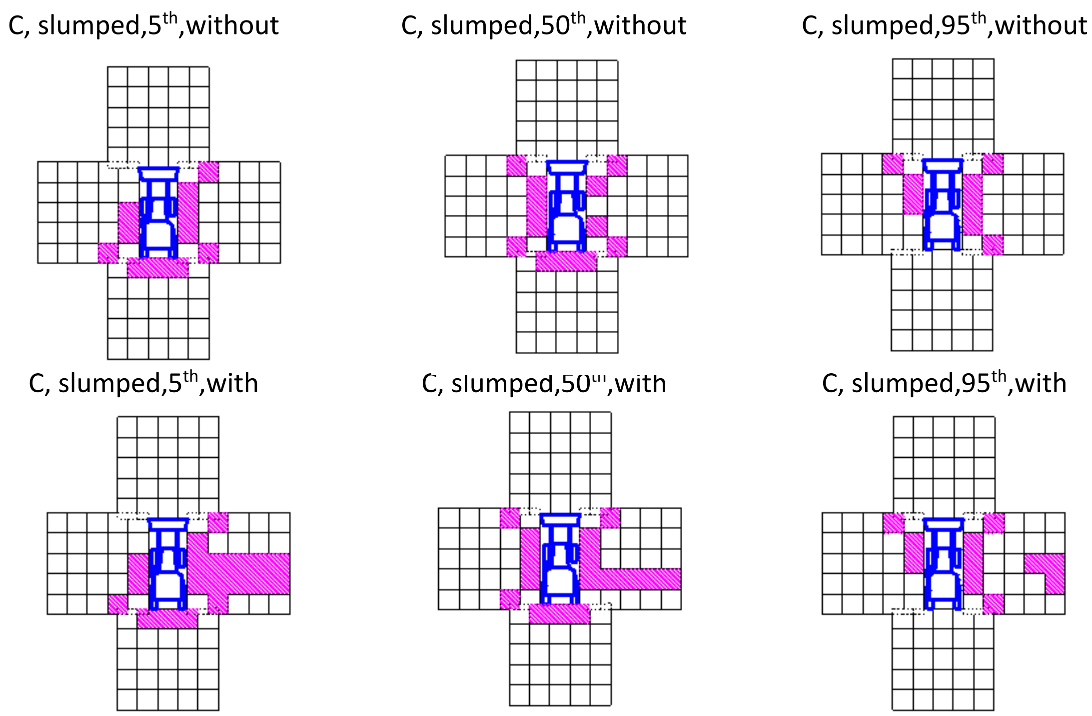


Figure 9 Visibility results for Tractor 1 at the child height for a slumped sitting position.

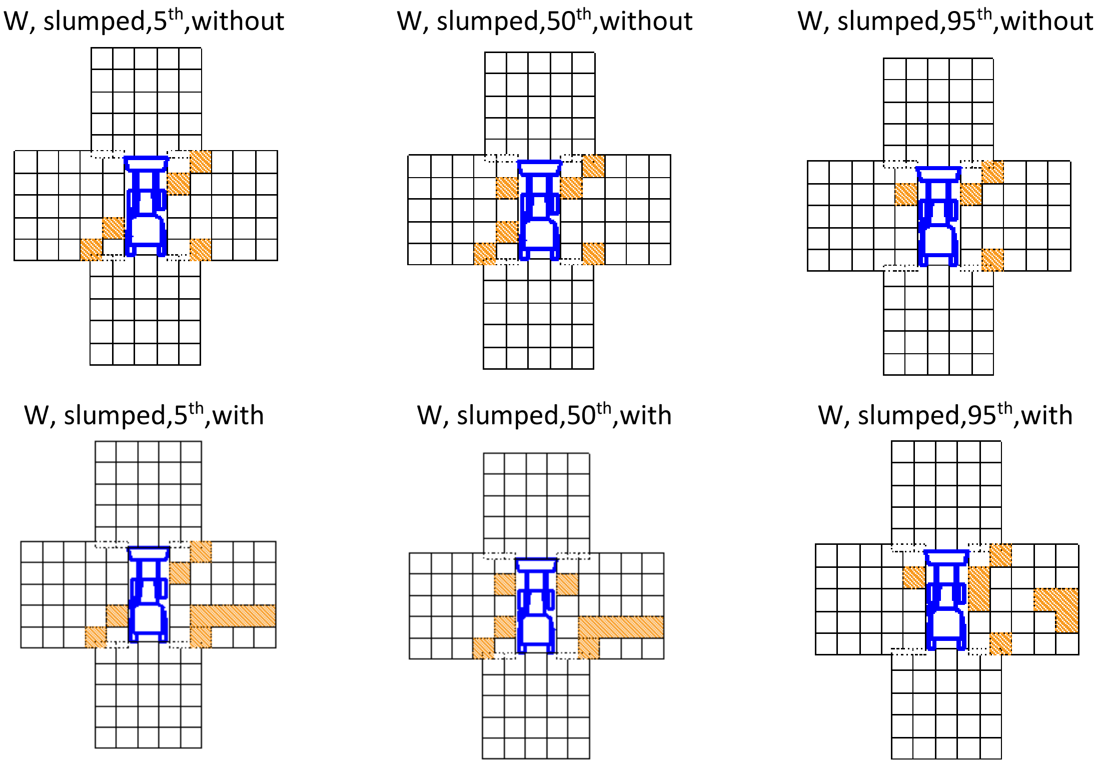


Figure 10 Visibility results for Tractor 1 at the woman height for a slumped sitting position.

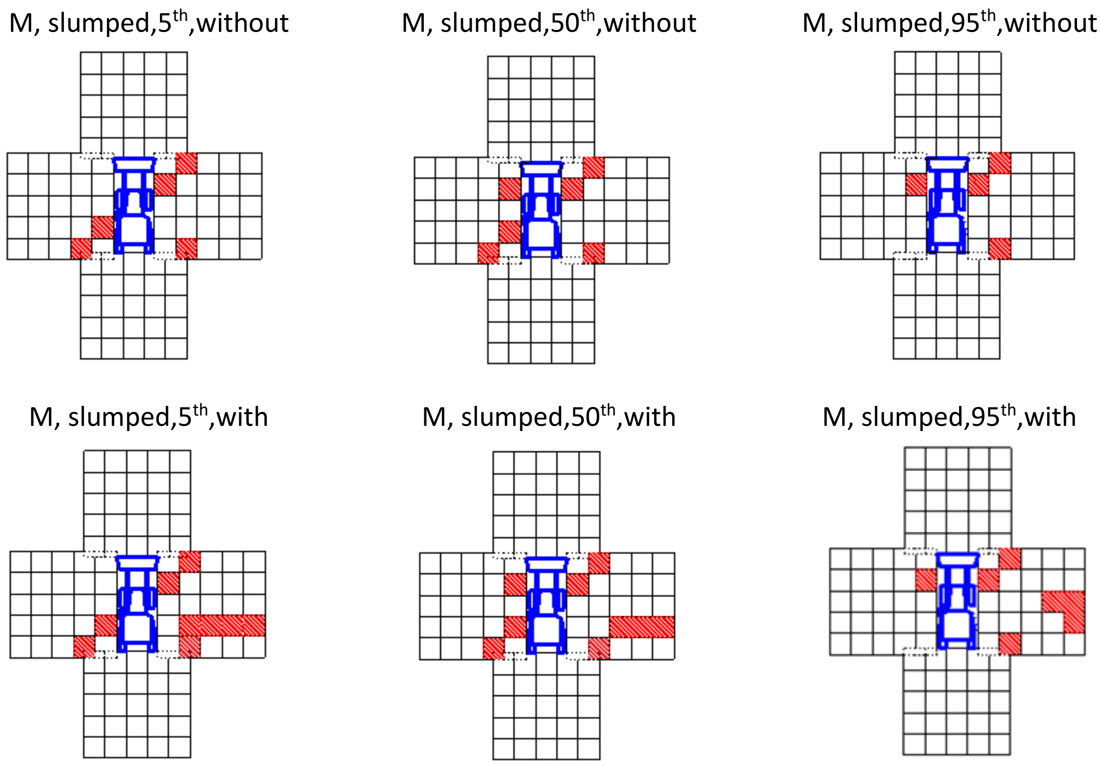


Figure 11 Visibility results for Tractor 1 at the man height for a slumped sitting position.

4.2. Blind-spots diagrams of Tractor 1 (Straight sitting positions)

Data presentation for blind-spots diagrams of Tractor 1 at straight sitting positions (Figures 12-15) were organized by the same approach as for slumped sitting positions. All the other factors were the same except for the sitting position.

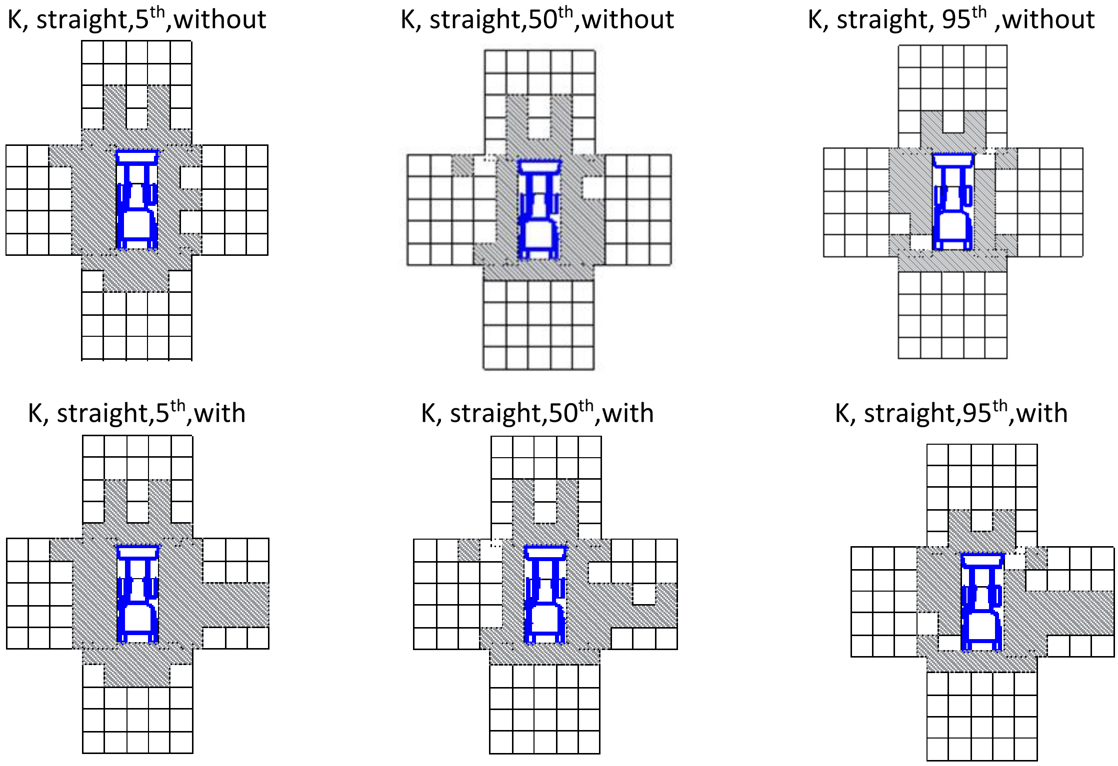


Figure 12 Visibility results for Tractor 1 at the kneeling worker height for a straight sitting position.

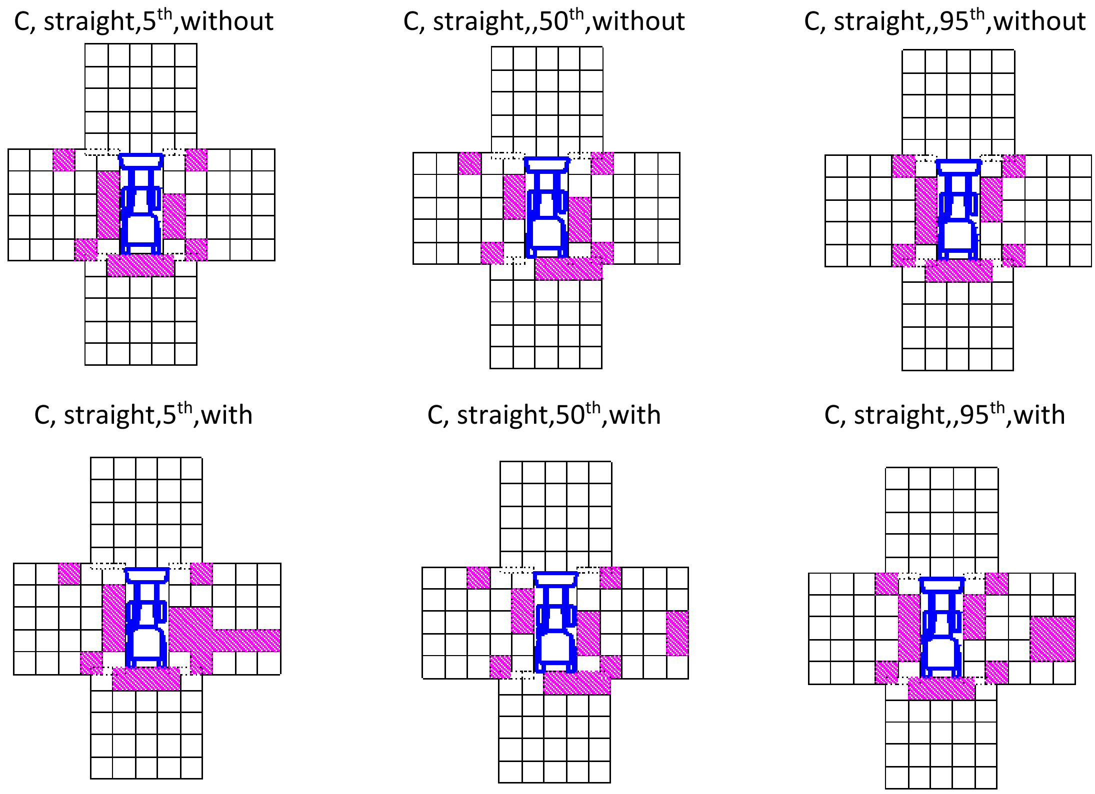


Figure 13 Visibility results for Tractor 1 at the child height for a straight sitting position.

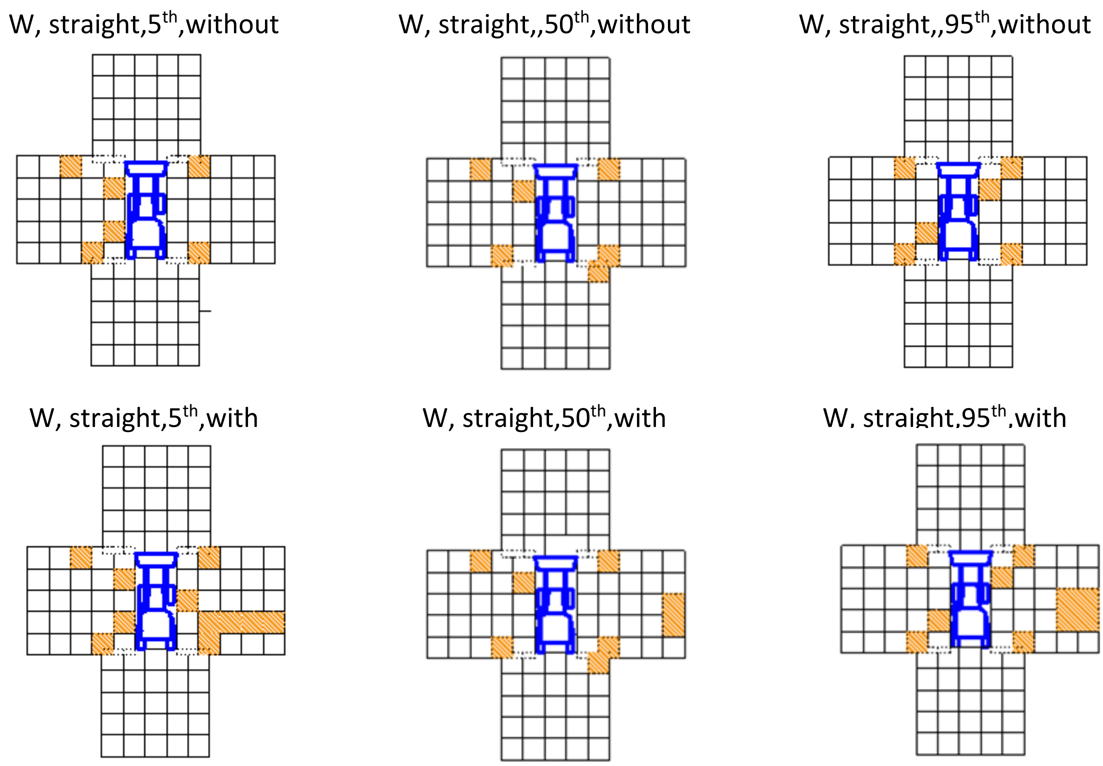


Figure 14 Visibility results for Tractor 1 at the woman level for a straight sitting position.

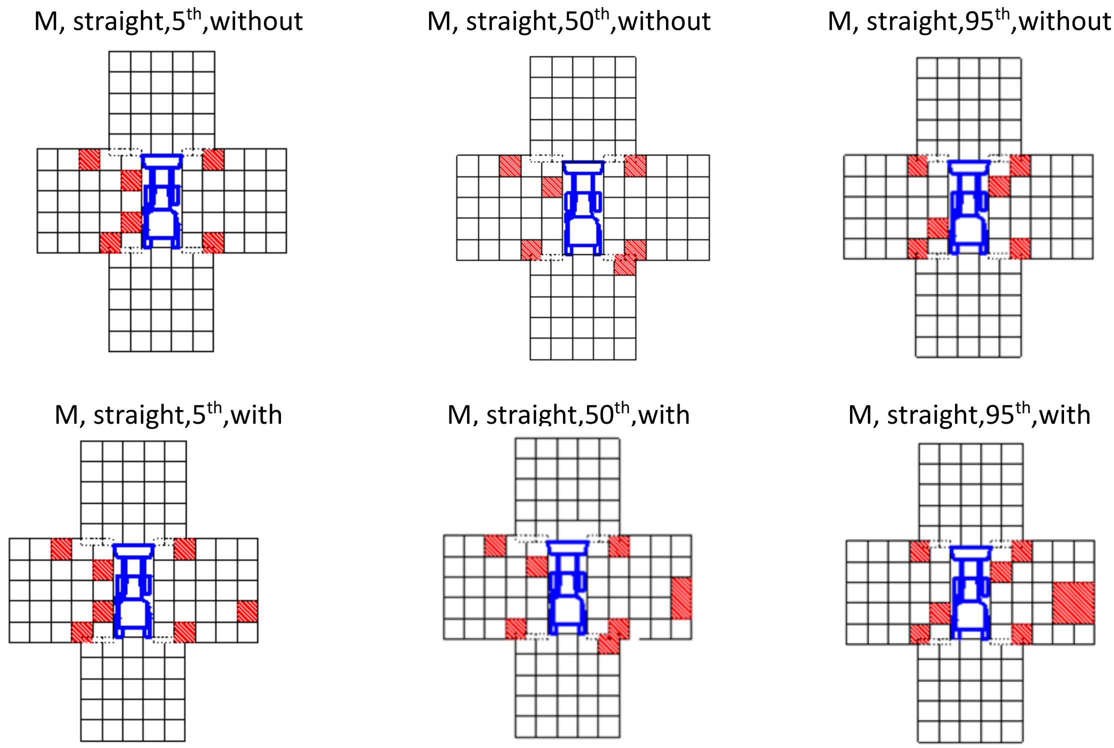


Figure 15 Visibility results for Tractor 1 at the man height for the straight sitting position.

4.3. Blind spots around the front loader

Additional grids were set up for Tractor 1. They aimed to identify blind spots between the front-end loader and the arm of the loader. The results showed that all the tested eye levels were not able to detect kneeling worker height and child height, except for an operator of 95th percentile straight sitting level. An operator of 95th percentile straight sitting level was able to detect man, woman, and children heights.

4.4. Blind-spots diagrams for Tractor 2

There were fewer blind spots for Tractor 2 (Figure 16-19) compared with Tractor 1. Blind spots only existed at the kneeling worker height and child height.

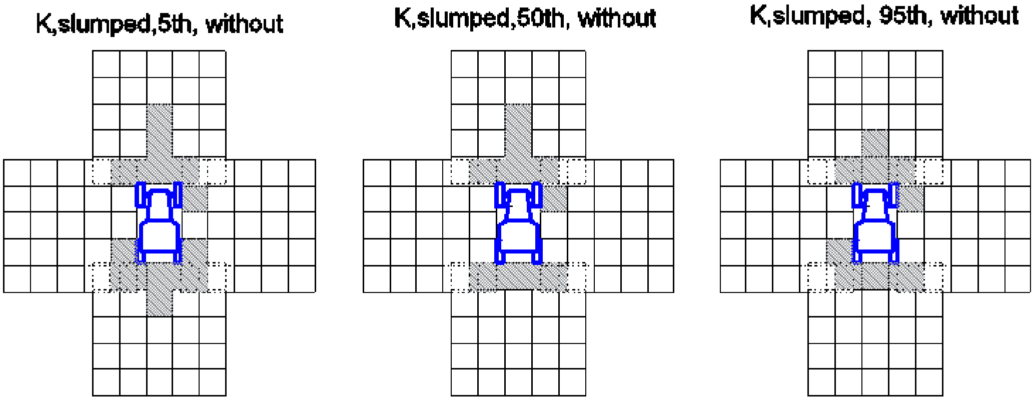


Figure 16 Visibility results for Tractor 2 at the kneeling worker level for a slumped sitting position.

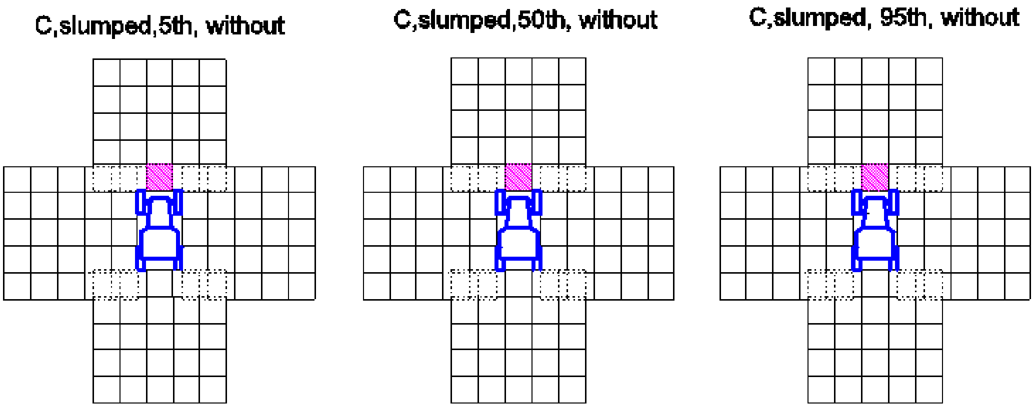


Figure 17 Visibility results for Tractor 2 at the child height for a slumped sitting position.

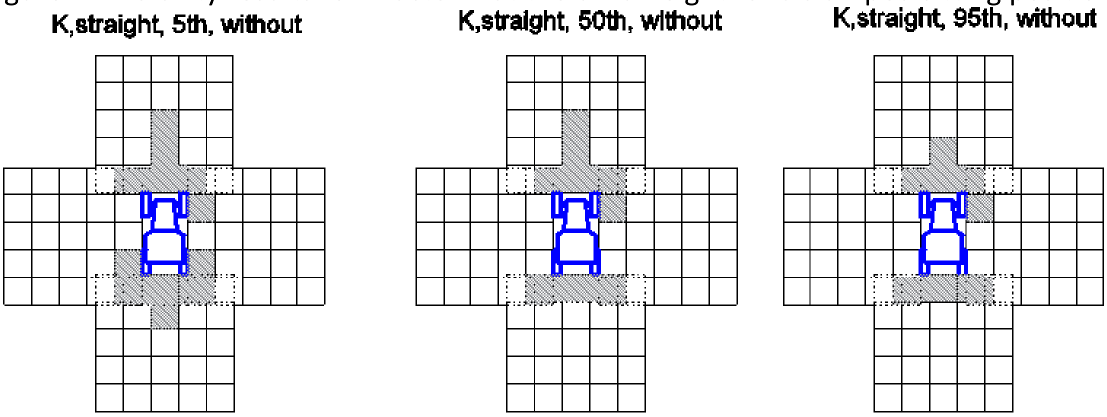


Figure 18 Visibility results for Tractor 2 at Kneeling worker height for a straight sitting position.

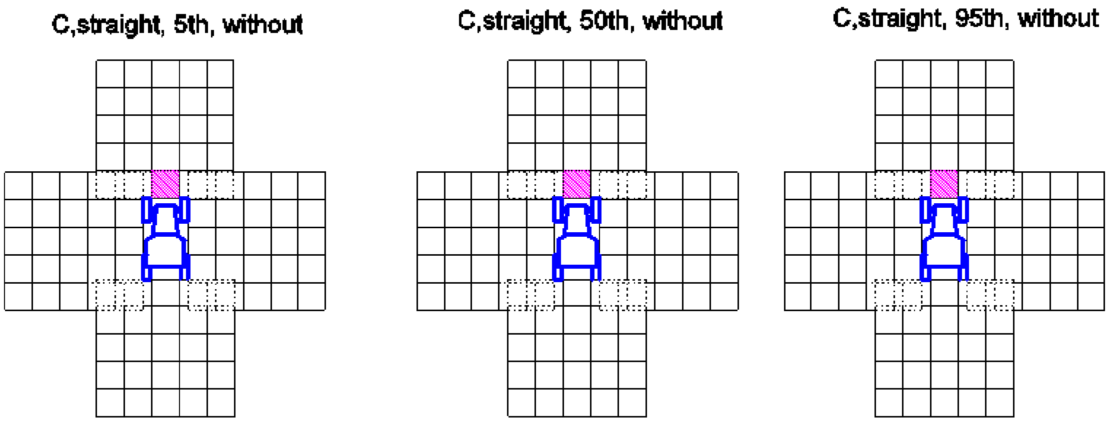


Figure 19 Visibility results for Tractor 2 at the child height for the straight sitting position.

5. DISCUSSION

5.1. Tractor 1

5.1.1. Distribution of blind spots

As the grid diagrams show, the operators, at all tested eye heights, were able to detect the kneeling worker if the worker was at least 5.33 m away from the edge of the tractor (if there was no passenger seated inside the cab).

The child height was more detectable for the operators in terms of comparing with the kneeling worker height. At the child height, there were no blind spots in front of the tractor. A child would not be visible near the rear tires for the operator with 5^{th} and 50^{th} eye levels for either slumped or straight sitting positions. However, the distribution of blind spots on the sides was more complicated. Operators with all the tested eye levels would be able to detect the children if they were at least 3.81 m away from the edge of the tractor, provided there was no passenger in the passenger seat. The percentage of blind spots at child height were half of those at kneeling worker height when no passenger was seated with the operator. Though it is important to note that a lower percentage of blind spots do not make children less vulnerable than kneeling workers because kneeling workers are trained with workplace safety while children usually lack safety awareness. The seated passenger increased the percentage of blind spots at the child height, making it the same as at kneeling worker height.

Results indicated that women could be detected by the operators with all tested eye levels in front of and behind the tractor. Comparing the result of the experiments between woman height and man height, blind spots were almost the same for Tractor 1.

5.1.2. The shape of the blind-spot zone

The distribution of the tractor's blind spot was the shape of a "U" in front of the tractor, which is mainly because the front end loader and the arm of the loader blocked the view. This result proved that blind spots can be caused by the tractor's design (Templeton & Strong, 1998).

5.2. Tractor 2

The grid diagrams showed that blind spots only exist at the kneeling worker height and child height for Tractor 2 (Table 5). The fact that Tractor 2 was relatively smaller than Tractor 1 was inferred to be the cause. The shapes of blind-spot zone from Tractor 2 were simple and were almost symmetrical. However, it is worth mentioning that on the right side there was a blind spot near the front tire because there was a control on the right-hand side which blocked the right side view (Figure 20). In the cab design of agricultural machines, controls should be placed logically and ergonomically, while sufficient visibility of the surrounding area is also critical for operator and bystander safety (Templeton & Strong, 1998).

Figure 20 control panel blocked the view.

5.3. Percentage of blind spot area

Total area of the grid around Tractor 1 and Tractor 2 is 223.97 m^2 and 216.34 m^2, respectively, after adjusting the area according to the slight overlap that occurred around each tractor. Percentage of bind-spot area under different experimental conditions was calculated and summarized in Table 4 and Table 5. The area of blind spots under an experimental condition can be calculated according to Table 4. For example, the area of blind spots, at kneeling worker height around Tractor 1 for an operator of 5th percentile slumped sitting level, without the passenger seated beside the operator, is 67.41 m^2 (223.97 m2 * 30.1 %)

Table 4 Percentage of blind spot area for Tractor 1.

Tractor 1	Marker height	Proportion of Markers Not Visible (%)					
		Sitting Position: Slumped			Sitting Position: Straight		
		5th	50th	95th	5th	50th	95th
Without Passenger	Kneeling worker	30.1	26.0	25.7	33.6	26.4	23.2
	Child	11.4	12.4	8.3	12.4	11.0	12.4
	Woman	5.2	6.0	4.1	6.2	6.2	6.2
	Man	5.2	6.0	4.1	6.2	6.2	6.2
With Passenger	Kneeling worker	36.3	32.1	33.0	41.9	32.6	31.5
	Child	19.7	17.6	11.4	17.6	13.1	16.6
	Woman	9.3	10.4	8.3	11.4	8.3	10.4
	Man	9.3	9.3	7.3	7.3	8.3	10.4

Table 5 Comparison about the percentage of blind spots for Tractor 2.

Tractor 2	Marker Level	Proportion of Markers Not Visible (%)					
		Sitting Position: Slumped			Sitting Position: Straight		
		5th	50th	95th	5th	50th	95th
Without Passenger	Kneeling worker	14.0	10.4	9.6	14.0	10.4	9.6
	Child	1.1	1.1	1.1	1.1	1.1	1.1
	Woman	0	0	0	0	0	0
	Man	0	0	0	0	0	0

The goal of testing two sitting postures was to find out how the sitting position influences the blind spots and to document blind spots under a wider range of eye levels. Results show that generally higher eye levels have a higher visibility. Other than this, there was no different tendency found between slumped eye level and straight eye level. Compared with the situation without the passenger, the proportion of blind spots increased when the passenger was sitting in the passenger seat (Table 4).

5.4. Performance of mirrors

For Tractor 1, there were two extended arm mirrors (one on each side of the tractor), and one mirror in the cab. Tractor 2 was manufactured with two mirrors inside the cab. One was located in the front right corner and the other located in the rear left corner. During the experiments, the mirrors remained in the position selected by the tractor operator (i.e., they were not adjusted by the researchers). All those mirrors were examined to test their ability to provide information about blind spots to the operator. The results for each tractor under 50th percentile of slumped eye level are illustrated below (Figures 21 and 22). The diagrams show that the detection zone via mirrors covers only a small amount of the blind spots. There was still a substantial number of blind spots that could not be eliminated solely with the assistance of mirrors. The limited detection performance of mirrors suggested that the operator cannot simply rely on these mirrors, more assistive technologies are needed.

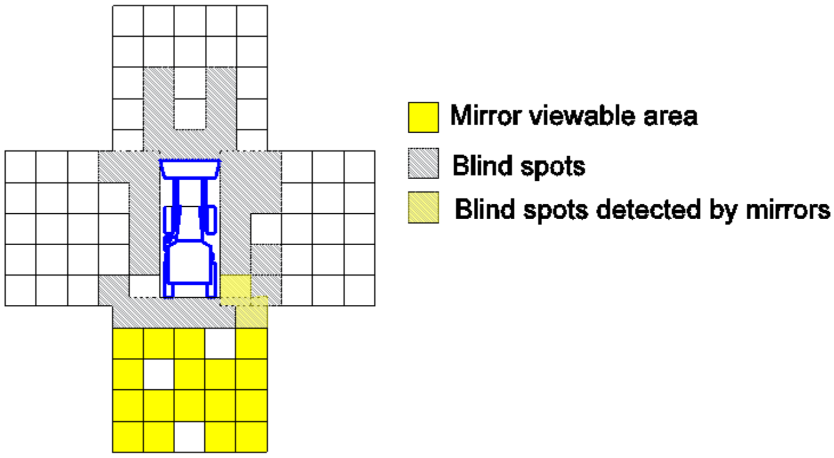


Figure 21 Mirrors detection area for Tractor 1.

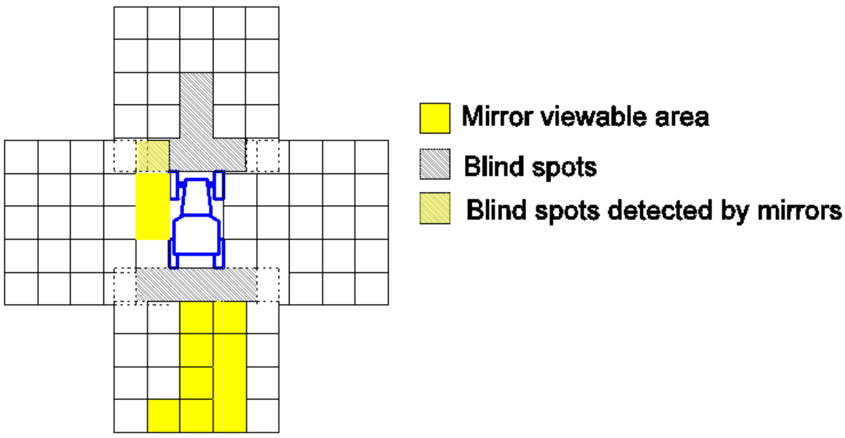


Figure 22 Mirrors detection area of Tractor 2.

5.5. Summary

The experiments identified the blind spots around two specific tractors. Several highlights from the results are:

1) A number of aspects of the tractor’s design affected visibility (i.e., size, design of control panel). Tractor1 had more blind spots than the smaller Tractor 2. Positioning of controls on the right side of the cab blocked some regions of the grid.
2) The operator’s eye level affected the visibility of the operator. In general, higher eye levels had higher levels of visibility. There were no big differences found between straight sitting positions and slumped sitting positions.
3) The seated passenger blocked the view of the operator and caused the number of blind spots to increase.
4) The mirrors provided by the manufacturer were not adequate to detect blind spots around the tractors; more assistive technologies are required.
5) All identified blind spots can be documented and provide information for the operator who runs the machine. The manufacturer can develop a better design by knowing these blind spots.

6. PROPOSED DESIGN SECTION

The second objective of this study is to propose a conceptual design for a blind-spot detection system, which is essential to overcome the problems of blind spots. In this section, a model called the Human Activity Assistive Technology (HAAT) model (Cook and Polgar 2015) was borrowed from the discipline of occupational therapy in an attempt to identify the requirements for a blind-spot detection system from the operator's perspective. The HAAT model includes four elements: a ***human*** using an ***assistive technology*** to complete a specific ***activity*** within a unique ***context*** and it is typically applied as a means of identifying the most appropriate technology to enable a person with a disability to complete a desired task. Within the context of the HAAT model, a blind-spot surrounding an agricultural machine may be considered to be a form of disability (i.e., blindness) experienced by the operator. The HAAT model considers the abilities of the human (i.e., the machine operator), the activity to be completed (i.e., to eliminate accidental run-overs while driving the machine), and the context in which the task occurs with the objective of identifying an appropriate technology solution (or assistive device) that should enable the human to complete the desired task in a satisfactory manner. The following sections describe three potential technologies (i.e., mirrors, cameras and proximity sensors) using the framework of the HAAT model.

6.1. Design overall

The operator of a modern agricultural machine is unable to physically see all around the machine, a factor that contributes to accidental run-overs. There is a need to devise an effective blind-spot detection system for agricultural machines to enable operators to avoid these accidental run-overs. The effectiveness of the design was evaluated by the HAAT model.

6.2. Four Components of the HAAT Model

6.2.1. Activity

The activity component of the HAAT model refers to something that the participant wants to accomplish. It is specific in time, space, place and so on. The activity component assists the understanding of the tasks in which the user of assistive technologies participates. It guides product research and development, selection of assistive technology, identification of functional outcomes (Cook & Polgar, 2008).

In this case, the activity that the operator wants to achieve is to be able to detect all blind spots around the machine during operation. However, it is also important to consider the other tasks that the operators are supposed to do because operating an agricultural machine is a multi-task activity and an activity that involves a human-machine system. Task analysis is of importance to the design and evaluation of all components constituting a human-machine system (Fastenmeier & Gstalter, 2007). For this study, the agricultural machine operator is supposed to have at least two tasks: i) steering the tractor, and ii) operating attached equipment. Environmental scanning is required to complete both tasks. For example, operating an agricultural spraying involves driving the sprayer along the demanded path by following instructions of a navigation device, and at the same time monitoring and controlling the rear-attached boom (Dey & Mann, 2011). Among all tasks, environmental scanning is along throughout the operation, and the driver often requires visibility all around the tractor (Sjoflot, 1980). Environmental scanning mainly involves observing through physical turning and via blind-spot detection systems. Besides, it is critical to mention that the operator is usually focused on monitoring the operation of the machine to maximize its efficiency. Scanning the environment for individuals who may be present near the machine is not the operator's priority. As a consequence, an ideal blind-spot detection system should allow the operator to monitor all the blind spots and at the same time it should not consume too much workload during the operation.

6.2.2. Human

With respect to the HAAT model, it is assumed that the user's abilities in motor, sensory, cognitive and effective areas are critical when considering appropriate assistive technologies (Cook & Polgar, 2008).

In this case, the human component in the HAAT model is the operator who is unable to see all the spots around the tractor. Many human factors should be considered for assisting operators to detect blind spots. For example, the stature of the human (height) depends upon the location of the driver's eyes when viewing the surroundings (Ehlers & Field, 2014). The eye level directly determined the visible view for the operator, and sitting postures (sitting slumped or sitting straight) also affect eye levels. Depth perception, which is a visual ability to perceive distance of an object, is critical when using camera-based detection systems, since it is often hard to estimate the distance to an object through the small lens of a camera (Ehlers & Field, 2014). Blind-spot detection systems should consider the user's depth perception, and make the system easy to use. In addition, characteristics of the individual, such as fatigue, were noticed to be critical factors in many industrial accidents (Griffith & Mahadevan, 2011). Most operations need to review the situation behind the tractor, requiring the operator to spend a significant amount of time looking backward (Sjoflot, 1980b). Therefore, how the blind-stop detection system affects the operator's fatigue should be taken into account. It can influence the comfort of operator's posture, which is also an important component of quality of work (Sjoflot, 1980b). A study found that different monitoring systems caused different degrees of physical impact on operators (Rakhra & Mann, 2013). Minimizing awkward postures by using assistive visibility technologies, such as mirrors, cameras, and "smart seats" enhance the operator's workday longevity, comfort, work quality and overall well-being (Ehlers & Field, 2016). There are still many human-related factors that could affect the efficiency of assistive technologies. The more of these human factors that are taken into consideration, the more efficient the system will be.

In conclusion, the HAAT model take as many human factors as possible into consideration when producing an assistive technology device. Producing a customized assistive technology device is an important principle of the HAAT model. The assistive technology should accommodate the user's identities and preferences (i.e., user's posture, mobility, and workload). In the previous section of the paper, blind spots were identified under different operator's eye levels by experiments. This proposed design was for the operator who was a 50th percentile male driver.

6.2.3. Context

Four contextual components are included in the HAAT model. Physical context includes elements of the natural and built environments that support or hinder participation; physical parameters of noise, light and temperature also form the physical context. Social context includes individuals in the environment who affect activity participation and use of assistive technologies. It also includes consideration of the society in which the individual lives and the social values and attitudes that affect his full social inclusion. Cultural context involves systems of shared meanings that include beliefs, ritual and values that are broadly held and that do not change as quickly as socially held attitudes and practices. Institutional context involves two key areas: i) legislation and related regulations, and ii) polices and funding.

In this application, the context component involves the following points. Firstly, agricultural operations occur in the field. The characteristics of the field environment (i.e., darkness, dust) that can negatively influence visibility and application of assistive technologies (i.e., night vision cameras used in the dark environment) must be considered. Secondly, as was mentioned before, farms and other agricultural sites are not just workplaces, but also places where people of all ages live and participate in recreational activities. Family members, including children may be present near large agricultural machines. In fact, compared to other industries, where victims of workplace injuries are usually workers, agriculture is unique in that children account for significant number of work-related injuries (Canadian Agricultural Injury Reporting, 2016). This also contributes to the context in which the blind-spot detection system must function. Also, different agricultural machines provide different physical contexts. The shape of agricultural machines affects the location of blind spots. Blind spots around two types of tractors were measured in the earlier section. The results of the measurement proved the physical contexts affected the blind spots.

6.2.4. Assistive technology

In the HAAT model, the human is enabled to perform an activity in a context through the use of an assistive technology. In other words, assistive technologies assist humans in managing their activities. This component has four aspects, the human/technology interface, the processor, the environment interface and two activity outputs.

As was mentioned in the literature section, three assistive technologies (mirrors, cameras, and sensors) can be used to create a blind-spot detection system.

Blind-spot detection mirrors

The most common assistive technologies in detecting blind spots are mirrors. Almost all types of agricultural machines are equipped with mirrors that can be used as visual tools. In large enclosed agricultural machines, blind-spot detection mirrors include interior mirrors in the cab, exterior mirrors in general, and exterior extended-arm mirrors. Compared to other assistive technologies, mirrors are easy to install and are affordable. They allow the operator to detect objects and bystanders while keeping their attention forward (Ehlers & Field, 2016). The operator can see behind or the sides of the tractor from the seat inside the cab without frequently turning or excessively straining their neck muscles. Big rear-view mirrors can improve the quality and capacity of work because they allow the operator to adopt a good working posture while operating most equipment (Sjoflot, 1980).

On the other hand, detection through rear-view mirrors still requires motion of the head and neck and this increases the neck muscle temperatures (Rakhra & Mann, 2013). Sjoflot (1980) observed that interior mirrors need a lot of space and this is a concern because they demand a greater open area in the cab. The ideal size of mirror that Sjoflot (1980) suggested was 600 cm^2, and if the mirrors are smaller than 400 cm^2, it presented a limited field of view. In addition, convex or aspheric mirrors, rather than conventional spherical or flat mirrors, are often used by manufacturers because they can achieve a wider angle (Lee et al., 2013). However, distorted images in convex mirrors are difficult for the operator to interpret (Ehlers & Field, 2016). Also, instead of being automatically alerted to the dangers, operators are required to observe the images in the mirror and detect the dangers. Dust or dirt, conditions in bad weather, and other special circumstances will impair visibility when using mirrors (Ehlers & Field, 2014), Mirrors have relatively limited viewing angles compared to using camera-based detection systems. Earlier experimental results (Ehlers & Field, 2016) showed that the mirrors provided by a manufacturer have limited detection capability. Therefore, operators cannot solely rely on mirrors to eliminate blind spots.

Sensor-based detection system

Sensor-based detection systems can detect objects and bystanders in a certain range when they are in the dangerous vicinity of agricultural machines. The highlighted advantage is that it will automatically make a warning alarm to the operator when there might be a danger and this saves some of the operator’s attention.

With regards to the performance of sensor-based systems, evaluation in previous research showed various results. For example, Ruff (2001) tested reliable detection zones using a radar system on different types of off-highway mining equipment. The assessments showed that radar was decent in detecting people and small vehicles but detection zones depended on the type of equipment. On the other hand, the National Highway Traffic Safety Administration (2006) conducted testing to measure the ability to detect objects by sensor-based systems. They found that the systems generally exhibited poor ability to detect pedestrians, particularly children, who were located behind the vehicle. The performance of the systems in detecting children was inconsistent, unreliable, and in nearly all cases quite limited in range. Based on calculations of the distance required to stop from a particular vehicle speed, detection ranges exhibited by the systems were not sufficient to prevent many collisions with pedestrians or other objects. According to those performance differences, it is believed that the true performance of sensor-based detection systems need to be assessed by putting them on the actual equipment and testing in real working conditions (Ruff, 2001).

Other potential disadvantages of sensor-based systems were found in the literature. For example, the exact location of near objects is hard to verify when solely using a sensor-based monitor. False alarms from sensor-based monitoring systems are difficult for the operator to check. Errors can be caused by wind factors on ultrasonic transition sensors (Song, Chen, & Huang, 2004). Song (2004) developed an ultrasonic sensor system for lateral collision avoidance of vehicles, which gives satisfactory results for a wind speed up to 35 km/hr. The same statement has been found in the research for train detection application (Wise, 2011). Wind generated by passing trains tended to interfere with ultrasonic sensors. However, ultrasonic sensors and radar-based sensors are not impacted by dust or dirt conditions, therefore they can be beneficial when used in the field environment (Wise, 2011).

In conclusion, due to the range of factors that can affect the performance of sensor-based detection systems, evaluation needs to be done in the designed applications.

Camera-based detection system

Camera-based detection systems usually include cameras detecting spots around the machine and a monitor mounted in the cab to display the view of the cameras. There are several advantages of camera-based detection systems. Firstly, it imposes the least physical workload on the operator compared with using rear-view mirrors and physical turning (Rakhra & Mann, 2013). Also, camera-based detection systems can provide a wider view than the other detection systems. The testing (Mazzae & Garrott, 2006) showed that the detection ability of camera-based systems is within a range of 15 or more feet, which is a wider range than was covered by the detection zones of sensor-based systems tested in the study.

Camera-based detection systems can provide a clear image of the blind-spots in daylight and indoor lighted conditions, but performance will be impaired with poor lighting. By comparison, a sensor-based system can be used even in night or dark conditions. Generally, more than one camera is needed to monitor the blind areas around the front, two sides, and rear of large agricultural equipment. The lenses of these cameras must be cleaned occasionally and more often in some operating conditions or in bad weather. Vibration is also a factor for camera-based detection systems in agricultural machines. Additionally, cameras cannot alarm automatically if they were not combined with other technologies; the operator has to look at the monitor and detect objects or bystanders in the screen. When the operator detects potential danger, he or she needs to respond quickly and with sufficient force applied to the brake pedal to bring the vehicle to a stop (Mazzae & Garrott, 2006). Therefore, the true efficacy of camera-based systems is determined by the drivers' use of the systems and how they incorporate the information into their visual scanning patterns.

6.3. Proposed design

The aim of this design was to propose blind-spot detection system for Tractor 1 and Tractor 2. The goal was to detect all the blind spots around the tractors in order to avoid accidental run-overs.

Three main assistive technologies for detecting blind spots are blind-spot detection mirrors, camera-based and sensor-based systems. Compared with those three assistive technologies, camera-based systems are the assistive technology that can be used independently. Therefore, this design chose cameras as the assistive technology to eliminate the blind spots.

According to identified blind spot locations for the tractors, cameras were placed in order to eliminate all the blind spots. Field experiments were conducted to test the effectiveness of the cameras. Different mounting positions were tried. The cameras positions recommended for the tractors (Figures 23-26) gave the best results according to the trials:

1) For tractor 1, eight cameras in total were recommended to detect blind spots (Figure 23). Using those eight cameras, all identified blind spots were eliminated. The camera locations are indicated in Figure 23. Camera 7 and camera 8 are used to detect blind spots between the front-loader and the arm of the loader. The performance of the other cameras is shown in Figure 24. Different color in the test grids indicated the detection zone of each camera. The coding pattern used to indicate blind spots is shown in the Table 6.
2) For Tractor 2, five cameras in total were recommended (Figure 25). By those five cameras, all identified blind spots could be eliminated. The locations and the functions of each camera were indicated in Figure 25 and Figure 26.

Table 6 Coding pattern for data presentation

Conditions	Code
Only kneeling Worker heights were invisible	○
Only woman and man heights were visible	⊗
Only man heights were visible	◉ (grey)
All heights were invisible	●

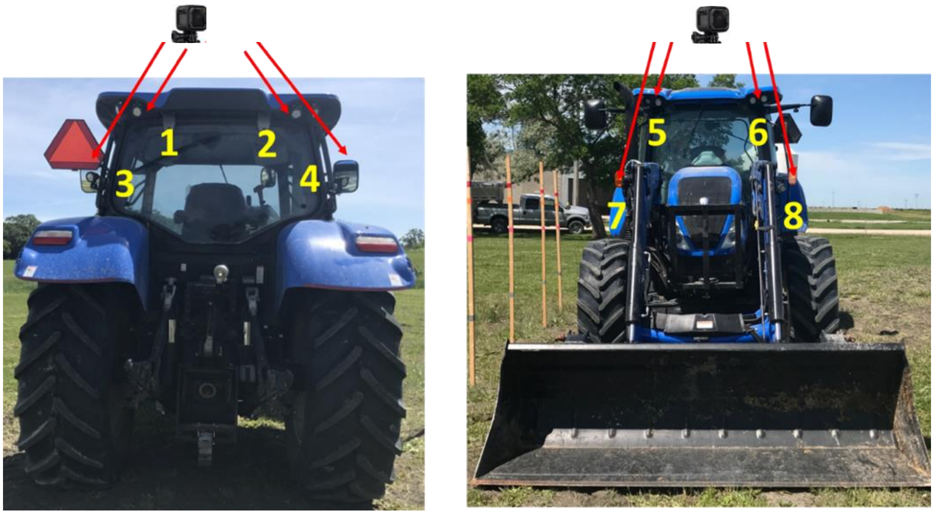
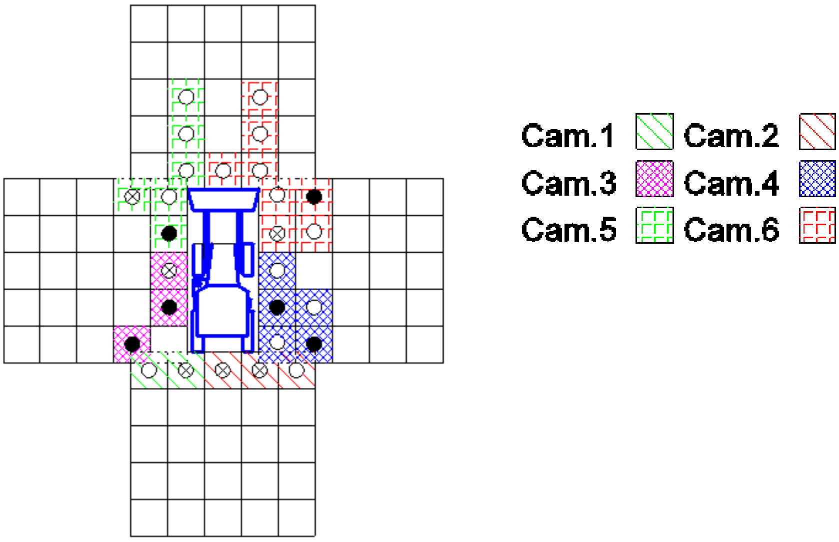


Figure 23 Locations of recommended cameras for Tractor 1.



T1_Slumped_50th_without

Figure 24 Detection zone for each cameras for Tractor 1.

Figure 25 Locations of recommended cameras for Tractor 2.

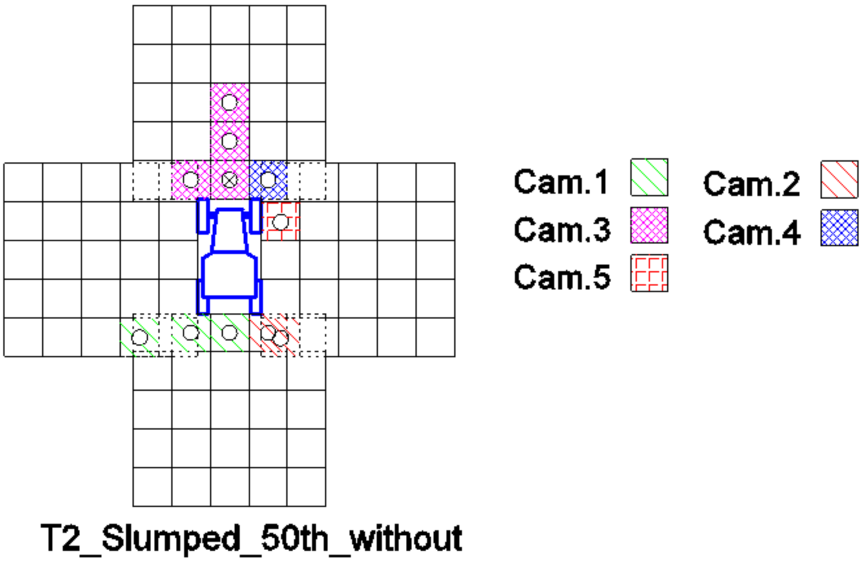


Figure 26 Detection zone for each cameras for Tractor 2.

6.4. Evaluation of the proposed design

Once the design was implemented, it is important to evaluate its outcome. The proposed design's fit into the model could be evaluated based on the four components of the HAAT model. First, the proposed design helped the operator eliminate all the blind spots by placing cameras to detect the blind spots. It achieved the goal of enabling the operator to see the blind spots.

However, this system only works well when the operator pays enough attention to the blind-spot detection monitor. Too many cameras providing information distracts the operator. This was the case since the activity component of the HAAT model stated that the priority activity for the operator is monitoring the operation of the machine to maximize its efficiency. Scanning the environment for individuals who may be present near the machine is not supposed to draw much attention of the operator. Besides, based on the location of identified blind spots, some of the cameras needed to be placed near the tires in order to monitor them, where dust and mud were easy to interfere with the performance of the camera-based detection system. The advantages and disadvantages of camera systems and sensors were discussed in a previous section. Making use of sensors to detect blind spots near the tractors would cause less distraction during the operation and could work better than the camera-based systems.

In conclusion, it turned out this preliminary design can be improved. The combination of cameras and sensors was recommended for further study. This was also an approach that previous researchers recommended (Mazzae & Garrott, 2006; Ruff, 2001). The effectiveness and reliability of the new design should be tested by field experiments.

7. CONCLUSION

In this study, blind spots were successfully identified around two selected tractors. Several factors were proven to be important to affect the number of blind spots and the blind-spot locations. These factors include size of the tractor, the tractor design, operator's eye levels and the seated passenger. However, operator's sitting postures (i.e., slumped vs straight sitting posture) were less significant to the size of blind spots.

Blind spot diagrams of the tractors could be documented. The locations of the blind spots can be helpful for at least three perspectives. Firstly, it could give information on high-risk spots to the operator in order to improve the operator's situational awareness during the operation. Secondly, researchers can conduct studies to overcome the problem of blind spots. Manufacturers also get benefit from blind-spot studies and then develop solutions to improve the visibility of the operator.

It is possible to eliminate all the blind spots by a camera-based detection system. However, many cameras were needed. A combination of cameras and sensors is recommended for the next possible study.

The HAAT model identified the requirements for a blind-spot detection system from the operator's perspective. It gives engineers a new idea to design better blind-spot detection systems for agricultural machines.

8. LIMITATION AND RECOMMENDATION

This paper showed how the methodology was applied specifically to the selected two tractors. How it applies to other types of agricultural machines was not conducted due to the limit of time. The variability in the results between the two tested tractors was attributed to a number of variables associated with the tractor design. Further research can be carried out to various agricultural machines since a wider range of vehicle designs could quantify the variability of design features which contribute to the size of blind spots.

In real life, the blind spot zone is a complex three-dimensional volume. The methodology used in this study can only identify blind spots at four heights (or elevations). A software-based method was used for presenting blind spots in three dimensions in the literature. Further study about developing a methodology that can identify three-dimensional blind spot zones and evaluate the performance of various detection technologies, is recommended.

The inadequacies of the proposed design highlighted further study is required. Blind-spot detection systems combining cameras and sensors were recommended.

The proposed design has explained how the HAAT model works in proposing detection systems. However, when proposing the design, four components in the HAAT model were not fully considered. For instance, four aspects of the assistive technology component, which are the human/technology interface, the processor, the environment interface and two activity outputs, need to be taken into more consideration. A better blind-spot detection system could be designed if more HAAT components are identified and understood earlier in the design.

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