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Ray-tracing method for fields of view simulation in agricultural and forestry vehicles

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Abstract

Fatal injuries represent a significant issue in activities involving agricultural machinery. The operator's low visibility is one of the main factors leading to such events. In this paper, a virtual prediction method of the field of view for a tractor is analyzed using a rendering based on the Ray-tracing algorithm. Its performance is compared with standardized experimental tests based on ISO 5006:2017, presented as the «mirror test» and the «shadows test». This novel method requires the use of a three-dimensional CAD model of the vehicle under investigation, as well as the test surfaces suggested by current standards. The accuracy of the produced simulations is evaluated using several metrics, such as the amplitude, amount, and position of the masking effects. The results show that the proposed method is consistent with physical machine tests, performing better than the mirror test in all cases. Small discrepancies are due to the difficulty in synchronizing the experimental setup with the virtual model. The system accurately estimates masking effects, with an average error of 8.69% when comparing the Ray-Tracing test with the shadows test, and 26.94% with the mirror test. After improvements, the error was reduced to 6.45%.

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Introduction

People working in the agricultural sector are daily exposed to numerous risks leading to various types of injuries. According to the Italian National Institute for Insurance against Accidents at Work (INAIL, 2021), the number of claims in the period between 2015 and 2019 has decreased, however, the number of fatal incidents has remained substantially the same. Analyzing the INAIL data, available on the Infor.MO platform (the Italian National surveillance system for fatal and serious workplace accidents), in a sample of 250 fatal events, 117 injuries involved an operator driving an agricultural machine (Infor.MO, 2021). Only in nine of these cases can the correlation with the driver's field of vision be excluded. Currently, two main standards define the allowed field of view (FoV) for tractors: ISO 5721-1:2013 (ISO, 2013) and ISO 5721-2:2014 (ISO, 2014), which describe how to determine, evaluate, and accept the front field of view and the fields of view to the sides and rear, respectively. The standards impose a limited number of masking effects, their maximum allowed amplitude, and a minimum distance between them, depending on the FoV region under examination. Both standards require the use of a standard device, defined in ISO 5353:1998 (ISO, 1998), capable of establishing the seat index point (SIP), which is the base reference for all subsequent measurements. Although an experimental procedure is explained in the standards to obtain the metrics of the masking effects (which will be described and used below), more accurate techniques can be found in the literature. By using a LiDAR positioned on the seat of a tractor, two scans were performed, one simulating the right eye and the other the left, with five spheres placed in a semicircle of 12 m radius in front as a reference (Zvěřina *et al* 2022). From the measurement, many points are obtained and inserted into the software «Faro scene», where all points above ground level and beyond the semicircle are ignored. Finally, a .DXF file is created to graphically visualize the FoV. This method improves accuracy compared to the one described by ISO, but the cost of measurement is significantly higher. To predict masking effects in the design phase of the machine, a virtual simulation of the FoV can be performed directly from its CAD model. This methodology, already introduced by Bayran *et al*. (2015), maps the driver's view by tracing a 20 mm diameter sphere, positioned in various circles around the machine at different radius. The operator's visibility is replicated using a digital human model (DHM), inserted into the simulation software «Jack,» from which masking effects can be revealed. Another approach to determine the FoV was proposed by Teizer *et al*. (2013), where Ray-Tracing algorithms are used to evaluate masked regions for forklifts. The virtual test was repeated for two models of the machine: the CAD designed by the manufacturer and the same reproduced using a LiDAR. A comparison of the FoV is explained in detail and reported in the full article.

The purpose of this document is to implement an economical, versatile, and accurate virtual environment for determining the FoV, based on knowledge gained from consulting the literature and observing current standards. This virtual environment is designed to be fully applicable to a CAD model directly in the design phase of the tractor, yielding results close to those obtained from testing on the physics machine. From the draft of the new standards regarding the visibility of self-propelled agricultural machinery (CEN, 2022), a new virtual FoV simulation should be performed on specific control surfaces, derived from the current (ISO, 2017) standards regarding earth-moving machinery.

Materials and Methods

Assembly construction of the virtual test environment

The first step of the experimentation involves constructing a virtual environment in which the FoV of an agricultural machine (in this case study a John Deere 6920S was used, but it can also be applied to any other machinery) can be verified, following the guidelines of ISO 5006:2017. This aim was entirely achieved using the «Autodesk Inventor» software and its «Inventor Studio» environment (Autodesk Inventor, 2024). Specifically, this virtual model was generated as an assembly, which the authors will call "virtual test assembly", that includes the 3D model of the agricultural machine, the test surface, a unified device for determining the Seat Index Point (SIP) and a support structure with lights simulating the operator's binocular vision. The phases that led to the complete system are outlined below.

3D CAD model of John Deere 6920S

First, the unified device for determining the Seat Index Point (Figure 1) is joined to the 3D model of the tractor under examination, forming a dedicated assembly that the authors will call the «tractor assembly», which will subsequently be inserted into the virtual test assembly. This device is constrained relative to the origin of the reference system of the tractor assembly (O). This approach makes its positioning parametric, allowing for easy and flexible adjustments (Figure 2).

Lights support

Subsequently, the lights support was inserted into the virtual test assembly and constrained to the SIP device by joining points B and A. It was designed in such a way as to then attach the luminous points to the correct position as indicated by the standards (Figure 3). Furthermore, it has been made rotatable by 360° around the vertical axis passing through the lights reference point (FPCP), according to ISO 5006:2017.

Test surfaces

The procedure dictated by ISO 5006:2017 requires performing the verification test for masking effects on two specific surfaces, one at the visibility test circle (VTC, Figure 4a) and the other in the rectangular boundary (RB, Figure 4b). Specifically, the RB corresponds to the rectangular profile on the ground reference plane at 1 m from the machine's boundary, while the VTC indicates the circle with a radius of 12 meters located on the ground reference plane with its center vertically below the FPCP (Figure 4). These surfaces were directly recreated as separate parts in Inventor and subsequently inserted into the corresponding virtual test assembly, constrained to its reference system (Figure 5). The height of the RB surface from the ground has been made parametric, allowing the user to easily adjust the test conditions. This flexibility is necessary because the reference standard specifies different height values for evaluating the masking effects depending on the type of machine being analyzed.

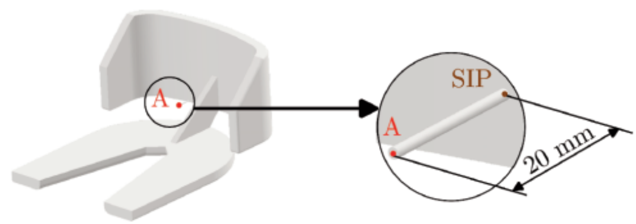

Figure 1. Virtual unified device for determining the seat index point (SIP).

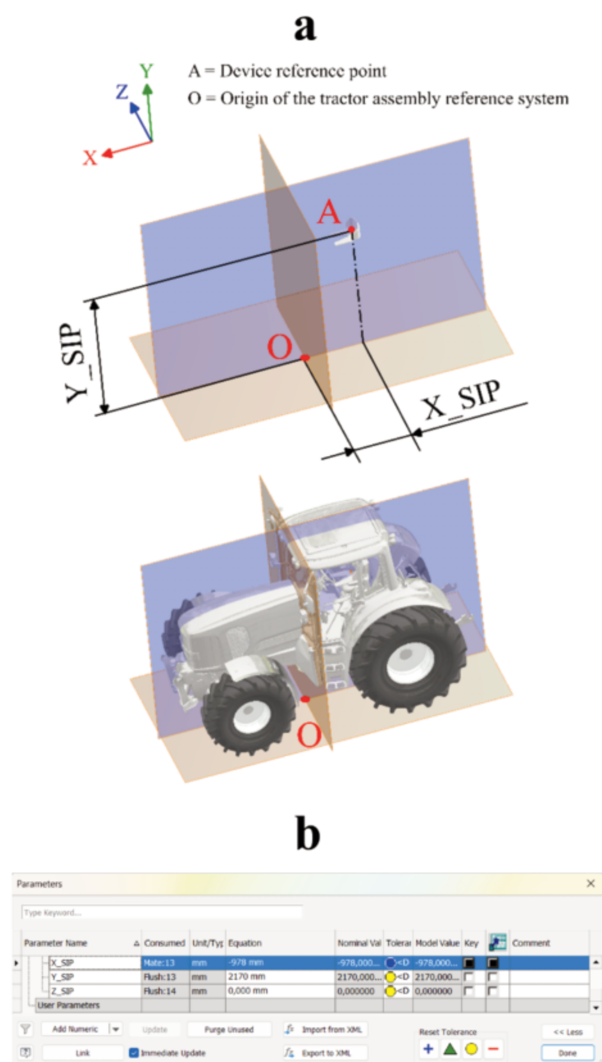

Figure 2. Preparation of the tractor 3D model for visibility virtual test. **a**) Positioning dimensions of the unified device in the machine model. **b**) Control window for the parameters related to the positioning of the SIP unified device.

Complete virtual test assembly

The tractor assembly was constrained to the reference system, aligning the XZ plane of the virtual test assembly with the XZ plane tangent to the wheels. The other two planes, XY and YZ, were aligned with the corresponding planes passing through point A (that is a rigid projection along the y axis of FPCP), in accordance with current standards (Figure 5). Similarly, the selected test surface is constrained to the reference system, ensuring that, in the case of the VTC, the planes passing through the center of the circle coincide with those passing through the FPCP (Figure 5a). Additionally, for the RB, it is necessary to ensure that the inner edge of the rectangle coincides with the tractor's boundary (Figure 5b).

Rendering execution in Inventor Studio

Once the assembly within the test surface and the 3D model of the John Deere 6920S were constructed, rendering with Ray-tracing was performed to derive the masking effects and thus evaluate the field of view for those specific test configurations. This process is carried out using the «Autodesk Inventor Studio» environment included within «Autodesk Inventor». Before the analysis, two spherical lights were inserted into the corresponding support. The colors of these light points were differentiated, specifically opting for green on ODX and red on OSX. This choice was made to distinguish the rendering areas with masking (shadows) from those with monocular vision (which will appear red or green) and from those with complete binocular vision, which will appear yellow (as additive synthesis of the adopted colors) (Figure 6a). Finally, cameras were positioned to generate the rendering exclusively for the areas of interest (Figure 6 b,c).The renderings of masking effects are presented in the "Result and Discussion" section.

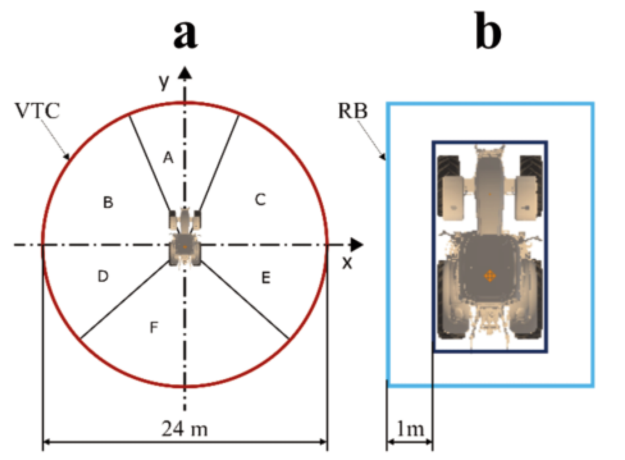

Figure 4. Visibility test location. a) Visibility test circle. b) Rectangular boundary.

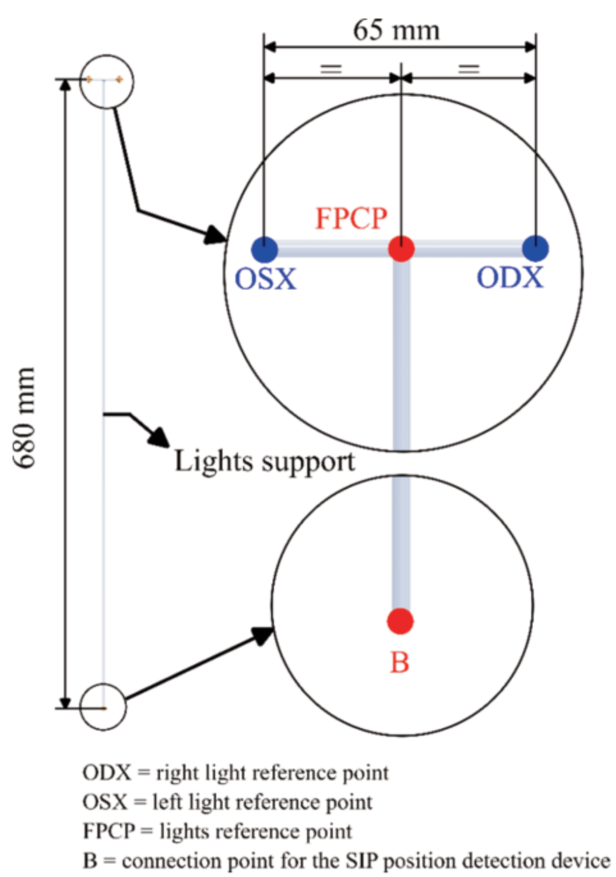

Figure 3. Virtual lights support.

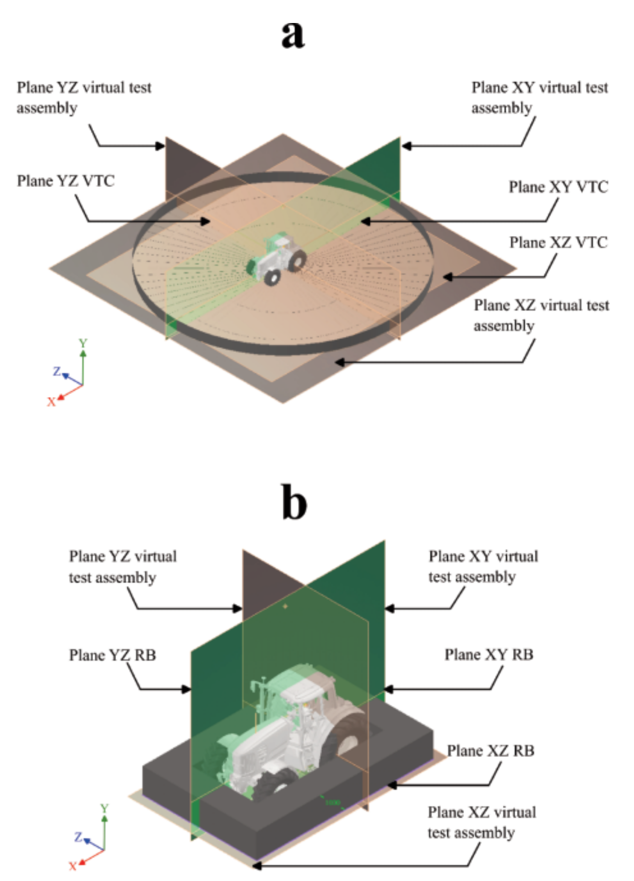

Figure 5. Assembly of test configuration. a) Visibility test circle. b) Rectangular boundary.

Experimental tests for verifying the field of view

In addition to the virtual test, the verification of masking effects on the physical tractor was carried out at the CREA laboratory in Treviglio (Province of Bergamo, Italy) using the procedures suggested by ISO 5006:2017.

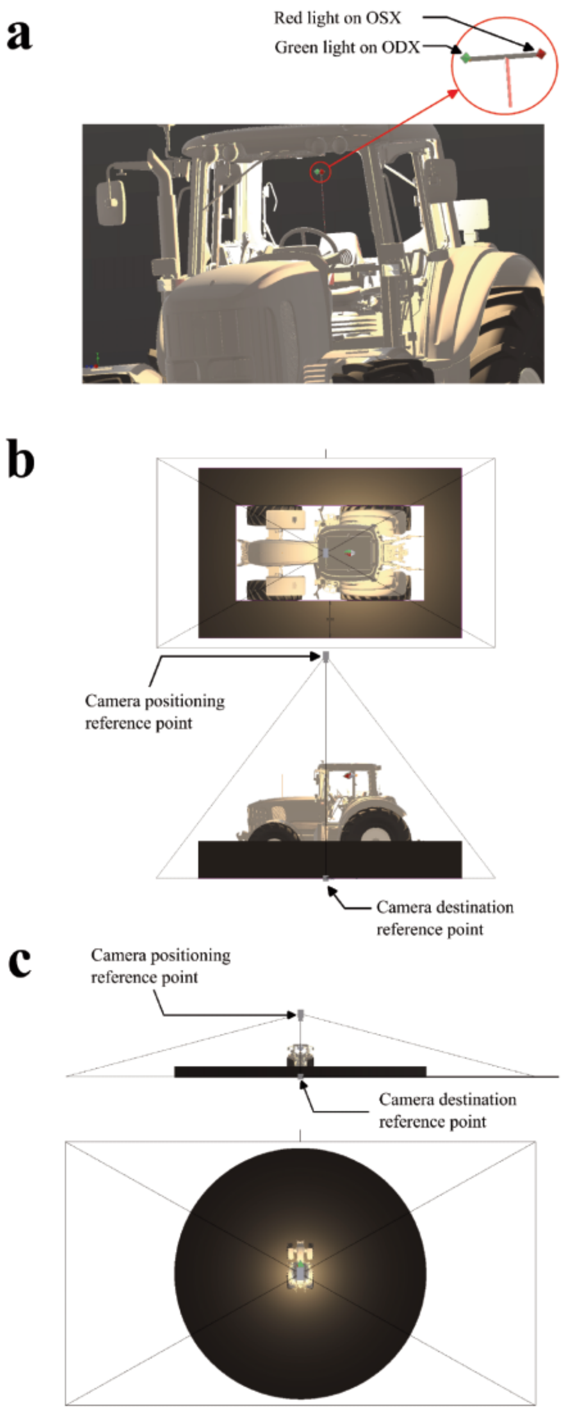

Figure 6. Inventor studio settings. **a)** Red and green lights. **b)** Framing of the rectangular boundary. **c)** Framing of the visibility test circle.

VTC physical test

The first step was to determine the seat index point (SIP) of the tractor using the unified SIP device, following the procedure indicated by ISO 5353:1998. From the identified point, a previously constructed support was inserted, designed so that the FPCP was vertically 680 mm from the SIP, with the lights positioned 32.5 mm from the FPCP, in accordance with ISO 5006:2017 (Figure 7). Then, a circle with a radius of twelve meters (VTC) was traced, with its center coinciding with the vertical projection on the ground of the FPCP. It should be noted that determining the SIP, the FPCP and its vertical projection on the ground with tolerances below one centimeter is particularly challenging and requires a high degree of operator skill. Finally, the FoV was determined using two methods:

i. The first one involves moving along the VTC while looking into a mirror positioned at ground level, marking any arc of the circumference as a masking effect where neither of the two lights is visible in the mirror (Figure 8);
ii. The second one involves directly marking the shadows projected by the lights onto the VTC at night. An aerial photograph was taken using a drone to capture these shadows, and it was then analyzed and measured in post-processing using Inventor.

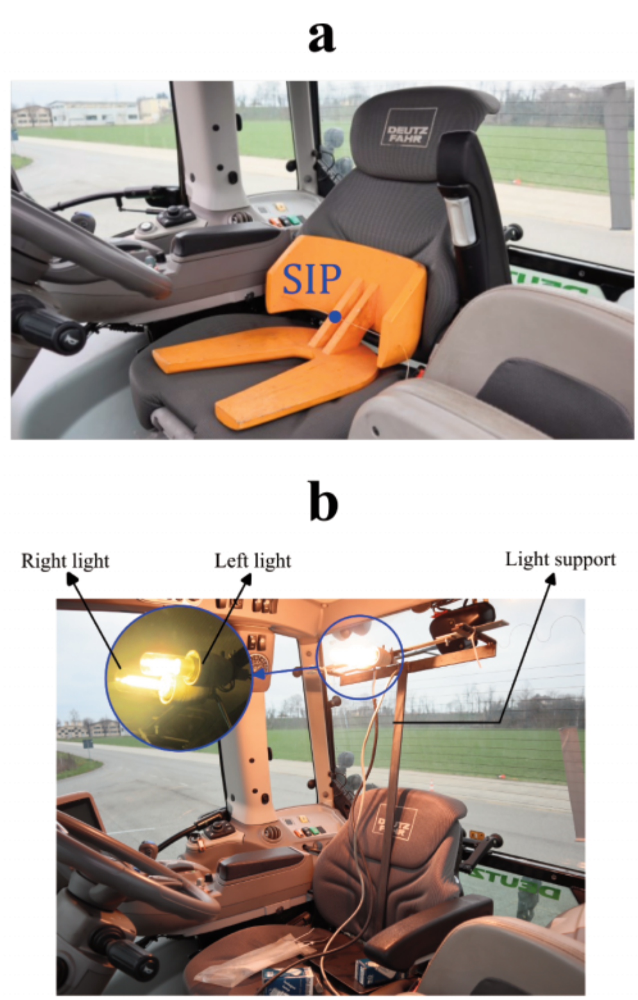

Figure 7. Configuration of the agricultural machine for the visibility test. **a)** Seat index point (SIP) determination. **b)** Light support. The images refer to a tractor model different from the one used in the test.

RB physical test

In addition to the verification test of the FoV at the VTC, another test was also carried out at the RB. In this case, the standards do not indicate a suggested procedure, but merely specify the height at which to check for masking should be done (for earthmoving machinery, it varies between 1 m, 1.2 m and 1.5 m depending on the type of vehicle and the side of the RB being analyzed). The solution chosen by the authors was to also conduct this test at night using a system composed of two height-adjustable stands, onto which three wooden planks and a white sheet were placed, respectively. In this case, aerial photographs were taken of each side of the RB, one at a time, and then combined in post-processing into a single image. With only one sheet available for the four tests to be conducted, the width and length of the specific outer rectangular border the tractor were marked (Figure 9). This operation made positioning the sheet faster during the test execution and provided a reference for combining the four images.

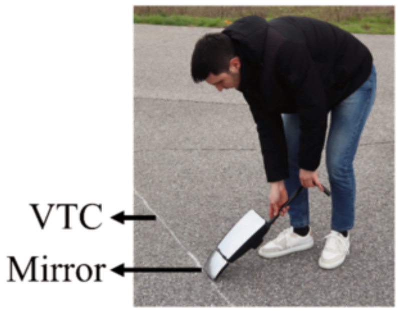

Figure 8. Visibility test circle (VTC) mirror test execution.

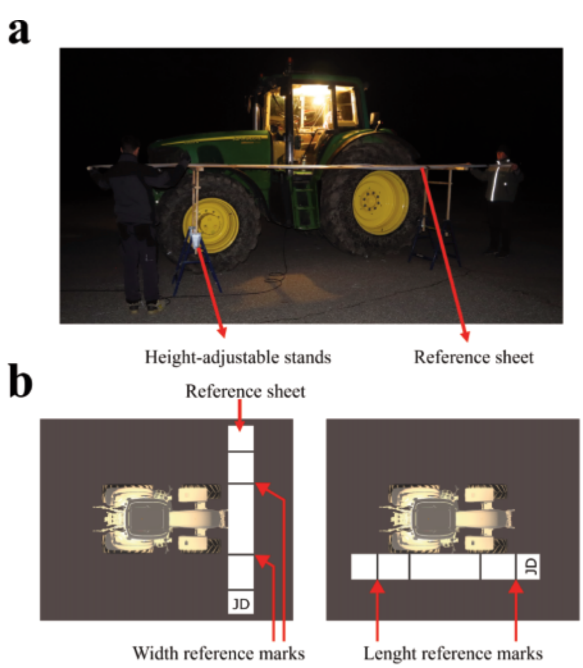

Figure 9. RB test configuration. **a**) Side view of the John Deere during the rectangular boundary test. **b**) Placing of the reference sheet.

Results and Discussion

For the compilation of the results, it is essential to carry out measurements of the masking effects. The method used involves directly inserting annotations within the Inventor environment, overlaying the images (rendering results and aerial photographs) onto the top view of the virtual surface test model.

Results on the VTC FoV

As described above, the number of masking effects and their amplitudes (measured as the chord of the circle of vision) have been evaluated in accordance with standard requirements. The first remarkable observation is that in both the simulation and the shadows test, as well as in the mirror test, the masking effects align with the same sectors, indicated as straight yellow lines in Figure 10 and previously shown in Figure 4a. Furthermore, when evaluating the extent of masking, a disparity between the two real tests conducted under identical conditions becomes evident. Upon comparing the simulated test with the shadows test, slight differences in the extent of masking are observed.

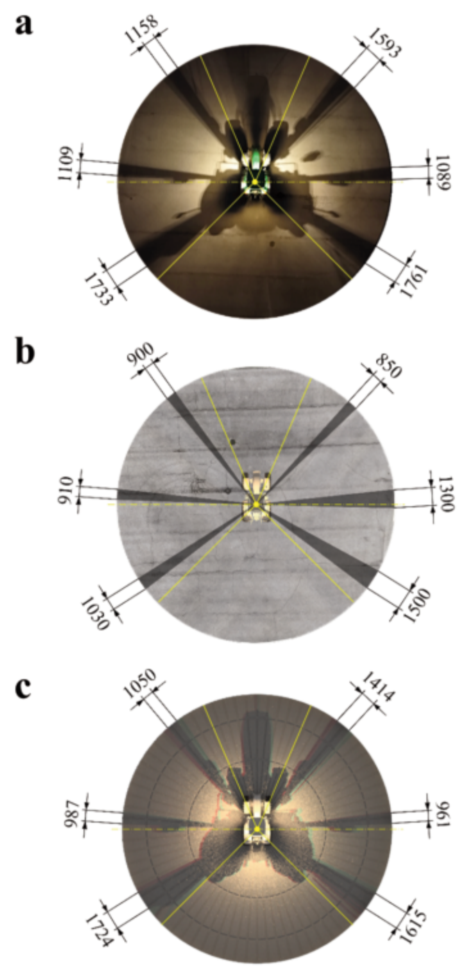

Figure 10. Measurement in mm of the masking effects on the visibility test circle field of view using different techniques. **a**) Shadows method. **b**) Mirror test. **c**) Virtual simulation, Raytracing method.

Specifically, by calculating the absolute percentage error between the extents of masking of the real nighttime test and the simulation, and averaging the errors, a value of 8.69% is obtained, as depicted in Table 1. Performing the same calculation and comparing the shadows test with the mirror test, an increase in the average percentage error is observed, reaching a value of 26.94% (Table 2). Regarding absolute error, calculated by determining the difference between the masking extents of the shadows test and those of the simulated test, an average of 115.33 mm is observed. This error, when compared to the circumference of the VTC FoV of approximately 75,400 mm, resulted the 0.15%. Conducting a similar analysis, the average absolute error obtained by comparing the two real tests increases to 395.83 mm, thus confirming the greater accuracy of the simulation compared to the real daytime test (Table 3). Another aspect emerged from the analysis of the experimental tests is that the configuration of the lights used can significantly alter the extent of masking. For the construction of the virtual model, indeed, point lights were used, following the current regulations. However, during the real tests executed at CREA laboratory, a different light configuration was used, with elongated halogen bulbs (Figure 11a). Additionally, these bulbs, positioned inside the light support, had different lengths from each other. The entire support was, therefore, asymmetric. To make the simulated test as realistic as the real nighttime test and to reduce instrumentation bias for a better comparison, efforts were made to replicate the light support configuration used in the real test. Specifically, a green light was added in the simulation, positioned longitudinally 40 mm from the left light source, and a red light was positioned longitudinally 60 mm from the right light source (Figure 11b). Comparing the results obtained from these simulations with those of the others conducted before the modification of the lights, an overall improvement in the values of the masking extents has emerged, bringing them even closer to the real ones, with the average percentage error reduced to 6.45% and the average absolute error to 84.55 mm (Table 4).

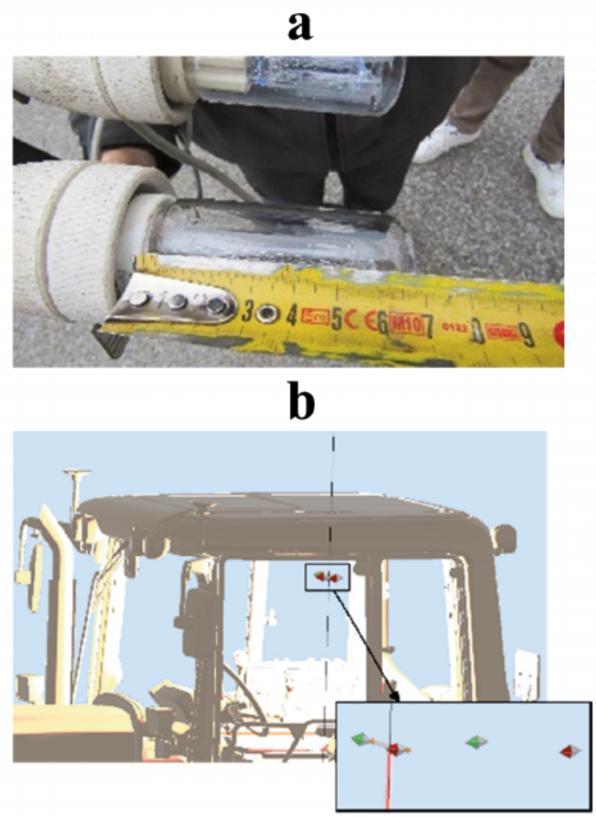

Figure 11. Light modifications on the virtual model. a) Halogen bulbs used in the experimental test. b) Updated light configuration on the virtual model.

Table 1. Measurement of the percentage and absolute error between the masking effects of the shadows visibility test circle and the Ray-tracing test performed on the John Deere 6920S.

Shadows test	Ray-tracing test	Percentage error	Absolute error	Magnitude of the absolute error
1593 mm	1414 mm	11.24%	179.00 mm	179.00 mm
1089 mm	961 mm	11.75%	128.00 mm	128.00 mm
1761 mm	1615 mm	8.29%	146.00 mm	146.00 mm
1733 mm	1724 mm	0.52%	9.00 mm	9.00 mm
1109 mm	987 mm	11.00%	122.00 mm	122.00 mm
1158 mm	1050 mm	9.33%	108.00 mm	108.00 mm
Average percentage error 8.69%				
Average absolute error in magnitude			115.33 mm	

Table 2. Measurement of the percentage and absolute error between the masking effects of the shadows visibility test circle and the mirror test performed on the John Deere 6920S.

Shadows test	Mirror test	Percentage error	Absolute error	Magnitude of the absolute error
1593 mm	850 mm	46.64%	743.00 mm	743.00 mm
1089 mm	1300 mm	19.38%	-211.00 mm	211.00 mm
1761 mm	1500 mm	14.82%	261.00 mm	261.00 mm
1733 mm	1030 mm	40.57%	703.00 mm	703.00 mm
1109 mm	910 mm	17.94%	199.00 mm	199.00 mm
1158 mm	900 mm	22.28%	258.00 mm	258.00 mm
Average percentage error 26.94%				
Average absolute error in magnitude			395.83 mm	

Results on the RB FoV

Analyzing the images at the RB obtained through the virtual and the shadows method, there is immediately a marked similarity both in the shape and in the positioning of the dark areas around the machine. As for the amplitude, measured on Inventor as previously explained. slight differences have been noticed. However, as highlighted in Figure 12, despite these slight differences, it can be confirmed that the virtual simulation is capable of accurately estimating both metrics required to evaluate compliance with the standard. Similarly, for the tests conducted in the RB, as with the VTC, some differences between the virtual model and the real case could explain the observed discrepancies. Although the CAD model has been verified in the main dimensions of the tractor's layout. some unverified or unverifiable details may differ. Another factor contributing to the imprecise correspondence of the results is the complexity of the procedure to determine the FPCP and its projection on the ground during experimental tests. To demonstrate this, two tests were simulated in the RB where 20 mm were respectively added and subtracted from the original height of the light support. Significant variations in masking were observed. despite the minimal change in the height of the light support. reaching a maximum of 454 mm (Figure 13). This indicates that the Ray-tracing model is very sensitive to the position of elements within the Inventor environment.

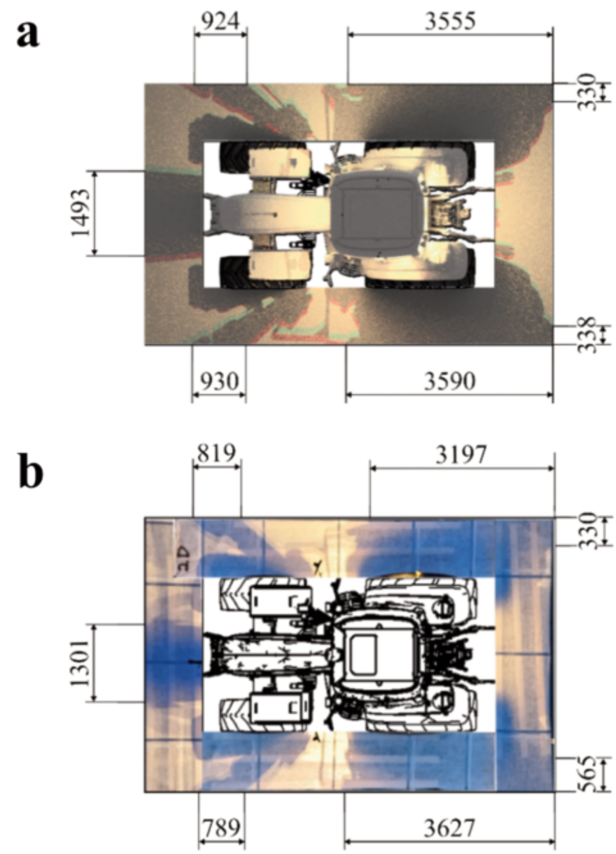

Figure 12. Measurement in mm of the masking effects in the 1 m high rectangular boundary field of view using different techniques. **a**) Shadows method. **b**) Virtual simulation, Ray-tracing method.

Discussion

The analysis of the results revealed that the virtual system is capable of accurately estimating the masking effects produced by various components of the tractor, as demonstrated by the close correspondence between the virtual simulations and the physical tests. However, slight discrepancies were observed. These differ-

Table 3. Measurement of the percentage and absolute error between the masking effects of the rectangular boundary test at a height of 1 m, comparing the shadows test and the Ray-tracing test performed on the John Deere 6920S.

Shadows test 1 m	Ray-tracing test 1 m	Percentage error	Absolute error	Magnitude of the absolute error
819 mm	924 mm	12.82%	-105.00 mm	105.00 mm
3197 mm	3555 mm	11.20%	-358.00 mm	358.00 mm
469 mm	330 mm	29.64%	139.00 mm	139.00 mm
565 mm	338 mm	40.18%	227.00 mm	227.00 mm
3627 mm	3590 mm	1.02%	37.00 mm	37.00 mm
789 mm	930 mm	17.87%	-141.00 mm	141.00 mm
1301 mm	1493 mm	14.76%	-192.00 mm	192.00 mm
Average percentage error			18.21%	

Table 4. Comparison of the accuracy between the mirror test and Ray-tracing test 4 lights with the shadows test for visibility test circle field of view.

Shadows test	Ray-tracing test 4 lights	Mirror test	Shadows-Ray-tracing error	Shadows-mirror error
1593.0 mm	1468.0 mm	850.0 mm	▼ 7.85%	▲ 46.64%
1089.0 mm	1010.0 mm	1300.0 mm	▼ 7.25%	▲19.38%
1761.0 mm	1666.0 mm	1500.0 mm	▼ 5.39%	▲14.82%
1733.0 mm	1741.0 mm	1030.0 mm	▼ 0.46%	▲40.57%
1109.0 mm	992.0 mm	910.0 mm	▼ 10.55%	▲17.94%
1158.0 mm	1075.0 mm	900.0 mm	▼ 7.17%	▲22.28%

ences are not attributable to shortcomings of the virtual system but rather to challenges in precisely recreating the same conditions between the simulated and experimental environments. The main critical issue lies in ensuring the correct positioning of the tractor and the light support on the test surface. Even minimal deviations in these parameters can lead to significant variations in the field of view, particularly near the tractor. An additional source of discrepancies stems from the differences in light configurations between the experimental and simulated tests. The real tests employed elongated halogen bulbs positioned asymmetrically, while the initial simulations used point lights in accordance with current regulations. Modifying the virtual model to replicate the experimental light setup improved the accuracy of the simulation, reducing both percentage and absolute errors. This adjustment underscores the importance of a realistic virtual environment to achieve results closer to those obtained in physical tests.

Moreover, some limitations in the CAD model used for the simulation might have contributed to the discrepancies observed. Although the main dimensions of the tractor layout were verified, certain details were either unverified or unverifiable, leading to slight inaccuracies. Sensitivity analyses confirmed that the Ray-tracing model is highly responsive to changes in parameters, such as the height and position of the light support, further emphasizing the importance of precise replication of physical test conditions.

Despite these challenges. the results confirm the superiority of the virtual simulation over traditional methods such as the mirror test. Unlike the mirror test, which heavily depends on the operator's skill, the virtual simulation provides a more reliable and reproducible assessment of the field of view. Additionally, the simulation offers the advantage of enabling evaluations during the design phase, significantly reducing costs and development time by minimizing the need for multiple physical prototypes.

It can be concluded that by obtaining a more sophisticated measurement of the SIP (and thus the positioning of the light support) and using a more accurate CAD model, the similarity between the two images in Figure 12 increases.

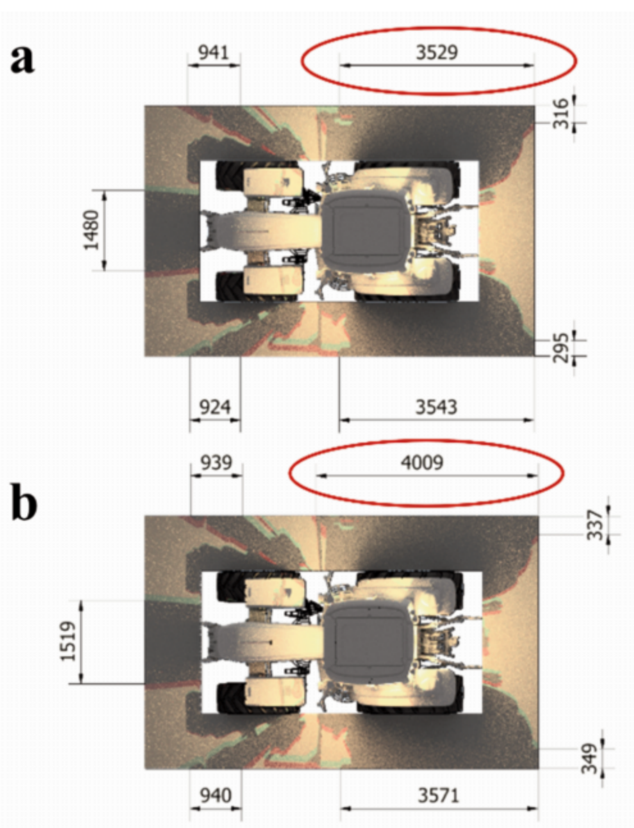

Figure 13. Measurement in mm of the masking effects in the virtual simulation 1 m high rectangular boundary field of view using different seat index point (SIP) height. **a**) SIP raised by 20 mm. **b**) SIP lowered by 20 mm.

Conclusions

In this paper, connected to the BRIC INAIL 2022 ID-04 project, the topic of the safety of agricultural and forestry machinery was addressed, with the objective of developing a system to identify and validate the operator's field of view. Initially, it was necessary to thoroughly analyze existing standards and scientific publications in both the agricultural sector and related fields, such as the industrial sector. The research focused on creating a virtual model capable of identifying the field of view through rendering based on the Ray-Tracing algorithm. The effectiveness of this model was then verified by comparing virtual simulations with experimental tests conducted on the same type of machine. Additionally, the same lights used in the experimental tests were recreated in the virtual model to better compare the results. The authors agree that adopting point lights is more consistent with the behavior of the human pupil and is therefore preferable.

This virtual system demonstrated a strong capability in evaluating the masking effects caused by different components of the tractor., as evidenced by its alignment with the results from physical tests. However, slight discrepancies were observed between the simulated and experimental data. These deviations are attributed not to the limitations of the virtual model but rather to challenges in replicating identical test conditions. Factors such as the exact positioning of the tractor and the configuration of its light support have a significant impact on the field of view measurements, particularly in the areas closest to the machinery.

To further improve the accuracy of the simulations and refine the correspondence between the two images in Figure 12, it would be helpful to address these issues with more precise alignment and calibration, as well as obtaining more accurate measurements of the SIP and the positioning of the light support, while also using a more detailed CAD model.

In conclusion, the presented simulation method proves to be superior to the current state-of-the-art method (mirror test), which relies heavily on the operator's skill in executing it, and it allows for estimating the field of view already in the design phase. For these reasons, it proves to be a valuable support tool for technical committees in the development of standards aimed at operator safety and provides manufacturers of agricultural machinery with a tool to accelerate the production of compliant vehicles, optimizing costs and times, as it reduces the number of prototypes that need to be physically tested.

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