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Visibility risk zone method to evaluate operator visibility for earth-moving machinery

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In Great Britain there are 25 fatal injuries each year on average, and hundreds of non-fatal injuries to workers as a result of being struck by moving vehicles in the workplace. Restricted operator visibility is often identified as a contributing factor in these accidents.

This report describes the development of a risk-based method to determine 'visibility risk zones' for earth-moving machinery such as dumper trucks and excavators. It considers operator visibility all around a machine from its boundary out to the far field of view. The method assists users to: define the areas around a machine that the operator needs to view; identify the areas the operator cannot see; and determine the areas where visibility aids such as mirrors and camera systems are required. The method takes into account the configuration of the machinery and how easy it is to manoeuvre during operation and travel. The method may be useful to assist in the following tasks: (1) Evaluation and verification of machines; (2) Installation of visibility aids and detection systems; (3) Assessment of risks to workers on a jobsite; (4) Organisation of a jobsite to ensure that risks are well controlled; (5) Incident investigation.

Two related reports describe the use of this visibility risk zone method to evaluate operator visibility for an hydraulic excavator (RR1157) and a large rigid frame dumper truck (RR1158).

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Visibility risk zone method to evaluate operator visibility for earth-moving machinery

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KEY MESSAGES

In Great Britain, there are 25 fatal injuries each year on average, and hundreds of non-fatal injuries, to workers as a result of being struck by moving vehicles at the workplace. Restricted operator visibility is often identified as a contributing factor in these accidents.

This report is the first in a series of three reports on the topic of evaluating visibility around earth moving machinery. It describes a practical method for evaluating the operator's field of view from earth-moving machinery, taking account of the machine's configurations and its manoeuvrability during operation and travel. This visibility risk zones method can be used to inform a risk assessment and define the areas around the machine that the operator needs to view, and the areas where visibility aids are required. The method would be useful for those with a role in ensuring that the areas around the machine where the operator cannot see are recorded and prioritised, and the residual risks are managed. This may include those involved in the evaluation and verification of machines, the installation of visibility aids and object detection systems, the organisation of the jobsite to ensure a safe working environment, and the investigation of incidents involving moving plant and machinery.

Compared to the test method specified in the International Standard (ISO 5006) "*Earth-moving machinery – Operator's field of view – Test method and performance criteria*", the visibility risk zones method is considered to be more risk-based, as it evaluates visibility all around the machine from the machine boundary out to the far field of view. This is especially critical for larger machines. It is also able to evaluate improvements to visibility that are now possible with more recent camera-based technologies, such as those able to provide a surround view (or "bird's eye view") around the machine.

These surround-view camera systems are useful supplements to the range of visibility aids available, with good potential to compensate for the lack of direct visibility and, in some applications, where there may be limitations in the effectiveness and coverage of mirrors and single camera systems. The strength of camera systems with a surround view is their ability to provide information relating to the presence or absence of pedestrians all around and close to the machine on a single monitor screen. However, for systems observed as part of this work, there was a trade-off in that they did not display the far field of view out to the horizon, which may also be important for the operator to maintain greater situational awareness. Installation and configuration of the systems also appears critical in ensuring that there are no gaps in their coverage of the collision risk areas around machinery, and that the systems provide the level of performance expected of them.

EXECUTIVE SUMMARY

In Great Britain, there are 25 fatal injuries each year on average, and hundreds of non-fatal injuries, to workers as a result of being struck by moving vehicles at the workplace. Restricted operator visibility is often identified as a contributing factor in these accidents.

ISO 5006 "*Earth-moving machinery – Operator's field of view – Test method and performance criteria*" specifies a static test method for determining the operator's field of view from earth-moving machinery. This approach is not considered to be particularly suitable when applied to large machines, while its visibility performance requirements typically represent what could be achieved by machines in production at the time, rather than a consideration of ergonomics and risk.

Visibility aids may be fitted to earth-moving machinery to meet the visibility performance requirements and supplement the operator's direct vision. More recently, there has been interest in the use of camera systems that take the images from multiple cameras fitted on a machine and typically merge these into a single image on a single monitor, which shows a surround view (or "bird's-eye view") of the area around the machine. The purpose of these systems is to improve the operator's awareness of pedestrians and other objects around the machine, while reducing the need for the operator to repeatedly turn their head and move their upper body (or view multiple mirrors and monitors). However, limited information was available on the effectiveness of these systems fitted to earth-moving machinery during travel and work, or the implications for how these systems may help earth-moving machinery meet or exceed their visibility performance criteria.

Aims

The aim of this project was to develop a visibility evaluation method based on risk and machine characteristics, such that machines designed to meet these criteria allow the reliable identification of hazards using either direct vision from the operator's position or indirect vision with the aid of mirrors or camera monitoring systems. A further aim of the project was to establish the generic advantages and limitations of camera systems providing a surround view around earth-moving machinery, and consider the implications for how these systems may help earth-moving machinery meet or exceed their visibility performance criteria.

Methodology and Main findings

The **visibility risk zones method** was developed for conducting a risk-based evaluation of the operator's field of view from earth-moving machinery, taking account of the machine's configurations and its manoeuvrability during operation and travel. This can be used to inform a risk assessment and define the areas around the machine that the operator needs to view, and the areas where visibility aids are required. The method involves the following stages.

1. Identify the machine configurations within scope of the evaluation.
2. Identify and record the collision risk area, taking into consideration the areas into which the machine can move quickly during operation and travel.
3. Identify and record the maskings (ie areas where operator visibility is obstructed).
4. Evaluate the visibility risk zones for direct visibility, achieved by merging a plot of the maskings onto a plot of the collision risk areas.

5. Incorporate indirect visibility (ie with the use of mirrors or camera monitoring systems) into the evaluation of the visibility risk zones.

Evaluating the visibility risk zones then prioritises the areas around the machine according to whether there is a risk of collision as well as whether the operator has direct visibility to the area, visibility only when using visibility aids, or obstructed visibility.

This method is intended for those with a role in ensuring that the areas around the machine where the operator cannot see are recorded, prioritised, and the residual risks are managed. This may include those involved in the evaluation and verification of machines, the installation of visibility aids and object detection systems, the organisation of the jobsite to ensure a safe working environment, and the investigation of incidents involving such machines.

The method has been trialled on a large rigid frame dumper and a medium-sized excavator. This demonstrated that the identification and evaluation of visibility risk zones was a useful concept to apply to these types of machinery. The trials also demonstrated limitations of the current approach in ISO 5006.

This report also describes the review of literature on field of view evaluation, engagement with machine manufacturers, and an appraisal of ISO 5006, which were also undertaken to inform development of the method.

Camera systems providing a surround view were found to be useful supplements to the range of visibility aids available, with good potential to compensate for the lack of direct visibility or, for some for some applications, where there may be limitations in the effectiveness and coverage of mirrors and single camera systems.

The strength of the camera systems providing a surround view is their ability to provide information relating to the presence or absence of pedestrians all around and close to the machine in a single monitor screen. However, for systems observed as part of this work, there was a trade-off in that they did not display the far field of view out to the horizon, which may also be important for the operator to maintain situational awareness. Installation and configuration of the systems appears critical in ensuring that there are no gaps in coverage and that the systems provide the level of performance expected of them. The selection of camera systems must take account of the machine’s characteristics, and what the operator needs to see for safe machine operation in its intended environment.

This report draws together requirements applicable to camera systems providing a surround view. The visibility risk zones method described can also be used to evaluate the extent to which these systems provide acceptable coverage within the collision risk areas around machinery.

Significant improvements in the performance of camera systems providing a surround view is likely to come through their integration with other technologies, allowing the strengths of these technologies to compensate for limitations associated with systems that are reliant on operator vision for reliable detection.

CONTENTS

1 INTRODUCTION

1.1 BACKGROUND

Over the past five years in Great Britain, there was an average of 25 fatal injuries each year, and hundreds of non-fatal injuries, to workers as a result of being struck by a moving vehicle at the workplace [1]. These have been more likely to occur in agriculture, forestry and fishing (7 fatal accidents per year on average), transport and storage (5 per year on average) and construction (4 per year on average). Restricted visibility for the vehicle operator is often identified as a contributing factor in these accidents [2].

ISO 5006 "*Earth-moving machinery – Operator's field of view – Test method and performance criteria*" specifies a static test method for determining the operator's visibility from earth-moving machinery (EMM) as well as the minimum visibility requirements that machines have to meet. Briefly, the test method involves placing a rotating light source apparatus at the operator's eye position, and measuring the width of shadows cast onto the ground along the circumference of a 12 m radius visibility test circle (VTC) around the machine [3]. The concept behind ISO 5006 reflects what could be achieved by machines in production at the time the standard was introduced in 1993.

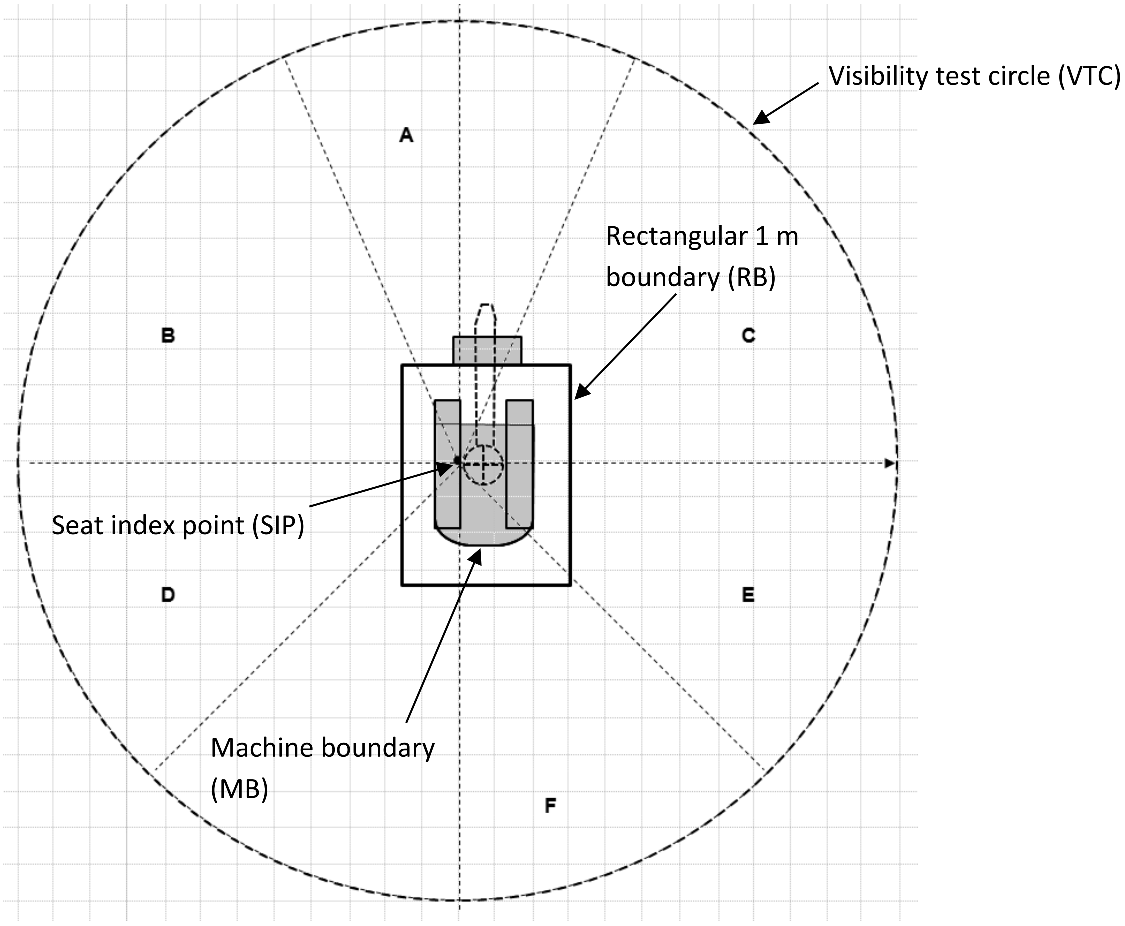
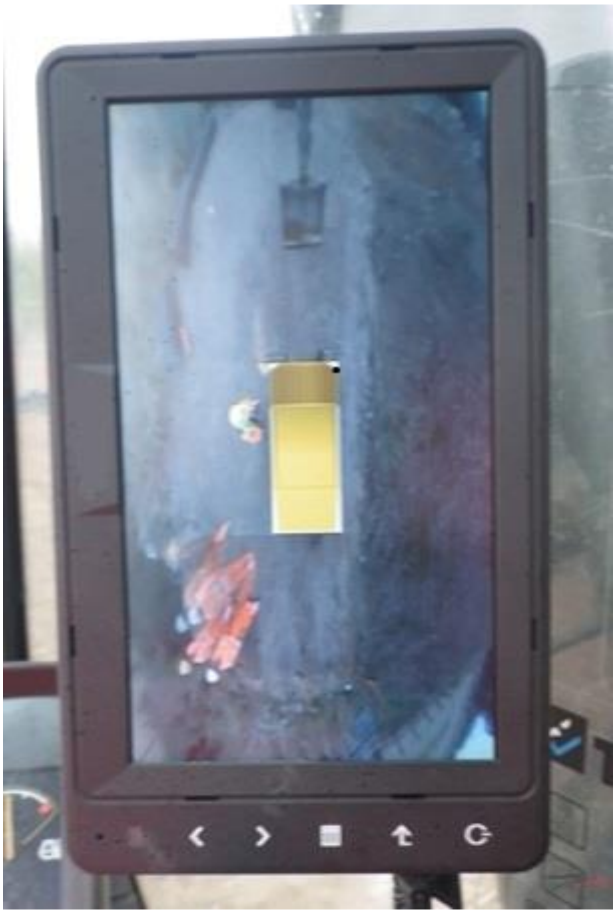


Figure 1 ISO 5006 test visibility test locations for an excavator. The sectors of vision (A, B, C, D, E and F) are also shown.

ISO 5006 was revised in 2006 to include more onerous performance criteria, as well as a test of the near field of view, along a rectangular perimeter, which for most machine types is marked out one metre away from the machine boundary. A further revision was completed in 2017. However, the approach described in ISO 5006 is increasingly viewed as unsuitable, especially for large machines. Some of its primary limitations are that it does not consider visibility between the rectangular boundary and the visibility test circle, or the working positions of the machines. It does not provide visibility performance criteria for some of the largest machines; for example, rigid frame or articulated dumper trucks with an operating mass exceeding 50 tonnes, or tracked excavators exceeding 40 tonnes. It also does not take account of dynamic factors, such as the turning circle and manoeuvrability, speed, and stopping performance, which are considered as being relevant to the hazards that these large machines present in their working environments.

Earth-moving machinery may be fitted with visibility aids to meet the ISO5006 visibility performance requirements and supplement the operator’s direct vision. More recently, there has been interest in the use of systems that take the images from multiple cameras fitted on a vehicle and typically merge these into a single image on a monitor, showing a surround view (or “bird’s-eye view”) of the area around the machine (Photograph 1)



Photograph 1 Example of a monitor display from a camera system, showing a surrounding view for an excavator

The purpose of these systems is to improve the operator’s awareness of pedestrians and other objects around the machine, while reducing the need for the operator to repeatedly turn their head and move their upper body (or view multiple mirrors and monitors) when scanning for objects.

They can be used on their own or in combination with other object detection systems (ODS) such as radar sensors or ultrasonic detector systems, to supplement the operator's direct visibility and use of mirrors. However, limited information was available on the use and effectiveness of these systems when fitted to earth-moving machinery for work and travel, or on the implications for how these systems may help earth-moving machinery meet or exceed the ISO 5006 [3] performance criteria for operator visibility.

1.2 AIMS AND OBJECTIVES

Where a worker in Great Britain is struck by moving plant and either fatally or seriously injured, Mechanical Engineering Specialist Inspectors, from the Health and Safety Executive (HSE), may be asked to examine the machine and provide a view on whether it was safe to operate and whether any further reasonably practicable measures could have been taken to prevent the accident (or similar potential accidents) from occurring. This examination may consider any restrictions to the machine operator's visibility. Within this group, there was a wish to explore the concept of developing a manoeuvrability-based approach to evaluate the field of view around earth-moving machinery. This was seen as being a more appropriate risk-based approach for evaluating operator visibility and its related risks, the principles of which may be useful in setting visibility performance criteria for earth-moving machinery.

Thus, the aim of this project was to develop a method based on risk and machine characteristics to replace the current approach and performance criteria in ISO 5006, such that machines designed to meet these criteria allow the reliable identification of hazards using either direct visibility from the operator's position or indirect visibility (ie vision with the aid of mirrors or cameras).

To meet this aim, the objectives were as follows.

1. Describe the findings of a review of literature and standards relating to field of view evaluation methods.
2. Liaise with manufacturers as to the extent that they use the ISO 5006 methodology in assessing visibility from the operator's position, and the provision of visibility aids at the point of supply.
3. Provide a review and appraisal of the ISO 5006 (2006) methodology.
4. Develop a risk-based method to evaluate visibility from the operator station based on the concept of a manoeuvrability zone around earth-moving machinery.
5. Undertake site testing in the development and validation of the proposed method, and its application to earth-moving machinery in general.
6. Suggest machine performance criteria for the manoeuvrability zone concept based on ergonomics principles.

A further aim of the project was to establish generic advantages and limitations of visibility aids that providing a surrounding view of earth-moving machinery, the implications for how these systems may help earth-moving machinery meet or exceed their visibility performance criteria, and any additional criteria to include in a risk zones approach. This was achieved as part of the objectives described above.

2 METHODS

2.1 REVIEW OF LITERATURE RELATING TO FIELD OF VIEW EVALUATION

A small-scale search and narrative review of literature and standards was undertaken relating to concepts and methodologies of field of view evaluation.

The HSE Information Services Search Team conducted two separate systematic searches of the OSH-ROM, OSH UPDATE, Ergonomics Abstracts, Web of Science, Science Direct, HIS, ANTE, Compendex, MTEA, NTIS, Healsafe, Conference Papers Index, ProQuest Dissertations, TRIS and HSE e-Library databases. The searches were restricted to literature published between 2005 and 2015. The first search focussed on methods for evaluating driver / operator visibility. The second search focussed on visibility aids. The search strategy applied is described in Appendix A. A separate search was conducted of the British Standards Online database, using 'visibility' as a keyword. The findings of the literature review are summarised in Section 3, while a more detailed description of the literature is provided in Appendix B.

2.2 DISCUSSION WITH MANUFACTURERS OF EARTH-MOVING MACHINERY

The initial concept of the method was informed through early engagement with manufacturers of earth-moving machinery.

A technical committee meeting for ISO 5006 (ISO/TC 127/SC 1/WG5) was attended at BSI London on 5 – 6 December 2015. The project aims, along with an initial concept of a risk-based approach, were presented at the meeting, in order to meet stakeholders and elicit early feedback from manufacturers represented on the committee. At the meeting, members generated their own 'wish list' of improvements that they would like to see incorporated into the next full revision of ISO 5006. This exercise helped to inform the appraisal of ISO 5006.

Responses were also collected from representatives of three manufacturers of earth-moving machinery. A briefing note and open-ended question set was developed with the intention of stimulating thought and discussion (see Appendix B). The issues covered several issues:

- how manufacturers specify user requirements for operator visibility;
- how manufacturers apply the ISO 5006 test method in practice and establish conformance;
- any current issues or barriers they experience when applying the test method;
- other approaches that they used in the design process to assess the operator's field of view from earth-moving machinery;
- how manufacturers assess what visibility aids to fit to a machine;
- the overall usefulness of ISO 5006 in helping to decide whether the machine provides the operator with an acceptable field of view and what visibility aids to fit; and
- their initial views on the manoeuvrability-based concept proposed for evaluating the field of view.

Each manufacturer, at their convenience, chose a different format in which to respond. Thus, feedback was collected via a written response, a one-to-one telephone interview to summarise the views collected of their design engineers across the UK and Europe, and an informal face-to-face discussion with a group of design engineers. The group discussion was particularly helpful as it was possible to meet directly with current cab and machine designers to gain a better insight into how ISO 5006 fits into their design process and ask follow-up questions. Only one of the three manufacturers consulted had products that exceeded the operating mass specified in the table of visibility performance criteria within ISO 5006.

The findings of this work are described in Section 4.

2.3 APPRAISAL OF ISO 5006

An appraisal of ISO 5006 [3] was carried out based on the review of literature, discussion with manufacturers, and previous experience applying the method in practice. This is provided in Appendix D.

The appraisal was limited to technical comments. It did not take account of editorial aspects, although these could also be important in terms of how those involved in machine design and evaluation try to interpret and apply the test method and performance criteria. During the lifespan of this appraisal, work was in hand to publish a revision to ISO 5006 in 2017.

2.4 DEVELOPMENT OF THE VISIBILITY RISK ZONES METHOD

The method was developed from existing observer-based target evaluation methods that have been used to evaluate the field of view from construction machinery [4] and heavy goods vehicles [5]. This was supplemented with an approach to consider the manoeuvrability of the machine, taking account of relevant learning from the literature review and consultation with manufacturers. The approach was refined in the process of applying it to an evaluation of the operator's field of view from two types of earth-moving machinery:

- a large rigid frame dumper truck (64,000 kg operating mass); and
- a medium-sized hydraulic excavator (14,200 kg empty operating mass), fitted with a camera monitoring system providing a surround view.

Further consultation on the approach was sought through project steering meetings involving a few members of ISO/TC 127/SC 1/WG 5 who were primarily based in the UK and had an interest in visibility from large machinery.

Section 5 describes the development and testing of the method in more detail, along with the learning that emerged from these trials. The method is described in Appendix E.

3 LITERATURE REVIEW SUMMARY

3.1 SEARCH RESULTS

The search strategies resulted in 121 papers in total (excluding duplicates). An initial sift was conducted based on the information contained within the abstract of each search result. Papers were excluded where it was perceived that they would not be relevant to the project objectives. The sifting process resulted in 19 papers (16%) of potential relevance that were reviewed in full. The results were primarily from the automotive sector, and most relevant papers were to do with the evaluation of the driver's field of view from heavy trucks / goods vehicles (HGVs). Two of the 19 papers were found to have potential relevance to establishing performance criteria for camera monitoring systems providing a surround view. In addition, a search of the British Standards Online database identified standards considering visibility on ten other types of mobile machinery, and these were reviewed where it was considered that they had potential to inform improvements to ISO 5006 [3].

This section summarises information pertaining to the evaluation of the operator's field of view, while more detail is provided in Appendix B. Information from the literature review pertaining to camera systems providing a surround view is described in Appendix F.

3.2 SUMMARY OF LITERATURE AND IMPLICATIONS FOR THE VISIBILITY RISK ZONES METHOD

3.2.1 Target evaluation methods

As a concept, the SAE J1750 Target Evaluation method [5] for evaluating the field of view from heavy trucks appears to offer a good balance in terms of scope, complexity and practicality. It focuses on visibility to all areas outside the vehicle boundary, and uses simple colour coding to display the approximate height that a target becomes visible to the operator when moved about a grid around the machine. The National Institute of Occupational Safety and Health (NIOSH) have described a similar target evaluation approach for construction machinery [4].

Robinson *et al* [6] point out that, before deciding where a person can been seen, users of target identification methods need to determine how much of a vulnerable person or object an operator needs to view in order to ensure timely and reliable detection, and how to represent this with a target or test object. In assessing the direct visibility performance of heavy good vehicles, they commented that just being able to see the top of a person's head may not be considered sufficient to attract the attention of the operator quickly and reliability. It is also not necessary to see the whole of a person in order to recognise them. However, they reported finding no scientific evidence that quantified the likelihood, speed or accuracy of recognition in relation to the proportion of the person in view.

In the absence of such information, target evaluation approaches are similar in suggesting two separate target heights:

- a maximum target height (in the region of 1.4 – 1.5 m) that would consider visibility to all but the smallest 1-5% of pedestrians; and
- a preferred target height (in the region of 0.9 – 1.0 m) that would allow visibility to all pedestrians, while also increasing the proportion of each person that can be seen and thereby potentially improve the speed and reliability of detection.

Such approaches are practical to apply as a manual test (using either a light source or human observer) or within software simulation. The literature describes how machine designers, suppliers of visibility aids, safety researchers, end-users and accident investigators could also all tailor the scope of the evaluation according to their particular purposes. The approach has also been advanced to take account of risk zones around heavy trucks [7].

3.2.2 Using simulation software to increase the scope of a field of view evaluation

Several authors describe their use of simulation software to conduct their evaluation of the field of view in three dimensions, either as spherical aperture projection [8], line of sight boxplots [9] or proportionate volumetric analysis [10]. They suggest that this is a more appropriate approach because many dynamic activities occur in the third dimension, for example the lifting of earth and construction material which, if done improperly, contributes to a large number of collision accidents. A common feature of these approaches, applied through software, is the ability to calculate the ratio of visible and masked areas on the surface of a three dimensional shape (sphere or rectangular solid, including the ground plane) that encloses the machine. This metric can then be used to make comparisons between machines, or to explore the optimal locations for cameras. In terms of informing risk assessment, they did not appear to take account of the machine's movement, or performance criterion related to the identification of pedestrians or other collision objects. However, it is conceivable that this information could be incorporated into the evaluation.

The concept of reporting the ratio of directly visible, indirectly visible and masked area was an interesting suggestion that could be possible on the ground plane, or for a specified target height, within the area of the visibility test circle. Any performance criteria for such a ratio would likely have to be specified according to the machine manufacturer, reflecting what was achievable at the time. However, as a supplementary approach, the requirement to provide this metric, or similarly differentiate between the area that is directly visible, indirectly visible and masked would allow the stated preference for direct visibility over indirect visibility to be reinforced through measurement. If included within a machine specification, such information could also help end-users to take account of the operator's field of view during machine selection, as they might do with other machine operating data.

3.2.3 Defining risk zones based on machine characteristics

The literature review could not find any previous examples where dynamic variables, such as speed, acceleration or manoeuvrability, were used to define the size and shape of the test area. However, for heavy trucks, the identification of risk zones has been suggested, as a risk-based approach to prioritise design improvements, compare different designs, and evaluate the performance of visibility aids [7]. In this case, the risk zones were simply rectangular in shape, with their size and location based on truck and road dimensions, rather than the detailed measurement of truck manoeuvrability. The risk zones were prioritised according to accident data and reports. Thus, a satisfactory compromise may be to define risk zones according to basic machine characteristics such as approximate working envelope, or the area into which the machine can travel.

3.2.4 Simulation of the operator's eye location

The lighting equipment and approach that ISO 5006 [3] applies to simulate the location of the operator's eye and movement of the head was found to be as complex as that used in any other manual methods to evaluate the field of view. The review of literature found that other methods typically applied a much simpler simulation of the operator's eye point; for example, using a monocular 'eye point' representing a small operator [5] [10]. This simplistic approach was considered sufficient to represent a 'worst case', where operators may not move their head or body much as they scan the field of view, or for the purposes of comparing the performance of different machine designs or visibility aids. Other methods, while not considering movement of the operator's eye location, did take account of differences in eye location between small and large operators with varying degrees of complexity [11] [12] [13]. Several occupant design packages, including software currently used in HSE's Science Division, also provide advanced human occupant simulation features to evaluate and problem-solve field of view issues early in the design process [14] [15] [16].

3.3 SUMMARY OF LITERATURE FOR CAMERA SYSTEMS PROVIDING A SURROUND VIEW

The search of published literature found only two papers about camera monitoring systems providing a surround view, which were also of limited value given that the technology was relatively new and evolving quickly. The most useful information was already contained within ISO 16001 [17] for object detection systems and visibility aids for earth-moving machinery. This contained some general requirements for visibility aids, some of which were applicable to camera systems providing a surround view, as well as an annex of additional performance requirements and tests specific for these camera systems. This is described in more detail in Section 13.1 (Appendix F) of this report.

During the course of this project, a further study [18] was identified which evaluated how factors such as pedestrian image size, screen size, and camera angle affect the detectability of a pedestrian by a driver using a single camera and screen system, which might be fitted to the rear and / or side of earth-moving machinery. This was a laboratory-based study in which 15 plant operators were shown a series of images, pre-recorded with three types of camera, on three different types of screens. The images were shown for 0.5 s, representative of a 'quick glance', and operators had to report if and where on the screen they had seen a pedestrian. The screen was positioned approximately 1 m away for the operator's eyes. The study design considered conventional single camera rather than camera monitoring systems providing a surround view. However, the researchers made several interesting observations and design recommendations, which were of wider relevance to the development of the visibility risk zones method.

- Moving pedestrians were detected with 100% reliability; errors in detection were only found for stationary pedestrians.
- Under optimum conditions, there were no detection errors when an apparent height of a pedestrian on the screen was 10 mm. However, the rate of non-detection did increase to

more than 25% when other variables related to the environment were taken into account (eg position of the pedestrian on the screen, pedestrian clothing, light pollution, and obstacles in the viewing environment). They recommend that, when defining the range of a camera-screen system, the height of a 5th percentile pedestrian (1.55 m in stature) on a screen should be a minimum of 10 mm.

- No pedestrians were detected on the screen when the height of their image was 2 mm.
- Screen size had little effect on the rate of detection, but the researchers suggested a tendency (non-significant) for smaller screen sizes to result in fewer detection errors, possibly because there is less screen surface area for the operator to scan. They suggested that the choice of screen size should more usefully take account of other factors such as space available within the cab and the extent to which the screen obstructs the operator's direct visibility.
- A pedestrian was seen four times less well at the edge of the screen than at its centre. Thus, when selecting a camera angle, the camera should cover an area that is broader than the surveillance zone, so as to avoid the edges of that zone coinciding with the edges of the screen. Once this criterion is satisfied, a camera should be chosen with the largest angle of view, which provided the lowest rates of detection errors.

The researchers also noted that, while operators recognised the risk of non-detection, they overestimated their performance. The majority of operators estimated their number of detection errors to be in the range of 51 – 100 (out of 340 images); however, the detection error was actually 140 on average.

4 DISCUSSION WITH MANUFACTURERS

This section of the report summarises discussions with several manufacturers of earth-moving machinery, which attempted to seek their views on the applicability and usefulness of ISO 5006 (2006) for evaluating the operator's field of view.

4.1 SUMMARY OF RESPONSES

4.1.1 Specification of user requirements for operator visibility

The responses received varied regarding how manufacturers specified operator visibility requirements, and the extent to which ISO 5006 met their own requirements for field of view evaluation.

One respondent described that they base their user requirements for field of view entirely on the ISO 5006 performance criteria. In contrast, another respondent expressed the view that ISO 5006 was just a 'tick-box' formality and of no practical use because their company standards for the operator's field of view were far more stringent.

Respondents described a range of other approaches used in practice to supplement ISO 5006 performance requirements, taking into account not only safety, but also machine performance and the desire to create a pleasant work environment / experience for the operator. The methods included:

- customer clinics;
- field testing and the collection of subjective operator feedback;
- competitor benchmarking;
- eye tracking studies to examine what operators are looking at during machine operation; and
- occupant accommodation studies, using operators (simulated and real) of various sizes.

4.1.2 How did manufacturers apply ISO 5006

All respondents reported applying the ISO 5006 test method within their design and simulation software, as this was the only way to know that there were no deficiencies in operator field of view before the first prototypes were built. The tests were applied once all machine components had been incorporated within the digital model, including hoses, lights and mirrors, and the design was 'frozen' prior to the build of a prototype. Informal checks of certain sectors of vision may also take place earlier where potential issues are flagged up.

One respondent reported that they still verified the results with a manual test on a physical prototype, to check the accuracy of their digital model, and mindful that slight changes to the body work during prototype build could have a significant effect on maskings at the test circle. The others reported that they had previously validated their simulations against manual test results, and were satisfied that their simulations provided sufficient accuracy.

4.1.3 Issues and barriers applying ISO 5006

For one manufacturer, the biggest issues were that the test method was not aligned to the use of the product, and did not reflect the different working configurations of the machine when the field of view was most restricted. They also commented that the test method did not reflect the working positions of operators. The ISO 5006 eye point reflected the 'average operator' according to ISO 3411, which was considered to be poor design practice and not protective, as smaller operators would suffer greater restrictions in their direct field of view. It also did not reflect the operator's eye location that they observed, with operators typically sitting in a more slumped position. The method also did not allow designers to take account of seat adjustment.

There were also issues with the structure of the ISO 5006 document, which their engineers found complicated to read and interpret. For example, the document mixes together descriptions of the test method and the performance criteria.

Respondents found it easy to apply the test method within simulation software, and reported no issues with this approach other than the need to ensure that the digital model is completely accurate and validated. They found the ISO 5006 method could be repeated easily within simulation software. They could easily load different attachments or machine configurations into the simulation, repeat the test for the relevant sectors of vision, and produce a single page extension to the technical file, showing any difference in the field of view.

Respondents described several barriers to applying the test method manually, including:

- having to wait until the machine is built;
- finding a large dark area suitable for testing;
- minimising the reflections of the light off cab windows, mirrors and other reflective surfaces; and,
- the practical issues of recording the locations of shadows / maskings in a generally dark environment.

4.1.4 Making decisions about visibility aids (eg mirrors, cameras) to fit to a machine

In general, respondents reported fitting mirrors as standard to meet the ISO 5006 performance criteria, and that ISO 5006 was useful for this purpose. Cameras and object detection systems were fitted as options to address specific risks on work sites.

Manufacturers used ISO 14401 and ISO 16001 to specify their requirements for visibility aids and object detection systems. The durability, reliability and performance of these were also assessed, for example through field testing.

4.2 SUMMARY OF VIEWS ON THE INITIAL CONCEPT OF A RISK-BASED APPROACH

Comments were also sought from manufacturers on the initial concept of replacing the visibility test circle with manoeuvrability-based risk zones, the size and shape of which would be based on a machine's characteristics such as its turning circle, acceleration from rest, and stopping performance.

Machine designers raised concerns about the added complexity involved in establishing the size and shape of the test area based on dynamic factors:

- The method would require manufacturers to establish separate test areas and conduct separate tests for each machine configuration (eg two / four / crab / track steering), if the test area were to be based on manoeuvrability, acceleration and braking performance. The existing visibility test circle was easily defined and geometrically simple to simulate, and this assisted field of view evaluation early in the design process.

- Many of the performance variables required to establish the precise size and shape of the risk-based zones are unknown, or cannot be fixed, until late in the design process. Thus, the field of view evaluation could not be completed until the machine design was almost at ‘final sign-off’. One manufacturer gave the example of a braking system that had to be redesigned at the last minute. This would have changed the performance criteria for the operator’s field of view at the very last moment, when scope to address the deficiencies would have been limited. Thus, the existing method, using software to plot maskings on a standard test circle (or area), would still be required for informal checks at earlier stages in the design process, prior to prototyping and endurance testing.

- Machine designers were concerned about how to standardise the dynamic factors such as acceleration from rest and braking performance, which could vary significantly with different operators, worksite, load, and weather conditions. Work would be needed to establish the ‘worst case scenario’; for example, to compare the acceleration of an empty machine to the braking performance of a fully loaded machine. New standardised tests may need to be developed and agreed to feed into ISO 5006.

Machine designers viewed the visibility test circle as a strength of ISO 5006, because it was easy to define and allowed different machine configurations and attachments to be evaluated quickly and easily within the simulation software.

One manufacturer questioned whether the additional effort to define the test area, based on a set of assumptions, would be proportionate to the benefit actually provided to end-users. They felt that there were other more significant limitations with the ISO 5006 method that deserved attention, as they could be addressed more easily and would provide a greater benefit to end users. These limitations included:

- the lack of field of view evaluation between the rectangular boundary and the visibility test circle;
- the exclusion of working and loaded machine configurations; and
- differences between the position of the light bulb filaments and the actual eye points of small operators.

They believed that companies using the machines, and given sufficient information about the visibility maskings, were better placed to identify the risk zones, as they could take account of local job site factors such as where the machines needed to operate on site, speed restrictions, surface and weather conditions, and other site rules to segregate people and smaller vehicles from the operating machines.

5 DEVELOPING THE METHOD TO IDENTIFY AND EVALUATE VISIBILITY RISK ZONES

This section provides an overview of the method, summarises the activities undertaken in the course of its development, and discusses some of outstanding issues.

The test method is described in more detail in Appendix E, and also includes a summary of results for the rigid frame dumper truck and excavator evaluated as part of the development work. Supplementary reports are also available describing these applications of the test method in more detail:

- RR1157 – Application of a risk-based method to evaluate operator visibility from an hydraulic excavator [19]; and
- RR1158 – Application of a risk-based method to evaluate operator visibility from a large rigid frame dumper truck [20].

5.1 OVERVIEW OF THE METHOD

The method describes an approach for conducting a risk-based evaluation of the operator's field of view from earth-moving machinery. It can be used to inform a risk assessment to define the areas around the machine that the operator needs to view and the areas where visibility aids are required.

This method is intended for those with a role in ensuring that the areas around the machine where the operator cannot see are recorded, prioritised, and the residual risks are managed. This may include those involved in the evaluation and verification of machines, the installation of visibility aids and object detection systems, the organisation of the jobsite to ensure a safe working environment, and the investigation of incidents involving such machines.

The method describes the use of observers sitting in the operator position. The intention was to develop a manual method that could appeal to the broadest range of users and ensure that the method was not dependent upon particular technologies. However, it could also be applied through the simulation of an operator within software, or with a light source apparatus at the operator position, provided that the method provides a valid simulation of the size, position and movement of machine operators. In this way, rather than serve as a replacement of ISO 5006 [3], which is limited to the scope of machine design, it can be viewed as a framework on which to base improvements.

The test method involved the following sequence of steps.

1. Identify the machine configurations within scope of the evaluation.
2. Identify and record the collision risk area, taking into consideration the areas into which the machine can move during operation and travel.
3. Identify and record the maskings (ie areas where operator visibility is obstructed).
4. Evaluate the visibility risk zones for direct visibility, achieved by merging a plot of the maskings onto a plot of the collision risk areas.
5. Incorporate indirect visibility (ie with the use of mirrors or camera monitoring systems) into the evaluation of the visibility risk zones.

For the measurement of maskings, the procedure evaluates the operator's visibility to ground level, which allows a baseline recording of the area that the operator can and cannot see around the machine. It also evaluates visibility of a vertical test object, 1.5 m in height. This height is representative of a standing person of small stature and is also equivalent to the shoulder height of a person medium / average stature [21]. However, for informative purposes, or risk assessment of a specific work environment, the height of the vertical test object can be reduced to 1.0 m to represent either a crouching person, or to record where a greater proportion of a person may be visible, possibly allowing the operator the opportunity for more reliable or timely detection.

Evaluating the visibility risk zones then prioritises the areas around the machine according to whether there is a risk of collision as well as whether the operator has direct visibility to the area, visibility only when using visibility aids, or obstructed visibility (Figure 2).

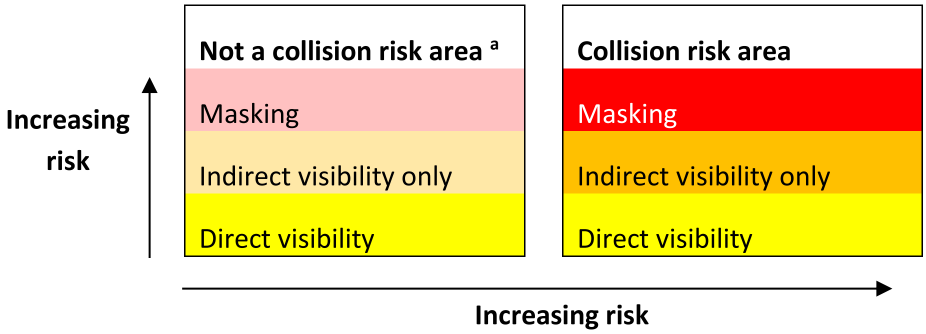


Figure 2 Classification of the visibility risk zones

This recognises the importance of also identifying maskings that are present outside a collision risk area, as they may contribute to reducing the operator's situational and hazard awareness even if the machine cannot quickly move into those areas. It is also identifies the areas that are only visible to the operator with the use of visibility aids. For these locations, operator visibility relies upon the performance of the visibility aids and measures such as proper adjustment, cleaning and maintenance that the end-user needs to ensure are in place so that the performance of the visibility aids does not degrade.

After incorporating indirect visibility into the evaluation, from a risk-based perspective based on ergonomics principles, there should be no maskings of the 1.5 m vertical test object that exceed a maximum width of 200 mm within the collision risk areas. The 200 mm maximum masking width represents where the operator may not see a sufficient amount of the pedestrian to recognise them as a person. At best, this represents half the width of a whole person, although it could also be a segment of the person, provided that the observer(s) deem that a sufficient amount to the person is visible for reliable recognition of a person at the location.

There are no specific requirements for the size or proportion of the test surface that can only be viewed with indirect visibility. Requirements are also not specified for areas where the machine cannot move or for maskings under more onerous test conditions (eg maskings of a 1.0 m vertical test object, or maskings at ground level). However, whenever possible, measures should be taken to minimise maskings to improve the operator's situational and hazard awareness. When designing for visibility, direct visibility is preferred. It is also suggested that the operator's manual should include diagrams to describe the visibility risk zones around the machine, including those at ground level, in addition to recommending that appropriate jobsite organisation is required for the safe use of the machine.

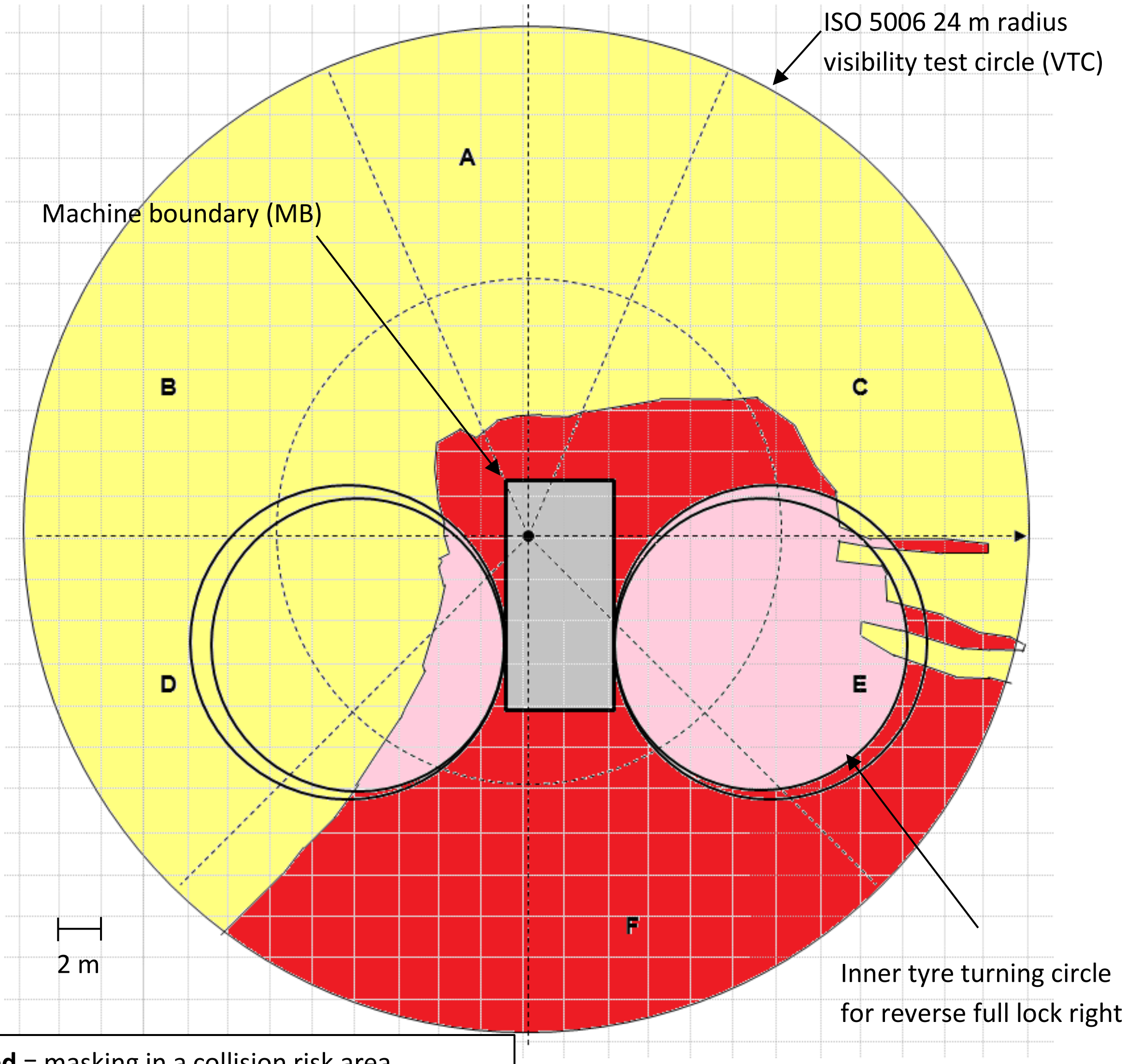
5.2 APPLICATION OF THE VISIBILITY RISK ZONES METHOD TO A LARGE RIGID FRAME DUMPER

The test method was first applied to the evaluation of a large rigid frame dumper truck (empty operating mass of 64,000 kg) used in surface mining [20]. The purpose of this evaluation was to trial the method, consider its validity and usability for large trucks, and inform further development of the method. Within Great Britain, the field of view from larger dumper trucks was of particular interest, following the death of two workers at a surface mine, which occurred when a large rigid frame dumper truck turned right from a parked position and collided with a Land Rover that was located within a masking area [22]. This accident raised questions about the suitability of ISO 5006 for this type of machinery, and whether improvements in the Standard would have led to the fitting of an additional camera system to improve the operator's indirect visibility to the right side of the dumper.

The visibility risk zones method defined the test locations according to the manoeuvrability of the machine. The inner tyre turning circles, measured at full steering lock, were used to define the collision risk areas into which the dumper truck could travel.

This trial confirmed that the identification evaluation of visibility risk zones was a useful concept to apply when evaluating the operator's field of view from a large rigid frame dumper. This example also demonstrated the limitations of the current approach in ISO 5006, which only considers maskings along a visibility test circle, 12 or 24 m away from the operator's position, and a rectangular boundary, 1 m away from the machine. For example, the visibility risk zones method recorded large maskings in an area to the right side of the machine (within sector C); however, applying the ISO 5006 approach at a distance of 24 m from the operator's position would allow the recording of no maskings for this sector (Figure 3).

This highlighted that where maskings are caused by structures located below the operator's eye position, such as the front body of the dumper truck, evaluating the operator's field of view over the whole area of the test surface is necessary to record the true shape and size of the areas of restricted visibility. This approach would then better inform the selection and positioning of visibility aids and record any residual risks. The visibility risk zones method suggested that slight adjustments to the position of some visibility aids would result in improved coverage to some areas around the machine.



Red = masking in a collision risk area
Pink = masking outside a collision risk area
Yellow = area of direct visibility (no masking)

Figure 3 Visibility risk zones for direct visibility to ground level for the rigid frame dumper truck. There are large areas of masking within sector C, although this would not be recorded at the 24 m visibility circle test location specified in ISO 5006. **(Direct_Visibility_Ground_ISO)**

5.3 APPLICATION OF THE VISIBILITY RISK ZONES METHOD TO AN EXCAVATOR

Following the trial of the dumper truck, the test method was trialled with a medium sized (14,200 kg operating mass) hydraulic excavator [19]. This machine type was chosen due to several fatal accidents in Great Britain in which excavators have struck workers who were positioned to the rear or right side of the excavator. Some excavators can have relatively large blind spots, with up to about 50% of the operator's direct visibility to the field of view obscured by the body of the machine and the boom. Mirrors and cameras are fitted to improve the operator's field of view and comply with visibility performance requirements specified in ISO 5006 [3]. However, the test method described in ISO 5006 for evaluating the operator's field of view is limited in scope for excavators and was not considered to reflect the hazards of these machines in operation. The selected machine also offered an opportunity to evaluate the performance, advantages and limitations of a surround view camera system that was fitted to the excavator in relation to the manoeuvrability of the excavator. The main findings in relation to the camera system are described in Section 13.6 (Appendix F) of this report.

Identifying and evaluating the visibility risk zones was a useful concept to apply when evaluating the operator's field of view from a medium-size excavator. In this case, the method defined the test locations according to the working envelope of the machine, taking account of the area where the rear body can swing and the area where there was the potential for the bucket to slew during travel (in its travelling position) and work. The maximum reach of the bucket defined the boundary of the area where the machine could move most quickly and the primary areas where the operator needed to view in order to identify hazards and avoid collisions.

The method identified that, with the use of the mirrors and a rear view camera fitted during manufacture (ie without using the surround-view system), maskings were present at the rear corners and to the right side of the excavator. These maskings were within collision risk areas defined by the swing of the excavator's rear body and potential swing of the bucket during operation. The process of overlaying maskings and areas of mirror coverage onto a plot of the collision risk areas was also helpful in examining the impact that certain machine configurations had on the operator's field of view, such as the potential for the boom, when it is raised back, to obstruct the operator's view to the right side mirrors.

5.4 FURTHER CONSULTATION

In additional to seeking feedback from manufacturers on the initial concept of a manoeuvrability-based approach (see Section 4.2), further feedback was sought during the project through presentation and participation at:

- a meeting of ISO TC 127 / SC 1/ WG 5 in June 2016, at which initial findings were shared when the method was applied to the large rigid frame dumper truck; and
- project steering meetings involving members of ISO/TC 127/SC 1/WG 5 who were primarily based in the UK and had an interest in visibility from large machinery.

5.5 LIMITATIONS OF THE APPROACH AND ASPECTS OF THE METHOD TO DEVELOP FURTHER

This project has brought attention to some underlying issues associated with evaluating the operator's field of view from earth-moving and other machinery, some of which could not be resolved within the scope of the project.

5.5.1 Factors included in the manoeuvrability-based approach

When considering which machine characteristics to include in a manoeuvrability-based evaluation of the field of view, initial discussion centred on whether and how to incorporate acceleration from rest, maximum travelling speed, steering, and stopping performance, as well as take account of the speed at which pedestrians and other vehicles may approach the machine, and the hazard detection time of operators for direct visibility or use of visibility aids. However, the suggestion of machine designers, and confirmed during trials of the method, was that the effort of trying to standardise and record these factors, while also accounting for variation in local site conditions, would outweigh benefit from their inclusion in the method. Further, the methods and technologies required to collect this information would also make the method impractical for many users who may have a role in evaluating the field of view from machines. In practice, the machine configurations and steering characteristics / working envelopes of the machine served as a sufficient indicator of the collision risk areas and helped to decide a suitable boundary for the field of view evaluation. For the rigid frame dumper truck and excavator that were evaluated in this project, the ISO 5006 [3] 24 m and 12 m visibility test circles respectively served as appropriate boundaries for the test area. Where cab pillars and other vertical structures (ie those extending above the operator's sitting eye height) may obstruct visibility further away, the geometrically simple shape and area typical of these maskings can be extrapolated beyond the test area boundary with reasonable confidence.

5.5.2 Proportionality

While the work was focussed on developing a method for evaluating the field of view from earth-moving machinery that was large and / or had maskings of more complex geometry, in principle, it is thought that the approach would be applicable to earth-moving machinery of all types and sizes, as well as other mobile plant.

Some questions were raised as to whether the effort of undertaking the visibility risk zones approach may be disproportionate to the risks that restricted visibility actually posed for small earth-moving machines. The development of an initial screening test was considered as a way to filter out small earth-moving machines where visibility from the operator's position was not expected to be restricted; for example, a test of direct visibility along the machine boundary. However, as it was not possible to apply the visibility risk zones method across all types and sizes of earth-moving machinery, this route was not pursued. There was concern that applying such a screening approach to machines with larger or more complex geometry may lead users to assume falsely that a check for restricted visibility at one distance from the machine was representative of the area all around the machine. This was a shortcoming identified with the current ISO 5006 approach. Where machines are smaller, have more simple geometry, and have fewer machine configurations / functions and visibility aids, the time and effort to apply the visibility risk zones method will be reduced. However, the suitability of the visibility risk zones approach for smaller machines is an area that could be examined further.

5.5.3 Simulation of the operator's eye point

The review of literature found that other methods can apply a much simpler simulation of the operator's eye point; for example, using a monocular 'eye point' representing a small operator [5]. These simplistic approaches were considered sufficient to represent a 'worst case', where operators may not move their head or body much as they scan the field of view, or for the purposes of comparing the performance of different machine designs or visibility aids. On the other hand, the light source apparatus produces a more favourable output, as it is apparently based on 50th percentile operator dimensions, and establishes the line of sight or 'opportunity' to see when applying an active visual search strategy. While the ISO 5006 test method remains to determine the absolute maskings and evaluate these against performance criteria, it is important to include a realistic and reasonable amount of operator movements so that the masked areas are not exaggerated. Otherwise, this may lead to an unnecessary number of visibility aids being fitted to machines.

Another reason for presenting an observer-based method was to do with shortcomings in the ability of the ISO 5006 light source apparatus, which assumes a 360° radius of viewing at a fixed height. Some improvements could be made to the existing light source apparatus, in order to better reflect ergonomics knowledge and principles. These include:

- reducing the height of the filament position centre point (FPCP) to represent a smaller operator sitting in a relaxed working posture [21];
- simplifying the derivation of the FPCP, avoiding the use of the seat index point device; and
- considering the use of an angled light bar that reduces the height of the light sources when positioned further away from the filament position centre point.

However, there remains a need to appraise the positioning of operators' eye locations and head / body movements during the typical operation of earth-moving machinery.

Discussions with manufacturers confirmed that the ISO 5006 tests are largely carried out within simulation software. One advantage of simulation software is that it allows machine designers to upload different machine designs or attachments, and repeat the evaluation relatively quickly for the relevant sectors of vision. In this way, it may also be possible to upload different light source apparatus, to simulate the location of the operator's eyes in a way that could take better account of how operators actually scan the different sectors of vision at the machine boundary and further away. However, in practice, during the design process, field of view evaluation has already moved to a digital platform for the most part. Several occupant design packages are available that provide advanced human occupant simulation features to evaluate and problem-solve field or view issues early in the design process. The extent to which field of view evaluation will be able to take account of operator movement will depend on the human simulation features, the accuracy of the digital models, and the skill of the analyst.

5.5.4 Defining when a pedestrian or representative target is 'in view'

As well as identifying where a person can been seen, target identification methods also need to specify how much of a person or object an operator needs to view in order to ensure timely and reliable detection, and how best to represent this with a target or test object. For example, assessing the direct visibility performance of heavy good vehicles (HGVs), Robinson *et al* [6] noted that just being able to see the top of a person's head may not be considered sufficient to draw the attention of the operator quickly and reliability. It is also not necessary to see the whole of a person in order to recognise them. However, they reported finding no scientific evidence that quantified the likelihood, speed or accuracy of recognition in relation to the proportion of the person in view. The issue of how much of a person needs to be visible in order to be recognisable is not limited to questions about the height of the target representing a person, but also the proportion of a person's body width or other body segments in view, either directly or within the camera monitor. For example:

- is it sufficient for a person's arm to be only in view?

- is it sufficient for a person's legs to be only in view (eg beneath the boom of an excavator)?

For earth-moving machinery, several standards and methods are required to evaluate different elements contributing to the operator's field of view and opportunity to monitor the work environment. These elements include requirements for surveillance mirrors (ISO 14401 [23]), object detection systems and camera monitoring systems (ISO 16001 [17]), as well as the overall evaluation of the operator's field of view (ISO 5006 [3]). These employ different test objects and criteria for judging when the target should be identified as 'in view', 'out of view' or within range of the system. Inconsistencies are apparent, while the extent to which these approaches are based on ergonomics principles and scientific evidence is unclear. The visibility risk zones approach has tried to apply a consistent approach in its consideration of when the test object is considered 'in view'. This has taken account of current and draft standards as well as one study of the reliability of operators to detect pedestrians within camera monitoring systems [18]. The method provides some consistency in the criteria for direct visibility and when using mirrors and camera monitoring systems. This includes criteria for the size (height and width) of the image of the test object / person in the visibility aid. However, these issues would benefit from further scientific investigation. The two machines evaluated as part of this project also highlighted a need to:

- clarify the minimum size of the image of a pedestrian that an operator can reliably detect in mirrors positioned at various distances away from the operator; and
- explore the most practical method of measuring the image size on a mirror or monitor.

However, in reality, the likelihood, speed and accuracy of an operator recognising a pedestrian will be influenced by many factors that characterise the pedestrian, operator, visibility aids, the machine and its operation, as well as the organisation of the work and the job site (Table 1).

Table 1 Factors affecting the likelihood of a machine operator detecting a pedestrian

Pedestrian	Movement, posture, location, clothing, and PPE, physical characteristics, training, experience
Machine operator	Expectation / general awareness of persons and objects nearby, training, experience, competence, attention, fatigue, attitude, motivation
Machine design	Field of view, number of visibility aids fitted, access to visibility aids, availability of other object detection systems (warning lights and alarms)
Visibility aids	Coverage, position relative to the operator, image distortion, resistance to glare, ease of access and adjustment, cleanliness, maintenance, relevance to the operator's task / machine operation
Work organisation	Presence of signallers, time available for detection, weather and jobsite conditions, lighting levels, communication between the machine operator and other workers, work pressures
Job site organisation	Extent of segregation between machinery and workers / smaller vehicles, site layout, space, site safety rules in relation to machinery operation, supervision, and control of work

6 CONCLUSIONS

The visibility risk zones method was developed for conducting a risk-based evaluation of the operator's field of view from earth-moving machinery taking account of the machine's configurations and its manoeuvrability during operation and travel. This can be used to inform a risk assessment and define the areas around the machine that the operator needs to view, and the areas where visibility aids are required. The method involves the following stages.

1. Identify the machine configurations within scope of the evaluation.
2. Identify and record the collision risk area, taking into consideration the areas into which the machine can move quickly during operation and travel.
3. Identify and record the maskings (ie areas where operator visibility is obstructed).
4. Evaluate the visibility risk zones for direct visibility, achieved by merging a plot of the maskings onto a plot of the collision risk areas.
5. Incorporate indirect visibility (ie with the use of mirrors or camera monitoring systems) into the evaluation of the visibility risk zones.

Evaluating the visibility risk zones then prioritises the areas around the machine according to whether there is a risk of collision, as well as whether the operator has direct visibility to the area, visibility only when using visibility aids, or obstructed visibility.

This method is intended for those with a role in ensuring that the areas around the machine where the operator cannot see are recorded, prioritised, and the residual risks are managed. This may include those involved in the evaluation and verification of machines, the installation of visibility aids and object detection systems, the organisation of the jobsite to ensure a safe working environment, and the investigation of incidents involving such machines.

A review of literature on field of view evaluation, engagement with machine manufacturers, and an appraisal of ISO 5006 were undertaken to inform development of the method. The method has also been trialled on a large rigid frame dumper and a medium-sized excavator, which demonstrated that the identification and evaluation of visibility risk zones was a useful concept to apply. The trials also demonstrated the limitations of the current approach in ISO 5006.

Camera systems providing a surround view were found to be useful supplements to the range of visibility aids available, with good potential to compensate for the lack of direct visibility or, for some applications, where there may be limitations in the effectiveness and coverage of mirrors and single camera systems.

The strength of the surround-view camera systems is their ability to provide information quickly regarding the presence or absence of pedestrians all around and close to the machine in a single screen location. However, for systems observed as part of this work, there was a trade-off in that they did not display the far field of view out to the horizon, which may also be important for the operator to maintain greater situational awareness. Installation and configuration of the systems also appears critical in ensuring that there are no gaps in coverage and that the systems provide the level of performance expected of them. The selection of camera systems must take account of the machine's characteristics, and what the operator needs to see for safe machine operation in its intended operating environment.

This report draws together requirements applicable to camera systems providing a surround view, while the visibility risk zones method described can also be used to evaluate the extent to which these systems provide acceptable coverage within the collision risk areas around machinery.

Significant improvements in the performance of camera systems providing a surround view is likely to come through their integration with other technologies, allowing the strengths of these technologies to compensate for limitations associated with systems that are reliant on operator vision for reliable detection.

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8 APPENDIX A – LITERATURE SEARCH STRATEGY

The HSE Information Services Search Team conducted two separate systematic searches of the OSH-ROM, OSH UPDATE, Ergonomics Abstracts, Web of Science, Science Direct, HIS, ANTE, Compendex, MTEA, NTIS, HEAL SAFE, Conference Papers Index, ProQuest Dissertations, TRIS and HSE e-Library databases.

The searches were restricted to literature published between 2005 and 2015.

The first search focussed on methods for evaluating driver or operator visibility, using the following search strategy:

- motorcar* OR car* OR automobile* OR automotive OR vehicle* OR bus* OR coach* OR truck* OR wagon* OR lorr* OR “low loader” OR “military vehicle*” OR tank* OR “armoured personnel carrier*” OR “combat vehicle* OR “troop carrier*” OR “armoured car*”

AND

- (Driver* OR operator* OR field or obstruct*) NEAR (vision OR visibilit* OR view*)

AND

- Assess* OR measur* OR analys* OR evaluat* OR estimat* OR determin* or method*

The second search focussed on visibility aids, using the following search strategy:

- motorcar* OR car* OR automobile* OR automotive OR vehicle* OR bus* OR coach* OR truck* OR wagon* OR lorr* OR “low loader” OR “military vehicle*” OR tank* OR “armoured personnel carrier*” OR “combat vehicle* OR “troop carrier*” OR “armoured car*”

AND

- (Visibil* OR vision OR view*) NEAR (aid* OR system* OR camera* OR equipment OR “birds*eye” OR mirror)

9 APPENDIX B – LITERATURE REVIEW FINDINGS

This section describes relevant papers identified during the search and review of literature. For the most part, the focus of this review has been on the methodologies applied to evaluate the driver / operator's field of view, rather than the particular outcomes of the research. The review is narrative and has been structured into the following categories:

- target evaluation methods;
- human simulation methods;
- light bulb methods;
- laser scanning methods;
- studies comparing different methods;
- simulation of the operator's eye point; and
- the study of head and eye movements in visibility evaluation.

9.1 TARGET EVALUATION METHODS

9.1.1 SAE J1750 (2010) Describing and evaluating the truck driver's viewing environment [5]

This SAE Recommended Practice establishes three alternate methods for describing and evaluating the truck driver's viewing environment:

1. target evaluation;
2. the polar plot; and
3. the horizontal planar projection.

This review will focus on target evaluation, as the preferred method in SAE J1750 [5]. The method can be used to evaluate both direct and indirect visibility; however, it cautions that additional work is necessary to specify requirements that appropriately consider valid image representation for cameras and monitors (eg image clarity, sharpness, distortion, size). Target Evaluation can be conducted in a geometrically accurate 3D simulated environment or manually with appropriate physical layouts around an actual vehicle.

The standard target is a cylinder, 1.2 m in height, and 0.4 m in diameter. It has three stacked sections, colour coded from top to bottom as red, amber and green. The field of view zone (or test area) is rectangular, and based on multiples of "L", which represents the standard road lane width in the USA (12 feet or 3.658 m). Within the field of view zones, the evaluation test is carried out on a 0.485 m x 0.485 m (1.5 ft x 1.5 ft) grid pattern around the vehicle. This grid pattern represents the volume occupied by a standing pedestrian, although it is possible to use a finer grid to produce smoother measures of the effects of vehicle geometry and to reduce the likelihood of missing a potentially important design feature [7].

The target evaluation method uses a single fixed cyclopean eye point, as a simplified model for representative purposes. This would be sufficient where the goal is to produce a relative measure to compare across different vehicle designs [7]. However, for studies that require a more refined eye point location, better reflecting ergonomics factors, the method refers to SAE J1050 *Describing and Measuring the Driver's Field of View* [24].

Manual application of the target evaluation method (or similar approaches)

Ferrone *et al* [25] point out that the time to set up the test can be significantly reduced by marking a pre-set grid pattern on a white tarpaulin, to serve as a mobile coordinate plane which can be moved around the vehicle during the evaluation. The measurement spacing can be tailored to the complexity of the obstruction causing the maskings to visibility. The portability of the grid permits the field of view assessment to be performed on a variety of terrains, including sloping and contoured terrain that might be relevant to an accident investigation on a construction or mining site. In this case, a surveyor is also required to determine the topographical position of the measurement points.

Instead of the SAE J1750 vision evaluation target, Ferrone *et al* [25] suggest using a level staff as the target object. The person sitting in the driver's seat then records the value that they observe on the level staff at each position. The numerical data is converted into a graphical format showing the spatial field of vision around the vehicle.

Determining the fraction of the population visible at the view height

Rather than display the direct view heights at each sampling point on the grid, Reed *et al* [7] suggest it would be more helpful to show the fraction of the pedestrian population visible at each sampling point. This can be calculated and then displayed as a vertical line where 1 m tall indicates that the population is fully obscured at that sampling point, and no vertical line indicates that the population is fully visible.

Calculating an aggregate obscuration score

Reed *et al* [7] have also proposed further steps to score the design of a heavy truck. This approach involves multiplying the fraction of the pedestrian population obscured by the plan-view area represented by each sample point, and summing across the sample points. A lower score indicates a better design with less obscuration. This approach may be desirable when comparing across different vehicle designs, or when evaluating alternative mirror or camera based systems.

Developing critical vision and risk zones

Reed *et al* [7] have also developed critical vision zones around heavy trucks, based on crash and driver performance data contained within the Trucks Involved in Fatal Accidents (TIFA) database and the National Automotive Sampling System General Estimates System (NASS GES):

The Trucks Involved in Fatal Accidents (TIFA) was a database of medium and heavy trucks involved in fatal accidents, compiled by the University of Michigan Transport Research Institute. It includes information on the relative position and movement of the vehicles prior to the crash, as well as supplemental information obtained from police reports, including (where reported):

- the position and movement of the other vehicle, pedestrian, or bicyclist with respect to the truck the position of the other party three to five seconds prior to the collision;
- the position at the decision point for the truck, that is, at the point where the truck driver initiated the manoeuvre;
- the location of contact, and the point of contact on the truck; and

- the use of mirrors prior to the crash (although they note that the use of mirrors was mentioned in only 10 of 160 cases reviewed and in none did the truck driver report seeing the other party in the mirror prior to the collision).

The National Automotive Sampling System General Estimates System (NASS GES) database was compiled by the US National Highway Traffic Safety Administration. This was used to cover non-fatal truck accidents. From this, three crash types were identified:

- start-up crashes, in which the truck starts from a stopped positions and strikes a non-motorist;
- right-turn crashes, in which the truck collides with a non-motorist while making a right turn; and
- lane-change / merge-right, crashes in which the truck collides with another vehicle while merging or changing lanes to the right.

For each crash type, the truck driver initiated the manoeuvre that leads to the crash.

The risk zones are geometrically simple, and based on road and vehicle dimensions. The risk zones can be incorporated into the aggregate obscuration score to make it more risk-based, for example, by assigning a greater weight to the obscuration scores at sampling points in the highest priority zones.

Reed *et al* [7] suggest that this method could also apply to the evaluation of indirect vision, so that these could be incorporated into the aggregate obscuration score for a vehicle. Since viewing an area with a mirror is less desirable than a direct view of the area, they suggest it would be possible to ‘penalise’ mirrors when evaluating designs. The penalty should be related to the performance of people using the mirror system to detect targets of interest, such as pedestrians or smaller vehicles, and would likely be a function of mirror curvature, the distance between the driver and mirror, size of the mirror, and perhaps even the weather conditions affecting the vehicle’s intended use. For example, through a pilot study, they found that truck drivers took approximately twice as long to detect a vehicle directly to the right of the cab using a convex mirror as they did on the left side using predominately direct vision. Thus, as a starting point, they suggest that vision near the cab using a convex mirror should be discounted 50% relative to direct vision.

The aggregate obscuration score could also be used to evaluate the potential benefits of different visibility aids, and for comparing alternative camera locations and display characteristics. However, this would rely on an appropriate performance-based scoring system to account for the differences in the quality of the field of view at each sampling point; for example, so that distortion and ‘minification’ of the target is penalised accordingly.

9.1.2 NIOSH manual method for creating blind area diagrams

The National Institute of Occupational Safety and Health (NIOSH) has published a manual method for creating blind area diagrams [4]. These are described as a low-tech alternative, which construction companies, labour unions, and training organisations can use to better understand the blind areas around their own equipment, without the need to locate the seat index point, mount light filaments, or produce computer design drawings. Using a surveyor’s transit, a polar grid is marked out on a test site using stakes, spray paint or paint stick markers. The polar grid consists of 16 m long lines radiating from the centre of the grid at 10° intervals, and a series of concentric circles, centred on the grid at 2 m intervals.

This is an observer-based method, using an average sized driver (1715 mm in stature) seated in the operator position to give feedback regarding what can and cannot be seen. The mirrors and operator's seat position are adjusted in accordance with the operator's manual. The test stipulates that the driver remain seated in the cab in a normal driving posture, keeping their body as still as possible in the seat. The driver may turn his/her head and torso, but not beyond what would be considered a normal driving posture, and may not lean out any windows. The driver may use any mirrors that are standard for that piece of equipment. The test recorder on the ground starts at the 0° line, as close to the machine as possible, and walks along the line and away from the machine until they receive a signal from the operator that their shoes are visible. The recorder then uses a level rod or pointing device to determine the exact location where the driver can see the ground, and marks this position on the ground. This is repeated for each degree line around the machine. Where a blind area fans out to infinity, the process can be shortened by simply marking the blind area at the outermost circle. After the initial test, the blind areas can be better defined by taking measurements at intermediate points between the markers where necessary. A similar procedure is then used to mark out the areas visible in the mirrors. Where after-market mirrors are fitted, the areas visible in these mirrors can be recorded, but should be noted as such.

The test can also be repeated for visibility of the level rod to a height of 900 mm to represent a construction barrel, or 1500 mm to represent a pedestrian.

This sort of approach would more naturally lend itself to the assessment of excavators in working mode. NIOSH has also published blind area maps for 43 different machines and vehicles used for construction in 2002 [4]. These were produced through computer simulation under contract to Caterpillar Inc.

9.1.3 Determining what an operator 'needs to be see' to reliably detect a vulnerable person

As well as considering where it is important to see, an important characteristic of target identification methods is the need to determine how much of a person an operator needs to view in order to ensure timely and reliable detection. Assessing the direct visibility performance of heavy good vehicles (HGVs), Robinson *et al* [6] noted that just being able to see the top of a person's head or cyclist's helmet may not be considered sufficient to attract the attention of the operator quickly and reliability. It is also not necessary to see the whole of a person in order to recognise them. However, they reported finding no scientific evidence that quantified the likelihood, speed or accuracy of recognition. Consequently, they selected a target height of 1.41 m, representative of 5^{th} percentile female stature, which would allow about 95% of vulnerable road users (pedestrians and cyclists) to be seen to some extent, although only the tallest 5% would be visible to a level at the centre of the chest or below. Direct visibility of a lower zone, defined as being between 0.93 m (corresponding to the waist height of a 5th percentile female) and 1.41 m, would allow visibility of the smallest 5% of the population, as well as increase the proportion of each taller person that can be seen, thereby potentially improving the speed and reliability with which they can be detected by the machine operator.

9.2 APPLICATION OF HUMAN SIMULATION SOFTWARE

The literature review found several papers describing the use of simulation software to evaluate the field of view from different types of vehicle. Each study applied a different method to evaluate the operator's field of view.

The benefit of using human simulation software is it allows for the accurate positioning of the virtual human in order to simulate more realistic operator postures and movement strategies, compared to laser scanners, panoramic cameras and light filaments that assume a 360° radius of viewing at a fixed height. More realistic targets can also be modelled for the field of view evaluation.

Discussions with manufacturers, described in Section 4 revealed that some have also used human simulation software to investigate specific operator accommodation issues. This included issues such as the potential impact of an obstruction to operator field of view. They had found that human simulation software available to them at the time was unreliable when used to apply the ISO 5006 test method. More stable software platforms were preferred for carrying out the ISO 5006 test method in full.

9.2.1 Aperture projections

Summerskill *et al* [8] used the SAMMIE digital human modelling system to evaluate the direct vision afforded to drivers of Category N3 vehicles (ie HGVs), and compared this to several design iterations of a concept vehicle. The concept vehicle was designed to explore the potential for additional vehicle length allowances to be exploited for improved aerodynamics and fuel efficiency. This study explored opportunities for design change to improve the drivers' direct vision. The field of view was evaluated with aperture projections. This involved the projection of the visible volume of space from the eye point of the driver through the apertures (windows) of the vehicle. Anything inside the projection was considered as seen directly by the driver.

Summerskill *et al* [8] have also identified the need for further research to identify how drivers interact with the six mirrors fitted to N3 vehicles, and if the requirement to examine six mirrors to obtain situational awareness is actually achievable in high workload situations.

Within simulation software, Ball *et al* [26] describe how they have combined aperture projections for a heavy goods vehicle (HGV) with video recorded from the driving position and outside the vehicle during a reconstruction to show the dynamic aspects of an accident sequence. This was to understand where, and for how long, the smaller vehicle would have been within the HGV driver's direct and indirect field of view as it carried out an overtaking manoeuvre.

9.2.2 The line of sight boxplot method

Godwin and Eger [9] used human simulation software (JACK v4.1 [16]) to evaluate the line of sight available to the operator of a medium-sized load haul dump (LHD) mining vehicle, examine the impact of design modifications, and test three camera locations for their ability to improve vision to the masking areas. The approach also used aperture projections. However, the test area was a cuboid box: 10m wide, 20m long and 4.5m high, and was divided into 11 separate panels for analysis. The simulated human was a 50th percentile male (for height and weight) positioned in the cabin seat with hands and feet positioned on the controls. A series of progressive head and truck rotations were applied to the human to evaluate line of sight to the side and behind the operator. These were based on observed motions of LHD operators. The position of the aperture projections on each panel were shown visually, and as a quantitative measure, the percentage of the area visible on each panel was measured.

9.2.3 Field of view sampling

Chang *et al* [27]used SAMMIE computer simulation software [15] to evaluate the field of view of young farm tractor operators. They evaluated 42 different farm tractors in popular use in the USA, and used photogrammetry software to create digital models of each tractor. To simulate young tractor operators, they used US child anthropometry data to create digital models of boys and girls, aged 12, 14 and 16 years, and with 5th, 50th, and 95th percentile body sizes.

Virtual 2 m high vertical bars, with 5 cm increments, were placed around the digital tractor mock-ups every 30° to form a semi-circle in front of the operator. Additional layers of semicircles were added at 1 metre intervals from the operator, extending up to 5 m away from the operator and 10 m directly in front of the operator. Through the software's Human View mode, the field of view for each digital human was sampled, by counting the number of increments that were visible on each bar.

This method of sampling the field of view for a wide range of young operators and tractors was selected to provide an overview of the issues. The researchers discounted the ISO 5721 [28] test method as too complicated and not feasible for the large number of young operators and vehicles included in the study.

9.3 LIGHT SOURCE SHADOW TEST METHODS

9.3.1 BS EN 15830 Rough terrain variable reach trucks – Visibility –Test methods and verification [29]

This British and European Standard specifies the test method and verification of operator visibility from variable reach rough terrain trucks. It follows the ISO 5006 approach, although it provides greater clarity in its description of the test method. The standard also evaluates visibility for several machine configurations, which are aligned to the intended use of the machine. These include:

- a test with a fork mounted load;
- a test without the load;
- a test with a suspended load;
- a test for a lorry trailer loading condition, where the risks are principally examined in the rearward direction during the reversing part of the manoeuvre and before the boom is lowered; and
- a test for visibility of the fork arms, in which the filament position centre point (FPCP) of the light source may be moved toward the load centre by up to 300 mm and above or below by up to 150 mm in order to represent the operator's additional movement when looking toward the fork arms.

9.3.2 Draft BS EN 16842 Powered industrial trucks – Visibility – Test method for verification [30]

The draft series of European Standards specify requirements and test procedures of all-round visibility for industrial trucks with a sit-on or stand-on operator, without load, and equipped with fork arms or load platform.

The method includes travelling tests, to consider movement of the truck over relatively long distances and open areas at faster speeds, and manoeuvring tests, which consider motion of the truck at low speed and for short distances.

In general, the tests involve moving a test body along test paths, parallel and perpendicular to the longitudinal axis of the truck, which are marked around the truck. The test body is 1200 mm high, 500mm wide and 500 mm deep, and intended to simulate an obstacle to be seen (eg person in a stooped position). The test body is marked with a grid pattern of 100 mm by 100 mm squares. For each test, the Standard specifies the number of lights and rotation of the lighting equipment (to simulate a range of operator head positions), as well as the minimum illumination area (ie number of illuminated squares) required on the test body as it is moved from a start position to end position. In this way, the approach attempts to consider dynamic collision / risk scenarios during manoeuvring and travelling, as well as the quality of the operator's view of pedestrians around the moving truck.

Compared to ISO 5006 [3], the draft Standard specifies slightly different lighting equipment to simulate the position and movement of the operator's eye point. One notable point is that the light source is positioned 650mm above the seat index point (SIP), lower than the 680 mm specified in ISO 5006 and BS EN 15830 [29]. The draft standard does not explain what the 650 mm value is intended to represent; however, a comparison to ISO 3411 [21] suggests that this height is between the sitting eye height of a small operator (610 mm above the SIP) and a medium sized operator sitting in a slumped position (667 mm above the SIP).

9.3.3 Light intensity contour plots

Barron *et al* [31] assessed the feasibility of using a light sensor to measure light intensity and quantify operator visibility in a three-dimensional field of view. This was to address several perceived shortcomings of existing light bulb shadow tests, namely that:

- Visibility is only evaluated on a two-dimensional visibility circles, however, machine tasks may be executed anywhere in three-dimensional space;
- Regions can only fall into either dark or bright areas, and areas of partial visibility where faded light exists cannot be evaluated; and
- Subjective decisions are required to determine the edges of the masked areas, and this compromises repeatability.

They used a light meter connected to a vertical array of 15 light sensors to measure light intensity at grid points around the light source. The lowest light sensor was located 0.06m above the ground, and subsequent sensors were located at 0.3 m height intervals above. The light bulbs were mounted inside an experimental cabin and turned on. The light intensities on the 15 sensors were then recorded at various grid positions around the cabin to produce a series of visibility contour plots.

Despite simulating a simplified visibility obstruction to demonstrate proof of concept, the results, as presented, would be difficult to interpret.

9.3.4 Field experience of conducting light source shadow tests

HSE investigators have described the practical difficulties of using the ISO 5006 light source apparatus in the process of conducting manual tests of the field of view from earth-moving machinery. These include the difficulties of using the light source apparatus to evaluate indirect visibility, and the need to apply the test outdoors because a sufficiently large and dark indoor space is not available at a work site. In this case, for larger machines, the test becomes impractical as it involves moving a small mirror at ground level along 12 or 24 m visibility test circles and trying to identify the reflection of the light sources in the flat and convex rear view mirrors fitted to the side of the machine.

9.4 LASER SCANNING METHODS

9.4.1 Proportionate volumetric blind spot analysis

Teizer *et al* [10] describes the development of a method of automated blind spot measurement using multiple laser scans from both the driver's position and outside the vehicle. The laser scan dot cloud is processed and imported into a ray-tracing algorithm. This allows the automated calculation of either:

- the ratio of total blind area on the surface of a 12 m radius sphere to the total area of the same sphere lying above the ground plane (the sphere is assumed to be centred at the operator's head position); and
- the percentage of a person that is visible to the laser scanner when standing at a particular location near to the machine.

Teizer *et al* [10] suggest that knowing the blind spot spaces (or volumes) is more helpful in construction applications since many dynamic activities occur in the third dimension, for example the lifting of earth and construction material which, if done improperly, contributes to a large number of collision accidents.

9.5 STUDIES COMPARING DIFFERENT FIELD OF VIEW EVALUATION METHODS

Bostelman *et al* [32] evaluated several advanced methods for measuring a forklift operator's visibility. These methods included:

1. analysis using an existing forklift CAD model;
2. analysis of a meshed model laser scan of a forklift;
3. analysis of panographic images taken from inside the vehicle;
4. volumetric analysis of the laser scan.

The paper considers the compatibility of these methods with ISO 13564-1 *Powered industrial trucks – Test methods for verification of visibility* [33]. It points out that, in comparison to the methods described in the Standards using a light source array, the advanced methods have the potential not only to measure blind spots, but also to aid in evaluating camera and sensor mounting locations.

Bhattacherya *et al* [34] compared the use of a manual light filament method and a simulation method, using a laser scanner with 3Dipsos modelling software, to evaluate the field of view from load haul dump vehicles used within the mining industry. The methods were considered in terms of the amount of time required to conduct the test (collect the data) and the repeatability of the test methods. They found the simulation method to be a slightly more repeatable method. There was 96% overlap of the visibility masking plots when using the laser scanner compared to 93% overlap when using the manual light filament method. The potential for error remained with the simulation method; however, errors were not associated with measurement, but rather the positioning of the laser scanner at the operator's position and interpreting the laser scan dot cloud when modelling the machine. The significant advantage of laser scanning was that data for one machine were collected in 30 minutes, compared to about 3 hours for the light filament method. They suggested the laser scanning method would have a more limited impact on mine productivity.

Choi *et al* [35] investigated forklift truck design factors influencing visibility using three different methods: the ISO 13564-1 light bulb shadow test [33], a test within human simulation software (CATIA V5R13 [36]), and a modification of ISO 13564-1 using observers in the driver's seat. The test using observers found fewer shadowed grid areas, which were more distributed across the test body. This was attributed to differences in eye movement, eye spacing and eye positioning of the individuals compared to that designed into the other approaches. However, the paper does not offer any wider conclusions on the limitations or benefits of each approach.

9.6 SIMULATION OF THE OPERATOR'S EYE LOCATION

9.6.1 ISO 4513 Establishment of eyellipses for road vehicle drivers' eye locations

ISO 4513 [11] describes the eyellipse - a contraction of the words 'eye' and 'ellipse' used to describe the statistical distribution of eye locations in three-dimensional space located relative to defined vehicle interior reference points. It is used to facilitate design and evaluation of vision in motor vehicles, for applications such as rear view mirror size and placement, wiped and defrosted windscreen areas, pillar size and location, and general exterior field of view. It is also used to determine the largest fields or obstructions that would be seen for a given percentage of the driving population.

The standard describes the shape and positioning of eyellipses for drivers of Class A vehicles (passenger cars and light trucks) and also Class B vehicles (heavy trucks, buses, and multipurpose vehicles with a driver's seat height between 405 mm and 530 mm above the accelerator heel point).

Applying the eyellipse to field of view evaluation

When projected at a specified angle or on to a specific target, a tangent cut-off plane from the eyellipse can be considered to be a sight plane (or sight line in a two dimensional view). A plane can be drawn tangentially to the upper edge of the 95th percentile eyellipse, whereby 95% of eye locations are below the line and 5% of eye locations are above it. If this tangent line is considered as a sight line (or sight plane) to the lowest point on the underside of the windshield header, 95% of the drivers would see at that angle or higher and 5% would see at that angle or lesser (restricted). Any targets in the forward field of view above the sight line would not be seen by 5 % of the drivers. If the target is on or below the sight line, at least 95% of the drivers would see the target.

Furthermore, if a similar plane is drawn tangentially to the lower edge of the 95th percentile eyellipse, then 95% of the eye locations, whether inside or outside the eyellipse, are above the line and 5% are below it. This might be used to evaluate the masking effect of screen position within a cab.

Neck pivot and eye points

To simplify application of the eyellipse for specific viewing tasks requiring head and eye rotation, ISO 4513 defines neck pivot points that provide a head rotation pivot centre so the eye points can be repositioned for these specific viewing tasks. These points are derived from a 95th percentile, 50/50 gender mix eyellipse. From these neck pivot points, the eye points are then determined. The neck pivot points are applicable to Class A vehicles, but have not yet been developed for the 99th percentile eyellipse or for Class B vehicles.

Application of the eyellipse to ISO 5006

The use of the eyellipse allows for a detailed analysis of driver accommodation for specific forward viewing tasks. In particular, it helps to take account of the variability in eye position, due to drivers of different size, and to estimate the proportion of the driver population excluded from a specific viewing task. It is interesting that the eyellipse, as applied in automotive design, provides a more static simulation of drivers primarily focussed on forward viewing, which compared to the ISO 5006 approach, permits significantly less movement of the eye location to see around obstructions. It would be a much more onerous (and arguably realistic) evaluation of the field of view to exclude significant amounts of movement of the eye location. This would seem more reasonable for normal machine travelling.

The eyellipse is most suited to use within software, and manufactures may use it to investigate specific occupant accommodation, masking or field of view issues. For example, NX General Packaging software [14] provides a suite of tools to automate many occupant accommodation tasks during vehicle design. It has an eyellipse wizard, depicting the location of eyes for a specified driver population within the digital model. It incorporates the eyellipse into its evaluation tools for direct field of view, instrument panel visibility, windshield vision zones, and mirror certification. However, the eyellipse would be more complicated to apply in a physical test than the ISO 5006 light source apparatus. A physical reference device (such as an H-point device or seat-index-point device) is still required to determine the position of the eyellipse centroid within the operator's workspace.

There is also uncertainty about the extent to which the current automotive eyellipse could apply to the operation of some earth-moving machinery types, where there may be a greater range of visual tasks and working postures required for safe operation. However, there are advantages in the concept of specifying a volume of space that represents the range of eye positions for the operator population. Incorporating this range would represent a significant step forwards in the simulation of the operators' eye location, which could be useful for machine design as well as evaluation. It is conceivable that three operator eye movement ranges could be developed, standardised and applied within simulation software:

- the range of operator eye locations based on operator dimensions;
- the range of operator eye locations based on operator dimensions and head movement; and

- the range of operator eye locations based on operator dimensions, head and trunk movement.

Subsequently, it may also be possible to develop physical devices that can be used during a manual test to represent each range of eye locations within a volume of space.

9.6.2 ISO 11591 Field of vision from engine-driven small craft helm position

ISO 11591 [13] specifies the field of vision from the helm position, forward and astern, in engine driven small craft up to 24 m. For craft capable of speed in the planning mode, the field of view is evaluated with the bow raised, with the angle of inclination based on factors such as hull length, engine power, and speed.

The standard specifies a low eye position and high eye position for a helmsman in the standing position (1480 mm and 1730 mm above the standing surface) and for a helmsman in the seated position (690 mm and 840 mm above the seat). For the seated position, rather than incorporate a SIP or H-point device, the standard describes eye positions in relation to the centre of the seat, at the intersection of the seat-back and seat-bottom when compressed by a 25 mm diameter spherical object under a 100 N vertical load. The eye position is set 400 mm horizontally behind the centre of the steering wheel rim.

A notable feature of this test is that it not only evaluates the near field of view below the eye position of a small operator, but also takes account of the eye position of the tall operator to ensure that they have an unrestricted view to the horizon. The standard also permits a degree of horizontal head movement to maintain clear vision and meet the requirements; for example, up to 35 mm for planing craft and 70mm for displacement craft in the centre field of vision, and up to 100 mm elsewhere in the forward field of vision. For the field of view astern, up to 500 mm is permitted from a seated position or 1000 mm from a standing position.

9.6.3 ISO 16121-2 Visibility for line-service buses

ISO 16121-2 [12] specifies the requirements for the bus driver’s field of view to the area in front of the vehicle, to the entrance opposite the driver’s seat, and the interior compartment. The standard does not describe a testing procedure. Presumably, it is undertaken within CAD software. The approach is noted for its attempt to take account of the range of seat adjustment. The standard evaluates line of sight from two vision points:

- vision point V1, 635mm vertically above the H point, with the seat adjusted to its rearmost highest position within the required adjustment range; and
- vison point V2, 635mm vertically above the H point, with the seat adjusted to its foremost lowest position within the required adjustment range.

However, it is odd that the vision points selected represent neither the most favourable or onerous positions. The key factor for operators when selecting a seat position is their ability to reach the foot controls comfortably. The operators’ field of view requirements probably play a more minor role when selecting seat position.

9.7 USE OF HEAD / EYE TRACKING IN VISIBILITY EVALUATION

As well as understanding, and appropriately representing the operator's eye location, it is important to know what the operator might be likely to look at during machine performance, when designing, selecting, and installing visibility aids.

9.7.1 Eye tracking of excavator operators

Koppenborg *et al* [37] [38] describe how they used eye tracking to better understand how excavator operators acquire visual information from mirrors, monitors and direct sight during reversing movements and . A head-mounted "Dikablis" eye tracker was fitted to operators for 3 – 5 hours to record eye movements as they used their excavator (ranging from 17 to 32 tons) at construction sites for typical activities such as trenching, grading, pipe-laying, sloping, transporting objects, and loading and spreading material. All excavators were equipped with a rear view camera monitoring system (CMS), one left rear view mirror, and either one, two or three right rear view mirrors.

Among a sample of nine operators, a total of 415 reversing movements were observed (with a median during of 4 seconds), which were defined as when the cab direction was opposite to the travelling direction. These were isolated from the data for analysis along with the 4 second period prior to the start of the movement. Excavator operators glanced, at least once, into the CMS on 57% of reversing manoeuvres, and the left rear view mirror on 64% of reversing manoeuvres. They looked over their shoulder during 19% of reversing manoeuvres, and rarely (7%) glanced at the right mirrors. In 12% of reversing movements, the operator did not look over their shoulder or into any visibility aid.

Among a sample of four operators, 997 rotating movements were observed, with an average movement duration of 6.6 seconds. Rotation movements were defined as rotations to the right (as operators have more limited visibility in this direction), that involved a rotation angle exceeding 45°, and had no prior travelling movements or left rotating movements within the previous 60 seconds. Where rotation movements were repeated in a cluster of activity, only the first three rotating movements were selected. These rotation movements were isolated from the data for analysis along with the 4 second period prior to the start of the movement.

Through direct visibility operators glanced the most at the attachment (90% of rotations), and the area to the right of the attachment (78% of rotations). They also looked under or through the hydraulic cylinders towards the front area of the right side of the excavator (25% of rotations) and over their shoulder to the left side of the excavator (9% of rotations). The most commonly used viewing aids during rotation movements were the CMS (34% of rotations) and left rear view mirror (22% of rotations). For the area on the right side, operators attended the CMS monitor, but rarely the right side mirrors. The right rear view mirror was used in only 0.8% of all rotation movements, and the researchers questioned how the operator obtains information about the area on the right side when the boom obstructs direct sight.

The researchers also found large differences between excavator operators. For example, use of the CMS ranged from 10% - 98% during reversing movements and 0% - 90% during rotation movements. However, they were not able to investigate how personal preference, training, habituation, work activity, or work environment might have played a role in different operator behaviours that were observed.

9.7.2 Dynamic field of view monitoring

With some success, Ray and Teizer [39] explored the use of range imaging cameras mounted in the cab to track the continually changing head orientation of equipment operators. Their view is that static blind spot measurements alone provide insufficient information to protect the workspace around construction equipment. With the advancement of proximity monitoring technologies in mind, they see a need to be able to merge knowledge of the dynamic field of view of the equipment operator with static blind spot measurements. They reason that monitoring systems would be improved if they only alerted when a worker enters areas outside of the operator’s field of the view. However, the tracking of head orientation to predict what the operator can see may overlook the point that operators may not ‘notice’ workers even within their field of view because their attention is focussed elsewhere (for example on their task).

10 APPENDIX C – BRIEFING NOTE AND QUESTION SET

Assessment of operator's field of view during the design of earth-moving machinery

Background:

The Health and Safety Executive (HSE) have asked the Health and Safety Laboratory (HSL) to review the processes and methods that manufacturers use to assess operator's field of view during the design of earth-moving machinery. It is intended that this would be through face-to-face or telephone discussion with several manufacturers of earth-moving machinery.

It is our intention that the discussion would be informal, and based around the set of questions on the following pages. The review will focus on the use of ISO 5006 (2006) *Earth-moving machinery – Operator's field of view – Test method and performance criteria*.

The issues that we would like to cover are:

- how you apply the ISO 5006 (2006) test method in practice;
- any current issues or barriers you experience when applying the ISO 5006 test method;
- other approaches that you use in the design process to assess the operator's field of view from earth-moving machinery;
- how you assess what visibility aids to fit to a machine; and
- the overall usefulness of ISO 5006 in helping you to decide whether the machine provides the operator with an acceptable field of view and what visibility aids to fit.

The aim of the discussion is to inform our work to develop an alternative risk based approach to assessing the operator's field of view from earth-moving machinery. We want to ensure that any new method proposed is practical to apply as part of the design process.

Ethics:

We work in accordance with the professional code of conduct for the Chartered Institute of Ergonomics and Human Factors (CIEHF)[1] . This includes:

- confidentiality – not sharing confidential or commercially sensitive information with others;
- anonymity – not revealing the identity of individuals or organisation without their expressed written permission;
- ensuring that data is stored securely; and
- before making visual recordings, seeking the expressed agreement from individuals both to the making of the recording and subsequent access to and use of the recordings.

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[1] http://www.ergonomics.org.uk/code-of-conduct/

Question Set:

These questions are intended to stimulate and guide thought and discussions about the evaluation of operator's field of view from earth-moving machinery. We appreciate that there may be multiple people, teams and processes involved in making design decisions affecting aspects of visibility and the operator's field of view, and you may not be able to provide answers to all of the questions.

Q1) How do you specify user requirements for operator visibility?

a) Are they based on ISO 5006 performance criteria, or do you use something else?

Q2) How do you apply the ISO test method in practice during the design of a machine?

a) Is the assessment performed within software (eg CAD) or manually on a physical layout / prototype of the machine?
b) When in the design process do you apply the ISO 5006 test method?
c) Why at this time? Could it be applied earlier?

Q3) What issues or barriers do you experience when applying the ISO 5006 test method?

a) When applying the test method manually, on a physical layout? (eg with the light array, performance criteria)
b) When applying the test method within software?
c) How useful are the test method and performance criteria in helping to decide whether the machine provides an acceptable field of view for the operator?
d) Can you use the test method to inform decisions about design?
e) If you apply the ISO 5006 test method to larger machines that exceed the operating mass specified in the standard, does this present any additional issues for you?

Q4) Do you use any other approaches to evaluate operator's field of view from the machinery?

a) What are they?
b) What works well?
c) What barriers are there to these approaches?
d) Do you perform any tests / user trials with operators to evaluate field of view? How do you select people for user trials, or take account of people of different sizes?

Q5) How do you decide what visibility aids are fitted to a product?

a) Do you find the ISO 5006 test method useful for this purpose? Why / why not?
b) What is the rationale for determining whether a visibility aid is fitted as 'standard' on all machines, or as an option?
c) To what extent are customers involved in decisions about the selection of visibility aids?
d) Do you specify the visibility aids that are acceptable to fit to your machines? What performance criteria do you use?

Q6) Do you have any views, experience, or issues that you can share regarding the supply and use of “bird’s-eye view” camera systems on your machines?

a) Do you have a specification for “bird’s eye view” camera systems fitted to your machines? What performance criteria does it specify?

Q7) Can you foresee any problems with the proposed risk-based concept for evaluating the operator’s field of view?

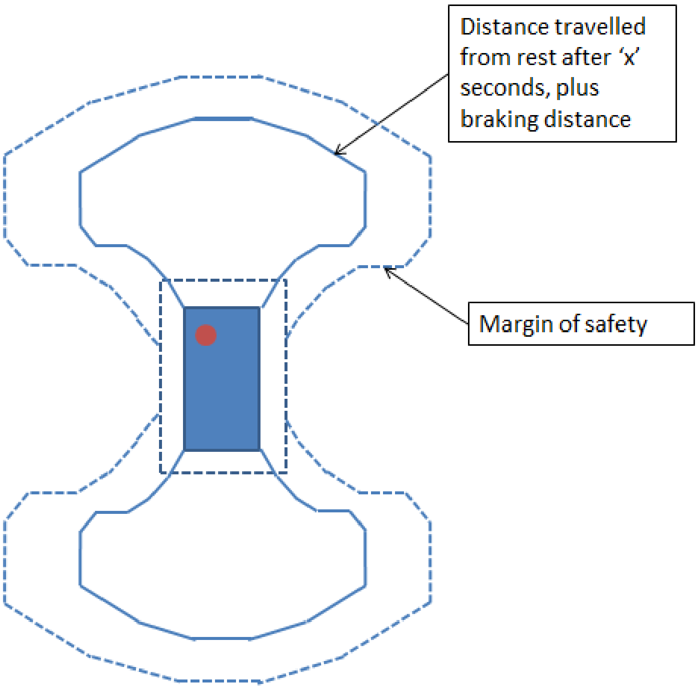
For example,

a) The method proposes to replace the 12 m visibility test circle with a ‘visibility test area’, the size and shape of which is based on information about a machine’s turning circle, manoeuvrability, and stopping performance. Would these machine characteristics be specified early enough within the design process, to inform an approximate size and shape of a visibility test area?

Rigid frame dumper example

The size and shape of the test area will depend on the machine characteristics. The travel time, ‘x’ will depend on the machine speed and acceleration.

Visibility will be assessed on the field of view that the operator has of the test area at start up.



b) Any other foreseeable issues at this stage?

c) Would changes to ISO 5006 have an impact on other visibility standards that you use?

Q8) Is there anything else you want to record that has not already been covered?

Thank you for your participation.

11 APPENDIX D – APPRAISAL OF ISO 5006

Table 2 provides an appraisal of ISO 5006 based on the review of literature, discussion with manufacturers, and experience applying the test method in practice. The appraisal is limited to technical comments. It does not take account of editorial aspects, although these could be important in terms of how machine designers try to interpret and apply the test method and performance criteria. The source raising each issue is also presented.

(1) Comments or feedback from members of ISO/TC 127/SC 1/WG5

(2) HSE experience applying ISO 5006 in practice

(3) Discussion with manufacturers

(4) Review of literature

For some of the issues, potential solutions have been suggested for further consideration.

Table 2 Technical critique of the ISO 5006 test method and performance criteria

Issue	Further thoughts and potential solutions to explore
1. Scope	
There is a narrow focus on visibility to the ground plane along the 12 m (or 24 m) visibility test circle (VTC), and to the 1.5 m test object along the rectangular boundary (typically 1 m away from the machine). There is a lack of evaluation in the field of view between the rectangular boundary and the VTC, with the potential that maskings may exist in this area but would not be recorded. This can also introduce arbitrary and unhelpful design constraints. For example, design decisions, such as the height of a monitor mounted on an A or B post, could be determined according to their impact on maskings at the VTC. However, this could have a negative impact on visibility to other areas, or other aspects such as the performance and comfort of operators. The positioning of a screen a few centimetres higher or lower within the cab could determine whether a machine can meet the performance criteria (1, 2).	Extend the scope of the test method to evaluate maskings from the machine boundary to the visibility test circle. Such a change in scope would require the development of revised performance criteria in the test area; for example, based on ergonomics criteria, such as the area or volume of space occupied by a standing pedestrian.
4.1 Light spacing dimensions	
To our knowledge, information has not been published to validate the 205 mm and 405 mm maximum light spacing positions and rotation of the light source apparatus in relation to the actual positioning of operator eye points during typical operator movements. The light spacing dimension of 65 mm is intended to represent "binocular eye spacing of 50% of seated earth-moving machinery operators". The 205 mm light spacing, together with rotation of the light source, is intended to simulate the eye movement (considering body torso and head movement) of 50% of operators when looking to a 45° angle to the rear (135° clockwise or anticlockwise from the straight ahead position).	Eye spacing dimensions and rotation of the light source apparatus together should be assessed against the positioning of operator eye points during typical earth-moving machinery movements (eg when looking to 45°, 90°, 135° from the straight ahead position). An initial scoping assessment could be done within human simulation software, along with some physical trials to verify the simulation.

Issue	Further thoughts and potential solutions to explore
The description of the 405 mm eye spacing is not clear, as it states "The 405 mm light spacing, together with rotation of the light source, is intended to simulate the eye movement (considering body torso and head movement) of 50% of operators when looking to the front (90° clockwise and anticlockwise from the straight ahead position)". These statements are unclear as to which 50% of the operator population is represented through the use of these eye spacings. It was suggested that the 405 mm eye spacing was established to approximate the movement of the eye points around the perimeter of the operator's seat.	
5.1 Light source apparatus	
The light bulb spacing can be adjusted to take account of side to side motion of the operator's eye locations. However, there is no adjustment in the vertical direction. This causes issues for long thin horizontal obstructions, as well as smaller items in the cab (eg grab handles, cup holders) and affects the performance of some machines. ISO 5006 states that for maskings that are wider on the visibility test circle than they are within 1 m (inside or outside) of the visibility test circle, the average of the narrower masking widths at 1 m inside and outside the test circle may be used as the masking width. However, this may provide little benefit (1).	ISO 18063-1 [40] considers a masking to meet its criteria, if it does so within a vertical distance of 950 mm from the test surface at the 12 m radius. It does not have to meet the criteria solely at ground level. The 950 mm dimension is based on small operator dimensions within ISO 3411 [21] to approximate waist height. It would also be prudent to require a minimum 200 mm length of the 950 mm vertical dimension to be illuminated to make it consistent with the ISO 5006 requirements at the rectangular boundary.
The height of the light source remains fixed as it is rotated, and fails to simulate reductions in eye height that result from sideways bending or rotation of the body torso (2, 3).	Consider the use of an angled light bar that reduces the height of the bulbs positioned 102.5 mm and 202.5 mm from the filament position centre point. With most testing undertaken using simulation software, it may be possible to upload multiple lighting apparatus to reflect the different

Issue	Further thoughts and potential solutions to explore
	operator positions that are adopted when viewing each sector of vision.
The height of the light source represents the eye height of a medium operator sitting in an upright posture. However, it is reasonable to assume that small operators will suffer the most restriction to their field of view. This is especially important for assessing the field of view from larger machinery, as a slight reduction in the sitting eye height of the operator can potentially result in a large increase in the area of masking at ground level (2). The height of the light source apparatus also fails to simulate a reasonable degree of slump in operator sitting posture (2).	Lower the vertical height of the light source apparatus to represent a small operator sitting in a working posture. ISO 3411 defines a 'small operator' as "an operator belonging to the worldwide earth-moving machinery operator population where approximately 5% of operators are smaller than the dimension listed" [21]. The values are derived from male and female data from the USA, Europe and Asia (China, Japan, Korea and Thailand). In ISO 3411 [21], Figure 2 shows the upright sitting eye height of a small operator to be 690 mm above the horizontal sitting surface, or 610 mm above an 80 mm high seat index point (SIP). It provides sitting eye height values in an upright posture, and suggests sitting eye height should be reduced by about 25 mm to simulate a relaxed working posture. This would lower the light source position to a vertical height of 665 mm above the horizontal sitting surface or 585 mm above an 80 mm high SIP. Other sources of anthropometry data (Pheasant and Haslegrave [41], and PeopleSize Pro software [42]) advise a reduction of up to 40 mm for 'sitting slump'. Alternatively, adopt the sitting eye point height of 650 mm above the SIP, as proposed in Draft BS EN 16842 [30], which is representative of a small to medium sized operator sitting in a slumped position.
ISO 5006 does not specify how the operator's seat should be adjusted for the test (2, 3).	Where operator seat adjustment is possible, the test report should include a description of the seat position (eg in terms of forward/rearward and height adjustment). The position of the seat should be appropriate to the machine configuration being evaluated (eg travelling or working) and the size of the operator that the light source apparatus intends to represent (eg a small or medium sized operator). Alternatively, evaluate visibility from more than one 'vision point' to take account of the range of seat adjustment.

Issue	**Further thoughts and potential solutions to explore**
The light source is positioned relative to the seat index point (SIP). The SIP is difficult to locate, as its position is measured from the back and bottom surfaces of the fixture, which are not accessible when the SIP device is weighted down into the driver's seat (4).	The design of the SIP device could incorporate an easier way to measure from the seat surface, or an alternative measurement location from which the position of the SIP can be calculated. Bostelman *et al* [32] recommend augmenting the fixture with a sphere, or partial sphere, located with its centre at the SIP. They suggest this would make it much easier to locate relative to other reference surfaces in the vehicle, whether measuring with a tape or laser scanner, and would not require specialist software to construct the geometry. Alternatively, the SIP device could be abandoned for another approach, as it is easier to measure eye position from the seat surface.
6 Machine test configuration	
The test method is applied with machines positioned in their travel mode, and according to the manufacturer's specification. Examples are provided in Annex A (informative). In many cases, this will not represent the operator's field of view during site operations, when buckets, arms and other attachments may move through positions that create greater maskings to the operator's field of view (1, 2, 3).	For each machine, apply the test method with the machine in its travelling configuration, and, if applicable, a sample of typical/representative working configurations.
7 Performance criteria for indirect visibility *(ISO 5006: 2017)*	
ISO 5006 (2017) states that "in designing machines, direct visibility shall first be maximised". However, the test method and performance criteria do not give any credit for direct visibility over indirect visibility.	Include a requirement to report the ratio of the 12m VTC (or test area) visible through direct visibility, indirect visibility, and not visible (masked). Alternatively, attempt to apply the method of Teizer *et al* [10] to determine an analysis of the percentage of the area on a 12 m radius sphere with direct visibility, and direct and indirect visibility, compared to the total area of the sphere lying above the ground plane.
ISO 5006 (2017) provides performance criteria for mirrors used to meet	This issue requires further investigation before it can be resolved. It also

Issue	Further thoughts and potential solutions to explore
the visibility criteria. This specifies that the height of the reflection of the 1.5 m pole shall be at least 7 mm for every 1.2 m that the mirror is positioned away from the filament position centre-point. ISO 5006 (2017) states that mirror performance shall be evaluated at the longest distance from the mirror to the vertical test object that the mirror is intended to be used at. It is not clear whether this would be limited to positions along the rectangular 1 m boundary, or in this instance, whether visibility to the test object should also be evaluated beyond the 1 m boundary. In terms of meeting the visibility performance criteria, the criteria for mirrors would be most relevant to mirrors used to provide indirect visibility to the rectangular boundary, as the visual target at the VTC is the ground. At the rectangular 1 m boundary, the ISO 5006 test method only requires visibility to the top of the vertical test object (or any other 200 mm section of the test object). Thus, it could be interpreted that the mirrors could meet the performance criteria based on the reflection of just a segment of the test object, which might be of insufficient height or width to be detectable to an operator. ISO 5006 specifies that the test object to be of 'suitable width (eg 150mm)'. However, the proposed performance criteria do not include the width of the reflection that shall be visible in the mirror.	depends on the future scope of ISO 5006 (eg the locations or areas around the machine where visibility is to be evaluated) ISO 16001 [17] provides performance criteria for determining the range or detection area of camera monitor systems, rather than with reference to the visibility test locations in ISO 5006. For more reliable detection of a pedestrian under optimal conditions, Jegen-Perrin *et al* [18] recommend a 10 mm image height in monitors that are less than 1.2 m from the operator. This may be more a more suitable measure on which to base performance criteria for mirrors used to meet ISO 5006. However, we are not aware of any tests that verify the appropriateness of extrapolating these results to mirrors, which will be mounted outside of the cab at a considerable distance away from the operator. Jegen-Perrin *et al* [18] also found that a pedestrian is seen four times less well at the edge of the screen than at its centre. Thus, performance criteria for indirect visibility must take account of the zone to be kept under surveillance. The visibility aid should cover an area that is broader than the masking so as to avoid the edges of that masking coinciding with the edges of the mirror or monitor. Other factors, in addition to image size, will have an impact on the ability of the operator to detect a pedestrian in the mirrors or camera system (eg lighting and weather conditions, as well as the movement of the pedestrian, the contrast of their clothing against the background environment, and their position on the mirror). The most suitable physical test method to evaluate image sizes on mirrors should also be described. In practice, this might require that photographs of the mirror, with the test object in the relevant positions, to be taken from the operator's position, and then compared to known reference dimensions such as the height and width of the mirrored

Issue	Further thoughts and potential solutions to explore
	surface.
9.2 Computer simulation	
Where the test method is applied through computer simulation, there is no requirement to specify the version of the machine design [1].	Where the test method is carried out within simulation software, the test report should include an indication of the CAD drawing or file number for the machine that the manufacturer tested.
10 Evaluation method and performance criteria	
There are inconsistencies in performance criteria according to the type and size of machine. For example, Table 2 allows different vertical test object heights and rectangular boundary dimensions for different machine types and sizes. It is understood that this has arisen because different principles have been applied to set performance criteria (eg ergonomics principles, physical reviews of machines, and trial and error of what could be achieved at the time) (1). Similarly, Table 2 in ISO 5006:2017 proposes different vertical test object heights (1.5 m, 1.2. m or 1.0 m) for evaluating different machine types and in some cases, different sides of the rectangular boundary.	Design the performance criteria according to justifiable ergonomics principles, standardised across the machine types and sizes, and where maskings cannot be eliminated, use the results to inform the end user about the areas of masking / residual risk.

12 APPENDIX E – METHOD TO IDENTIFY AND EVALUATE VISIBILITY RISK ZONES

Earth - moving machinery: Evaluation of the operator's field of view – Test method to identify and evaluate visibility risk zones

1. Scope

This document describes a test method for conducting a risk-based evaluation of the operator's field of view from earth-moving machinery. The method can be used to inform a risk assessment to define the areas around the machine that the operator needs to view and to define the areas where visibility aids are required. The method can be applied to earth-moving machinery of all types and sizes.

This method is intended for those with a role in ensuring that the areas around the machine where the operator cannot see are recorded, prioritised, and the residual risks are managed. This may include those involved in the evaluation of machines, the installation of visibility aids and object detection systems, and the organisation of the jobsite to ensure a safe working environment.

The method describes the use of observers sitting in the operator position. It could also be applied through the simulation of an operator within software, or with a light source apparatus at the operating position (eg see ISO 5006), provided that the method provides a valid simulation of the size, position and movement of machine operators.

2. Terms and definitions

For the purposes of this method, the following terms and definitions apply.

observer
test person seated in the operating position

direct visibility
visibility by direct line of sight as determined by the observer

indirect visibility
visibility with the aid of mirrors or camera monitoring system

machine boundary
the line dividing the area of the test surface occupied by with machine, when in a static position, from the unoccupied areas of the test surface. For excavators, the machine boundary at the front is the most forward edge of the base machine, or dozer blade if it is standard.

masking
area on the test surface where the vertical test object is not visible to the observer, or where the section of the test object visible to the observer is not sufficient to indicate that the operator could identify a pedestrian in the intended work environment.

collision risk area
area around the machine which the machine, or machine components, can enter and present a risk of collision with people, other machines, vehicles, obstacles, voids, and other environmental hazards.

seat index point
the point on the central vertical plane of the seat as determined by the design and installation of a device specified in ISO 5353**.** The SIP may be considered equivalent to the intersection on the central vertical plane through the seat centreline of the theoretical pivot axis between a human torso and thighs.

visibility test circle
circle with 12 m or 24 m radius located on the ground reference plane with its centre vertically below the midpoint between the operator's eyes

3. Test apparatus

3.1 Test area, a surface that forms the ground reference plane for the visibility measurements, which is made of compacted earth or hard standing surface, with a gradient of no more than 3% in any direction. The size of the test area should be commensurate to the size, manoeuvrability, and maskings of the test machine, at least 25 m x 25 m in area, or larger if appropriate. The visibility test circle, with 12 m or 24 m radius, can be used initially as a test area boundary, and until the masking and movement characteristics of the machine are determined.

3.2 Vertical test object, a closed top cylinder of suitable diameter (eg 50 mm) and a height of 1.5 m used to evaluate direct visibility. It is helpful for the vertical test object, and 200 mm segments of it, to be easily distinguished when viewed against the background of the test surface. This can be achieved by marking the vertical test object with coloured bands.

NOTE The 1.5 m height of the test object represents a standing person of small stature. It is also equivalent to the shoulder height of a person of medium stature.

NOTE A vertical test object with a diameter of 50 mm is typically suitable. However, a greater diameter (eg 100 – 200 mm) may be easier for the observer to detect when evaluating larger machines.

3.3 Test body, a closed top cylinder with a diameter of 400 mm and a height of 1.5 m used to evaluate indirect visibility. The vertical centre line should be marked on the outside of the test body. It is helpful for the test body, and 200 mm segments of it, to be easily distinguished when viewed against the background of the test surface. This can be achieved by marking the test body with coloured bands.

NOTE The 400 mm diameter of the test object represents the width of a small operator. The 1.5 m height of the test body represents a standing person of small stature. It is also equivalent to the shoulder height of a person of medium stature. To evaluate indirect visibility, a person of equivalent dimensions can be used in place of the test body.

For informative purposes, or risk assessment of a specific work environment, the height of the vertical test object and test body can be reduced to 1.0 m to represent a crouching person, or also used to evaluate visibility at ground level.

4. Safety precautions

Before applying the test method, risk controls should be put in place to ensure the health and safety of the people moving around the machine, including the person holding the vertical test object. The necessary controls should be identified through risk assessment, as these will depend on the machine and environmental characteristics. However, they are likely to include measures that:

- segregate the test area from pedestrians and vehicle movements;

- ensure that the person holding the vertical test object does not enter the test area while the machine presents a hazard;
- ensure that the machine cannot be placed into a hazardous state while pedestrians are within the test area;
- prevent access under any unsupported machine structures, for example, booms and raised buckets.
- ensure that there is safe access to the operator's position and visibility aids; and
- provide easy communication between the observer and the person holding the vertical test object, for example, the use of two-way radios.

5. Test method

4.1 Machine test configuration

The machine configurations to be evaluated should be determined through risk assessment. They should be representative of how the machine is intended to be used during travel and operation.

For example:

- for machines with an articulated frame, it may be appropriate to evaluate the maskings when positioned straight ahead, and in a fully articulated position.
- for load carrying machines, it may be appropriate to evaluate the maskings with the machine in loaded and unloaded conditions.
- for excavators and backhoe loaders, it may be appropriate to evaluate the maskings with the boom in several positions.

4.2 The observer

The method involves the use of observers in the operator's position. The observers selected should be representative of earth-moving machine operators. Sitting eye height is a critical anthropometric measurement. As a general rule, selecting an observer with a sitting eye height representative of smaller operators will be more protective; for example, approximately 690 mm above the sitting surface when measured in an upright sitting position (see ISO 3411).

NOTE ISO 15537 contains information on selecting and using test persons for testing anthropometric aspects of designs including transportation equipment.

The method can also be applied through the simulation of an operator, for example, within software or with a light source apparatus at the operating position. The height of the simulated eye point should be reduced by at least 25 mm to represent a more relaxed working posture.

4.2.1 Positioning the observer

Throughout the tests, the observer should sit in the operator's position in a relaxed working posture and capable of operating the hand and foot controls as per normal operating practice. Where the seating position is adjustable, it should be set appropriately for the size of the observer. The observer should also wear the safety restraint as per normal operating practice.

NOTE In a relaxed working posture, sitting eye height is reduced by about 25 – 40 mm from an upright sitting position (see ISO 3411, or Pheasant & Haslegrave).

Measure and record the position of the seat index point relative to the front and side boundaries of the test machine.

Measure and record the vertical eye height of the observer above the cab floor and the sitting surface.

4.2.2 Movement of the observer

The observer is permitted to move their head to the same degree as the operator would be able to do whilst operating the machine. The observer should wear their seat restraint, keep their lower back in contact with the operator's seat (to limit torso movement) and keep their hands on the relevant controls. Observer movement should be restricted to within the confines of the cab if applicable.

NOTE Where a light source apparatus is used to simulate the observer eye position, a maximum light spacing of 205 mm is permitted. See ISO 5006. However, further work is required to assess the position, spacing and movement of the light sources against operator eye points during typical earth-moving machinery movements.

4.3 Overview of the measurement procedure

The procedure considers visibility of the vertical test object as well as visibility at ground level. It involves the measurement of maskings on the test surface area (section 0), the measurement of the collision risk area (section 0), and the evaluation of visibility risk zones for direct visibility alone (section 6) and with the use of visibility aids (section 7). The procedure requires one person to hold the vertical test object and mark the location of the maskings on the test surface, and at least one person to act as the observer.

For informative purposes, the procedure can also be adapted for risk assessment of a specific work environment.

4.3.1 Measurement of maskings of the vertical test object

The test should be performed for each machine configuration under evaluation. Position the machine such that the operator's position is at the centre of the test surface.

Measurements should first be made considering direct visibility of the vertical test object. To consider the vertical test object in view, the following conditions should be met:

- the test object is held vertically;
- the base of the vertical test object is in contact with the ground; and
- the observer is able to see the top of the vertical test object, or a section of the vertical test object that, through risk assessment, is determined to be sufficient to identify a pedestrian in the intended work environment (eg a length of at least 200 mm).

Step 1: To start the test, position the vertical test object to the front of the observer and at the boundary of the test surface area. This starting position should be sufficiently far from the machine that direct visibility is possible. Move the test object horizontally towards the machine, perpendicular to the machine boundary.

Mark any position on the test surface where the observer reports that the vertical test object has been moved out of view, or where the vertical test object when masked comes into direct view. This may require several iterations of the movement to pinpoint the threshold of the observer's line of sight to the vertical test object.

Step 2: Repeat step 1, moving around the entire machine, marking the boundary of the maskings.

In communication with the observer, who can indicate the machine components causing the masking, move around the machine marking the position of any maskings at a suitable number of visibility check locations. The intervals between each visibility check location should be commensurate with the shape and complexity of the machine components with the potential to cause the masking. At some locations the intervals should not exceed 200 mm. However, greater intervals are likely to be appropriate at other locations around the machine. This may be where there is clearly no masking, or where a masking is geometrically simple.

Step 3: Measure and record, on a scaled diagram, the location of the maskings relative to the machine boundary.

4.3.2 Measurement of maskings to consider visibility at ground level

Repeat the procedure (as defined in 4.3.1) considering visibility of the vertical test object at ground level. The vertical test object is considered visible when the observer can view the position where it contacts the ground.

4.4 Measurement of the collision risk areas

Through risk assessment, determine and record on the test surface the areas where the machine can move, when starting from a position of rest.

NOTE ISO 7457 describes a method for determining the turning dimensions of wheeled and articulated steer machines. Recording the inner tyre clearance diameter will identify the areas where wheeled and articulated steer machines cannot enter with a single turn.

The method applied may vary according to the type of machine and movement characteristics. For example:

- for excavators, consider and record where the machine can travel, as well as where the bucket and rear body may swing or reach during travel and work.
- for backhoe loaders, consider and record where the machine can travel, as well as the where the bucket may swing or reach during work.
- for tracked machines, it is prudent to consider that such machines can travel into any region of the test area.
- for large dumper trucks, it is prudent that the collision risk area includes a margin of safety around the machine, from the machine boundary out to a distance equivalent to half the machine width.

6. Evaluation method and performance criteria for direct visibility

5.1 Evaluation of maskings to direct visibility

For each machine configuration, identify the visibility risk zones on the test surface:

1. masking within a collision risk area
2. masking outside of a collision risk area, but where the masking may reduce the operator's situational and hazard awareness
3. area of direct visibility (no masking)

Measure and record the dimensions of the maskings in each collision risk area. Measure the masking width as the maximum width perpendicular to the operator's position.

NOTE When considering risk reduction measures, it may be helpful to distinguish further visibility risk zones, for example, areas of temporary masking during machine movement, areas where the vertical test object is partially masked (eg which may be caused by hoses or screens), areas of machine access, or to take account of accident data.

5.2 Performance criteria for direct visibility

The machine meets the requirements if the measurement results show no maskings of the 1.5 m vertical test object that exceed a maximum width of 200 mm within the collision risk area.

NOTE The 200 mm maximum masking width represents where the operator may not see a sufficient amount of the pedestrian to recognise them as a person. At best, this represents half the width of a whole person, or at worst a segment of that width that is 200 mm in length.

Requirements are not specified for areas outside of the collision risk areas or for maskings under more onerous test conditions (eg maskings of a 1 m vertical test object, or maskings at ground level). However, whenever possible, measures should be taken to minimise maskings to improve the operator's situational and hazard awareness.

5.3 Maskings that exceed the performance criteria for direct visibility

Where maskings remain that exceed the performance criteria for direct visibility, additional measures should be taken to eliminate the maskings or reduce the maskings to a size that meets the requirements.

It is preferable that measures are taken to improve direct visibility. However, additional measures are likely to include the installation of visibility aids such as mirrors or camera monitoring systems.

7. Incorporating indirect visibility into the evaluation

Indirect visibility should be incorporated into the evaluation of each machine configuration that cannot meet the requirements for direct visibility.

6.1 Measurement of the area of indirect visibility

On the test surface, previously marked with the maskings to direct visibility, mark and record where the test body (or a representative pedestrian) comes into view at the edges of the mirror or camera monitoring system.

To consider the test body in view:

- the vertical centre line of the test body should be in view for a section (or length) of the test body which is determined to be sufficient to identify a pedestrian in the intended work environments (eg a length of at least 200 mm).

- the image in the monitor should be at least 10 mm in length (along the longitudinal axis) and 2 mm in width (along the sagittal or frontal axis), with the monitor positioned within 1.2 m of the operator’s eye position.
- the image in the mirrors should be at least 10 mm in length (along the longitudinal axis) and 2 mm in width (along the sagittal or frontal axis) for every 1.2 m that the mirror is positioned away from the operator’s eye position.

  NOTE Further work is required to clarify the minimum size of the image of a pedestrian that an operator can reliably detect in mirrors positioned at various distances away from the operator.

However, larger image sizes are preferred as, in principle, these should lead to a greater likelihood that the pedestrian will be detected within the mirror or camera monitor.

While a view of both the head end and foot end of the test body in the mirror or monitor can help the operator to interpret the image, this is not required to consider the test body in view. For example, in a camera monitor, only the top part of a pedestrian or test body positioned at the machine boundary may be in view. However, the section of the test body that is in view should meet the image size criteria described above.

Where maskings to direct visibility have been measured with a 1.0 m vertical test object, or at ground level, the area of indirect visibility at these heights should also be determined.

NOTE Further work is required to explore the most practical method of measuring the image size on a mirror or monitor. For reasonably flat mirrors, one approach is to photograph the mirror from the operator’s position and compare the image size to the mirror dimensions. Alternatively, it may be possible to fit some fine gauge (eg 10 mm) mesh over the mirrors and monitors as a reference.

NOTE ISO 16001 contains additional requirements for the testing and performance of camera-monitor systems on earth-moving machinery.

Visibility aids can also play a role in providing a rear view to the distance for surveillance beyond the boundary of the test surface. However, the scope of this method is limited to an evaluation of the test surface area.

NOTE ISO 14401 contains additional requirements for the testing and performance of rear view surveillance mirrors. ISO 5006 contains additional requirements for mirrors.

6.2 Evaluation of residual maskings to direct and indirect visibility

Identify the visibility risk zones on the test surface:

1. Masking in a collision risk area
2. Masking outside of a collision risk area, but the masking may reduce the operator’s situational and hazard awareness
3. Collision risk area only visible with the use of visibility aids
4. Area outside a collision risk area, only visible with the use of visibility aids
5. Area of direct visibility (no masking)

NOTE To prioritise risk reduction measures, it may be helpful to distinguish further zones, for example, to record temporary maskings during machine movement, areas of partial masking (eg caused by hoses or screens), access areas, or accident data.

NOTE It is helpful to identify areas where operator visibility is reliant on the maintenance and performance of the visibility aids.

Visibility aids should cover an area that is larger than the masking so as to avoid the boundary of the masking coinciding with the edges of the mirror or monitor.

Measure and record the dimensions of the maskings in each collision risk area. Measure the masking width as the maximum width perpendicular to the operator's position.

6.3 Performance criteria for direct and indirect visibility

The machine meets the requirements if the measurement results show no maskings of the 1.5 vertical test object that exceed a maximum width of 200 mm within the collision risk areas.

NOTE The 200 mm maximum masking width represents where the operator may not see a sufficient amount of the pedestrian to recognise them as a person. At best, this represents half the width of a whole person, or at worst a segment of that width that is 200 mm in length.

There are no specific requirements for the size or proportion of the test surface that can only be viewed with indirect visibility. Requirements are also not specified for areas where the machine cannot move or for maskings under more onerous test conditions (eg maskings of a 1 m vertical test object, or maskings at ground level). However, whenever possible, measures should be taken to minimise maskings to improve the operator's situational and hazard awareness. When designing for visibility, direct visibility is preferred.

The operator's manual should include diagrams to describe the visibility risk zones around the machine, including those at ground level. It should recommend that suitable/appropriate jobsite organisation is required for the safe use of the machine.

8. Test report

The results of the tests should be recorded as scaled drawings, showing the size and location of the risk zones using direct visibility and the size and location of the risk zones using direct and indirect visibility. Scaled drawings should be provided for maskings of the 1.5 m vertical test object and maskings at ground level.

The test report should also contain the:

- description and images of the machine configuration
- description of the visibility aids, including the area that should be covered by each visibility aid
- height of the vertical test object
- description of the size and movement of the observer (or how the observer was simulated)
- source of the maskings
- masking widths

9. Example test reports

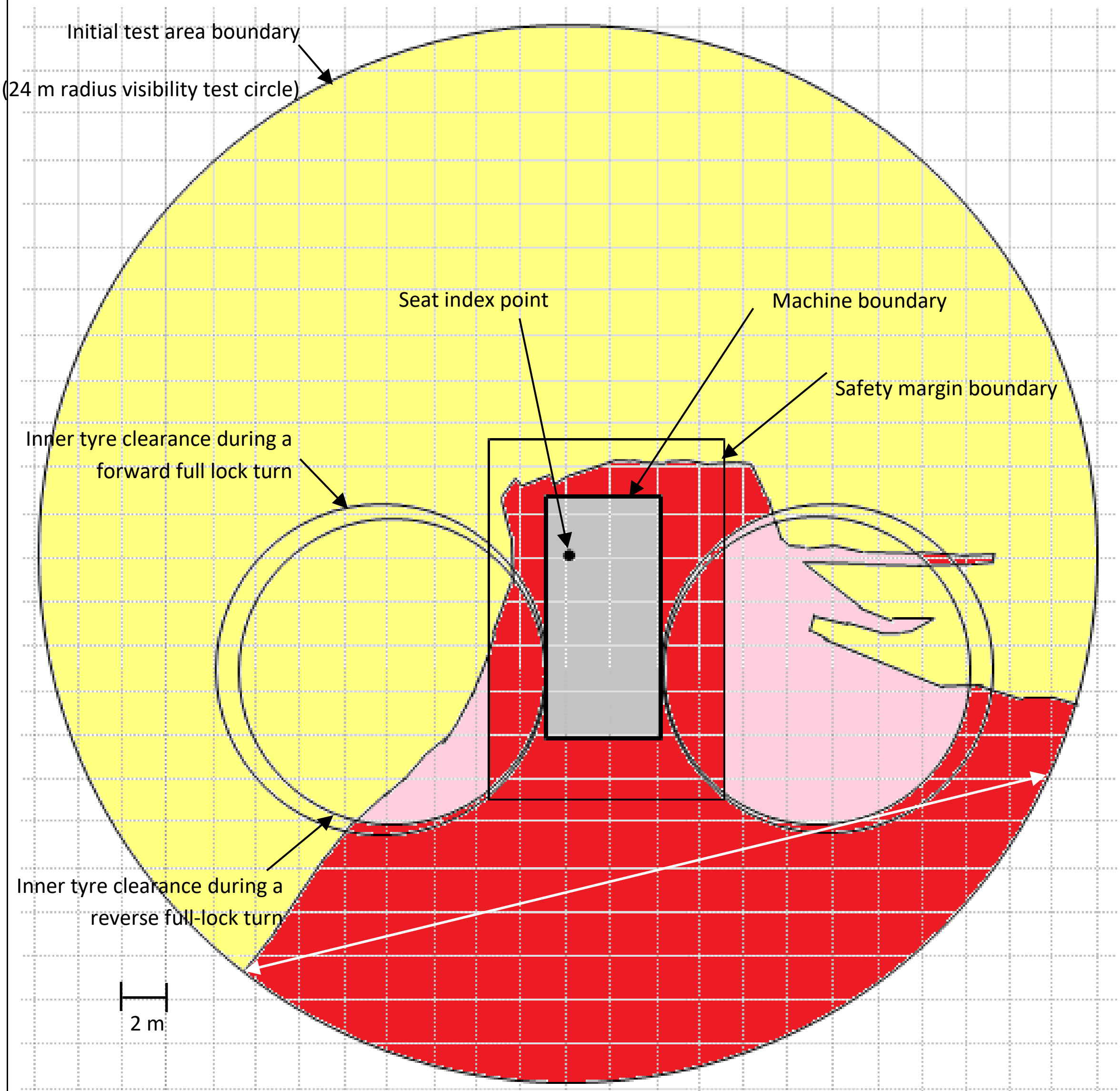
The following examples are summaries of the test reports.

8.1 Evaluation of visibility risk zones for a rigid frame dumper

Photograph 2 The large rigid frame dumper truck included in the trial of the visibility risk zones method

Photograph 3 The large rigid frame dumper truck

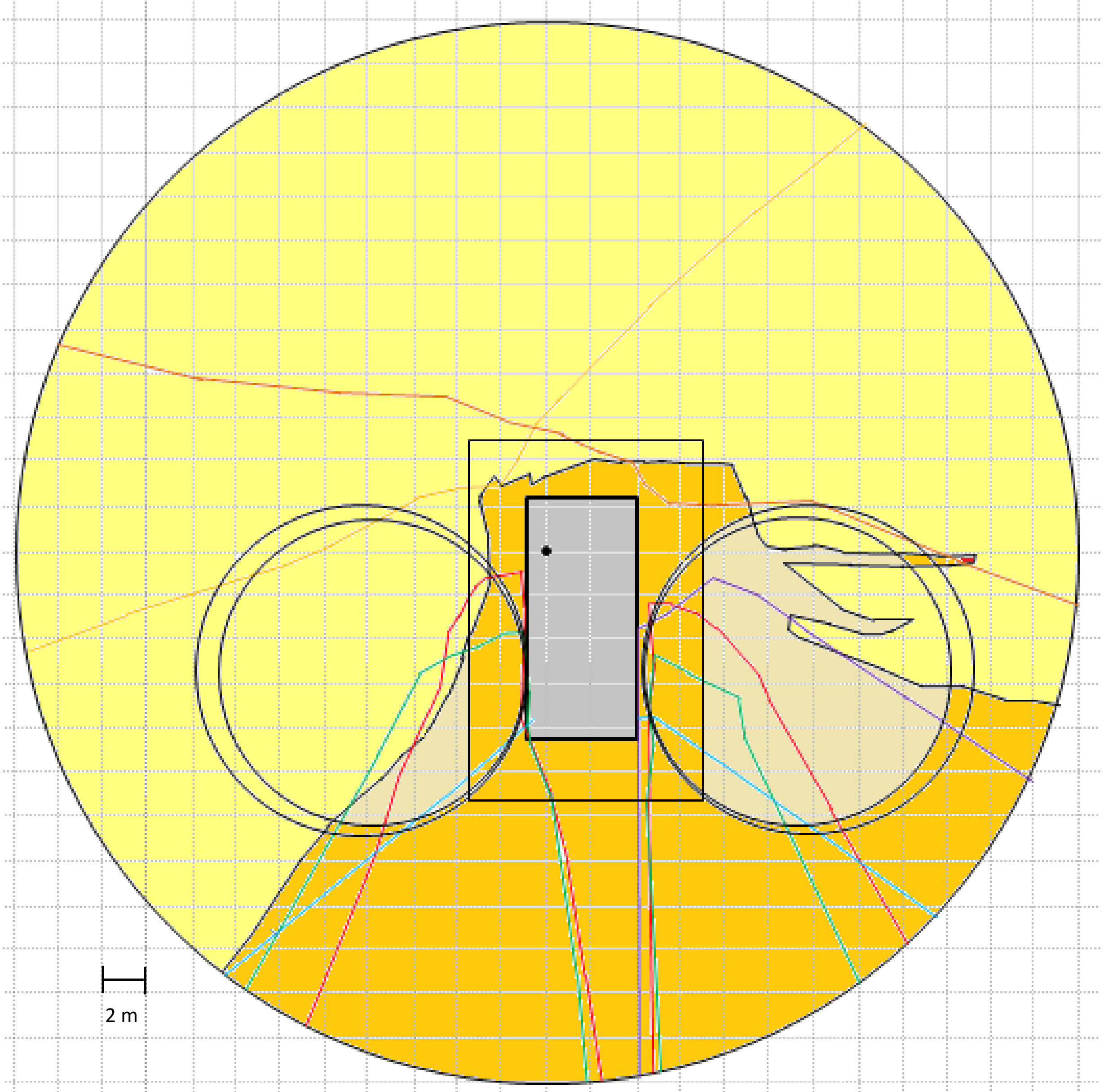
Machine: Rigid frame dumper (41)	Scale: 1:333 (approx.)
Operating mass: 64 000 kg	Machine configuration: Travel
Test: Direct visibility	Height of vertical test object: 1.5 m
Observer: JF 830 mm sitting eye height (75th percentile for British 18 – 64 year old population)	Observer eye height above cab floor: 1290 mm Observer eye height above sitting surface: 750 mm Observer movement:: Head and torso movement



Red = masking within a collision risk area
Pink = masking outside a collision risk area
Yellow = area of direct visibility (no masking)

Maximum masking width: At the rear, caused by the machine body: 37.5 m	Masking in the collision risk area: 432 m^2 approx.

Machine: Rigid frame dumper	Scale: 1:333 (approx.)
Operating mass: 64 000 kg	Machine configuration: Travel
Test: Direct and indirect visibility Left side (x2) and right side (x2) mirrors Front left and front right corner mirrors Rear view camera Right side camera	Height of vertical test object: 1.5 m
Observer: JF : 830 mm sitting eye height (75th percentile for British 18 – 64 year old population)	Observer eye height above cab floor: 1290 mm Observer eye height above sitting surface: 750 mm Observer movement: Head and torso movement



Red = masking in a collision risk area

Pink = masking outside a collision risk area

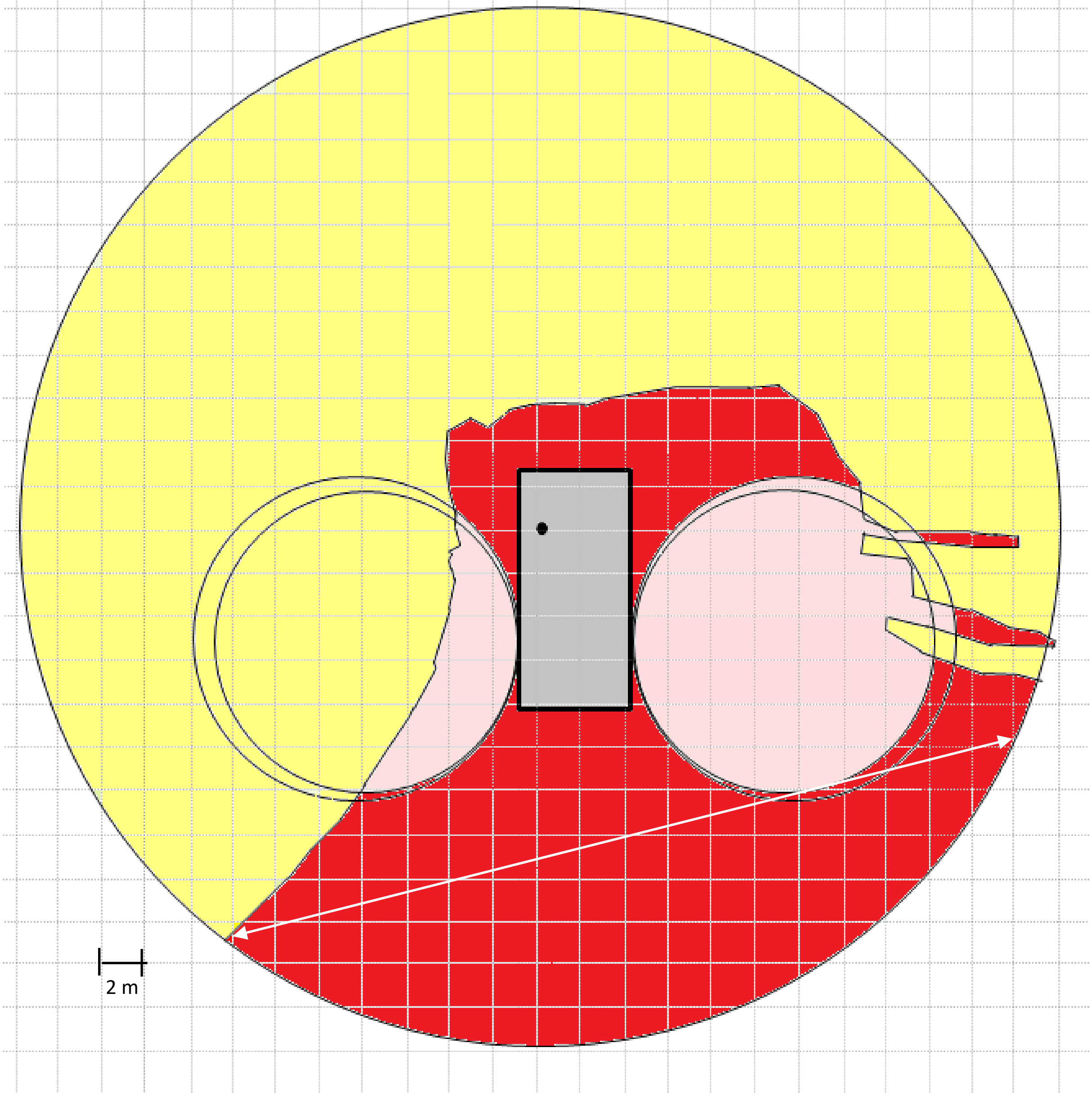
Amber = collision risk area only visible with the use of visibility aids

Beige = outside collision risk area, only visible with the use of visibility aids

Yellow = area of direct visibility (no masking)

Maximum masking width: 0 m	Masking in the collision risk area: 0 m^2

Machine: Rigid frame dumper (41)	Scale: 1:333 (approx.)
Operating mass: 64 000 kg	Machine configuration: Travel
Test: Direct visibility	Height of vertical test object: Ground level
Observer: JF 830 mm sitting eye height (75th percentile for British 18 – 64 year old population)	Observer eye height above cab floor: 1290 mm Observer eye height above sitting surface: 750 mm Observer movement:: Head and torso movement



Red = masking within a collision risk area

Pink = masking outside a collision risk area, but he masking may reduce the operator’s situational awareness

Yellow = area of direct visibility (no masking)

Maximum masking width: At the rear, caused by the machine body: 37.5 m	Masking in the collision risk area: 456 m^2 approx.

Machine: Rigid frame dumper

Scale: 1:333 (approx.)

Operating mass: 64 000 kg

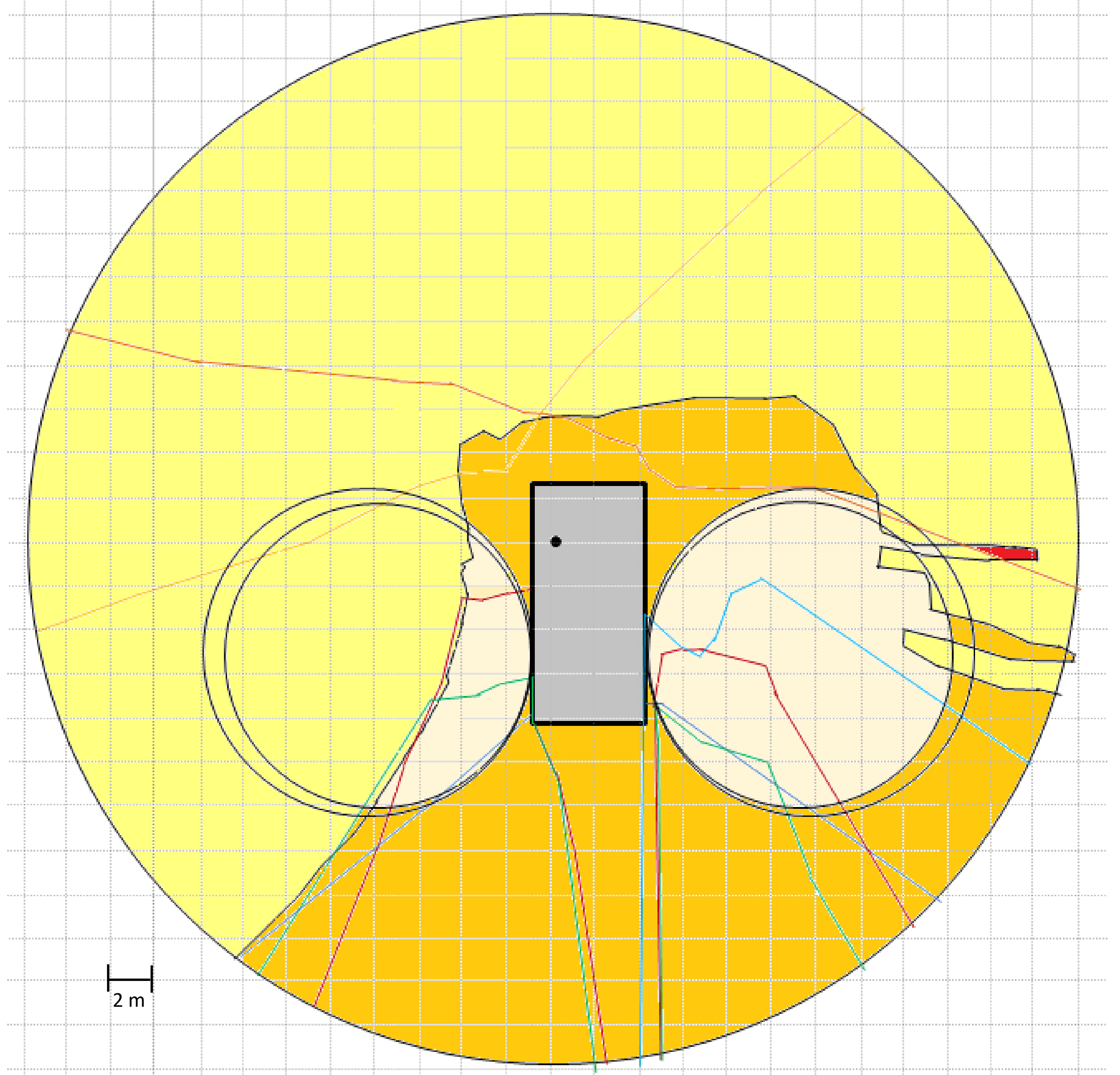
Machine configuration: Travel

Test: Direct and indirect visibility
Left side (x2) and right side (x2) mirrors
Front left and front right corner mirrors
Rear view camera
Right side camera

Height of vertical test object: Ground level

Observer: JF : 830 mm sitting eye height
(75th percentile for British 18 – 64 year old population)

Observer eye height above cab floor: 1290 mm
Observer eye height above sitting surface: 750 mm
Observer movement: Head and torso movement



Red = masking in a collision risk area
Pink = masking outside a collision risk area
Amber = collision risk area only visible with the use of visibility aids
Beige = outside collision risk area, only visible with the use of visibility aids
Yellow = area of direct visibility (no masking)

Maximum masking width:
To the right side, caused by mirror support: 670 mm

Masking in the collision risk area: 2 m^2

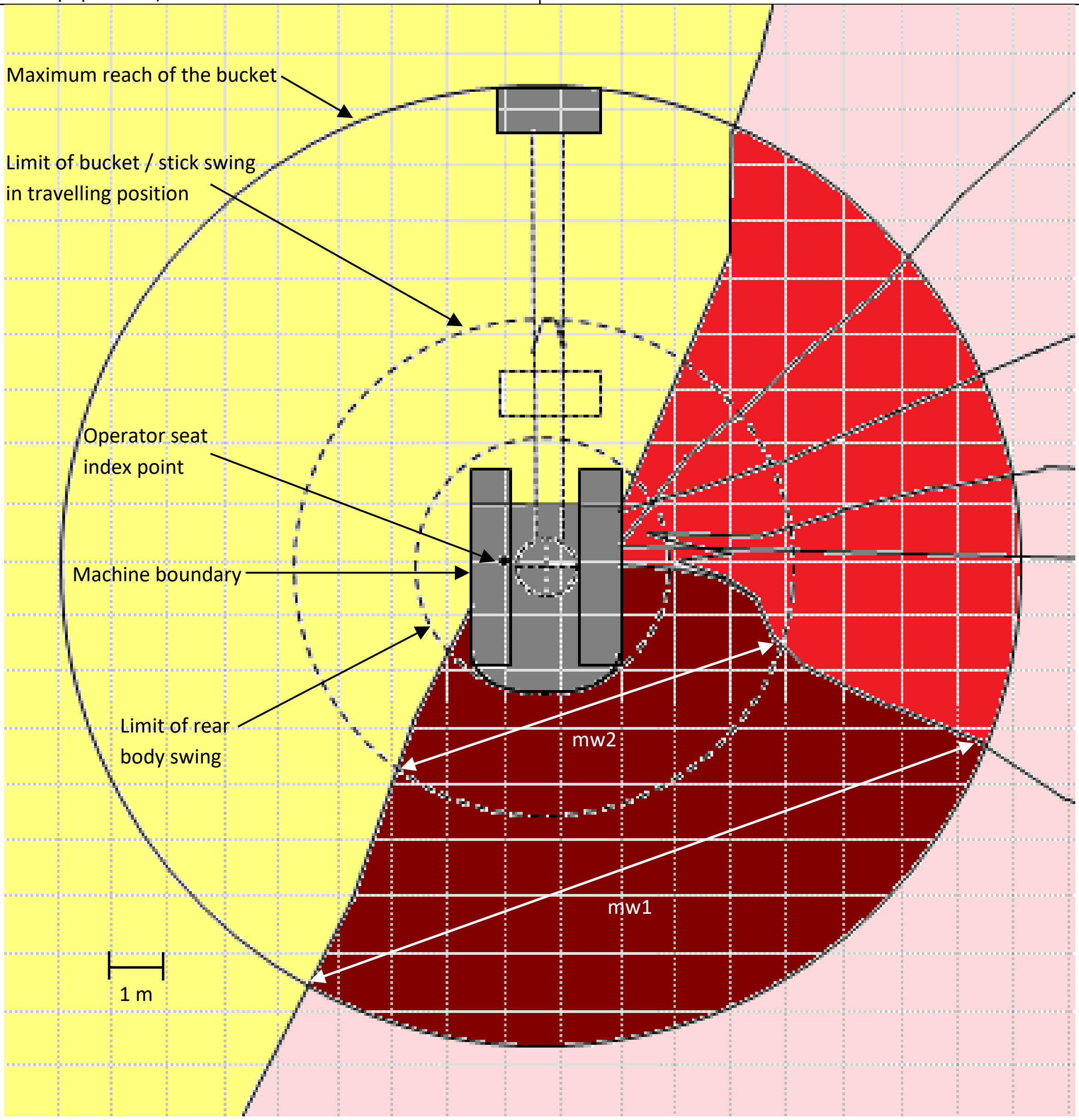
8.2 Evaluation of visibility risk zones for a hydraulic excavator, fitted with a camera monitoring system providing a surround view

Photograph 4 Travel position of the hydraulic excavator included in the trial of the visibility risk zones method

Photograph 5 Boom raised back

Photograph 6 Maximum reach at ground level

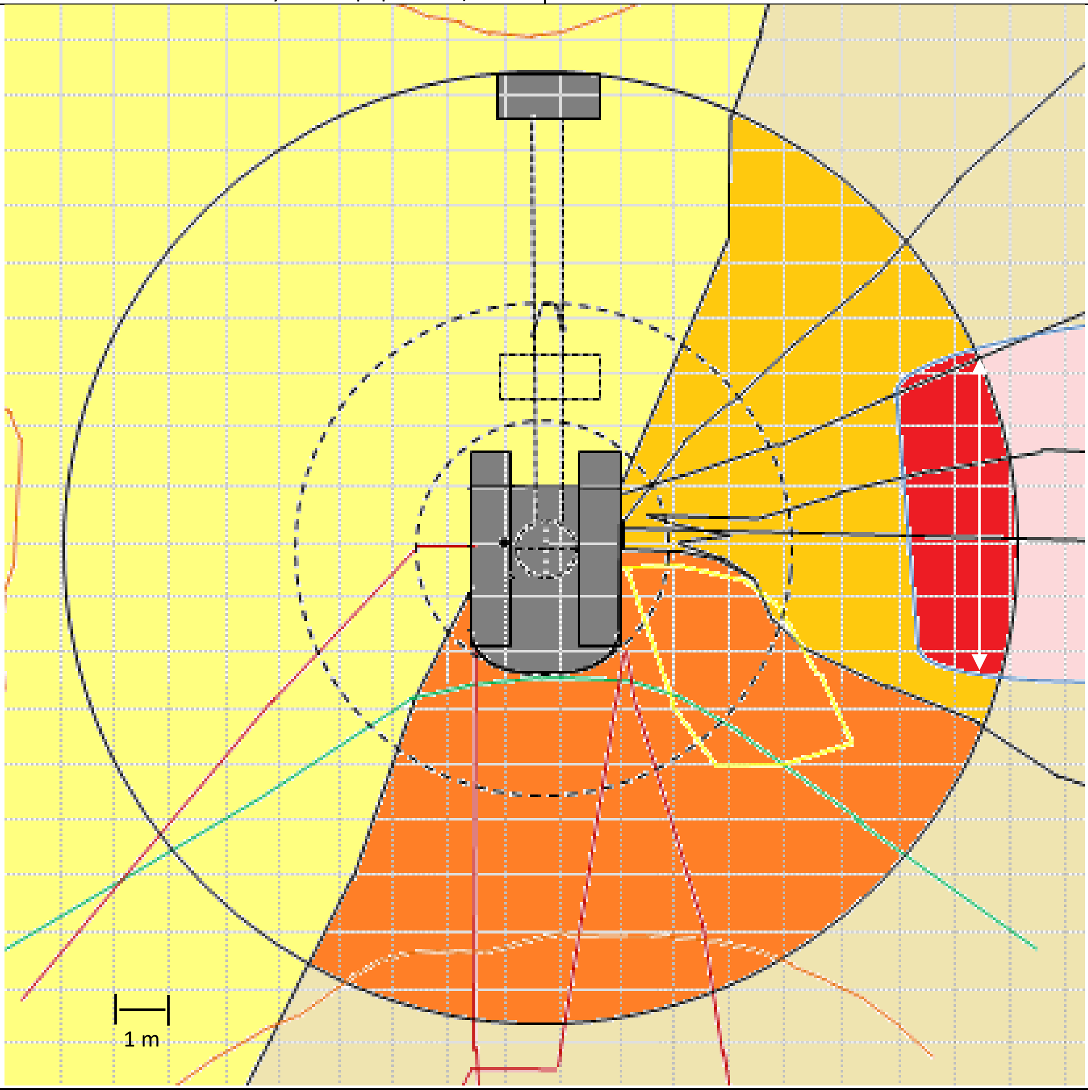
Machine: Hydraulic excavator	Scale: 1:154 (approx.)
Operating mass: 14,200 kg Attachment: Ditching bucket (1830 mm x 730 mm)	Machine configuration: Working Boom position ranges from fully raised back position to maximum reach at ground level
Test: Direct visibility	Height of vertical test object: 1.5 m
Observer: JF 830 mm sitting eye height (75th percentile for British 18 – 64 year old population)	Observer eye height above cab floor: 1250 mm Observer eye height above sitting surface: 750 mm Observer movement: Head and torso movement



Dark red = masking in a collision risk area, caused by the machine body
Red = temporary masking in a collision risk area, caused by the boom
Pink = masking / temporary masking outside the collision risk area
Yellow = area of direct visibility (no masking)

Maximum masking width: Caused by machine body: 12.70 m within limit of maximum bucket reach (mw1) 7.14 m within the limit of bucket swing in the travelling position (mw2)	Masking in the collision risk area:: 64 m^2 masking caused by the machine body 45.5 m^2 temporary masking caused by excavator boom

Machine: Hydraulic excavator	Scale: 1:154 (approx.)
Operating mass: 14,200 kg Equipment: Ditching bucket (1830 mm x 730 mm)	Machine configuration: Working Showing the range of boom position, from fully raised back position to maximum bucket reach at ground level
Test: Direct and indirect visibility Left side mirror Rear view camera monitoring system Surround view camera monitoring system	Height of vertical test object: 1.5 m
Observer: JF 830 mm sitting eye height (75th percentile for British 18 – 64 year old population)	Observer eye height above cab floor: 1250 mm Observer eye height above sitting surface: 750 mm Observer movement: Head and torso movement



Red = temporary masking in the collision risk area

Pink = masking outside the collision risk area

Orange = collision risk area only visible with the use of visibility aids

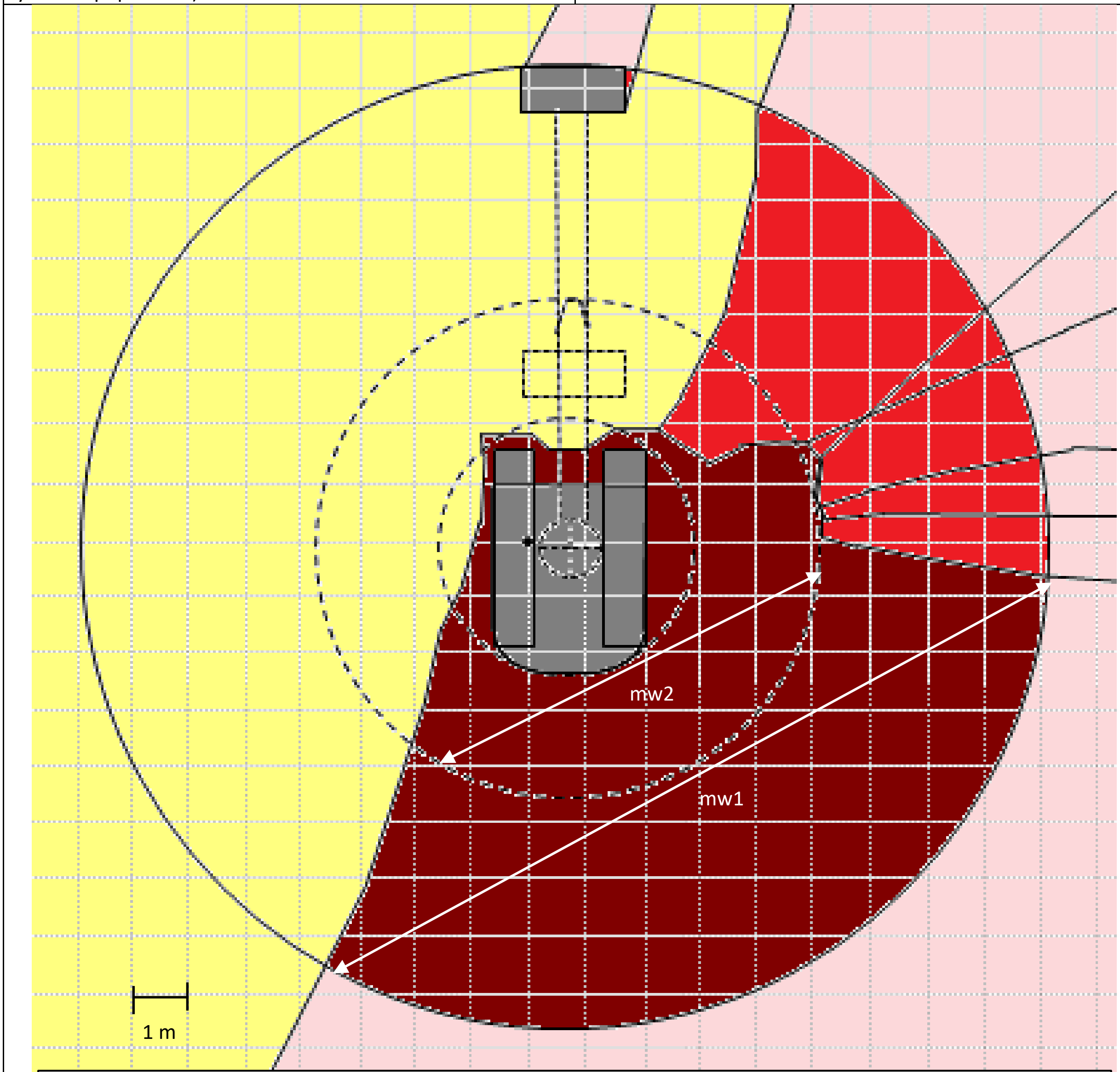
Amber= collision risk area, temporarily only visible with the use of visibility aids

Beige = outside the collision risk area, only visible with the use of visibility aids

Yellow = area of direct visibility (no masking)

Maximum masking width: 5.70 m temporary masking caused by boom movement	Masking in the collision risk area: 0 m^2 masked by machine body 9.5 m^2 temporarily masked by excavator boom

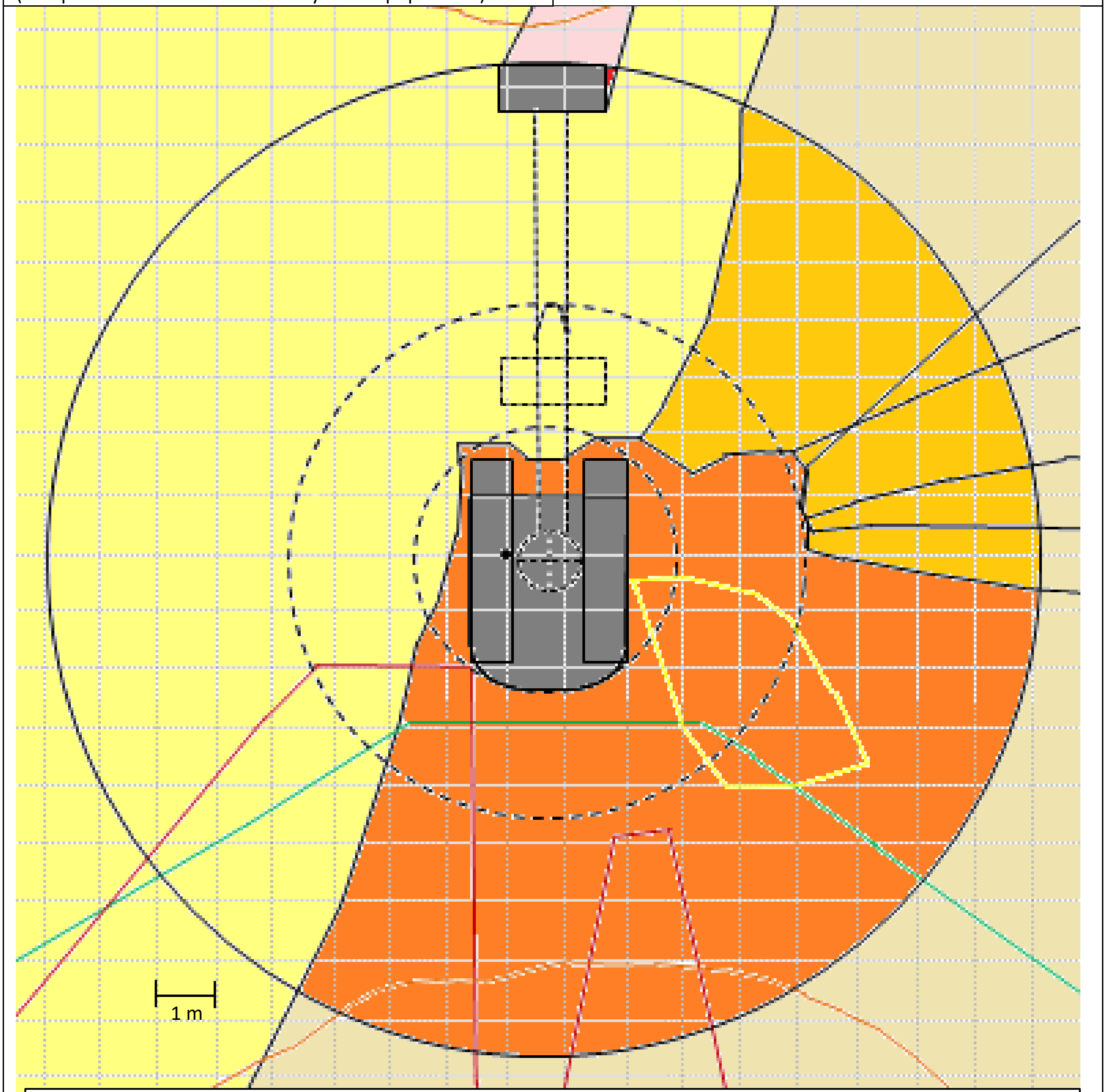
Machine: Hydraulic excavator	Scale: 1:154 (approx.)
Operating mass: 14,200 kg Attachment: Ditching bucket (1830 mm x 730 mm)	Machine configuration: Working Boom position ranges from fully raised back position to maximum reach at ground level
Test: Direct visibility	Height of vertical test object: Ground level
Observer: JF 830 mm sitting eye height (75th percentile for British 18 – 64 year old population)	Observer eye height above cab floor: 1250 mm Observer eye height above sitting surface: 750 mm Observer movement: Head and torso movement



Dark red = masking in a collision risk area, caused by the machine body
Red = temporary masking in a collision risk area, caused by the boom
Pink = masking / temporary masking outside the collision risk area
Yellow = area of direct visibility (no masking)

Maximum masking width: Caused by machine body: — 14.2 m within limit of maximum bucket reach (mw1) — 7.6 m within the limit of bucket swing in the travelling position (mw2)	Masking in the collision risk area: 92 m^2 masking caused by the machine body 34.5 m^2 temporary masking caused by the boom

Machine: Hydraulic excavator	Scale: 1:154 (approx.)
Operating mass: 14,200 kg Equipment: Ditching bucket (1830 mm x 730 mm)	Machine configuration: Working Showing the range of boom position, from fully raised back position to maximum bucket reach at ground level
Test: Direct and indirect visibility Left side mirror Rear view camera monitoring system Surround view camera monitoring system	Height of vertical test object: Ground level
Observer: JF 830 mm sitting eye height (75th percentile for British 18 – 64 year old population)	Observer eye height above cab floor: 1250 mm Observer eye height above sitting surface: 750 mm Observer movement: Head and torso movement



Pink = masking / temporary masking outside the collision risk area
Orange = collision risk area only visible with the use of visibility aids (masking caused by machine body)
Amber= collision risk area, temporarily only visible with the use of visibility aids (masking caused by moving boom)
Beige = outside the collision risk area, only visible (or temporarily only visible) with the use of visibility aids
Yellow = area of direct visibility (no masking)

Maximum masking width: 0 m	Masking in the collision risk area: 0 m^2

10. References

The following referenced documents are indispensable for the application of this document:

ISO 5006, Earth-moving machinery – Operators field of view – test method and performance criteria

ISO 3411, Earth-moving machinery – Human physical dimensions of operators and minimum operator space envelope

ISO 7457, Testing earth-moving machinery – Determination of turning dimensions of wheeled machines

ISO 14401, Earth-moving machinery – Field of vision for surveillance and rear view mirrors

ISO 15537, Principles for selecting and using test persons for testing anthropometric aspects of industrial products and designs

ISO 16001, Earth-moving machinery – Hazard detection systems and visual aids – Performance requirements and tests

13 APPENDIX F – CAMERA SYSTEMS PROVIDING A SURROUND VIEW

Visibility aids are available that take the images from multiple cameras fitted on a vehicle and typically merge these into a single image on a monitor, showing a surround view (or “bird’s eye view”) of the area around the machine (Photograph 7).

Photograph 7 Example of the monitor screen for a surround-view camera system (left) and conventional rear view camera system (right) fitted to an excavator (SDV_0428 (2:03))

The purpose of these systems is to improve the operator’s awareness of objects, such as pedestrians and other vehicles, around the machine, while reducing the need for the operator to repeatedly turn their head and move their upper body, or to view multiple mirrors and monitors.

Camera systems that provide a surround view can be used on their own, or in combination with other object detection systems (ODS) such as radar sensors or ultrasonic detector systems, to augment the operator’s direct vision and use of mirrors. This project has only considered the use of surround-view camera systems on their own, and has not considered how their performance might differ if combined with other ODS.

13.1 ISO 16001 (2017)

General requirements, test methods and performance criteria for CCTV camera systems providing a surround view are described in *ISO 16001 – Earth-moving machinery – Object detection systems and visibility aids – Performance requirements and tests* [17].

13.1.1 General requirements applicable to camera systems providing a surround view

Table 3 shows the general requirements of ISO 16001 that are applicable to camera systems providing a surround view.

Table 3 General requirements applicable to camera systems providing a surround view (ISO 16001 **[17]**)

Category	***Requirements***
4.2 Location and fixing	Components shall be located and arranged on the machine in accordance with the specification of the component manufacturer, so that: • the component does not restrict any function or operation of the machine; • the component is protected against external damage; • the component is affixed to the machine so as to deter unauthorised disablement or removal; • the component is mounted so as to limit exposure to, or amplification of, dynamic loads, temperature, shock or vibration that could permanently damage the device; and • the attachment and fixings do not affect the integrity of the protective structures (eg rollover protective structures).
4.3.1 Location of monitor	The monitor shall be located within the 180° arc centred in front of the operator. Restriction of the operator's view of the working area or machine working equipment shall be minimised. The image on the monitor should be displayed in the most intuitively logical way for the application, typically as a 'normal' image and not a 'mirror' image.1 The monitor should be within 1.2m of the operator's eye point. If the monitor location is more than 1.2 m from the operator's eye point, the displayed images shall be enlarged proportionally according to the monitor. The monitor shall be positioned so as to minimise the glare caused by direct sunlight.
4.4 System activation and initial check	The system shall activate automatically on engine start or power-on, shall perform an initial system check, and shall give a proper function indication (e.g. displaying the image from a camera on the monitor fulfils this requirement). The system may remain in stand-by mode unless the relevant machine movement mode is selected. If stand-by mode is provided, the system shall wake up and provide information from the camera or about the direction of machine motion when the machine moves. If multiple cameras are fitted, the system shall provide the camera view appropriate to the direction of travel or other machine movement, for example: • by using multiple monitors each of which provides information about its corresponding camera; • by using a single monitor which sequentially provides information about multiple cameras; or • by using a single monitor which simultaneously provides information about multiple cameras.
4.6 Continuous self-checking	The availability of an image of the detection zone on the monitor is sufficient as a monitoring function for a visibility aid.

Category	*Requirements*
4.8 Electromagnetic compatibility and physical environment and operating conditions	The electromagnetic compatibility of visibility aids shall comply with ISO 13766 [43]. The physical environmental conditions in which the visibility aids are used shall be according to ISO 15998 [44].
5 Marking and identification	Each major component (e.g. camera, sensor, monitor and controller) shall bear legibly and indelibly the manufacturer, type and model, product serial number, and regulatory markings as required.
6.1 Operator’s manual	An operator’s manual complying with ISO 6750 shall be provided (or may be integrated into the appropriate manual for the base machine), and shall contain he following: • description of system function; • detection area shape and size, and variances according to operational and external factors (e.g. interference, weather, presence of other systems); • information for job-site organisation as it relates to the use of visibility aids; • weather limitations; • topography limitations, as required; • instructions for routine maintenance, including necessary countermeasures against environmental conditions that could impair the systems sensitivity or its ability to discriminate objects; • instructions for activation; • description of controls; • instructions concerning safe operation; • instructions on action in the event of malfunction; • regulatory certifications; • countries for which type approval has been achieved; and • recommended routine for regular performance checks by the user.
6.2 Other documents	If separately placed on the market, visibility aids shall have additional instructions covering: • detailed description of performance and operating limits, in particular the effect of different mounting heights and angles; • instructions for installation and assembly, including mounting location, if required; • instructions for perfromance verification; • information for connection with other components, if required; and • electrical supply requirements, as required.

13.1.2 Factors to consider during the selection of visibility aids, including camera systems

Annex A (informative) of ISO 16001 describes the functional aspects (eg user needs, operating environment, and machine functions) that should be considered when selecting an object detection system or visibility aid. This includes a list of the advantages and disadvantages of the various technologies, including closed-circuit television (CCTV) camera systems (Table 4).

Table 4 Advantages and disadvantages of camera systems described in ISO 16001 **[17]**

Description	Device uses wide-angle lens cameras with a monitor in the cab.
Advantages	Scratch, dirt and water resistant. Works in low light conditions.
Disadvantages	Distortion makes distances hard to judge. Direct light in the camera causes visibility problems. Direct sun on monitor blocks the image. Objects in shadows are difficult to distinguish. Mud and dust on camera lens can distort the image (but can be removed by built in wash/wipe systems).

13.1.3 Test method for CCTV camera systems providing a surround view

Annex G describes a test method to determine the detection area for CCTV camera systems providing a surround view. The test object is a closed top cylinder, 1600 mm in height, 400 mm in diameter, and with the top and bottom painted or marked so that they are discriminated as mock-head and feet. These dimensions are based on the Rotakin test body that has been developed for testing CCTV surveillance systems (EN 50132-7 [45]).

With the camera set up on the parent machine as designed, a grid is then marked on the ground covering the detection area. The size of the grid mesh is determined through risk assessment. The test body is then placed on each point of the grid mesh, while the size of the test body image on the monitor is measured to confirm whether it is equal to or larger than 7 mm and whether both the head end and leg end of the test object are represented on the screen at the same time. Locations where the size of the test body image on the monitor becomes less than 7 mm, or where either end of the test body is not represented are considered outside of the detection area. ISO 16001 [17] states that the 7 mm minimum screen image height “is approximately 10% of the vertical screen height, which is normally considered acceptable for visual detection purposes”, although more recent research [18] suggests that this should be increased to a minimum screen height of 10 mm for more reliable detection.

For each camera in the surround view system, the performance requirements and tests for single CCTV camera systems (Annex B) would also apply. These specify requirements for determining the:

- horizontal and vertical field of view;
- range;
- system resolution;
- effect of light on resolution;
- edge distortion;
- screen edge resolution;
- effect of high intensity light (direct sunlight);
- recovery from radial change in light levels;
- functional tests to verify the operation of additional features; and
- recording of test results.

13.2 LITERATURE SEARCH RESULTS

The search of published literature found only two papers relevant to performance criteria for surround-view camera systems. Such a small number of papers was expected, given that the technology was relatively new and evolving quickly. One of the two papers was subsequently excluded during the full paper review, as it considered the human factors criteria when using this technology to drive vehicles from a remote location. A further paper was published during the course of this project

Kivett *et al* [46] describe how it is a challenge for designers of in-vehicle technology to balance the right level of information to improve driver awareness without adding so much that the increased mental workload presents a distraction beyond that which can be processed safely by most drivers. They propose to identify relevant factors not presently incorporated into standard procedures, and recommend how to quantify the performance of a visibility system beyond simply the field of view. They coin a new metric, "Clarity of View", to provide a quantified framework for evaluating these systems that takes account of the response time and accuracy of technology, as well as the response time and accuracy of the driver. The factors are:

- field of view;
- image detection time;
- image distortion;
- gap acceptance; and
- glare discomfort.

The researchers do not actually describe measurement techniques or performance criteria for these factors other than what already exists for field of view evaluation. This would appear to be the focus of further experimental work using driving simulators.

Jegen-Perrin *et al* [18] evaluated how factors such as pedestrian image size, screen size, and camera angle affect the detectability of a pedestrian by a driver using a single camera and screen system, which might be fitted to the rear of side of earth-moving machinery. This was a laboratory-based study in which 15 plant operators were shown a series of images, pre-recorded with three types of camera, on three different types of screens. The images were shown for 0.5 s, representative of a 'quick glance', and operators had to report if and where on the screen they had seen a pedestrian. The screen was positioned approximately 1 m away for the operator's eyes.

Although the research did not consider surround-view systems, the researchers made several of interesting observations and design recommendations:

- Moving pedestrians were detected systematically; errors in detection were only found for stationary pedestrians.
- Under optimum conditions, there were no detection errors when an apparent height of a pedestrian on the screen was 10 mm. However, the rate of non-detection did increase to more than 25% when other variables related to the environment were taken into account (eg position of the pedestrian on the screen, pedestrian clothing, light pollution, and obstacles in the viewing environment). They recommend that, when defining the range of a

camera-screen system, the height of a 5th percentile pedestrian (1.55 m in stature) on a screen should be a minimum of 10 mm.

- No pedestrians were detected in the screen, when at the height of their image was 2 mm.
- Screen size had little effect on the rate of detection, but they suggested a tendency (non-significant) for smaller screen sizes to result in fewer detection errors, possibly because there is less screen surface area for the operator to scan. They suggested that the choice of screen size should more usefully take account of other factors such as space available within the cab and the extent to which the screen obstructs the operator's direct visibility.
- A pedestrian was seen four times less well at the edge of the screen than at its centre. Thus, when selecting a camera angle, the camera should cover an area that is broader than the surveillance zone, so as to avoid the edges of that zone coinciding with the edges of the screen. Once this criterion is satisfied, a camera should be chosen with the largest angle of view, which provided the lowest rates of detection errors.
- Operators recognised the risk of non-detection, however, they overestimated their performance. The majority of operators estimated their number of detection errors to be in the range of 51 – 100 (out of 340 images); however, the detection error was actually 140 on average.

13.3 OBSERVATIONS FROM A SITE VISIT

In 2015, HSE undertook a preliminary examination of camera systems providing a surround view, which were fitted to excavators and compaction rollers in use at a highways construction project. Key observations and lessons were as follows.

- Although there is no substitute for direct vision and risk appropriate management of the vehicle and pedestrian interface based upon an understanding of the direct visibility limitations of the vehicle, the introduction of camera systems providing a surround view was generally seen as a positive step.
- The systems (products) seen in use appeared to be useful supplements to, or even possibly viable alternatives to, mirrors. They provided information relating to the presence or absence of pedestrians around the vehicle in a single screen location. This could also have operational advantages.
- The operators spoken to valued the information the systems provided, trusted in them, and quickly learned how to use them to establish the presence / absence of pedestrians around the vehicle, provided those pedestrians provide high contrast with the background. They were not reported to be as useful for judging the position or movement of the machine during manoeuvring.
- The best installations seen were considered to fall short of the performance standards envisaged from supplier promotional material. Screen quality varied, resulting in some poor image viewing conditions during daylight. In particular, screen surface reflectance and contamination needs to be minimised for systems to be effective under sunlight conditions. Screen location also needs careful consideration. It should not obstruct direct vision in any way. The location needs to be selected to best compliment the visual tasks being performed.
- For some systems observed, there was too much complexity in the setup available to the machine operators. While complexity and flexibility in the capability of the product may be

advantageous, for operator usability, these features may need to be restricted according to the particular context of use.
- Whilst this was not established with any certainty, it was suspected that the combination of physical and software set up is critical to overall system performance.

13.3.1 Additional requirements identified during a site visit

From this site visit, some additional requirements were also identified that do not appear to be covered in ISO 16001 [17].

- The cameras should be mounted to minimise the overlapping of images at the key risk areas around the machine (eg access and fuelling areas).
- The device should be adjusted to minimise any ‘ghosting’ effect of the test object within the area of overlapping images.
- The camera should be mounted so that they are not obscured or impaired by the opening of doors or windows.
- The device should provide a clear indication in the event that the operation of one or more of the cameras is impaired (eg using a visual and / or audible signal, or removing the image from the monitor).
- For operator usability, customisation features may need to be restricted according to the particular context of use.

13.4 FINDINGS FROM DISCUSSION WITH MANUFACTURERS

Respondents were not forthcoming with much information on camera systems providing a surround view. They acknowledged that there was good potential for them to compensate for the lack of direct visibility, but that additional development was still needed to improve performance and reliability. Some reservations were also expressed about the introduction of this technology. For example, it was still not well understood how operators might use the systems during machine operation. There was a view that operators need to take account of the ‘blind spots’ on these systems (ie where the cameras are out of range or the image is too distorted for reliable detection).

13.5 TRIALS OF SYSTEMS FITTED TO RIGID FRAME DUMPERS AT A SURFACE MINE

In combination with a visit to a surface mine (see section 5.2), discussions were held with the Site Project Manager to discuss their trial of camera systems providing a surround view that they had fitted to their rigid frame dumper trucks during 2013. The trial was run over a period of 6 months of operations. Three systems were trialled during this period, fitted to the following selection of the vehicles used at the site. These replaced the two conventional camera monitoring systems, directed to the right side and rear of the dumper truck, which were normally used at the site.

A total of 10 – 12 drivers were reported to have been included, spanning all shifts. However, since drivers tended to operate a particular vehicle, there were only 2 or 3 drivers per vision system, as a result of the shift rota. It was not possible to discuss the trials with the group of drivers involved.

The following usability feedback was reported from the drivers:

- Drivers reported that they preferred the conventional right side camera view, as this provided greater range than the surround-view systems.
- All systems caused the drivers problems during night working because the screens were too bright, even when fully dimmed. This interfered with normal driving.
- All systems seemed to have problems in wet weather when water on the cameras distorted the images displayed.
- Mud contaminated the cameras and caused problems.
- Drivers generally expressed that the images displayed can be distorted and unclear.
- Drivers using one system that incorporated a proximity detection and warning system, reported receiving too many warnings from the system, causing distraction, and it was considered as a nuisance.

It is not clear where the cameras for these systems were mounted for the trial. This may have been a factor in their performance, such as weather and contamination, and with the ability to be cleaned. Some of these issues would also be applicable to mirrors and conventional camera monitoring systems.

The consensus reached at the review meeting (seven drivers, plus a supervisor present) was to return to the conventional approach of having two cameras and two monitors directed into the particular zones where direct and mirror visibility was lacking (ie the right side and rear).

13.6 EVALUATION OF A SURROUND VIEW CAMERA SYSTEM FITTED TO AN EXCAVATOR

As part of the application of the visibility risk zones method to a medium sized excavator (see Section 5.3) a camera monitoring system providing a surround view was evaluated, which included consideration of the extent to which the system provided coverage across the entire collision risk area of an excavator. Further detail of this evaluation is contained within a supplementary report [19].

The evaluation found that the surround-view system was able to compensate for limitations with the use of the excavator's right side mirrors, providing the operator with indirect visibility to the right side of the excavator regardless of the boom position or surrounding light levels, and without requiring the operator to turn and look over their right shoulder. The system eliminated the residual masking areas at the rear corners of the machine and to the right side of the excavator. It was particularly useful at eliminating residual maskings of a person standing to the right side of the excavator and within 5 m of the machine boundary, which was roughly equivalent to the area into which the machine bucket could rotate while the machine was in its travelling position.

However, to the right side and rear of the excavator, where a pedestrian is standing more than 5 m away from the machine boundary, their image on the surround-view camera monitor may not have been of a sufficient size to allow for the operator to detect them reliably. For this excavator, a trade-off of the system providing a surround view on the monitor was that it did not show the far field of view. In contrast, a conventional camera monitoring system, that the original equipment manufacturer fitted to the rear of the excavator, provided indirect visibility out to the edge of risk zone for machine operation (as defined by maximum reach of the bucket) and further away to the horizon. This improved coverage of the far field of view may improve the operator's situational awareness in that they would be provided with the opportunity to view pedestrians and other vehicles outside of the working envelope moving towards the excavator. The opportunity to see the far field of view would also be important when the machine is tracking in reverse or to the right; for example, tracking to the right during trenching work. In this case, providing the operator with the opportunity to view the far field of view would help them to anticipate the potential for collision with obstacles outside the working envelope. This evaluation also showed that the rear view camera monitor provided larger image sizes of pedestrians on the display at further distances, and reduced image distortion, which may help to improve the reliability of detection.

On the surround-view camera system evaluated, the image of the pedestrian was observed to disappear where the pedestrian was standing at the rear corner of the machine boundary. The effect was less apparent when the pedestrian was moving. The extent to which it may be possible to eliminate the disappearance effect at the boundary between cameras with changes to the camera or software configuration is not known. However, where the disappearance cannot be avoided, adjustments may be possible so that the overlap between cameras is located in either an area of direct visibility to the operator or, if this is not possible, then within an area which is more clearly ‘in view’ of another visibility aid, such as the rear view camera.

13.7 CONCLUSIONS

Camera monitoring systems providing a surround view have been found to be useful supplements to the range of visibility aids available, with good potential to compensate for the lack of direct visibility and, for some applications, limitations in the coverage and effectiveness that can be achieved with mirrors and single camera systems.

The strength of the surround-view camera systems is their ability to provide information quickly about the presence or absence of pedestrians around the machine on a single monitor. However, system installation and configuration appear critical in ensuring that there are no gaps in coverage and that the systems provide the level of performance expected of them. This review along with the visibility risk zones method described in this report (Appendix E) offers end-users an approach to evaluate the extent to which these systems provide acceptable coverage within the collision risk area.

Where these systems are being considered as an alternative to conventional single camera systems, careful consideration needs to be given to what the operator needs to see to maintain greatest situational awareness. With the surround-view systems, operators have the potential to view all around and close to the machine; however, there is a trade-off in that these systems observed as part of this work did not display the far field of view out to the horizon. The selection and configuration of a system providing a surround view must take account of the machine’s configurations, and what the operator’s needs to see, as well as the environment in which the machine is intended to be used.

Technologies are advancing to improve the reliability and performance of camera systems and other object detection systems. Significant improvements in the performance of systems providing a surround view is likely to come through their integration with other technologies, allowing the strengths of these technologies to compensate for limitations associated with systems that rely on operator vision for detection.

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Visibility risk zone method to evaluate operator visibility for earth-moving machinery

In Great Britain there are 25 fatal injuries each year on average, and hundreds of non-fatal injuries to workers as a result of being struck by moving vehicles in the workplace. Restricted operator visibility is often identified as a contributing factor in these accidents.

This report describes the development of a risk-based method to determine 'visibility risk zones' for earth-moving machinery such as dumper trucks and excavators. It considers operator visibility all around a machine from its boundary out to the far field of view. The method assists users to: define the areas around a machine that the operator needs to view; identify the areas the operator cannot see; and determine the areas where visibility aids such as mirrors and camera systems are required. The method takes into account the configuration of the machinery and how easy it is to manoeuvre during operation and travel. The method may be useful to assist in the following tasks: (1) Evaluation and verification of machines; (2) Installation of visibility aids and detection systems; (3) Assessment of risks to workers on a jobsite; (4) Organisation of a jobsite to ensure that risks are well controlled; (5) Incident investigation.

Two related reports describe the use of this visibility risk zone method to evaluate operator visibility for an hydraulic excavator (RR1157) and a large rigid frame dumper truck (RR1158).

RR1156

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