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Investigation of Machine-Mounted Area Lighting to Reduce Risk of Injury from Slips-Trips-Falls for Operators of Mobile Surface Mining Equipment

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Abstract

Nonfatal injuries from slips, trips, and falls (STF) that occur at surface mines can result from inadequate lighting. Mobile equipment operators are among the occupations associated with the nonfatal incidents reported to the U.S. Mine Safety and Health Administration (MSHA). In addition, getting on/off the equipment (ingress/egress) frequently adds to the highest proportion of nonfatal incidents. Accordingly, researchers at the Pittsburgh Mining Research Division (PMRD), National Institute for Occupational Safety and Health (NIOSH) conducted a field study to investigate lighting on haul trucks and wheel loaders with regard to glare and illuminance levels recommended by the Illuminating Engineering Society (IES). The objective was to determine whether two light-emitting diode (LED) area luminaires—a Mr. Beams® (model MB390 Ultrabright) (area luminaire-1) and a NIOSH-developed Saturn (custom-designed for a mine roof bolter study) (area luminaire-2)—could complement a headlamp luminaire. Measured levels of visual tasks, with the headlamp alone and the area luminaires plus the headlamp, demonstrated that illuminance met or exceeded IES-recommended levels. Nevertheless, the area luminaires illuminated a much broader area, which is key to increasing hazard awareness. Discomfort and disability glare were lower with area luminaire-1 than with area luminaire-2. Differences in glare were more noticeable for newer models of haul trucks and loaders featuring updated ingress/egress system designs. This study demonstrates that commercially available luminaires, such as area luminaire-1, are capable of complementing headlamp lighting, and can thus improve a miner's ability to detect and avoid STF hazards.

Keywords

Surface mining equipment; Machine-mounted lighting; Slip-trip-falls; Glare; Ingress/egress systems

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Compliance with Ethical Standards

Conflict of Interest The authors declare no potential conflicts of interest with respect to the research, authorship, and/or publication of this article. The mention of any company or product does not constitute endorsement by NIOSH. The findings and conclusions in this paper are those of the authors and do not necessarily represent the official position of the National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention.

1 Introduction

Mobile equipment operators in the surface mining industry are routinely exposed to slip-trip-fall (STF) hazards. Insufficient or ineffective lighting is a factor associated with nonfatal incidents and injuries [1], which constitute a significant burden to the mining industry [2]. Injury/illness data from the Mine Safety and Health Administration (MSHA) show the second leading cause of nonfatal incidents is related to STF hazards [2]. Among the most common surface mine worker occupations associated with nonfatal incidents reported to the MSHA [3] is that of mobile equipment operators. Getting on/off the equipment (ingress/egress) is associated with the highest number of mobile equipment related nonfatal incidents. The results of a recent study revealed that mobile equipment operators believe that proper illumination is an important element of safety for ingress/egress systems [4].

Sammarco et al. have performed mine illumination studies of miner headlamp and machine-mounted systems with regard to glare, visual performance, and hazard detection for workers in underground coal mines [5–7]. In more recent works, Sammarco and his research team investigated lighting on an underground coal mine roof bolting machine [8–10]. The study evaluated the existing machine lighting system compared with a novel custom-designed and custom-built Saturn luminaire. The NIOSH-developed Saturn luminaire features a light-emitting diode (LED) array with 12 cool-white LEDs and a secondary optic to provide a type III lighting distribution intended for luminaires mounted at or near the side of medium-width roadways. The intensity of the luminaire was dimmed to 75% and 50% of full intensity to investigate how light intensity affects glare. The design of the Saturn luminaire focused on (1) enhancing floor illumination for better trip hazard detection and (2) minimizing glare, routinely an issue of concern for mine roof bolter operators.

An earlier preliminary study [11] gathered data regarding illuminance levels on and about mobile surface mining equipment and their ingress/egress systems. Thirty-eight mobile mining machines were included: 19 haul trucks, 12 front-end wheel loaders, 3 bulldozers, 3 excavators, and 1 motor grader. All measurements were made during pre-dawn hours to mimic start-of-shift activities that drivers/operators experience during fall-winter-spring seasons of the year. The findings indicated that illuminance levels on the first rung of the equipment ladder were poor with no-task lighting, whereas illuminance on the ground below the first rung was poor with task lighting (provided generally by a headlamp luminaire), possibly as a result of shadows. Illuminance on the platform above the ladder was generally the highest compared with levels measured on the ground below the first rung and at the first rung of the equipment ladder. It is worth noting that illuminance levels were inadequate when compared with standards recommended by the Illuminating Engineering Society's (IES) lighting handbook, as presented in Table 1 [12, 13]. The IES recommends 100–200 lx for working areas where visual tasks are only occasionally performed. This was the case for the first rung on ladders and the ground below the first rung, even when task lighting was present.

This paper reports the results of a field study at a crushed limestone mine in northwestern Pennsylvania. More than 1370 photometric, angular, and distance measurements were performed on and around two haul trucks (HTs) and two front-end wheel loaders (FELs).

One HT was older, and one FEL was smaller and older, as shown in Fig. 1 and Table 2. The objective of the study was twofold: (1) to assess whether illuminance levels could be improved for ingress/egress systems and pre-shift walkaround inspections of equipment during nighttime hours, and (2) to compare illuminance and glare levels when using a commercially available LED area luminaire—Mr. Beams® (model MB390 Ultrabright) (area luminaire-1)—and the prototype NIOSH-developed Saturn (area luminaire-2), together with the existing headlamp luminaire provided by the mine operator (Fig. 2). An online search was carried out to determine what commercially available luminaire(s) might be appropriate and available for the intended surface mine equipment application to compare with luminaire-2. Several lighting products were considered, and luminaire-1 was selected based on its features and low cost and on the personal knowledge and experience of one of the study's authors. Moreover, luminaire-1 is typically marketed to residential customers. We selected the Saturn luminaire because of the positive results demonstrated in the mine roof bolter study [9, 10]. The two LED luminaires would constitute glare sources, whereas the headlamp would not be a glare source and instead would account for ambient lighting during trials of the ingress/egress and pre-shift walkaround activities.

2 Methods

2.1 Study Description

The equipment and instrumentation used in the study included illuminance and luminance meters (models T-10A and LS-100, respectively, Konica Minolta Sensing Americas, Inc., Ramsey, NJ, USA), a laser distance and angle finder (Bosch model GLM 80), and a reflectance standard (Photo Research model RS-3). The luminaires included (1) area luminaire-1, a commercially available wireless LED area luminaire (although area luminaire-1 is advertised as a "spotlight"), (2) area luminaire-2, a custom-designed LED luminaire, and (3) the LED headlamp (Fig. 2). While area luminaire-1 operates with four D-cell (1.5-V) batteries, area luminaire-2 requires a separate 110-V power supply and the use of an extension cord. Lumen output of the area luminaires corresponded to 400 lm and 663 lm for area luminaire-1 and area luminaire-2, respectively. The mine-issued headlamp (Bushnell model Rubicon H150L LED luminaire) provided the existing task illumination at 173 lm. Other items included adjustable light-weight tripods, aluminum mounting brackets and magnets for positioning and securing the area luminaires, duct tape to tightly secure brackets to a handrail, and rope for hoisting luminaires and brackets to the machine upper deck contiguous with the machine operator cab.

The test luminaires were first mounted to the haul truck, then positioned and secured after obtaining the desired light distribution pattern and area coverage, as follows. For the HTs, both LED luminaires were placed on the handrail or the side of the operator cab near the door of the operator cab and adjusted to avoid shadows from the handrail, deck leading into the cab, or other machine components. This was also the location selected for both FELs. Another location for the luminaires during measurements of the more elaborate ingress/egress system of the newer, larger FEL (CAT 992 K) was the handrail at the mid-location of the deck leading to the operator cab door. Locations for mounting the two luminaires were similar but not identical, owing to the differences in the luminaire design, beam distribution pattern, and mounting brackets. The desired light patterns were visually selected for the areas of interest on the ground and ingress/egress systems. Area luminaire-1 provided a clearly defined circular pattern (Fig. 3) but a smaller area than area luminaire-2. In contrast, area luminaire-2 displayed a somewhat irregular and large elliptical-shaped pattern (Fig. 4). For measurements at the rear of the HTs and FELs, area luminaires were mounted in the vicinity and slightly above the row of lights and reflectors mounted in this location (back-up lights, warning lights, etc.).

Next, the selected tripod, representing the machine operator, was equipped with a mine worker's hardhat fastened to a rectangular plastic structure that allowed the T10A sensor head to be bolted at the approximate location of the worker's eye height of 1.7 m (66 in.). The tripod was positioned approximately 1.8 m (72 in.) from the ground at a marked target location and 0.3 m (12 in.) from the first rung of the ladder and on the ground at the driver's side front tire of the haul truck during pre-shift walkaround at approximately 1.2 m (48 in.) from the sidewall edge of the truck tire (Fig. 5a and b).

The visual targets of interest for the ingress/egress condition (depending on the equipment type included) were the ground below the first rung, the first rung, handrail-left, handrail-right, platform (front edge), platform 2, and first stair step. The newer models of HT and FEL feature the second platform, stairway rung, and extension of the handrail. The tasks comprising the pre-shift walkaround condition included the ground (driver's-side, front wheel), ground (driver's-side, mid-truck), ground (driver's-side, rear wheel), and ground (rear of the truck, 1.2 m [48 in.] out from the rear edge of the tire tread). Photometric, distance, and angular measurements were performed for each of these visual tasks, as follows: task target illuminance (measured directly using the RS-3), distance to the target, linear size of the target, target illuminance at the eye, target luminance, background luminance (an average of 2 to 4 measurements about the target depending on the shape and size), light source illuminance, ambient illuminance, surround illuminance, glare source illuminance at the eye, and angle at the eye between the light source and the target. Measurement units included lux (illuminance), nits (luminance), meters (feet or inches) for linear distance or target size, and degrees (angles). Some angles were obtained directly, whereas others had to be derived from geometric triangular distance measurements. The surround illuminance (Es) was obtained using a baffle arrangement affixed to the T-10A sensor head mounted to the tripod hardhat location that Sammarco et al. used in their lighting study [10]. The baffle, RS-3 reflectance standard, and LS-100 photometer are shown in Fig. 6.

2.2 Task Illuminance Levels

Considering the earlier study [11], the researchers were interested in determining whether adding a simple, inexpensive area LED luminaire and a custom-designed luminaire could improve illuminance levels on and about mobile surface mining equipment during nighttime hours. This would occur when using ingress/egress systems and performing pre-shift walkaround inspections. In view of the IES-recommended illuminance levels for industrial tasks of interest, luminance measurements were made on the visual task target with the LS-100 photometer and the RS-3 reflectance standard. Since the reflectance standard is considered to have a reflective surface of nearly 100%, illuminance is equivalent to luminance given this condition. Thus, in order to obtain illuminance from the measured luminance, one simply multiplies by π to convert from nits to lux, as shown in Eq. 1. This method was utilized in a previous surface mine lighting study by Mayton [14].

$$E = L * \pi \quad (1)$$

where E = illuminance (lux), and L = luminance of the visual task target/object (nits).

2.3 Calculating Discomfort Glare

To determine values of discomfort glare for the different area luminaires, the objective method was used to predict subjective values that make up the subjective De Boer rating scale. The De Boer method features a nine-point rating scale with odd-numbered verbal descriptors (Fig. 7). It was developed as a qualitative method for estimating discomfort glare from lighting systems [15].

The objective method used to predict the De Boer subjective rating was developed by Bullough et al. [16] and used by Sammarco et al. [6] in earlier mine lighting research. This prediction method employs Eqs. 2 and 3 to obtain the De Boer rating value, as follows:

$$DG = a(\log(E_1 + Es)) + b(\log(E_1 / Es)) - c(\log(Ea)) \quad (2)$$

where

DG discomfort glare;

E_l luminaire source illuminance (in lux);

Es surround illuminance (in lux);

Ea ambient illuminance (in lux).

Coefficients a, b, and c are set at 1.0, 0.6, and 0.5, respectively;

$$DB = 6.6 - 6.4 * \log(DG) \quad (3)$$

where DB = predicted De Boer rating.

As mentioned above, the surround illuminance *Es* was determined by designing and 3D-printing small baffles of different sizes ranging in diameter from 0.026 to 0.046 m (1–1.8 in.) that slid along a small cantilevered rod 0.18 m (7 in.) in length and 0.0032 m (0.13 in.) in diameter. The baffle allowed a shadow to be cast on the sensor surface in order to measure surround illuminance. A similar reading of ambient illuminance (*Ea*) was taken without the baffle attached.

2.4 Calculating Veiling Luminance to Indicate Disability Glare

Disability glare from the luminaire sources can be determined by calculating veiling luminance. This photometric quantity is used to indicate the extent of the glare issue owing to contrast reduction in the scene being viewed. To calculate the extent of veiling luminance, Eq. 4 was employed to obtain values for the different area luminaires and the visual tasks of interest [17].

$$L_v = 9.2E_o/\theta(\theta + 1.5) \quad (4)$$

where L_v = equivalent veiling luminance in cd/m^2 (nits); E_o = illuminance from the glare source at the eye in lux; θ = angle between the primary object and the glare source in degrees.

3 Results

3.1 Task Illuminance Levels

Overall illumination levels with the headlamp were higher than those in the earlier study mentioned above [11]. Measurements using the RS-3 to determine illuminance were taken and available for all but 2 of the 43 ingress/egress and pre-shift walkaround tasks. Figure 8 illustrates the average illuminance levels for the headlamp and the two area luminaires compared with the recommended levels from the IES standard. On average, all luminaires, including the headlamp, provided adequate illumination.

3.2 Discomfort Glare

Figure 9 displays the results for the ingress/egress visual tasks for all four machines. Considering the newer Komatsu haul truck (Fig. 9a), the De Boer ratings for area luminaire-1 show better results for all eight tasks and lower glare compared with area luminaire-2. The ratings for area luminaire-2 varied from a low of 4 to a high of 5, in contrast to area luminaire-1 ratings, which show a low of 6 and a high greater than 8. Figure 10a displays the predicted De Boer ratings for pre-shift walkaround tasks for the newer Komatsu haul truck. Area luminaire-1 results indicate lower discomfort glare values relative to area luminaire-2 at the driver’s side and rear areas for the pre-shift walkaround visual tasks. In Figs. 9b and 10b, glare values for the 777D haul truck show little difference between the two area luminaires for the ingress/egress tasks, and slightly better values for area luminaire-1 in the walkaround tasks.

Regarding the results (Fig. 9c) for the CAT 992 K wheel loader, the ingress/egress tasks showed slightly better values again for area luminaire-1, with a median value of 6 (one unit between satisfactory and just permissible) versus 5 (just permissible) for area luminaire-2. The walkaround tasks (Fig. 10c) showed dramatically lower glare (higher values) for area luminaire-1, ranging from between just noticeable and satisfactory to 7 units above just noticeable. This contrasted with area luminaire-2, which showed values ranging from just permissible to satisfactory. Similarly, the CAT 980C wheel loader results (Fig. 9d) for ingress/egress tasks showed only slightly better values again for area luminaire-1 versus area luminaire-2 for the front driver’s side tire location and the midpoint between the front and rear tires. Other task location values were the same, with a median value of 4, which is between just permissible and disturbing. On the other hand, the walkaround tasks (Fig. 10d) showed dramatically lower glare (higher values) for area luminaire-1 ranging from 8 to 10, one to three units above satisfactory, versus 7, satisfactory, for area luminaire-2.

3.3 Disability Glare

Concerning veiling luminance or disability glare, the data showed distinct differences in veiling luminance values for area luminaire-1 versus area luminaire-2. Depending on the visual task, the equipment, and the activity, the current available data illustrate that for most of the tasks, area luminaire-1 performs significantly better with regard to veiling luminance or disability glare. Eighty-six percent of the 43 tasks evaluated showed area luminaire-1 with lower levels of veiling luminance or overall better performance. There were three instances where area luminaire-1 did not show better veiling luminance. One was at the driver's side rear tire for the Komatsu HD785 (Fig. 12a). The other two were platform 1 (Fig. 11b) and the driver's side forward tire for the CAT 777D (Fig. 12b). Moreover, we observed instances where veiling reflections occurred during measurements of the handrails. Veiling luminance values varied from about 1 nit to 643 nits for area luminaire-1 versus 4 nits to 616 nits for area luminaire-2; the median values for the same luminaires were 14 nits and 80 nits, respectively. The average veiling luminance values with standard deviations were 75 ± 138 nits for area luminaire-1 and 178 ± 203 nits for area luminaire-2. Figures 11 and 12 illustrate differences in log veiling luminance for the two area luminaires and all four machines during ingress/egress tasks and during pre-shift walkaround tasks, respectively.

4 Discussion

When considering the IES-recommended illuminance levels for industrial tasks of interest, illuminance levels calculated by measuring visual task luminance with the RS-3 demonstrated that the headlamp and the two area luminaires coupled with the headlamp lighting provided adequate light levels on the HTs and FELs selected in this study. With very few exceptions, illuminance met or exceeded IES-recommended levels. The current work showed that the headlamp itself provided adequate lighting, in contrast to previous work suggesting that headlamps were not adequate [11]. This can be attributed to the way measurements were taken and the different headlamps used, which were not the mine-issued headlamp. In this study, a reflectance standard, RS-3, was used to measure illuminance, which provides a more accurate measurement. In addition, as part of this study, the headlamp was pointed directly at the area where the measurements were taken to mimic a miner pointing his light at the object/area being viewed. It should be noted, however, that a headlamp provides only a narrow beam of light with limited surrounding coverage (Fig. 13). In contrast, the two area luminaires illuminate a much larger area (Figs. 3, 4, and 13), which would be beneficial for hazard recognition and especially useful for recognizing slip, trip, and fall hazards on the ground surrounding the equipment.

The overall results for the discomfort and disability glare analysis indicated that area luminaire-1 is distinctly better than area luminaire-2 for use as supplemental lighting on mobile equipment. In various instances, the results were similar or slightly better for area luminaire-1. For the older and smaller CAT 980C wheel loader, the results were the same for both luminaires considering visual tasks performed for ingress/egress and walkaround inspection. These results were also better for the older CAT 777D haul truck. The more dramatic differences in discomfort and disability glare between the two area luminaires involved the newer Komatsu HD785 haul truck and CAT 992 K wheel loader. These machines featured newer, more updated ingress/egress system design, with easier mounting and placement of the luminaires for measurements.

When considering the differences between area luminaire-1 and area luminaire-2, an obvious difference is the lumen output for area luminaire-2, which was 66% higher than that of area luminaire-1 (400 lm). We noted earlier that neutral density filters were used in the Sammarco bolter study [10] test trials that enabled the area luminaire-2 to be evaluated for three variations of intensity (lumen output), i.e., at 100% (663 lm), 75% (494 lm), and 50% (332 lm). It also is important to note that the best results in that study [10] were obtained for area luminaire-2 intensity at 50%.

Another difference between the two area luminaires was the light distribution patterns. Area luminaire-1 is circular in shape and appeared better suited for the ingress/egress system, whereas area luminaire-2 feature an irregular elliptical-shaped pattern. Moreover, area luminaire-1 operates with four D-cell (1.5-V) batteries and features a motion-activated component. It is ideally suited for haul truck and wheel loader operators when boarding their equipment for the first time during nighttime hours and performing their pre-shift walkaround inspections. The area luminaire-2, on the other hand, requires a separate 110-V power source and extension cord to operate and does not presently include a motion activation feature.

The need for LED area lighting to supplement the task illumination provided by a headlamp is certainly demonstrated in this study. During data collection, we noted the presence of ruts 0.5–0.10 m (2–4 in.) or greater in the ground surface created by tire treads. These ruts are most pronounced after a rainfall that causes muddy operating conditions. Awareness and discernment of these hazards is critical to detecting and avoiding these slip-trip-fall (STF) rut hazards, and such awareness is not possible with the limited spot lighting from the headlamp. Rather, a broad beam and distribution pattern is needed, which can only be provided by an area luminaire that is preferably fitted with an LED source. The simple and low-cost area luminaire-1 appears to be a quick and practical solution for reducing STF injury risk. Other commercially available lights could be evaluated for use by carrying out the measurements described earlier. Of course, the location and placement of the area luminaires is critical to improving illuminance levels on the ingress/egress systems and the ground surfaces for the walkaround inspections. After optimization and securing of the area luminaires, maintenance and housekeeping are the next priority to ensure that dust, dirt, or debris does not accumulate on the lens or motion sensor that would diminish light levels.

4.1 Limitations

The testing in this study was conducted using a limited number of equipment types and ingress/egress system designs. Placement of the area luminaires was not always optimal, owing to the design features of the equipment and luminaire mounting devices available.

The Sammarco study [10] employed neutral density filters to reduce the light output of area luminaire-2 by a factor of 25% and 50% in the underground miner roof bolter study. In the present study, time constraints and mounting challenges did not permit an evaluation of area luminaire-2 using neutral density filters, and there was insufficient time for walkaround measurements on the passenger side of the vehicles studied. Nevertheless, we believe that similarities to the ground surface and vehicle components on the opposite side of the vehicles and similar luminaire mounting locations would yield results similar to those for the driver's/operator's side of the vehicle. Moreover, measurements of the area luminaires without the headlamp task lighting were initially considered, but it was determined that they did not accurately reflect actual mining conditions and activities, and also required more time than was available. The absence of this data was deemed to have little effect on the study findings in view of the reported data. Tests could not account for the likely accumulation of dust, dirt, or other debris that may occur during actual mining operations.

5 Conclusions

Area luminaire-1 showed superior performance relative to area luminaire-2 with regard to discomfort and disability glare and IES-recommended illuminance levels for generic types of outdoor activities. The installation of area lighting is needed to augment the task illumination provided by a worker's headlamp. Such lighting is vital for awareness and discernment of tire tread ruts (or various other debris) caused by rainy, muddy operating conditions that eventually dry and lead to the formation of STF hazards. Headlamp lighting alone with its beam and distribution pattern is not enough. Although its plastic construction is a limitation in view of harsh mining conditions, the field trials with area luminaire-1 demonstrated that it can be mounted in a manner to avoid damage. Thus, an area luminaire can provide a cost-effective and practical solution for enhancing equipment operator safety that is simple to install and easy to use. The area luminaire would aid in reducing STF injury risk for drivers/operators of haul trucks and wheel loaders during ingress/egress and pre-shift walkaround activities. The results from both luminaires demonstrate that they can improve lighting under the conditions presented in this study to achieve compliance with IES recommendations. However, these results apply to the visual tasks discussed in this study and are not necessarily associated with a general assessment. Optimization of luminaire placement, along with proper housekeeping and maintenance, is considered an important next step for future research activities.

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Appendix

Definition of terms

1. Luminaire: a complete lighting unit consisting of a lamp or lamps together with the parts designed to distribute the light, to position and protect the lamps, and to connect the lamps to the power supply.
2. Luminance: light the eye sees that is directed from a surface.
3. Illuminance: light that strikes a surface.
4. Veiling luminance (also disability glare): a luminance superimposed on the retinal image that reduces its contrast. The veiling effect produced by bright sources or areas in the visual field results in decreased visual performance and visibility.
5. Veiling reflection: regular reflection, superimposed upon diffuse reflection from an object, that partially or totally obscures the details to be seen by the reducing the contrast (sometimes called reflected glare).
6. Discomfort glare: glare producing discomfort that does not necessarily interfere with visual performance or visibility. Also described as an annoying sensation, causing pain in extreme cases, that results from high or non-uniform distribution of brightness in the field of view.
7. Disability glare: the glare that results in reduced visual performance and visual ability caused by the action of stray light that enters the eye and produces a scattering effect within.
8. Nit: a unit of luminance equal to 1 cd/m^2.
9. Lux: the unit of measure of illuminance. One lux is 1 lm/m^2.
10. Luminous flux: the time rate of flow of light.
11. Luminous intensity: the luminous flux per unit solid angle in the direction of interest.
12. Candela: the SI unit of luminous intensity. One candela is 1 lm/sr.

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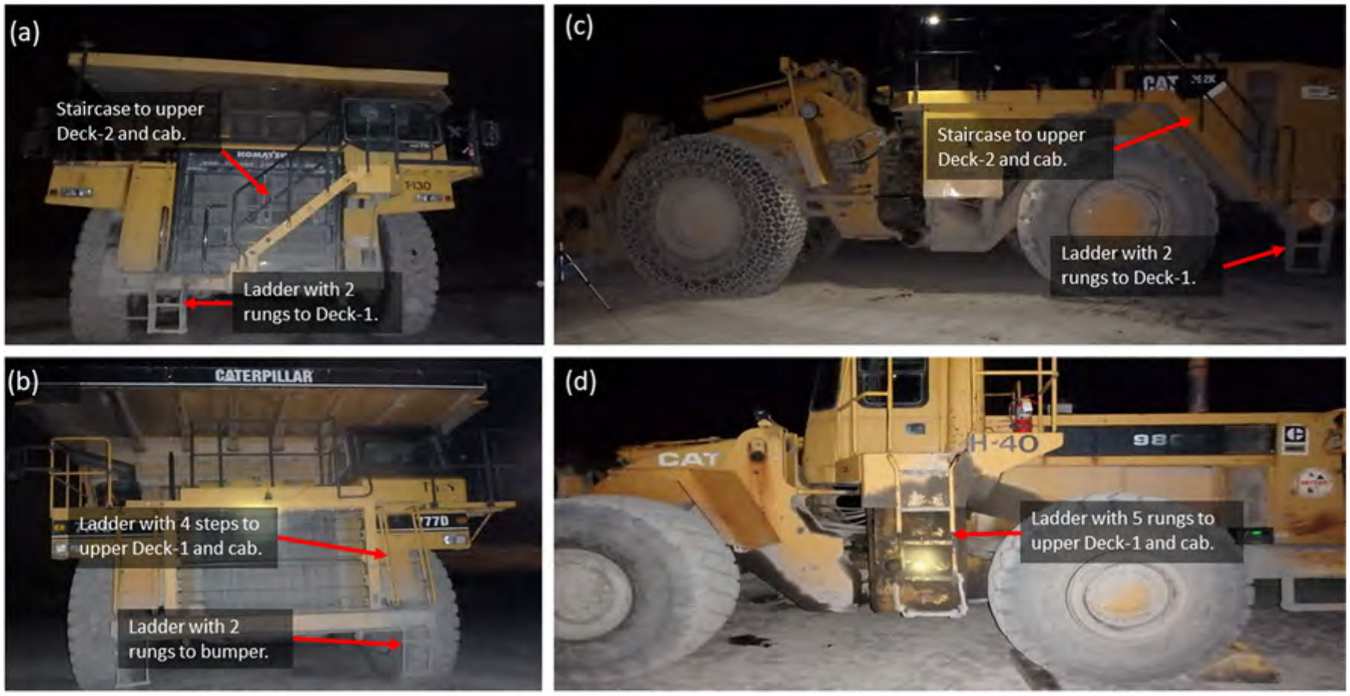

Fig. 1.

Equipment evaluated as part of the study: (**a**) Komatsu HD 785 haul truck, (**b**) Caterpillar 777D haul truck, (**c**) Caterpillar 992 K wheel loader, and (**d**) Caterpillar 980C front-end loader. Inherent differences in the designs of the ingress/egress systems are evident in the photographs

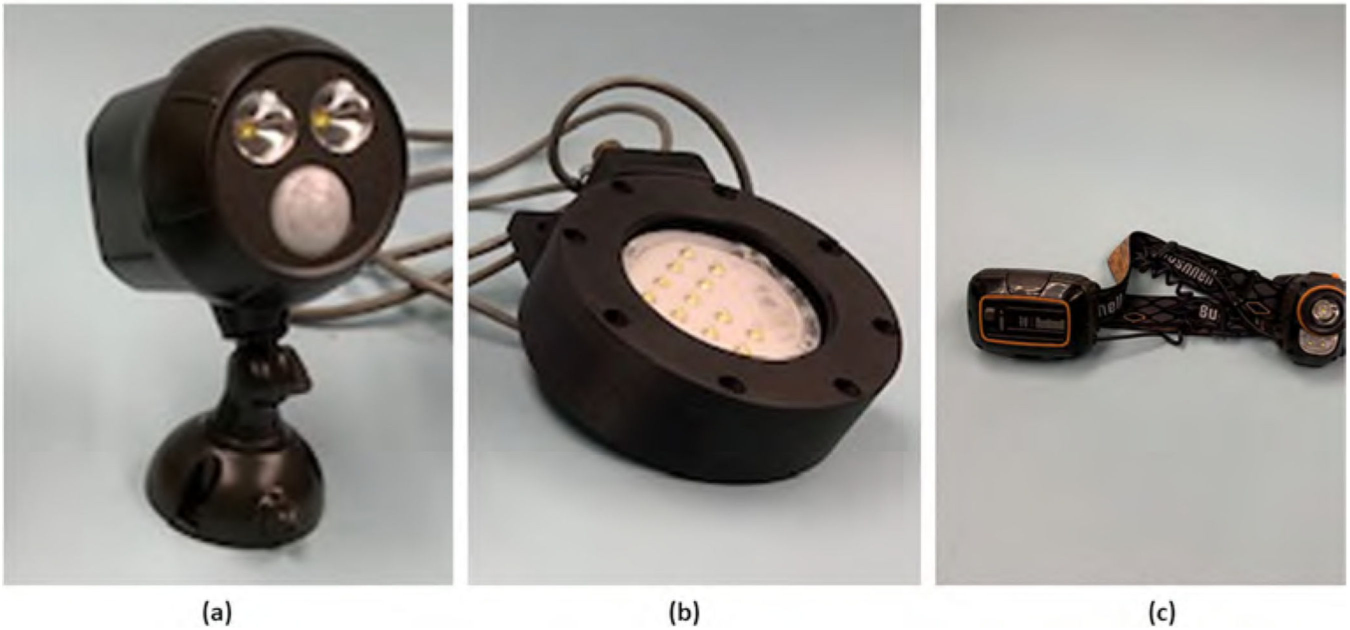

Fig. 2.

Luminaires used in the study: (**a**) area luminaire-1, (**b**) area luminaire-2, and (**c**) headlamp

Fig. 3.
Area luminaire-1 pattern displayed in setup for measurements associated with ingress/egress on the CAT 980C wheel loader

Fig. 4.
Area luminaire-2 beam pattern displayed in setup for measurements associated with the pre-shift walkaround tasks on the Komatsu HD785 haul truck

Fig. 5.

The setup for measurements that represent a mine worker at (**a**) the ladder (first rung) of the smaller front-end loader and (**b**) the ground at the driver's side front tire of the haul truck during pre-shift walk-around

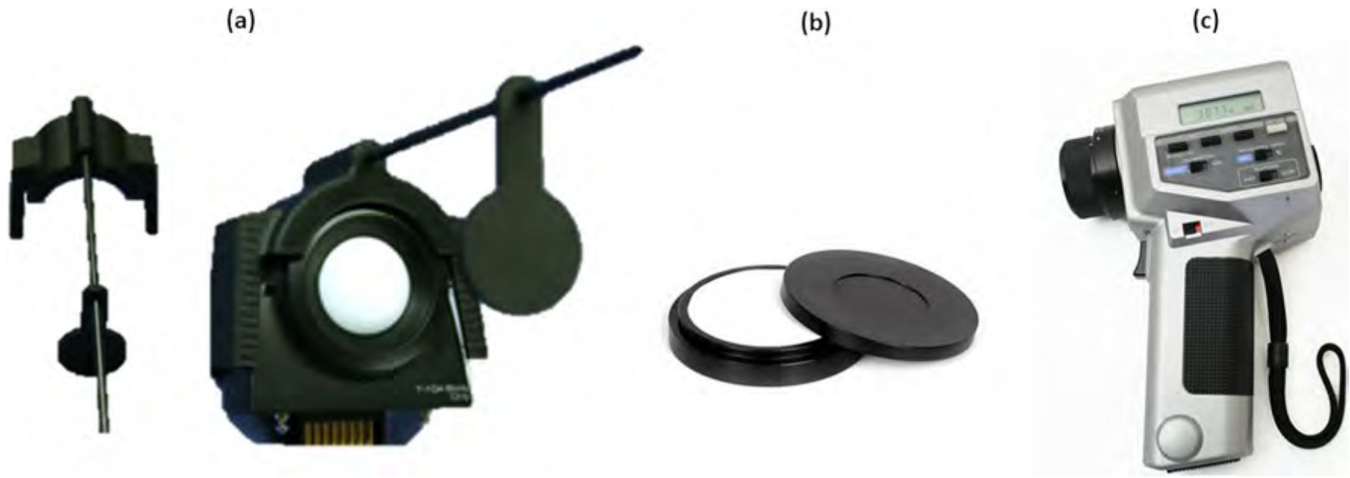

Fig. 6.

Instruments used for measurement: (**a**) shroud and baffle assembly 3D-printed to fit over the T10A sensor head, (**b**) RS-3 reflectance standard used (Apogee Instruments), and (**c**) LS-100 photometer to measure luminance (Konica Minolta)

1:	Unbearable
2:	_
3:	Disturbing
4:	_
5:	Just acceptable
6:	_
7:	Satisfactory
8:	_
9:	Just noticeable

Fig. 7.

The subjective rating scale for discomfort glare from De Boer

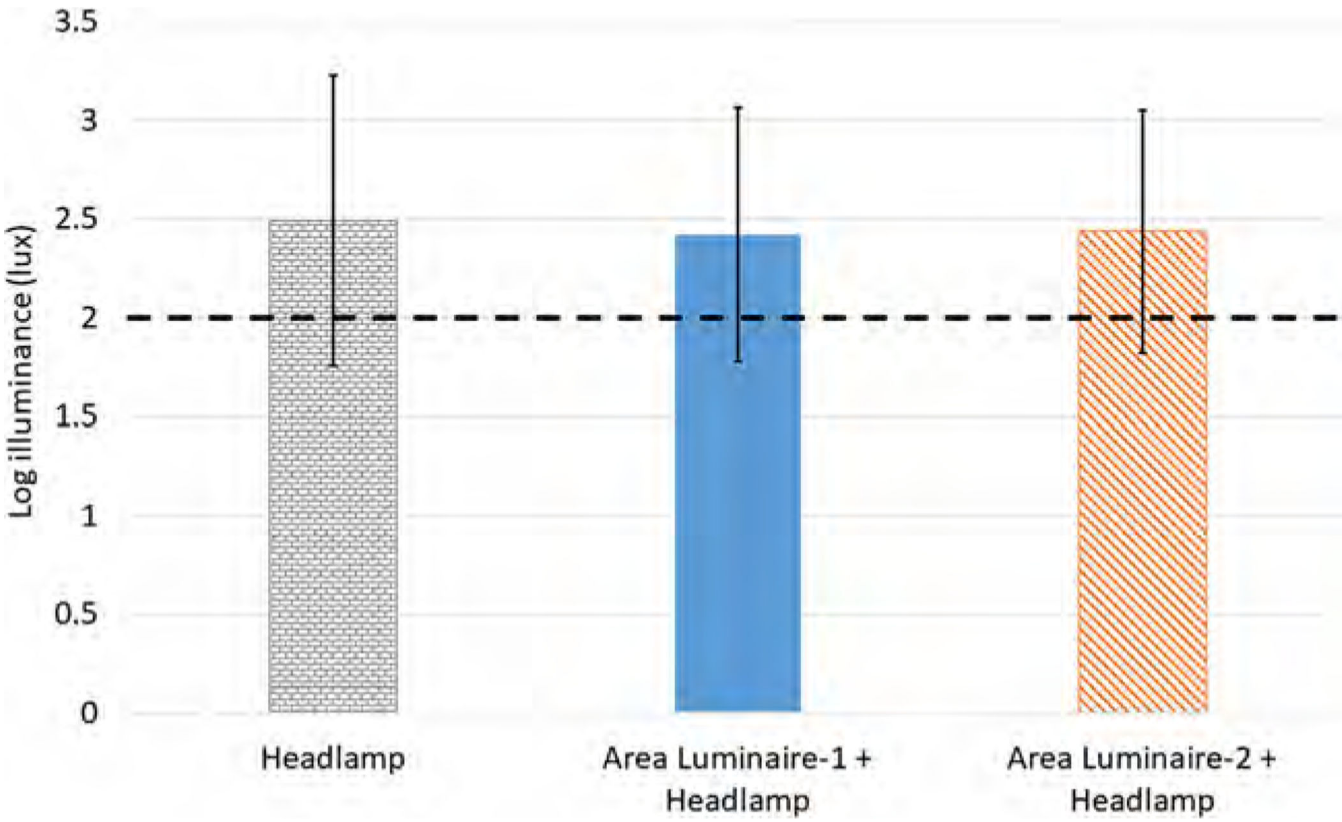

Fig. 8.

Log task illuminance using the RS-3 reflectance standard for all ingress/egress and pre-shift walkaround tasks using the headlamp and the two area luminaires. The dashed line indicates the IES recommended illuminance level

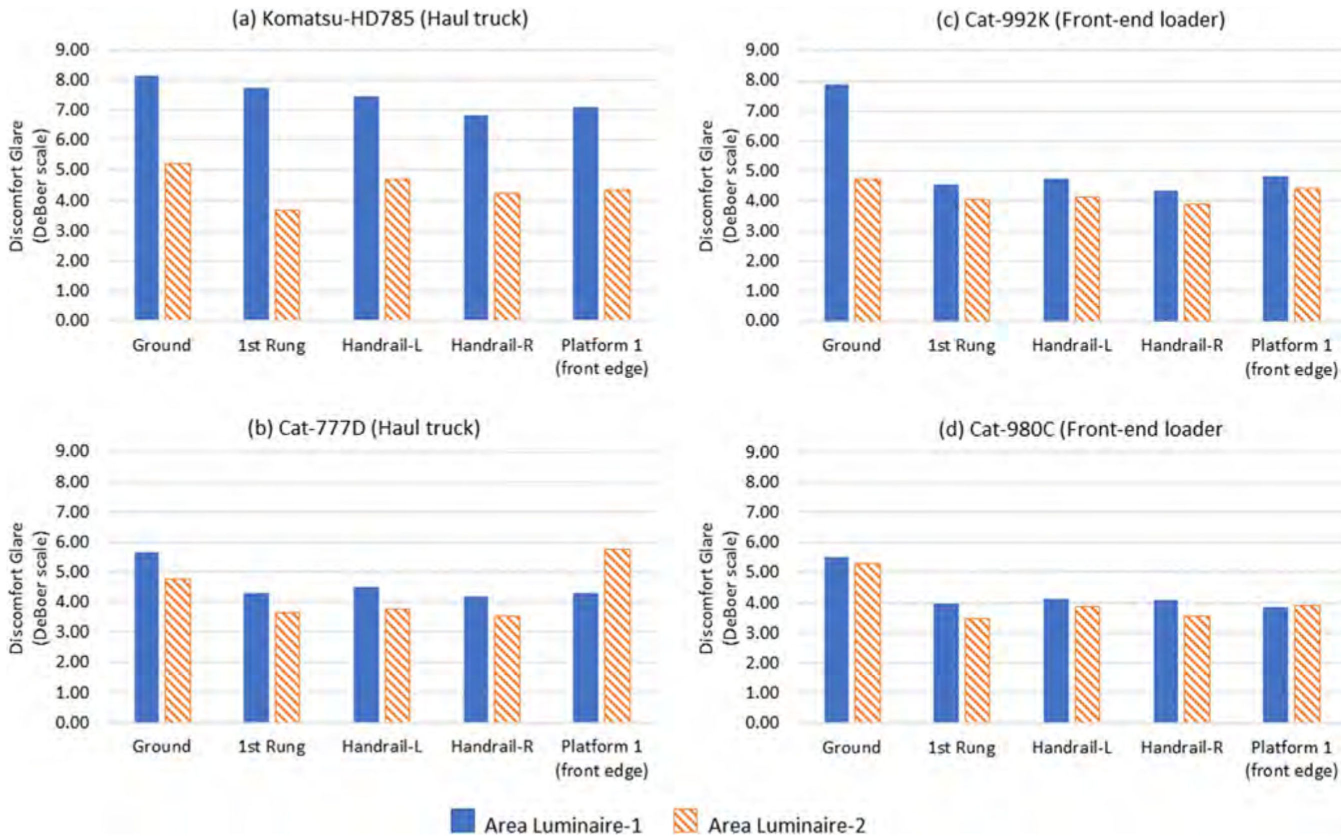

Fig. 9.

Comparison of discomfort glare ratings for area luminaire-1 and area luminaire-2 ingress/ egress tasks. The larger value is the better rating. L indicates left handrail and R indicates right handrail when facing the equipment

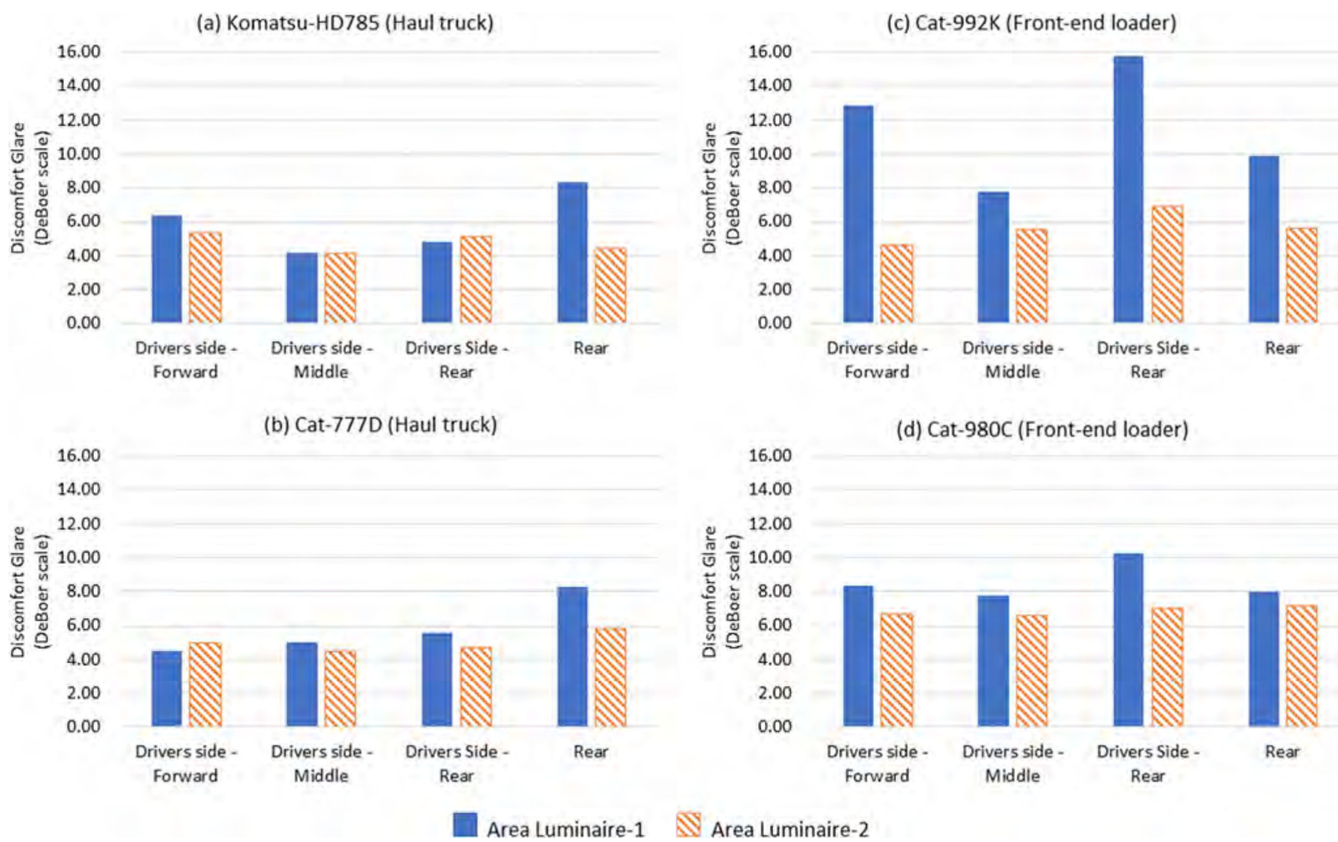

Fig. 10.

Comparison of discomfort glare ratings for area luminaire-1 and area luminaire-2 during pre-shift walkaround tasks. The larger value is the better rating

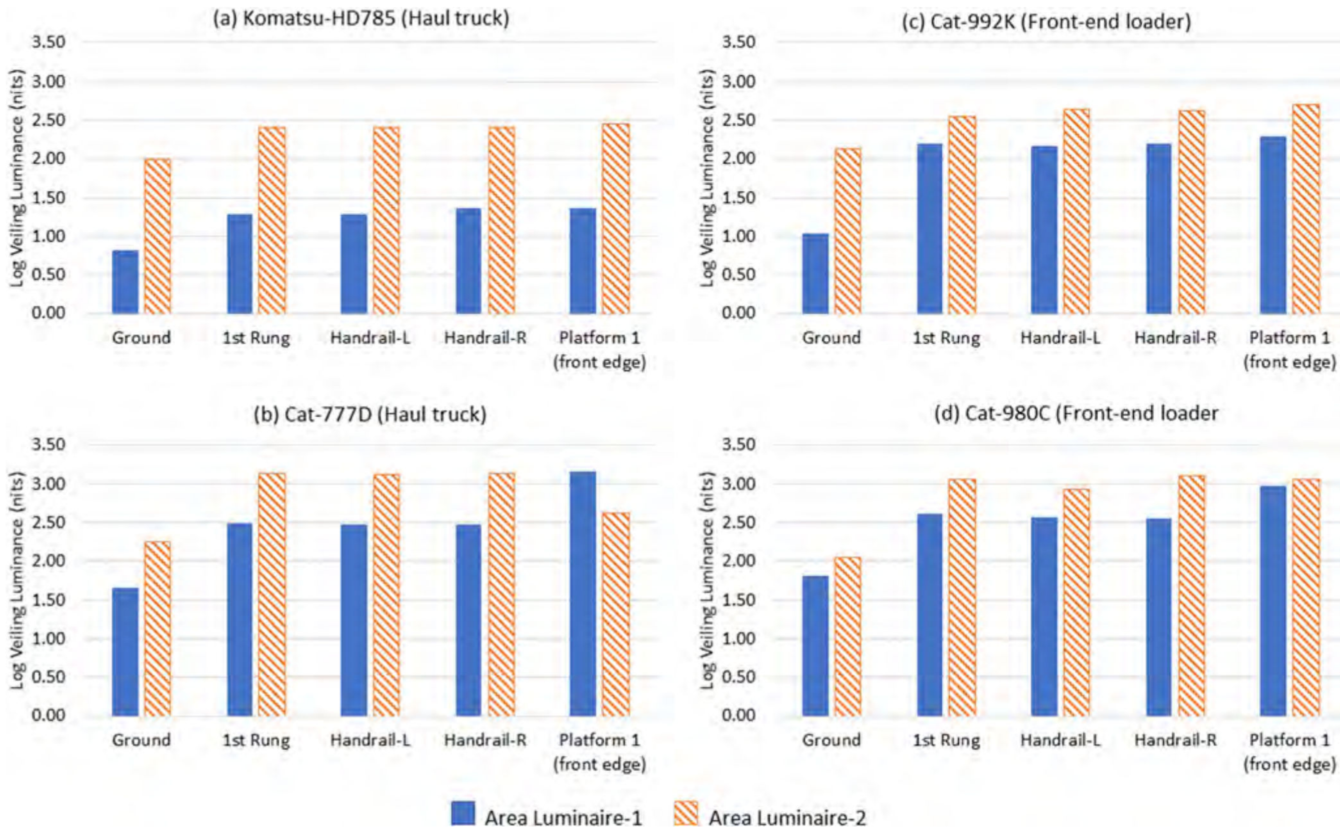

Fig. 11.

Comparison of disability glare (veiling luminance) for area luminaire-1 and area luminaire-2 for all the equipment during ingress/egress tasks. The lower values reflect better levels of veiling luminance. L indicates the left handrail, and R indicates the right handrail when facing the equipment

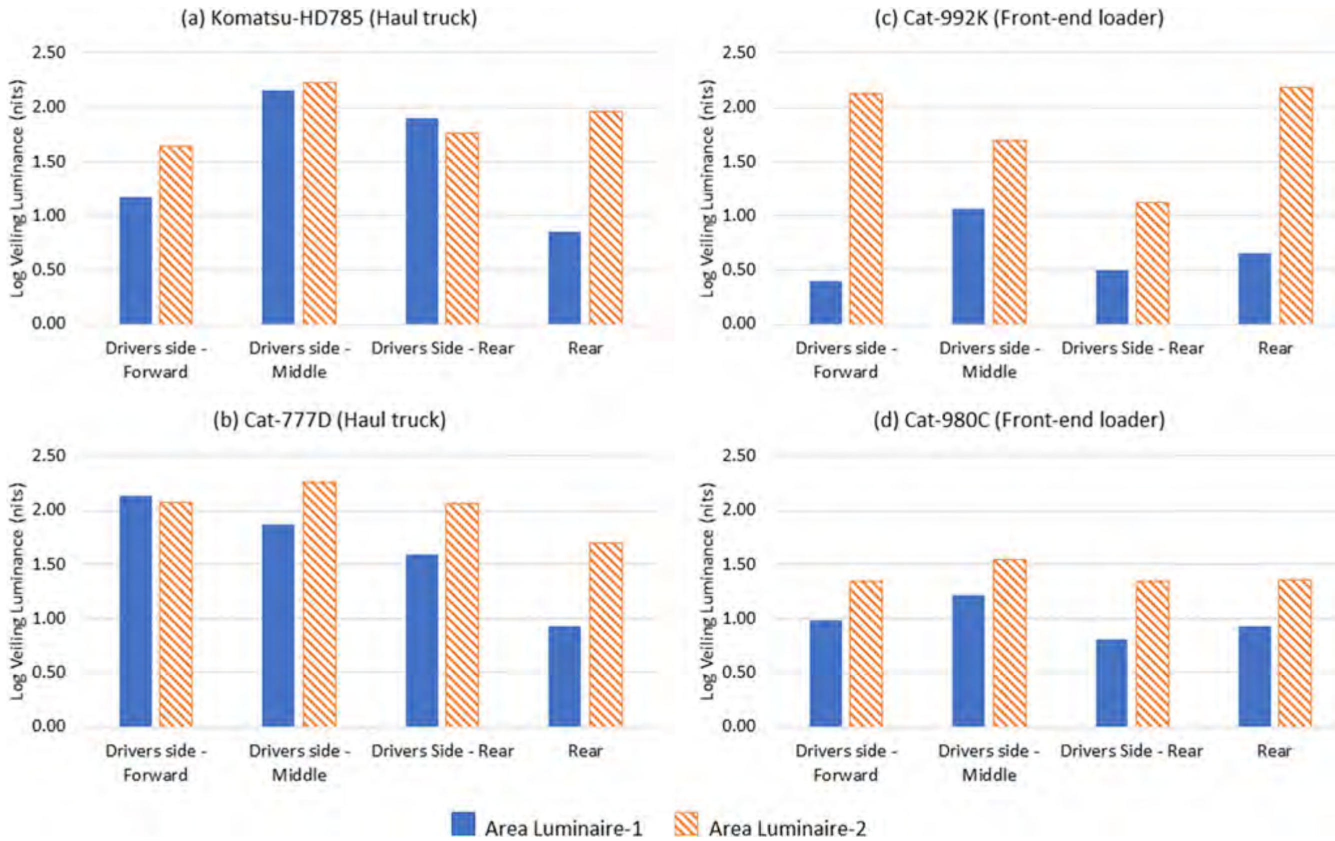

Fig. 12.

Comparison of disability glare (veiling luminance) for area luminaire-1 and area luminaire-2 for all the equipment during pre-shift walkaround tasks. The lower values reflect better levels of veiling luminance.

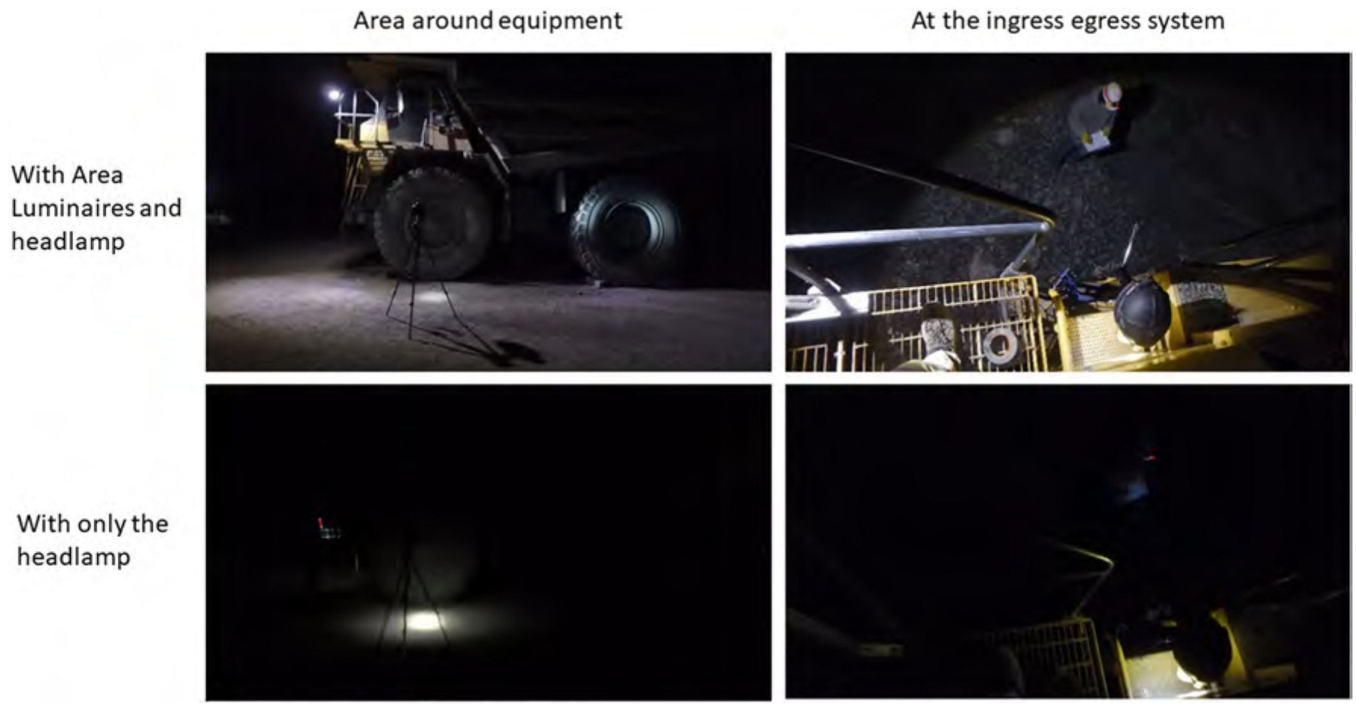

Fig. 13.

Comparison of the area illuminated using the LED area lighting plus the headlamp (top left and right images) versus the headlamp only (bottom left and right images). The scenes depicted are at ground level on the driver's side of the equipment (left images) and at the top platform of the ingress/egress system (right images)

Table 1

IES-recommended illuminance for generic types of activities, outdoor facilities, and common applications [12, 13]

Type of activity/location	Recommended illuminance (lux)
Working spaces where visual tasks are only occasionally performed	100–200
Parking areas (main)	20
Parking areas (secondary)	10
Building exteriors - entrances - active (pedestrian or conveyance)	50
Building exteriors - vital locations or structures	50

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Table 2

Description of equipment for which ingress/egress and walkaround measurements were collected

Equipment	Make/model	Capacity, kg or m^3 (short tons or yds^3)	Year
Haul truck	Komatsu HD785	90,718 kg (100 tons)	2012
Haul truck	CAT 777D	90,718 kg (100 tons)	2000
Front-end wheel loader	CAT 992 K	10.7 m^3 (14 yd^3)	2015
Front-end wheel loader	CAT 980C	4 m^3 (5.25 yd^3)	1987