Heavy Mobile Equipment - Ergonomics and the Prevention of Musculoskeletal Injuries

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Abstract

Heavy equipment includes machines such as scrapers, dozers, heavy haul trucks and loaders. Operators of heavy equipment have elevated reports of musculoskeletal discomfort. Equipment operation is characterized by hazards such as awkward postures, whole body vibration and jarring and static sitting all correlated with musculoskeletal injuries. The application of ergonomics can reduce the impact of heavy equipment operation on the operator. Effective cab layout, seat design, suspension techniques, maintenance, operator work habit and work schedule all are techniques that should consider the user. If designed effectively, it can improve operator health, safety and performance.

1.0 Introduction

Heavy mobile equipment includes machines such as scrapers, dozers, heavy haul trucks, backhoes, graders, and loaders. Equipment is operated by trained operators and is used to perform tasks such as excavating, earth moving, paving, etc. Operators have higher rates of musculoskeletal injuries than non-operators (Jorgensen et al., 2007).

Operators face numerous health hazards, including exposure to: whole-body vibration, awkward postures due to the placement of controls or monitors, dust, diesel exhaust, noise, temperature extremes, and psychosocial health risks such as time pressures and shift work (Kittusamy and Buchholz, 2004). Work-related risks to musculoskeletal injuries among heavy mobile equipment operators include static sitting, awkward postures, and exposure to whole body vibration (Jorgensen et al., 2007). A number of aspects are related to these risk factors such as equipment or task design and operator habit/behaviour.

Work risk factors must be evaluated using a system approach that takes into consideration the health, safety, and performance of the worker (Figure 1). Ergonomics is the science that uses a system approach to examine the interaction between people and their work environment. It helps to identify potential hazards with tools, equipment, the environment and job design that can place stress on an individual. By identifying ergonomic risk factors in the work environment, solutions can be devised to help eliminate identified risks.

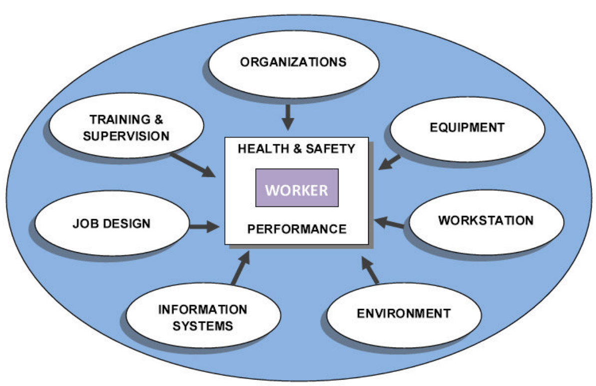

Figure 1 – Systems Approach to the Occupational Environment

The paper discusses causes and risk factors for work-related musculoskeletal injuries associated with heavy equipment operations and provide practical solutions to help prevent these injuries.

2.0 Musculoskeletal Injuries and Heavy Equipment Operations

Musculoskeletal injuries (MSI) are injury or dysfunction of the muscles, bones, nerves, tendons, ligaments, joints, cartilages and spinal discs, including: sprains, strains, tears, soreness, pain, carpal tunnel syndrome, hernias, and connective tissue injuries. MSI can be acute or cumulative in nature. Cumulative MSI starts as body part discomfort or irritation. If the cause of discomfort is not removed or the activity is not modified, discomfort may progress into pain - affecting function and activities both at home and work.

A number of factors have been linked to MSI. Occupational activities associated with MSI include awkward posture, repetition, force, duration of exposure, vibration, mechanical stressors (exposure to hard edges) and extreme temperatures. Predisposing risks, such as size of body segments and height, previous injury, physiological response to injury, body weight and overall fitness of the worker, and mismatch between workers' capabilities and task requirements have also been linked.

Heavy equipment operators frequently report musculoskeletal discomfort in the neck, shoulders, lower back and knees. In a previous study, Zimmerman (1997) found that longer employed operators were more likely to have missed work or seek out medical treatment than newer operators. In that study, operators using older equipment reported higher rates of missed work and physician visits related to musculoskeletal symptoms than operators working on newer equipment. If musculoskeletal symptoms are untreated and their causes are not modified, then the symptoms may progress to the onset of an MSI such as tendonitis, carpal tunnel syndrome, localized muscular pain/irritation and low back pain.

Heavy equipment operation often involves awkward postures, high repetition, prolonged exposure and whole body vibration and jarring. Exposure to individual risk factors is not as concerning as the combined exposure to two or more risk factors. However the relationship is non-linear and is still somewhat unclear.

In cases of low back pain, the combined effect of prolonged seated posture and whole body vibration is thought to have a significant contribution to the precipitation of lower back pain in operators, more so than vibration or seated posture alone (Okunribido et al., 2006). Vibration effects can be aggravated if the spine is in an awkward posture; the risk of MSI increases with the intensity and duration of exposure to whole body vibration and postural requirements (Johanning, 2000).

It is important to understand how both posture and vibration affect heavy mobile equipment operators and to develop strategies for reducing MSI. Exposure to whole body vibration and awkward postures can be reduced at the source (e.g. engine and cab design, respectively). However, two other methods may also help to minimize the risk for MSI: inserting suspension devices between the operator and the source of vibration, and improving workstation ergonomics (seat profiles, cab dimensions, and visibility) (Donati, 2001). These methods may seem unrelated, but they are in fact complementary as they enable a closer match to be achieved between man-machine interaction and the job to be performed (Donati, 2001).

3.0 Awkward Posture

Zimmerman et al. (1997) reported that the job factors most problematic in heavy mobile equipment operations are: bending and twisting of the back and working in the same position for long periods of time. Working postures can be influenced by many factors, such as workstation layout, location and orientation of work, individual work methods, and the workers' anthropometric characteristics (Kittusamy and Buchholz, 2004). For example, in older equipment, seat height adjustment in many cases is not independent of the suspension of the seat. Shorter operators often adjust the suspension so that they can gain vertical height in the seat to improve their positioning in relation to the visual task. Visibility in the task is critical and often work posture or features of the seating (suspension to control whole body vibration) are compromised. Thus, proper and adjustable equipment is important for MSI prevention among heavy machine operators.

Awkward postures pose a significant risk for the development of musculoskeletal injuries (National Institute for Occupational safety and Health, 1997). Operators working in twisted and bent positions have been shown to have increased pressure in and loading on the vertebral discs as well strain in the neck and shoulders (Okunribido et al., 2006; Jorgensen et al., 2007). Factors impacting body posture include:

- Placement of controls – both foot and hand controls,
- Operating Posture – dictated by nature of viewing task, and
- Size and fit of the seat as it relates to the operators size and stature.

Anthropometry

Individuals are highly variable and have a wide range of body dimensions (Parkinson et al., 2007). When considering design of a work area, it is not suitable to design for the 'average person' (Kroemer and Grandjean, 2003). When equipment is going to be operated by a number of users, the equipment should accommodate the 5th to the 95th percentile of personnel. Figure 2 illustrates the variance between a 5th percentile female and a 95th percentile male when seated.

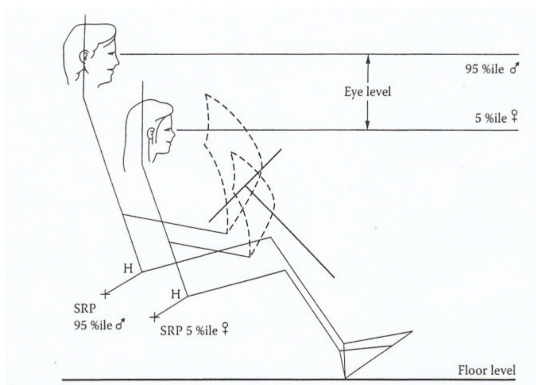

Figure 2 – Variance 5th to 95th percentile (Pheasant 2006, Page 36)

To accommodate a variety of users, the work space must have adjustment capabilities that can accommodate a range of statures, postures, and behaviours (Kroemer and Grandjean, 2003). Human diversity is the single most important characteristic of people that must considered in the design process (Pheasant and

Haslegrave, 2006). Therefore, the design of any product or work place must be user-centred with the goal of designing the best possible match for the greatest possible number of people.

Anthropometry deals with body measurements and variability in body size, shape, strength, mobility, flexibility, and working capacity (Pheasant and Haslegrave, 2006). Factors that impact anthropometry include: age, gender, weight, ethnicity, secular trend and occupational selection. Furthermore, operating postures, the tasks that need to be performed, the clothes and required protective equipment need to be considered for optimum design.

The design of a vehicle cab interior is one problem in which human variability is of primary concern (Parkinson et al., 2007). The layout and location of the seat, hand controls, foot pedals, and other components are often a challenge due to the size of the cab or placement of the equipment in relation to the visual task. In addition to human anthropometrics, operator posture and the postural and movement requirements to safely and efficiently accomplish the work tasks can also significantly affect the design of vehicles interior (Parkinson et al., 2007).

Individual Operating Posture

In addition to human anthropometrics, driver posture can also significantly affect the design of a vehicle's interior (Parkinson et al., 2007). Individuals who have the same body dimensions often drive with substantially different postures throughout the shift, which should be accounted for when organizing the layout of interior components (Parkinson et al., 2007). If equipment adjustability is not present, variance in working posture cannot be achieved. Poor cab design in heavy mobile equipment can directly result in awkward work postures and increase risk for fatigue, pain, and MSI. In the figure 3, a number of postures commonly identified in cab evaluations are illustrated.

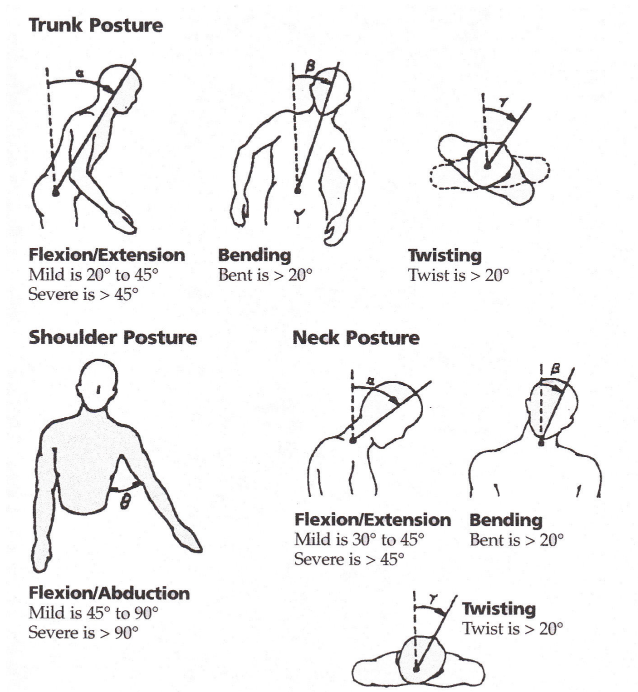

Figure 3 – Frequently Assumed Body Postures

Visibility

Visibility of the task is paramount in heavy equipment operation. If the individual cannot adequately see the task, he/she will adjust the work area or adopt awkward work positions to adequately view the activity. In particular, good visibility is important for safe machine operation and should be possible without requiring the operator to adopt awkward postures or movements (Donati, 2001).

Intervention for Awkward Postures

Poor visibility of the task, limited room in the cab, positioning and operation of controls and improper seat design are all factors that can affect work posture (Kittusamy and Buchholz, 2004). Kittusamy and Buchholz (2004) identified several factors in their literature review that can help reduce postural stress for heavy mobile equipment operators. Postural requirements of work can be minimized with the use of big mirrors, swivel lockable seats if the individual is often twisted to view the visual task, and seats with an adjustable sitting angle (Kittusamy and Buchholz, 2004).

Donati (2002) reinforces the point that proper posture is essential to minimize the effects of vibration stress and potential MSI. Donati breaks down his approach to optimising operator work posture into two areas: (1) reduce the need for awkward postures by improving cab visibility and relocating machine controls and (2) Improve the driver's posture by providing a seat with the correct profile and adjustments, which is compatible with drivers' anthropometric dimensions, cab internal dimensions, and the dynamic environment. To gain the benefit of adjustability, it is important to reinforce with operators through education and training, the importance of adjustment and proper use of equipment.

Seats and cabs should allow multi-directional visibility and accommodate different statures from the 5^{th} to 95^{th} percentile of the user population (Donati, 2002). Partial lockable seat rotation (15-20^{o}) can be advantageous for tasks that involve multiple observations of viewing forward and behind the operator and can help minimize awkward twisting (Donati, 2002).

Seat location should also allow proper use of controls. Operation of controls should prompt a relaxed operating position for the upper limbs, minimizing extended reach and forceful movements. Many equipment manufacturers now offer adjustability for controls both horizontally and vertically, which can support operators to achieve postural variation throughout the shift.

If a steering wheel is present, or consoles are on either side of the operator, it is important that the operator's legs fit underneath the steering wheel or between the consoles - not placing pressure on the legs. If adequate clearance is not provided, operators will often adjust the seat too low to allow for clearance under the steering wheel or turn the legs inward to provide adequate clearance. Consider PPE or clothing type and how it will affect body size.

Seat dimensions and seat adjustments should accommodate users from the 5^{th} to the 95^{th} percentile population and be able to adjust vertical, forwards, backwards, recline, and weight adjustments (Donati, 2002). Cab dimensions should not impede the horizontal travel of the seat.

The seat pan should accommodate the 95th percentile user so that larger individuals will fit. The profile of the seat pan should provide some lateral support, but not restrict postural movement. Some newer style seats allow the operator to adjust the degree of lateral support. The seat pan is designed to support the hips and thighs, and therefore should not place pressure into the back of the knees, but still be long enough to provide support for the upper leg. Again, some seats now feature an adjustable length seat pan.

The seat back should support the back and accommodate an adjustable lumbar support for the lower back. The seat back height should consider the nature of the visual task - for operations where the operator is primarily viewing in the forward direction, consider providing upper back support and an adjustable headrest. For operations where the operator needs to rotate the body frequently to view the task, limit the height of the back to just below the shoulder blades. The two different styles of seating are provided in the illustrations below.

 Lower Back Supported	 Upper Back and Head Supported

Note, upholstery should be of a breathable surface and prevent the operator from slipping. Seat suspension is also critical, but will be discussed in the next section. Finally, it is important that the controls of the seat should be:

- Easy to understand and operate,
- Accessible,
- Conveniently located and require little effort to operate,
- Reliable,
- Safe and avoid injuries to the hands and fingers (Donati, 2002)

Consider if forearm support can be provided to support the arms when repetitively operating controls (specifically joysticks or levers). Again, the support should be height, angle and width adjustable to accommodate a variety of operators, should not have sharp ends, and should be padded and soft.

When the operator sits, their feet should be able to touch the floor or a foot support and their head should not touch the overhead guard (Donati, 2002). Finally, access and egress from the seat and cab need to be considered. Access and egress should allow the operator to comfortably and safely move in and out of the seat. When mounting and dismounting the cab, hand rails and steps should allow the operator to maintain three point foot and hand contact when climbing in and out of the cab (Donati, 2002).

Cab dimensions should accommodate human variability for both anthropometrics and operator work behaviour (Parkinson et al., 2007, Donati, 2002). Workers should be educated on the importance of adjustability, the influence of work behaviour and the importance of postural variation throughout the shift. When on a break, an individual should stand up and move to minimize the static nature of the work task.

When selecting new equipment or identifying possible concerns with existing equipment, the operators should be involved in a review of the equipment. The review should include a number of operators of various sizes and statures that represent the 5th to 95th percentile of the population. Kittusamy (2003) has developed a checklist of questions for evaluating cab design that can be completed by experienced operators. Ideally, the checklist should be completed after a 30 to 60 minute period of operation of the equipment. The checklist can be found in Appendix A.

4.0 Whole Body Vibration

Whole body vibration exposure in heavy mobile equipment operations has long been associated with MSI and specifically with low back pain (Tiemessen et al., 2007). The International Standards Organization (ISO) (1997) states that long term, high intensity whole body vibration increases the risk of disorders of the lumbar spine and connected nervous system. The effects of whole body vibration depend on the intensity, frequency and length of exposure over the shift. In mining and heavy equipment operation, it is not atypical for the operator to be exposed to a 10 hour exposure over a 12 hour shift.

Kumar's (2004) study on overburden mining heavy haul trucks is an example of the effects of whole body vibration on heavy mobile equipment operators. In his study, Kumar (2004) investigated reasons for the high occurrence of lumbar and cervical problems in overburden mining truckers. Kumar (2004) found that driving heavy haul trucks generated hazardous magnitudes of the most harmful frequencies of vibration, which exceeded exposure limits set out by ISO and posed a significant health risk to drivers.

Whole body vibration is a function of the equipment, surface conditions, operating behaviour and overall maintenance of the equipment. The literature reveals a number of strategies for reducing vibration. Tiemessen et al. (2007) categorizes these strategies as: (1) design considerations and (2) skills and behaviour.

In the design of equipment, manufacturers consider a number of techniques to minimize vibration through key points: the tires and wheels, suspension/undercarriage chassis, attachment coupling, the cab and the seat.

Seat Suspension

Seat suspension is considered the final stage of control before the operator. Most seats are designed to isolate vibration in the vertical axis only, even though the operator can be exposed to vibration in all three planes (Donati, 2002).

Seat suspension has been studied repeatedly in the literature. Successfully reducing vibration magnitude using seat suspension depends on the type of vehicle, the nature of the task and the appropriateness of seat suspension to its use (Tiemessen et al., 2007). Seat suspension should be designed with regards to:

(1) The characteristics of the vibration to which it will be exposed,

(2) The dynamic characteristics of the machinery,

(3) The frequency content of the driving forces, and

(4) The nature of the machinery operation.

(Tiemessen et al., 2007)

At low frequencies, the body responds much greater to vibration than the seat (Tiemessen et al., 2007). Therefore, seat suspension design should aim at minimizing vibration in the body rather than minimizing seat response (Tiemessen et al., 2007). In some cases, improper seat suspension can actually amplify the vibration and increase the risk to the operator. Therefore, seat suspension should be selected with careful consideration and proper information on suspension.

Regular Maintenance

Equipment maintenance and surface operating conditions can also contribute to whole body vibration. Ensure equipment is regularly maintained including drive-train isolation, vehicle suspension systems and the operator platform, including the seat.

On haul roads, surfaces should also be repaired through regular maintenance programs. Also, mark particularly rough areas with clear signage so that operators can be alerted to adjust driving behaviour. High intensity lighting on vehicles can also illuminate areas so that operators can judge surface conditions. Computers are available on some haul trucks that are capable of monitoring pitch and yaw and roll of haul truck frames/suspension indicating haul road conditions. Savings in both machine maintenance and operator discomfort/injury.

Operator Behaviour

Other vibration exposure reduction strategies focus on operator behaviour. Techniques such as reducing driving speed, rest pauses during the shift and work schedules in which an operator works fewer hours per day can minimize vibration exposure during the work day (Tiemessen et al., 2007). A recent document published by the Alberta Government 2008, suggests operators of equipment should take periodic rest breaks of 10 to 15 minutes for every one to two hours of exposure.

However, vibration exposure is determined by many factors so it is essential to combine a variety of techniques to address the concern. An example is the study performed by Shinozaki et al. (2001) on the effects of two different strategies to reduce the incidence of back pain among drivers. Initially, drivers were provided with lumbar support, arctic jackets, and physical exercises which reduced the prevalence of back pain by 7%. The forklifts were subsequently fitted with suspended seats and pneumatic tires, which reduced the occurrence of back pain a further 23% for an overall reduction of 30% from previous levels. The combination of design and driver behaviour strategies helped to significantly reduce the incidence of lower back pain among forklift operators.

5.0 Conclusion

The variability and complexity of the human body is an important factor to consider in the design of a cab. Many heavy mobile equipment operators experience numerous work-related health hazards, including awkward postures, static sitting, and whole-body vibration, which can lead to injury and discomfort. Particularly, the combination of awkward postures and prolonged exposure to vibration can result in discomfort, pain and MSI.

The need for using awkward postures can be addressed in the design by considering the workers' anthropometric characteristics, work behavior and the work environment when designing a cab. The interior of the cab requires a full range of adjustment capabilities and features that can accommodate the 5^{th} to 95^{th} percentile of the population. This includes layout and location for the seat, steering wheel, controls, pedals, adjustability features, visibility of the task, and overall cab dimensions. Again, it is important to educate and train the user to identify factors that can increase the intensity as well decrease the impact of heavy equipment operation.

The exposure to whole-body vibration can be controlled by both design and behavior strategies to help decrease the duration and intensity of vibration exposure during the work day. Behavior modifications include reducing driving speed, scheduled work breaks, and changing work patterns. But as studies show, these changes need to be accompanied by design strategies to achieve a greater effect.

Designing the equipment to fit the worker, rather than having the worker adjust to the equipment is essential in minimizing the risk of MSI and discomfort in heavy mobile machinery operators.

6.0 References

Donati, P. 2002, *Survey of technical preventative measures to reduce whole-body vibration effects when designing mobile machinery,* journal of Sound and Vibration, 253, 169-183.

International Standards Organization, ISO2631. 1997, *Guide for the evaluation of human exposure to whole-body vibration, Part 1. ISO 2631/2-1997.*

Johanning, E. 2000, *Evaluation and management of occupational low back disorders,* American Journal of Industrial Medicine, 37:94-111.

Johanning, E., Landsbergis, P., Fischer, S., Christ, E., Gores, B., Luhrman, R. 2006, *Whole-body vibration and ergonomic study of US railroad locomotives,* Journal of Sound and Vibration, 298, 594-600.

Jorgensen, M., Kittusamy, N.K., and Aedla, P. 2007, *Repeatability of a checklist for evaluating cab design characteristics of heavy mobile equipment,* Journal of Occupational and Environmental Hygiene, 4, 913-922.

Kittusamy, N. and Buchholz, B. 2004. *Whole-body vibration and postural stress among operators of construction equipment: A literature review*, 35, 255-261.

Kroemer, K., and Grandjean, E. 2003, *Fitting the task to the human,* 5th edition, Taylor and Francis: London and New York.

Kumar, S. 2004, *Vibration in operating heavy haul trucks in overburden mining,* Applied Ergonomics, 35, 509-520.

National Institute for Occupational Safety and Health (NIOSH). 1997, *Musculoskeletal disorders and workplace factors: A critical review of epidemiological evidence for work-related musculoskeletal disorders of the neck, upper extremity, and low back.* NIOSH Technical Report No. 97-141. Cincinnati, Ohio: US Department of Health and Human Services, NIOSH.

Okunribido, O.O., Magnusson, M., Pope, M.H. 2006, *Low back pain in drivers: The relative role of whole-body vibration, posture, and manual materials,* Journal of Sound and Vibration, 298, 540-555.

Parkinson, M., Reed, M., Kokkolaras, M., Papalambros, P. 2007, *Optimizing truck can layout for driver accommodation,* Journal of Mechanical Design, 129, 1110-1117.

Pheasant, S., and Haslegrave, C. 2006, *Bodyspace: Anthropometry, ergonomics, and the design of work,* 3rd Edition, Taylor and Francis: London and New York.

Shinozaki, T., Yano, E., Murata, K. 2001, *Intervention for prevention of low back pain in Japanese forklift workers,* American Journal of Industrial Medicine, 40, 141-144.

Tiemessen, I., Hulsof, C., Frings-Dresen, M. 2007, An *overview of strategies to reduce whole-body vibration exposure on drivers: A systematic review,* Industrial Ergonomics, 37, 245-256.

Zimmerman, C.L., Cook, T.M., and Rosecrance, J.C. 1997, *Operating Engineers: Work-related musculoskeletal disorders in the trade,* Applied Occupational Environmental Hygiene, 12, 670-680.

7.0 Appendix A

Checklist Questions – Kittusamy (2003)

Question	Yes	No	N/A	Comment
Is the seat height adjustable?				
Can the seat be adjusted horizontally?				
Is the seat set at the proper height?				
Does the seat have a back support?				
Does the seat have a lumbar support?				
Are the armrests available?				
Are the armrests adjustable?				
Do you feel any vibration from the equipment through the seat?				
Do you feel any vibration from the equipment through the floor?				
Do you feel any vibration from the equipment through the controls?				
Is the seat firmly mounted to the floor of the cab?				
Can the seat be tilted backward?				
Can the seat swivel?				
Is the location of the controls or levers adjustable?				
Can you easily reach the lever or controls?				
Can you easily operate the levers or controls?				
Can you easily reach the pedals?				
Can you easily operate the pedals?				
Is the cab area large enough (e.g. uncramped area) for you?				
Do you have sufficient upward visibility?				
Is your view of the operation obstructed (e.g. cab guards, pipes/hose, etc.)?				
Do you feel the cab is noisy?				
Can you control the temperature of the cab?				
Does the equipment have steps?				
Does the equipment have handrails?				
Can you easily open/close the cab doors?				
Does the equipment have proper means of entering the cab?				
Does the equipment have proper means for exiting the cab?				
Do you have a good general view of the ground?				
Are the cab windows free from distracting reflections?				