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Mining equipment human factors design for workforce diversity

Danellie Lynas
University of Queensland

Gary Dennis
University of Queensland

Robin Burgess-Limerick
University of Queensland

MINING EQUIPMENT HUMAN FACTORS DESIGN FOR WORKFORCE DIVERSITY

Danellie Lynas[1], Gary Dennis[2] and Robin Burgess-Limerick[3]

ABSTRACT: The minerals industry is a complex system in which procedures, equipment and people need to interact safely and efficiently to achieve operational requirements. The sector is also an attractive employment option, creating an environment of significant workforce diversity within equipment operators and maintainers. While a variety of standards and guidance materials exist to assist designers to provide equipment that accommodates workplace diversity, designers face significant challenges in applying this information, and may unnecessarily restrict the range of potential employees who can operate and maintain this equipment, and in turn create elevated injury risk. Understanding how equipment design impacts safe and comfortable operation and maintenance will provide additional assistance to designers. Information gathered at seven Australian surface coal mines was used to undertake a comprehensive review of the limitations of current equipment designs with regard to accommodating diversity in physical characteristics required to perform operational and maintenance tasks on site. A control framework approach to equipment design for diversity was developed where two required operating states were defined, (i) earth-moving equipment can be safely and comfortably operated by people of a maximum range of anthropometric diversity; and (ii) earth-moving equipment can be safely and comfortably maintained by people of a maximum range of anthropometric diversity. The general business case for increasing workforce diversity in mining is well established. Improving earth-moving equipment design is required to remove significant anthropometric and other work demand impediments to supporting this diversity. This paper highlights the inadequacy of currently available guidance material to equip designers to understand and address these challenges.

INTRODUCTION

Workforce diversity is often assumed to mean gender distribution however, a range of additional worker attributes is encompassed, including physical and cognitive abilities, cultural background, language and communication styles. While the minerals industry is seen as an attractive employment option by many, within the industry a number of challenges arise including a diversity of company cultures reflected in different procedures, rules and practices at mines; a variety of national laws, regulations and guidelines; many different equipment manufacturers and suppliers; differences in the mining environment, and significantly, the diversity within the workforce employed across mine sites.

A project funded by the Australian Coal Association Research Program (ACARP) was undertaken to identify and describe design issues with current mining equipment which created a barrier to diversity within the workforce and to communicate the results of these investigations to equipment designers and

mine sites. The information gained during the project was used to populate an Earth Moving Equipment Safety Round Table (EMESRT) control framework for equipment design for diversity. EMESRT is a global initiative involving major mining companies which engages with key mining industry Original Equipment Manufacturers (OEMs) to advance the design of equipment to improve safety operability and maintainability beyond standards (www.emesrt.org).

Seven surface coal mines in Queensland and NSW were visited during the project. Utilising a participative ergonomics approach equipment operators and maintainers were actively involved in on-site focus groups. Information was gathered to demonstrate the anthropometric issues arising from equipment designed for the mining sector, and where the design of this equipment may place unnecessary employment restrictions, and potentially create elevated risks of injury for those who

[1] Research Fellow, Sustainable Minerals Institute, University of Queensland. Email: d.lynas@mishc.uq.edu.au
Tel: +61 417 791 138
[2] Industry Fellow, Sustainable Minerals Institute, University of Queensland. Email: g.dennis@ergoenterprises.com.au
Tel: +61 7 5668 3422
[3] Professor of Human Factors, Sustainable Minerals Industry, University of Queensland. Email: r.burgess-limerick@uq.edu.au
Tel: +61 401 714 511

currently undertake tasks associated with operating and maintaining the equipment. This information was supplemented with previously documented assessments of manual tasks associated with earth-moving equipment maintenance, including attempts to reduce manual tasks risks undertaken by a range of mine sites. Two required operating states were defined: (i) earth moving equipment can be safely and comfortably operated by people of a maximum range of anthropometric diversity, and (ii) earth moving equipment can be safely and comfortably maintained by people of a maximum range of anthropometric diversity. Twelve credible failure modes were identified for equipment operation and two credible failure modes were identified for maintenance tasks.

CHALLENGES POSED BY EXISTING DESIGN GUIDELINES

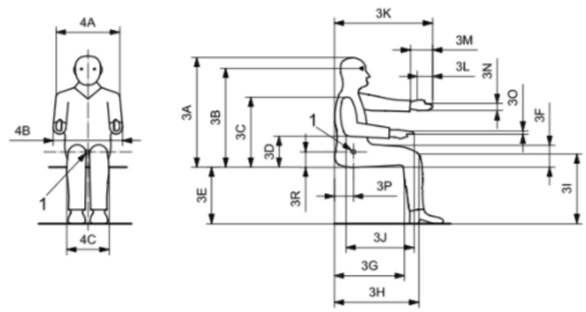
A variety of standards and guidance materials currently exist to assist equipment designers accommodate workplace diversity. This material may include guidance on visibility; noise measurements; whole body vibration assessments; ergonomics and human factors; controls and displays; manual tasks risk analyses; and audits against relevant standards and Mining Design Guidelines (MDGs). However, designers of equipment for mining operations face significant challenges in applying this information. It is therefore important to understand how the design of mining equipment restricts the range of potential employees who can safely and comfortably operate and maintain the equipment to provide additional assistance to equipment designers.

The main reference material is found within ISO standards, however, the ISO standards process is formal and change often lags behind technology development. In some cases this may result in weak or ineffective standards that need to be written in general terms to accommodate future technology developments. In this way the general nature of some standards may only establish minimum requirements and not be overly helpful to equipment designers, in particular when designing for diversity and inclusivity within the workforce. In contrast, Mining Design Guidelines (MDGs) as produced by the New South Wales regulator are able to respond more quickly to changes in technology. Standards do however have a safety and productivity focus, and therefore provide design consistency between equipment manufacturers. Standards also provide a basis for auditing purposes, and assist in mining regulation, compliance, and the development and application of safety management systems. For example, ISO12100 (2010) “Safety of machinery - General principles for design - Risk assessment and risk reduction”, provides a general framework approach to equipment design, including basic terminology, principles and a method for achieving safety in the design of machinery. More specifically, IS0 9241-210 (2010) proposes a human-centred design approach to design that has substantial economic and social benefits for users, employers and suppliers. In summary, it provides a set of principles based on explicit understanding of users, tasks and environments; users are involved throughout design and development; the design is driven and refined by user-centered evaluation; the process is iterative; the design addresses the whole user experience; and the design team includes multidisciplinary skills and perspectives (Horberry, et al 2018).

ISO3411 “Earth-moving machinery - Physical dimensions of operators and minimum operator space envelope” provides data approximating the 5th, 50th and 95th percentile of the “earth-moving machinery operator population”, for numerous static dimensions relevant to the design of earthmoving equipment (eg. Figure 1) and these data are utilised in ISO6682 to provide recommendations regarding the location of controls (eg. Figure 2). There are considerable limitations to the use of such data. The standard notes for example, that: “In some areas of the world, more the 5% of the operators have leg lengths less than the value given for the smallest operators” and suggests that “special adjustments may be provided”, without specifying the nature to these adjustments. This note highlights an example of one area in which current equipment designs limit the diversity of the potential workforce by providing insufficient seat adjustment to accommodate short leg lengths. It is noteworthy that the limitation will disproportionately affect potential female employees.

Attempting to utilise the data provided in ISO3411 (or other sources of static anthropometric data) creates further problems for equipment designers, in that the reference percentiles offered is problematic for design purposes. There is no “5th percentile operator” or “95th percentile operator”. Rather, individuals vary along each dimension (Robinette and Hudson, 2006) and although dimensions have some degrees of correlation, when multiple dimensions are considered, the range of individuals which fall within a given range on all dimensions reduces substantially. For example, only about 82% of individuals in a population will fall within the 5th to 95th percentile ranges for both height and weight. The more dimensions are considered, the smaller the range of people who actually “fit” the description. Looking at this issue in another way, Figure 3 provides a representation taken from whole body scans of two people with the same sitting height; and also illustrates a hypothetical person generated case using all 95th% male dimensions.

ISO 3411:2007(E)



Reference	Designation	Dimension mm		
		Small operator	Medium operator	Large operator
3A	Sitting height [a]	800	894	976
3B	Eye height, sitting	690	780	858
3C	Shoulder height, sitting	530	585	651
3D	Elbow height, sitting	200	239	285
3E	Horizontal sitting surface height [c]	400	449	495
3F	Thigh clearance [c]	120	146	170
3G	Buttock to calf distance [c]	420	474	525
3H	Buttock-knee length	530	601	670
3I	Knee height, sitting (with shoes)	500	558	627
3J	Forearm-fingertip length [c]	410	464	515
3K	Anterior arm reach [c]	750	832	909
3L	Decrement for control grasp [c]	–65	–73	–80
3M	Hand length	170	190	207
3N	Hand breadth [b, c]	80	87	96
3O	Hand thickness [c, d]	25	30	35
3P	SIP (seat index point) length	113	125	137
3R	SIP (seat index point) height	80	88	97
4A	Shoulder (bi-deltoid) breadth	380	450	514
4B	Elbow-to-elbow breadth [c]	385	454	521
4C	Hip breadth, sitting	320	378	456
1 seat index point (SIP)				
NOTE These columns represent the measured size range of the world population. Small is approximately the 5th percentile measurement, medium is approximately the 50th percentile measurement, and large is approximately the 95th percentile measurement. Small operator = 51,9 kg, medium operator = 74,4 kg, large operator = 114,1 kg				

Figure 1: Example of static anthropometric data currently available with ISO3411 "Earth-moving machinery - Physical dimensions of operators and minimum operator space envelope".

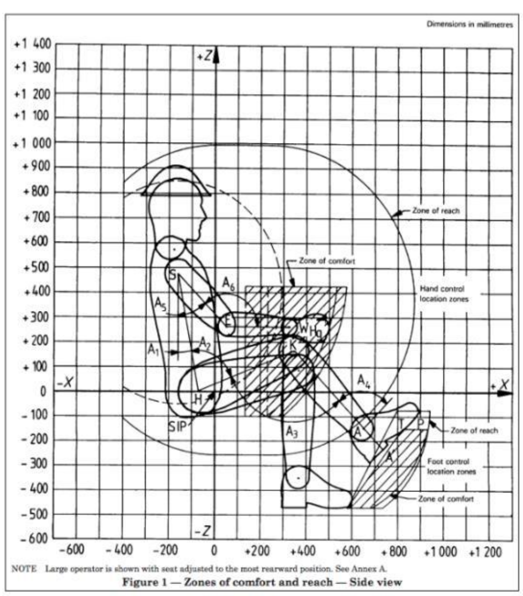


Figure 2: ISO6682: Earth-moving machinery - Zones of comfort and reach for controls

BS 6912-19:1996, ISO 11112:1995 (part 19) provides specifications for dimensions and requirements for operator's seat. This International Standard specifies the dimensions, requirements and adjustment ranges for operator seats on earth-moving machinery as defined in ISO 6165. Additionally, it provides dimensions for armrests when fitted on these machines. Again, whilst providing nominal values of dimensions regarding seat features, their mutual locations and adjustments are established on the basis of ergonomic requirements. Taking into consideration operator sizes it is referenced according to ISO 3411, and considers from the 5th percentile through the 95th percentile. Seat dimensions and adjustments, if provided, are referenced to the Seat Index Point (SIP) determined in accordance with ISO 5353. Confusion arises as the standard advises “dimensions and adjustments other than those specified in this International Standard may be used only if they provide better accommodation for the operator”.

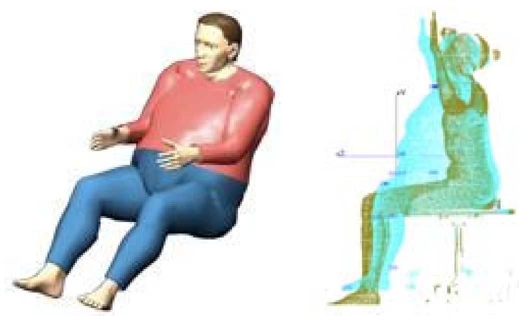


Figure 3: (left) Two individuals with the same sitting height, and (right) a hypothetical 95% male.

Seat design, condition and adjustment is known to influence operator whole-body vibration exposure levels (Lewis and Johnson 2012; Paddan and Griffin, 2002), meaning seat installation needs to suit both the vehicle and its operating environment. Performance differences across seats have shown significant health implications for drivers and equipment operators (Blood et al, 2010). Seating remains a design problem, with “standard fitment” often stipulating mass range from 80-150 kg, and limited fore-aft adjustability, which clearly provides a restriction on the diversity of operators who could be employed. This highlights another example of an area in which current equipment designs limit the diversity of the potential workforce by providing insufficient seat adjustment to accommodate in particular smaller operators. It is noteworthy that these limitations disproportionately effect potential female employees, typically those smaller in stature. The potential implication of providing a seat that is not matched to operator mass was illustrated in ACARP project 26016 (Continuous Monitoring of Whole-body Vibration Jolts and Jars Associated with Operating Earth Moving Equipment at Surface Coal Mines). During the project data was collected from a haul-truck being driven at a central Queensland surface coal mine where accelerometers placed in the seat of the truck, and on the floor under the seat. The data collected at the operator-seat interface was frequency weighted according to ISO2631.1 to provide an assessment of the whole-body vibration exposure of the driver relative to the Health Guidance Caution Zone (HGCZ) provide by the standard. Comparing the magnitude of the accelerations collected on the floor under the seat with these data provides an assessment of the effectiveness of the seat in attenuating biologically relevant accelerations. A 2 hour 13 minute measurement yielded a ratio of seat to floor acceleration amplitude of 0.63 when the data are expressed as RMS, and 0.67 expressed as VDV (a measure more sensitive to high amplitude shocks) which indicates that the seat is effectively attenuating the relevant vibration frequencies and as a consequence the vertical whole-body vibration exposure assessment of 0.45 m.s2 RMS lies below the ISO2631.1 HGCZ for an 8 hour daily exposure, and just within the HGCZ when expressed as VDV. Another 2 hour 26 minute measurement taken from the same truck driving the same circuit earlier on the same day indicates that during this period the seat has provided less effective attenuation. When the accelerations are expressed as VDV the seat appears to be amplifying the floor accelerations. The difference between the two measurement periods is the driver. It is likely in the second example that the driver was relatively light and either did not, or could not, adjust the suspension of the seat to match their mass. The resulting whole-body vibration levels are likely to be associated with detrimental health effects across multiple body systems if exposure is prolonged.

ISO 5006: “Earth moving machinery-operators field of view” provides a test method and performance criteria to address the operator’s visibility in such a manner that the operator can see around the machine to enable proper, effective and safe operation that can be quantified in objective engineering terms. While the test method uses two lights placed at the location of the operator’s eyes, it does not include all aspects of the operator’s visibility. However, it does provide information to assist in determining the acceptability of visibility from the machine.

Mine Design Guideline MDG15 (2002) “Mobile and transportable plant for use at mines and petroleum sites “ was developed by the NSW regulator with the aim of improving an unacceptable rate of injury to people operating and maintaining mobile plant; fires on mobile plant; and unplanned movement of mobile plant. Whilst not a mandatory compliance document, it includes advice from a number of A/NZ and ISO Standards to inform safe mining equipment design features such as provision of safe access and egress via ladders and stairs, walkways and handrails; and location of controls within the zones of comfort and reach of intended users. It does not provide specific design information regarding diversity within the population of equipment operators and maintainers. It does however, in a very general statement, indicate a person competent in ergonomics should provide an assessment of the equipment, which should take into consideration the intended use of the equipment and the operating environment, and consider “all relevant ergonomic matters relating to human factors”.

Additionally, whilst not specific to the design of mining equipment, ANSI Z590.3 (2011) “Prevention through Design Guidelines for Addressing Occupational Hazards and Risks in Design and Redesign Process” provides guidance on the avoidance, elimination, reduction or control of occupational safety and health hazards and risks in design and redesign processes. Overall, these standards and guidelines have limited utility for designers in that they can only consider a limited range of typical tasks, such as those undertaken while sitting in a driver’s seat, rather than the complete range of tasks associated with the operation and maintenance of equipment. As well as differing in static dimensions, potential employees differ in terms of dynamic capabilities such as strength, flexibility and reach distances. Taking all task components into account requires a task-based assessment to be undertaken during the design process, such as that provided by the Earth Moving Equipment Safety RoundTable (EMESRT) Design Evaluation for Equipment Procurement (EDEEP) process (Burgess-Limerick, et al., 2012). The most common manifestation of the failure to accommodate diversity is the design of equipment such that hazardous tasks are required to operate and maintain the equipment.

A CONTROL FRAMEWORK APPROACH TO EQUIPMENT DESIGN FOR DIVERSITY

Six central Queensland surface coal mines (two different mining companies) and one New South Wales surface coal mine participated in the study. The focus groups identified equipment, tasks and situations in which the range of potential operator or maintainer characteristics were not accommodated, including both situations which had been resolved by design changes made onsite, situations which were currently managed through administrative controls, as well as any situations for which no solution had been identified. Extensive time was spent in the workshop and in-field with equipment maintainers who identified a number of tools and platforms purpose built to assist with maintenance tasks. Both equipment operators and maintainers identified similar issues across sites and across companies. Working within individual site requirements, video footage and still images were captured to illustrate the design issues identified during the focus groups. Manual task analysis was undertaken using Ergoanalyst an injury management software system that utilities participative ergonomics to identify and assess manual task risks and potential control implementation to reduce risk and maximise productivity.

The information gathered during the project was used to gain an improved understanding of the limitations of current equipment designs with respect to accommodating diversity in operator and maintainer physical characteristics (static anthropometric variability); and with equipment operation and maintenance tasks which require combinations of high exertion, awkward or static postures, repeated similar movements and long duration which do not accommodate potential variability in operator and maintainer strength, flexibility and reach distances (dynamic anthropometry). Additional information was sourced from previously documented assessments of manual tasks associated with earth-moving equipment maintenance, including attempts to reduce manual tasks risks undertaken by a range of mine sites. The information obtained was used to construct and populate an EMERST Control Framework for equipment design for diversity.

Two required operating states were defined:

(1) Earth-moving equipment can be safely and comfortable operated by people of a maximum range of anthropometric diversity.

(2) Earth-moving equipment can be safely and comfortable maintained by people of a maximum range of anthropometric diversity.

A range of credible failure modes were identified including:

1.1 Small operators have difficulty reaching isolation points, fire suppression and emergency stop.
1.2 Small operators find access systems initial step height uncomfortable
1.3 Height and weight of refuelling hose and attachments makes refuelling difficult
1.4 Location of displays requires excessive neck extension and/or shoulder extension
1.5 Controls difficult or uncomfortable to operate for smaller operators
1.6 Equipment operation requires extended periods of neck rotation
1.7 Seat suspension cannot be adjusted sufficiently to suit the mass of small operators
1.8 Seat height cannot be adjusted to suit leg length of small operators
1.9 Routine maintenance or inspection tasks performed by operators require excessive reach
1.10 Seat belt height cannot be adjusted to be comfortable for small operators
1.11 Mirrors do not provide the field of view required by small operators
1.12 Truck handrail impedes vision for smaller truck drivers
2.1 Maintenance tasks require excessive exertion
2.2 Maintenance tasks require awkward postures

DISCUSSION AND CONCLUSION

The consistency observed across focus groups and workshop observations undertaken confirms the concerns regarding the current design of mining equipment which prompted the initial ACARP project were justified in that aspects of earth-moving equipment designs may unnecessarily restrict the range of potential employees who can operate and maintain the equipment, and in turn create elevated risks of injury for those who undertake tasks associated with operating and maintaining the equipment. The observations also confirm the concerns are not limited to one particular mine operator, mine site or original equipment manufacturer.

During the focus group discussions most operational concerns were raised by female members of the workforce, with concerns related to anthropometric issues associated with seating; visibility whilst operating haul trucks; inability to reach isolation points, and procedures regarding in-pit refuelling. A number of female operators commented they felt most mining equipment was “designed for a 6 foot male”, however shorter stature male operators reported somewhat similar operating concerns. Smaller stature female operators reported difficulty with in-cab seat adjustments that suited their weight; provided comfortable foot pedal, dashboard control and switch reach; and allowed adequate operational visibility. Female operators reported shoulder, neck and chest discomfort from the seatbelt sash component. A female operator (55 kg / 157 cm) reported habitually operating a wheel dozer with the seat air cushion mechanism completely deflated. In this position she reported her foot often slipped off the pedals, however this set up was her preferred operating positions she believed removing as much air as possible from the seat provided a less jarring ride. To the contrary, removing the air completely negated seat attenuation to reduce exposure to excessive whole-body vibration levels, placing her at significant risk of musculoskeletal injury and other associated tissue damage associated with excessive exposures.

Maintenance tasks associated with heavy earth moving equipment are a frequent and significant source of exposure to musculoskeletal injury risks. In general across mine sites, the majority of the maintainer workforce is male dominated, however, an increasing number of female maintainers both as apprentices and fully qualified maintenance personnel are joining the workforce. Typically, design inadequacies associated with maintenance tasks related to poor access, inadequate provision of lifting points, inappropriate tooling, and the need for excessive manual forces to undertaken and complete maintenance tasks. Female maintainers face additional challenges in undertaking routine maintenance tasks, with a female apprentice approximately 3-4 months into her apprenticeship commenting “she wasn’t yet strong enough but would get stronger”. Comment was made that the torque of many bolts required excessive exertion to undo them, with it often not possible to get a rattle gun into a confined working space to assist with the task. On observation, awkward postures were often needed to complete tasks such as accessing oil service points which are generally located higher up on equipment. Consistent problems identified by male maintainers included narrow flame rails (e.g. on 709C trucks) which caught their tool belts. Absence of lifting points to assist hose change outs on haul trucks, lack of appropriately sized working platforms and lack of specific tools were also highlighted as significant impediments to safe task completion. Maintainers frequently commented “everything is big and heavy, we need proper lifting gear and tools which we don’t have”. Maintainers also considered adoption of regular maintenance scheduling rather than waiting until damaged components such as hoses needed replacement would reduce the frequency of working in awkward postures.

Recommendations arising from this research included the following: (i) EMESRT promotion of earth-moving equipment design improvements to reduce barriers to workplace diversity though communication of the findings of this project to Original Equipment Manufacturers, and standards committees. The equipment design limitations identified in this research frequently led to the performance of manual tasks associated with equipment operation, and especially maintenance, that involve hight exertion and/or awkward postures. Frequent or prolonged performance of such tasks increases the risk of musculoskeletal disorders. A combination of task redesign and administrative controls should be employed to reduce the identified risks. Harnessing the expertise of the workers who undertake the tasks through a participatory ergonomics process has potential to both ensure that the solutions proposed are optimal, and will be accepted by workers. Training in ergonomics principles, team work and problem solving is likely to be required; as well as the provision of tools for the efficient analysis of manual task risks and for the development and documentation of proposed and implemented changes. If this can be achieved, the evidence is that such a program will reduce injury risks (Burgess-Limerick, 2018) and such approaches are recommended by resource industry regulators. It is also recommended that:(ii) mine operator implement participatory ergonomics programs that assess hazardous manual tasks associated with equipment operation and maintenance, including a combination of design and administrative controls to reduce risks as far as reasonable practical.

Many of the challenges documented during the focus groups and workshop observations may have been arisen because original equipment designers and manufacturers do not see or understand the conditions under which maintenance tasks in particular are performed, however, and more importantly the standards and guidance material available to designers does not adequately equip them to understand how to address these challenges. While the general business case for increasing workforce diversity in mining is well established, and improving earth-moving equipment design can remove significant anthropometric and other work demand impediments to establishing a more diverse mining workforce, it is clear both practical on-the-ground improvement of current operational practice and improvements in equipment design is required, particularly for maintenance tasks.

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