

User-centred design for civil construction: Optimising productivity by reducing safety and health risks associated with the operation and maintenance of on-road vehicles and mobile plant

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A range of productivity implications, injury and health risks are associated with the operation and maintenance of road construction equipment. Potential unwanted events giving rise to these risks include: slip, trips and falls from ground or at height; performance of hazardous manual tasks; exposure to heat, chemicals and whole body vibration; vehicle roll overs; and collisions. It may be possible to remove or reduce the risk of these events through improved design of the equipment and wider organisational systems. Design analysis techniques and a risk assessment tool (Design OMAT and EDEEP) were applied in the review of an asphalt job truck. Findings have led to preliminary design considerations for improvement and there are implications for organisational system changes.

Practitioner Summary: The design of heavy work vehicles requires input from users – operators and maintainers – as well as operations management, safety, and human factors practitioners to achieve optimum health, safety, and productivity outcomes.

Keywords: User-Centred Design, Participatory Ergonomics, Civil and Road Construction

1. Introduction

1.1 Industry Profile and Injury Trends

The construction industry is the fourth largest contributor to Gross Domestic Product (GDP) in the Australian economy (Australian Bureau of Statistics, 2010). In 2011–12, the contribution represented 7.7 per cent (\$106.5b) to the national economy. The construction industry employed 1.01 million people in Australia in 2011 – 2012 (9 percent of the workforce) (Safe Work Australia, 2013). The majority works full-time (86 percent) and is male (89 per cent), (Australian Workforce and Productivity Agency, 2013).

Fatality incidence in 2014 in construction was the third highest among all industries in Australia representing 15.2% of all deaths (28 of 184 total deaths) (Safe Work Australia, 2015). Over the five years from 2007–08 to 2011–12, the construction industry accounted for 11% of all serious workers' compensation claims and, on average, 39 claims daily were arising from employees who required one or more weeks off work owing to work-related injury or disease. Safe Work Australia (2013) reports that between 2007–08 and 2011–12:

- *Body stressing* accounted for 34% of claims—more than half of these were due to muscular stress while handling a range of materials, tools and other equipment.
- *Falls, trips and slips of a person (from height or same level)* accounted for 26% of claims.
- *Being hit by moving objects* accounted for a further 16% of claims—many of these involved being hit by falling or moving materials and equipment.

Most industries employ transport-related workers and this is true for construction – operators of job trucks, trucks for specialised purposes (eg. bitumen sprayers), and mobile plant equipment, for example. Safe Work Australia (2011^a) reveals that in 2009 – 10 the serious claim rate in transport and storage was almost double the national average (24.0 claims per 1,000 employees). The primary mechanisms of injury included muscular stress, falls, trips and slips, and being hit by moving objects, mirroring trends noted in construction. Safe Work Australia (2011^b) also highlighted that, across Australia, the groups with the highest serious claim rate include labourers, intermediate transport, and trades workers. Construction includes all three occupational groups.

1.1.1 Design as a Contributing Factor to an Unwanted Event

A wide range of design-related issues contribute to workplace fatalities (National Occupational Health and Safety Commission, 2004). The most frequently cited include: design error with roll-over protective structures; seat belt design; inadequate guarding; lack of residual current devices; inadequate fall protection; failed hydraulic lifts; braking errors; and inadequate protection on mobile plant and vehicles, such as enclosed cabins. In this analysis of incidents and fatalities in 2001-02, it was estimated that 90% of incidents involving humans and machinery or fixed plant appeared owing, at least in part, to design issues. Design considerations may also extend beyond the nuts and bolts of equipment to workforce strategy, organisational systems, and resource planning.

1.2 Risk-Taking Knowledge and Behaviour

Storseth et al (2010) explains that people at all levels face safety-critical decisions where there may be competing goals with budgetary compliance and project-timelines. A study of 57 accidents at sea concluded that few accidents occurred owing to deliberate risk-taking behaviour among workers, however. Rather, they were systemically risk-exposed in their work and simply “ran the risk” (Wagenaar and Groenweg, 1987).

Safe Work Australia (2014) reported that construction labourers were a cohort most likely to be accepting of risk-taking at work, inferring that workplace culture contributes to risk-taking and rule-breaking. As such, they call for a “need to rethink the way work is designed to help to remove pressures that lead to risk-taking and rule-breaking” (Safe Work Australia, Dec 2014, pp. vi).

1.3 Risk Management Practice

Many businesses fail to conduct a broad, integrated systems approach to risk assessment (MacDonald & Evans, 2006). A participatory team approach to safe work design may help with a balanced risk management strategy. Those working at the coal-face, who know their work best as subject-matter experts for effective work analysis, are also subject to the enticement of complacency and personal reference and this may sway their ability to identify hazards or escalate risk. In short, the more familiarity a person has with a product or system, and the more frequently that task is performed, the less hazardous the product, system, or task is believed to be (Sanders & McCormick, 1993; Noyes, 2001). People tend to rely heavily on personal knowledge and historical performance. That is, if they have not been injured or have not known others injured by the hazard, they may underestimate risk (Sanders & McCormick, 1993).

In terms of human factors, the emphasis for risk management is on higher order controls: elimination, substitution/isolation, and engineering design. Further, the practice involves consultation with workers at every stage of analysis of productivity and safety: hierarchical task analysis, hazard review, risk determination, design strategy, control strategy, trial, redesign, communication strategy, implementation, and measurement of ongoing effectiveness (Horberry et al, 2011).

1.4 Participatory Ergonomics and User-Centred Design

Participatory ergonomics involves practice that actively engages end-users as participants in risk-based task analysis (Burgess-Limerick, 2011). In this way, valid and contextualised analysis of work provides meaningful rationale for control intervention.

The involvement of human factors engineering contributes to overall user-centred design strategy. User-centred design organises technology around the users’ goals, tasks, capability, and need; minimises exposure to hazards; mitigates safety and operational risks; organises technology around the ways users process information and make decisions; keeps users in control and aware of the state of the system; employs appropriate alerts to provide the user vital information; optimises situational awareness; results in error reduction and improved productivity; and increases user acceptance (Endsley & Jones, 2012; Horberry et al, 2014). User-centred design enables product interaction that is intuitive or consistent with past adaptive habits and behaviours (Noyes, 2001). When applied to a system lifecycle, human factors engineering and user-centred design is a subset of “human systems integration” (Booher, 2003; Horberry et al, 2014).

Participatory ergonomics, human factors engineering, and user-centred design helps mobilise a workforce beyond engagement, wherein workers become the architects of their work systems, procedures, and equipment; they become co-authors of superior work design with assistance, coaching, and facilitation

from skilled human factors design professionals that draw upon a large body of science and validated research.

1.4.1 User-Centred Design: Initiatives and Cost Benefits

“Healthy and safe by design” is one of seven key action areas of the Australian Work Health and Safety Strategy 2012 – 2022 (Safe Work Australia, 2012). Safe design and human systems integration is considered to be the most resilient means to create a healthy and safe work environment. Design is inclusive of equipment, task, and workstation design; management practice; and work processes. In alignment, The National Institute for Occupational Safety and Health (NIOSH) (2004) cite the American Society of Safety Engineers (2011): *“One of the best ways to prevent and control occupational injuries, illnesses, and fatalities is to design out and minimise hazards and risks early in the design process.”*

User-centred design saves money and prevents injury. To illustrate, Cantley et al (2014) provide outcome studies of a six-year large-scale participatory ergonomics program in industrial manufacturing involving 17 aluminium plants with manufacturing, production, and maintenance staff. This resulted in reduction of overall relative risk most significant for musculoskeletal disorders. Each ergonomic hazard control was associated with a 7% reduction in relative risk (5 injuries per 100 person-years). In a project commissioned by the Australian Department of Defence, Burgess-Limerick (2010) conducted a review of publications describing benefits of human systems integration in design and risk management strategy in which return on investment was determined in ratios of 40 – 60:1 (Burgess-Limerick, 2010).

1.5 Project Scope

The equipment, trucks, and plant used in heavy industry pose a major occupational hazard – they may be fast, heavy, and powerful but not crash tolerant, used in at-risk environments among pedestrian workers and other plant in close proximity. The design is likely to have been focussed on the work outcome required and durability rather than human interaction needs (Horberry, 2011; and Horberry et al, 2011).

Potential unwanted events giving rise to these risks include: slip, trips and falls from ground or at height; performance of hazardous manual tasks; exposures to heat, chemicals and whole body vibration; vehicle roll overs; and collisions with other vehicles, equipment, or pedestrians. Given the tenets of human factors and safety by design, it was considered theoretically possible to remove or reduce the risk of these events through design improvement. This case study describes hazard identification, risk determination, design development ideas, and organisational outcomes following review of an asphalt job truck. The Design for Operability and Maintainability Analysis Technique (Design OMAT), combined with the EMESRT (Earth Moving Equipment Safety Round Table) Design Evaluation for Equipment Procurement (EDEEP) process and tools were used to facilitate this process.

2. Project Overview

2.1 Design OMAT and EDEEP

Design OMAT refers to “Design for Operability and Maintainability Analysis Technique”. It is a hierarchical task-oriented risk assessment process that focuses on risks in relation to the human interface with equipment. Key terms include consideration of safety and productivity, defined as (Horberry et al, 2011):

- *Operability: The ease with which equipment can be operated safely and in the optimal amount of time*
- *Maintainability: The ease with which equipment can be repaired safely in the least time.*

The Design OMAT was an integral component of the development of the EMERST Design Evaluation for Equipment Procurement (EDEEP) process. The Earth Moving Equipment Safety Round Table (EMERST), is a collaboration of multi-national mining companies which formed in 2006 with the aim of engaging with equipment manufacturers to facilitate design improvements for mining equipment. This process provides purchasers and manufacturers with guidance material to assess how well the EMESRT design philosophies are addressed in equipment design (Burgess-Limerick et al, 2012). The design philosophies include eight key functions associated with human-equipment / system interface and these include: 1) Access and working at heights; 2) Tyres and rims; 3) Exposure to harmful energies; 4) Fire; 5) Machine operation and controls; 6) Health impacting factors; 7) Manual tasks; 8) Confined spaces and restricted work areas.

The design philosophies outline potential unwanted events (PUE's) associated with foreseeable human behaviour and equipment use. These have been grouped to include 20 events including: falls from height or

same level; blocked emergency egress; contact incident; caught between moving objects; wheel assembly, rim, or tyre failure or explosion; fire; exposure to manual tasks; collision; loss of machine stability; inadvertent or erroneous operation of a control; incorrect interpretation of a display or label; failure to respond to an alarm; extreme temperature exposure; respirable dust exposure; exposure to diesel particulate material or other particulates; noise exposure; whole-body or peripheral vibration exposure; failure of control system; and exposure to irrespirable atmosphere in a confined space.

It was believed that enough similarities existed with mining equipment and human interface as that which may present with construction equipment that the research conducted in the minerals industry could be harnessed in a meaningful way through application of these risk management practices.

2.2 Work Process

Design OMAT involves a six-step process as listed below (Adapted below from Horberry et al, 2011). These steps formed the cornerstone of the work process conducted at Boral Asphalt Queensland for the review of the asphalt job truck. Additional organisational activity, including application of the EDEEP tool, is indicated in alpha order with text in italics, with the Design OMAT step indicated in numeric form below:

Table 1: Work Flow Process.

Organisational	Design OMAT	Description
a.		<i>Management consultation for project support and initial job role / equipment selection</i>
	1.	Prioritisation of critical tasks
b.	2.	Conducting task analysis: identification of the step-by-step physical, cognitive, or communicative sub-components of the task required within the job role: multiple on-site visits coordinated with work crew <i>Truck measurements and analysis with worker consultation: multiple visits at depot and/or on site</i>
c.		<i>Documenting findings with review of workers and management</i>
d.	3.	Hazard identification, escalation, and risk determination <i>Collaborative team review of findings and application of EDEEP tool</i>
	4.	Control strategy (solution) development
	5.	Consultation with workers through seeking feedback (an iterative design process)
e.	6.	Maintenance of a risk register imbedded in project management planning <i>Presentation to management and procurement for process and design review</i>

As this design review method was new to the organisation, additional communication and resource was necessary. To underpin the significance of this work, a South-East Queensland regional manager assigned himself as a representative to oversee and champion the activity through their project management reporting system which is communicated to higher levels of management, effectively making him accountable for the project completion. Additional time was spent to develop a checklist of vehicle features for description and measurement: such as stairwells for ingress/egress – step height, width, and length; grab rail height reaches and diameters; hand and foot control types; alarms and indicators; access points to the truck body; fixed and portable equipment stored on the body of the truck; and similar. This enabled the principal investigator, whose background is more aligned with human and biological studies than engineering truck design, to develop familiarity with the “language of truck” and aid in dealings with engineering and procurement teams. As this step involved in-depth investigating, probing, simulated work activity and observation in the natural environment with worker consultation occurring over multiple visits, it also revealed additional, relevant hazard reporting that may have been omitted during the initial task analysis. Work crew did not initially realise the opportunity to voice concerns regarding design-related issues, nor to speak out against the way things had always been done. Their familiarity with the equipment and work process also meant that several lines of questioning presented in different ways was required to elicit the most comprehensive response.

2.3 Findings

The narratives were telling, with work crew reporting issues such as:

“(Our) head hits the rear overhead hang when we climb the stairwell to the body of the truck”.

“The guys do not use the lift platform to retrieve the whacker packer vibe plate (up to 80kg) or the jack hammer (40kg) if the truck is not already operating; it takes too long to start the truck and wait for the hydraulics to kick-in”.

“Workers typically exit the rear of the dual cab forward-facing as the design of the steps are not conducive to cab facing exit (egress) (difficult to see, flush with the body, require legs to cross midline)”.

“Night visibility is poor with the steps; there are interior lights only and these are not adequate”.

“The plastic tread on the top step for cab entry is worn and offers poor traction”.

“The truck awning set-up is cumbersome; it is a 10-minute set-up process (and this is deterring)”.

Other issues were raised such as poor access to reach grab rails embedded in the stairwell cabinet wall for egress from the truck body; right hand contact stress among taller operators between the steering wheel and emulsion spray control panel; occasional misunderstanding of the emulsion spray panel control buttons and this impedes productivity; extended reaches required of shorter operators; lack of faith in the functioning of the crane given the truck hydraulics and remarkably infrequent report of crane use in metro areas; discomforting and restricted seating space for crew sitting in the rear of the dual cab; inadequate storage capacity and access to work equipment and tools; exposure to manual tasks with heavy and awkward reaches, such as diesel bath bucket retrieval; excessive reaches to close doors from the cab; and poor engine access with secondary and tertiary reach envelope requirements of mechanics to reach beyond the rear cab stairwell when the cab is raised. The application of the EDEEP spreadsheet tool and risk management process indicated these risks and the top 5 areas of concern and preliminary design considerations have been outlined (refer to Table 2 below):

Table 2: Top 5 Issues Raised: EDEEP Tool and Design Considerations.

No	Consequence	Likelihood	Description	Design Considerations: Preliminary
1.	Major	Unlikely	Crane lift failure risk for loss of machine stability or hitting object or person	Capacity routinely engineering rated; training to workers; escalate for review with management as to cost-benefit ; assess rural versus metro use
2.	Serious	Possible	Retrieval of diesel bath bucket: Manual task exposure with risk for sprain/strain	Referral for further ergonomic risk assessment; re-design diesel bath bucket, paver lug attachment, storage and transportation strategy
3.	Serious	Possible	Retrieval of vibe-plate and jackhammer: manual task exposure - sprain/strain risk	Independent quick-activation control for hydraulics of lift platform or cradle release with hydraulic or air ram to lower items to ground
4.	Medium	Possible	Rear cab egress: fall from height	Redesign stepwell for uniform step height, swing away access (for mechanics) and improved visibility and access; add night-time lighting; add coated safety high-vis yellow tread.
5.	Medium	Possible	Front cab ingress/egress: fall from height and sprain/strain	Replace plastic top tread with metal step and add coated safety high-vis yellow tread to steps; design for even risings $\leq 5\text{mm}$ variation; add focal lighting and strip lighting; design for visibility day and night

Findings were presented to a management team and a national procurement representative who asked for the following activities which are now active in the business:

1. Begin a plan for design improvement of the immediate issues raised – whether after-market changes are required or make recommendations for their design specification to aid procurement.
2. Make recommendations generally for a next-generation procurement document that may be of benefit nationally within the division.
3. Consider a position statement for the organisation with regard to user-centred design philosophy and strategy.

Healthy debate ensued among safety, operational and management teams with regard to risk rating and the application of the EDEEP tool. In particular, it was determined that the most severe incidents leading to fatality or severe disablement may be least likely to occur but design consideration was of merit. This suggests that commonly used 5x5 risk rating schedules may not be adequately sensitive to indicate design review needs; that is, events of significant consequence but low frequency ratings may indicate non-urgent action on a traditional risk-rating measure. This review team rated an unlikely but potentially potent event as a number one issue of concern on the priority review table.

3. Conclusion

This ongoing work has shown that using a structured, task-based method is beneficial in identifying design deficiencies for a road construction job truck. The Design OMAT and EDEEP tools and processes as used in the minerals industry show excellent promise for use in the construction industry. This project has cemented management interest to do so. The participatory ergonomics method employed is helping to produce effective redesign solutions for this domain. Bringing together civil construction operators and maintainers with designers and engineers is therefore helpful in the potential to reduce safety and health risks associated with the operation and maintenance of on-road vehicles and mobile plant. Early findings have revealed other important implications for organisation systems changes. This includes the importance of conducting hierarchical risk-based task analyses for key operational job roles; reconsideration of traditional risk assessment methods, a philosophy shift toward user-centred design, and an interest to shift elements of procurement practice from detailed, prescriptive schedules toward placing the onus on the supplier to explain their human factors design methodology, records of successful trial of design controls, and to provide comprehensive training support. This practice may lead to industry change as the organisation has shared their findings with technical officers of relevant industry councils who have indicated their interest to review engineering design needs with manufacturers.

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