Human factors for the design and operation of mobile equipment

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Why heavy equipment?
Zimmerman Profile of MSD’s in heavy equipment operators

- **Bulldozer**: stiff shoulder, fatigue, LBP
- **Crane operator**: back disorders, vibration
- **Earth moving**: LBP, discomfort, spine disorders
- **Forklift**: stiff shoulder, LBP, fatigue
- **Power Shovel operator**: stiff shoulder, LBP
- **Tractor operator**: vibration and LBP

Longer employed

Older equipment
The field of **human factors** is concerned with the **interaction** between **people** and **work systems**, in order to **maximize** human well-being and system performance.
What are some of the concerns with heavy equipment operation?

- Line-of-sight and visual field
- Seating quality
- Cabin space
- Control layouts
- Ingress and egress
- Work scheduling
Poor LOS is a cause for concern

Heavy equipment operators are at increased risk for back and neck musculoskeletal disorders
Large Machines and Line-of-Sight

What DOESN’T an operator see?

Recent Coroner’s Inquests (Ontario, Canada) recommend renewed focus on LOS and earth moving equipment (2009, 2010)

The pedestrian is no longer visible.
Machine Components and LOS

- Cab Design (posts & windows)
- Light Posts/Brackets
- Bucket size
- Engine profile
Machine Design Impacts LOS
Driving posture during LHD operation has neck rotated more than 45° for over 89% of the shift.

Limits for awkward neck postures have been documented by only a few sources:

Swedish National Injury Criteria (Eklund et al. 1994)
- Neck should not be rotated >45deg for more than 50% of the shift.

Suggested Neck Postures (Gellerstedt et al. 1999)
- Operators should not be required to rotate head <30deg.
- Operators should not have to tilt head > 5deg upwards or >25deg downwards.
Reduce postural requirements

- Seat adjustability
  - Seat height
  - Seat angle
  - Seat swivel

- Cabin space

- Improve line of sight

- Enhance mirrors or camera use
To the Ministry of Labor:

Communication recommendations:

1) Implement two-way radio communication for all underground workers.
2) Implement audible warning procedure by sounding vehicle horn prior to all vehicle movement.
3) Implement underground proximity warning system for all workers.

Visibility recommendations:

4) Strobe lights and/or laser lightning to be placed in the area of all stationary workers.
5) Height adjustable seats on LHD vehicles, with a 360 degree swivel.
6) Implement industry standard for reflective helmet striping, and consider fully reflective helmet.

Research and Development:

7) Continue research on underground mobile equipment cameras.
8) Share best practices industry-wide and globally.
Seat rotation resulted in significantly less trunk lateral bend, trunk rotation and neck rotation.
# Ergonomic Checklist for Cab Design on Construction Machinery

<table>
<thead>
<tr>
<th>Seat adjustability factors</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Is the seat height adjustable?</td>
</tr>
<tr>
<td>2. Can the seat be adjusted horizontally?</td>
</tr>
<tr>
<td>3. Is the seat set at proper height?</td>
</tr>
<tr>
<td>4. Does the seat have a back support?</td>
</tr>
<tr>
<td>5. Does the seat have a lumbar support?</td>
</tr>
<tr>
<td>6. Are there armrests available?</td>
</tr>
<tr>
<td>7. Are the armrests adjustable?</td>
</tr>
<tr>
<td>8. Are the armrests set at proper height?</td>
</tr>
<tr>
<td>9. Do you feel any vibration from the equipment through the seat?</td>
</tr>
<tr>
<td>10. Do you feel any vibration from the equipment through the floor?</td>
</tr>
<tr>
<td>11. Do you feel any vibration from the equipment through the controls?</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Armrest adjustability factors</th>
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</thead>
<tbody>
<tr>
<td>Yes</td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>4</td>
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<td>7</td>
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<td>10</td>
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<table>
<thead>
<tr>
<th>Vibration overview</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yes</td>
</tr>
<tr>
<td>13</td>
</tr>
</tbody>
</table>
Cab space interacts with design features
Dynamic armrest by Michele Oliver
University of Guelph

* Pictures from Murphy and Oliver, 2011
**Patent pending
Kittusamy Ergonomic Checklist for Cab Design on Construction Machinery

12. Is the seat firmly mounted to the floor of the cab?
13. Can the seat be tilted backward?
14. Can the seat swivel?
15. Is the location of the controls or levers adjustable?
16. Can you easily reach the levers or controls?
17. Can you easily operate the levers or controls?
18. Can you easily reach the pedals?
19. Can you easily operate the pedals?
20. Is the cab area large enough (e.g., uncramped area) for you?
21. Do you have sufficient upward visibility?
22. Is your view of the operation obstructed (e.g., cab guards, pipes/hoses, etc.)?
23. Do you feel the cab is noisy?
24. Can you control the temperature of the cab?
25. Does the equipment have steps?
26. Does the equipment have handrails?
27. Can you easily open/close the cab doors?
28. Does the equipment have proper means for entering the cab?
29. Does the equipment have proper means for exiting the cab?

II. Environmental
30. Do you have a good general view of the ground?
31. Are the cab windows free from distracting reflections?
ISO 3411:2007
Earth-moving machinery -- Physical dimensions of operators and minimum operator space envelope
Provides the dimensions of operators of earth-moving machinery and specifies the minimum normal operating space envelope within the operator enclosures.

ISO 6682:1986
Earth-moving machinery -- Zones of comfort and reach for controls
Defines zones of comfort and reach for controls derived from the overlapping reach capability of large and small operators in the seated position. Is intended as a guide for the design of the operator compartment controls for earth-moving machinery.
Seat Adjustment

ISO 11112:1995
Earth-moving machinery -- Operator's seat -- Dimensions and requirements

Specifies the dimensions, requirements and adjustment ranges for operator seats on earth-moving machinery. Additionally, it contains dimensions for armrests when fitted on these machines.
Seat Features

Lower Back Supported

Upper Back and Head Supported

Miller and Gariepy, 2011
Environmental: Cab

- Temperature consistency
- Temperature distribution
- Loudness of alarm
- Type of alarm (frequency, tone, etc)
- Ventilation concern

ISO/CD 1996-2
Acoustics -- Description, measurement and assessment of environmental noise -- Part 2: Determination of environmental noise levels
Volvo Cab

Take command with all-day ergonomic comfort features such as multi-adjustable seat, steering column and ergonomically placed controls. Increased interior space, cab ventilation through 13 vents and an air conditioning (AC) option provide an operator-friendly environment. Excellent through large windows, narrow pillars and a sloping hood.

Adjustable steering column

The optional Deluxe Cab features a steering wheel with both tilt and telescopic adjustments, permitting changes to fit any operator’s preferences.

The next-generation Volvo backhoe is here. Step into the redesigned, roomier cab and raise your productivity with durable, high-performance equipment. Volvo is known as the market leader in comfort and the cab is now better than ever with ample amounts of personal storage space. The ergonomic layout, controls and instruments put you in command. With large glass areas, all-around visibility has been enhanced, improving safety and productivity.
Ingress and Egress
Ingress/Egress

A. Ground to handrail or handle 85-130 cm
B. Step to handrail or handle 85-100 cm
C. Ground to first step ≤ 40 cm
D. Maximum pitch ≤ 50°
E. Rise 20-30 cm
F. Step depth ≥ 24 cm
G. Horizontal clearance ≥ 15 cm
H. Distance to handle or handrail ≤ 63 cm
I. Centre width of door ≥ 85 cm
J. Width at bottom of door ≥ 45 cm
K. Step width ≥ 40 cm
L. Height of door ≥ 170 cm

<table>
<thead>
<tr>
<th>Green</th>
<th>Yellow</th>
<th>Red</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Foot steps</td>
<td>Slight divergence from recommended measures. The operator has to enter/exit the machine only with great difficulties.</td>
<td>The operator can enter/exit the machine only with great difficulties.</td>
</tr>
<tr>
<td>2 Handrail or handle</td>
<td>Handrail or handle available but with shortcomings in construction. They can be used but with some difficulties.</td>
<td>Handrail or handle lacking or can be used only with great difficulties.</td>
</tr>
<tr>
<td>3 Risk of slipping</td>
<td>Some difficulties in keeping steps clean. Slip protection available.</td>
<td>Difficult to keep steps clean and/or slip protection lacking. Wheel or track used.</td>
</tr>
<tr>
<td>4 Cabin entrance</td>
<td>Shortcomings concerning recommended measures.</td>
<td>Too narrow opening; height &lt; 130 cm or centre width &lt; 45 cm or bottom width &lt; 25 cm</td>
</tr>
<tr>
<td>5 Cab door</td>
<td>Cab door is not sufficiently easy to handle or cannot always stay open when needed. No risk for pinching.</td>
<td>Cab door heavy and difficult to handle, does not remain open when needed.</td>
</tr>
<tr>
<td>6 Emergency exit</td>
<td>Emergency exit with limited space or no emergency exit provided.</td>
<td></td>
</tr>
</tbody>
</table>

Number of green marks:

Yellow marks:

Red marks:
Ingress/Egress
An Analysis of Injuries to Haul Truck Operators in the U.S. Mining Industry

Brenda R. Santos, William L. Porter, Alan G. Mayton
National Institute for Occupational Safety and Health, Office of Mine Safety & Health Research, 626 Cochrans Mill Road, P.O. Box 18070, Pittsburgh, PA 15236

Because haul trucks are used extensively in mining, the operators of these trucks are exposed to various risks and hazards inherent to this occupation. The objective of this work was to profile injuries sustained during haul truck operations, to identify priorities for further investigation, and to determine potential injury prevention strategies. Data from the Mine Safety and Health Administration (MSHA) annual administrative database were sorted and reviewed to select records identifying a subset of injuries sustained during haul truck operations. Records covering a 5-year period (2004–2008) involving haul trucks were reviewed. The majority of the injury records were for injuries classified as “struck against moving object” (STRUCK) (N=613) and “slip or fall of person from an elevation or on the same level” (SLIPFALL) (N=359). Each injury narrative was read to determine the activity being performed during the injury (such as ingress, egress, driving, maintenance), the incident results (such as operator impact and truck impact), contributing factors to the event, and environmental factors. The nature of the injury, body parts affected, as well as lost work days were also quantified. The average lost work days for STRUCK and SLIPFALL injuries was 60 and 62, respectively. The majority of the total incidents resulted in sprain and strain injuries; the back was the most frequently injured body part injured. For STRUCK injuries, the majority of activities being performed at the time of the injuries involved driving (63%). More than one-third of the total incidents resulted in vertical jarring of the haul truck (36%), and the majority of the total incidents caused jolting and jarring to the operator (75%). For SLIPFALL injuries, the majority of incidents occurred during egress from the vehicle (46%), and of the total incidents, 32% resulted in the worker falling. Almost one-third of the total incidents were due to the operator’s foot slipping (32%). Further investigation should focus on the factors contributing to haul truck operators being struck against a moving object and those related to operators slipping and falling.
1.6 Injury from falls caused by using chains as part of the handrail or ladder opening protection.
“Employee did not have hold of hand hold that was provided to enable him to have 3 point contact.”

Table 6: Contributing factors leading to an event (N=359).

<table>
<thead>
<tr>
<th>Factor</th>
<th>N</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Foot slipped</td>
<td>116</td>
<td>32</td>
</tr>
<tr>
<td>Unknown</td>
<td>86</td>
<td>24</td>
</tr>
<tr>
<td>Other</td>
<td>30</td>
<td>8</td>
</tr>
<tr>
<td>Lost footing/slipped</td>
<td>27</td>
<td>8</td>
</tr>
<tr>
<td>Equipment failure</td>
<td>24</td>
<td>7</td>
</tr>
<tr>
<td>Missed step</td>
<td>22</td>
<td>6</td>
</tr>
<tr>
<td>Lost hand grip/hand slipped</td>
<td>20</td>
<td>6</td>
</tr>
</tbody>
</table>

Environmental factors were noted for 11% of all incidents (N=40). Wet, icy, and muddy conditions were each only indicated for less than four percent of the incidents.
Controls and Displays
ISO 6405-1:2004
Earth-moving machinery -- Symbols for operator controls and other displays -- Part 1: Common symbols

ISO 6405-2:1993
Earth-moving machinery -- Symbols for operator controls and other displays -- Part 2: Specific symbols for machines, equipment and accessories

The symbols given apply to controls and displays specific to backhoe loaders, dozers, loaders, graders, scrapers, excavators and dumpers, and for controls and displays for stabilizers, outriggers, grapples, rippers and winches.
Checklist Items to Consider

- Protection against movements
- Controls activate functions according to figures
- Controls follow directional compatibility
- Primary controls within the comfortable zone
- Secondary controls within reach zone (no excessive movement)
- Control adjustability desirable
- Location of visual displays within 30° cone of operator position
- Legible displays in all lighting conditions
Potential Unwanted Events (PUEs)

5.8 Harm from incorrect use of equipment controls, incorrect/inaccurate calibration or ineffective maintenance due to poorly designed controls and displays, including:
   a. lack of understanding or misunderstanding about function of the control or display
   b. counter-intuitive design and configuration
   c. inconsistency in display or function in comparison with other controls or displays (within vehicle)
   d. not appropriately considering simultaneous control operation
   e. ability for unintentional operation or selection
   f. unexpected operating mode (mode errors)
   g. frequently used and/or safety critical controls not being located within the zone of reach
   h. insufficient clearance around controls and other workstation equipment
Potential Unwanted Events (PUEs)

5.9 Harm from misinterpretation of information due to displays or labels being:
   a. Illegible
   b. Incomprehensible
   c. Not visible
   d. Inappropriately located
   e. Not using universal symbols or standardized terminology
   f. Not durable
Testing Control Layouts (Steiner et al. 2013)

Fig. 3.
Actual roof bolter set up (a) and changed set up for experiment (b).

Fig. 4.
Typical lever shape (a) and suggested MDG3E shape-coded controls (b).
Controls and Displays
Controls and Displays: Overview
Control Design Principles
Reducing Control Errors: Guarding, Feedback, Mode Errors, Coding, and Directional Control–Response Relationships
Display Principles
Case Study: The EMESRT Controls and Displays Design Philosophy
Final Thoughts

Although we have presented many of the challenges with heavy equipment design in isolation – the issues are often more complex and interrelated.
Reducing adverse health effects associated with mobile equipment operation (poor LOS, awkward postures; whole-body vibration exposure; controls/displays; ingress/egress) will require a multifaceted approach involving participation of workers, industry leaders, equipment manufacturers, and researchers.
Questions?
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- Ontario Mining Industry
- Northern Ontario Steel Manufacturing Industry

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References

- Kvalberg, J. L. (2010). Head-up display in driller and crane cabin.