

Case study

Bow-tie analysis of a fatal underground coal mine collision

Robin Burgess-Limerick¹, Tim Horberry¹ and Lisa Steiner²

¹ Minerals Industry Safety and Health Centre, The University of Queensland, Australia

² Office of Mine Safety and Health Research, National Institute for Occupational Safety and Health, USA.

Abstract

Background: Bow-tie analysis combines aspects of fault-tree analysis and event-tree analysis to identify an initiating event; its causes and consequences; and potential preventive and mitigating control measures or barriers. **Aims:** The aim of the research is to analyse a fatality which occurred in a Queensland underground coal mine in 2007 to illustrate this technique. **Method:** The case study concerns a fatality which occurred at an underground coal mine in Queensland in 2007. **Results:** A continuous mining machine operator was crushed against the mine wall by a shuttle car following a loss of situation awareness by the shuttle car driver. The causes included the use of shuttle cars in close proximity to pedestrians, and driver inexperience. A directional control-response incompatibility contributed to the severity of the final consequence. A range of potential control measures are identified including: (i) replacing shuttle cars with a mobile conveyer; (ii) non-line-of-sight remote control of continuous miners; (iii) proximity detection interlocked with shuttle car controls; (iv) “always-compatible” shuttle car steering design. **Conclusions:** Proximity detection sensors interlocked with shuttle car control systems is a technically feasible control measure which should be implemented at all underground coal mines. Non-line-of-sight remote control of continuous mining machines or automation of continuous mining machines would remove operators from this hazard entirely. A bow-tie representation provides an effective way of systematically examining the causes, consequences, and potential preventive and mitigating control measures or barriers associated with a previous incident.

©Burgess-Limerick et al: Licensee HFESA Inc.

Background

Bow-tie analysis (sometime called “cause-consequence” analysis) is widely used in high hazard industries (e.g. aviation, chemical, petro-chemical) as a risk analysis technique which combines elements of fault-tree analysis and event-tree analysis [1-3]. Pitblado and Weijand [4] suggest that the barrier diagram or bow-tie diagram was developed simultaneously in Australia and the Netherlands in the early 1990s, building on the work of James Reason and Patrick Hudson; although the authors of the Bow-tie Pro software website attribute the term to David Gill of ICI stating “it is generally accepted that the earliest mention of the bowtie methodology appears in the ICI Hazan Course Notes 1979, presented by The University of Queensland, Australia” (www.bowtiepro.com/bowtie_history.asp).

While there is no universally accepted standard bow-tie terminology and method, this paper will employ the terminology used by RISKGATE (riskgate.org), a major project funded by the Australian Coal Association Research Program [5,6]. RISKGATE is an on-line knowledge database which uses the bow-tie method to capture and present knowledge regarding the management of safety and health risk associated with coal mining.

At the centre (or knot) of each bow-tie is an initiating event (or “top-event”). This is the point in time when there is a loss of control of a hazard (a source of energy with potential to do harm). The next step is to determine the causes of

the initiating event, and the potential consequences of the event. For each cause, both the control measures (barriers) which can reduce the probability of the initiating event occurring (preventive controls), and the measures which can be taken to reduce the severity of the consequences of each initiating event (mitigating controls) are then identified. The bow-tie analysis can be further elaborated to examine the effectiveness of controls or barriers by including “barrier decay mechanisms” and assessment of the likely effectiveness of control measures.

One of the particular strengths of the bow-tie method is that it provides an easily understood overview of the risk controls linked to initiating events. Equally, it can show both existing controls and potential/recommended controls for hazards. The aim of this paper is to illustrate the utility of a bow-tie analysis of an underground coal mine fatality as a means of identifying and communicating the potential control measures which may be adopted to reduce the risk of similar events.

Method

A case study of a fatality which occurred at an underground coal mine in Queensland in 2007. The first author was retained as an expert witness during the subsequent coronial inquiry [7]. A bow-tie analysis of the fatality was constructed by the first author based on the information presented during the inquest.

Case Study

The victim was an experienced underground miner in the process of undertaking a deputy's qualification. On April, 9, 2007, he was working as a continuous mining machine operator at Moranbah North mine. This shift was the first shift after a period of days off. After leaving Mackay at 4 am, he had started work at 7.15 am.

The victim's task was to operate a Jeffrey continuous mining machine. The continuous mining machine is powered by a trailing electrical cable and operated via a hand held remote control. The continuous mining machine operator, and a cable hand, stood behind the continuous mining machine on the left side of the heading (the ventilation discharge was on the right of the machine). The heading (G heading) was narrower than previous headings due to a strata abnormality. The continuous mining machine cable was located on the left rib, supported by hangers. Brattice (ventilation curtains) was hung on the right side of the heading about 80cm from

the rib, and this reduced the effective roadway width further. Some protrusions existed on the left rib. At the start of the shift the continuous miner was located on the left side of G heading.

Two shuttle cars were used to transfer coal from the continuous mining machine to the conveyer boot end (Figure 1). Shuttle cars are bi-directional vehicles driven from an operator's cab located at the out-bye (discharge) end of the car. The cab contains two seats and the driver changes seat with each change of direction to face the direction of travel.

The continuous mining machine operator commenced cutting coal. One shuttle car had been filled and left the heading to travel to the boot end. A second shuttle car entered the heading. The wheeling road required a left hand turn to enter the heading (Figure 2). In evidence, the shuttle car driver indicated he had some difficulty in negotiating the turn, and that he was very close to the left rib as he entered the heading.

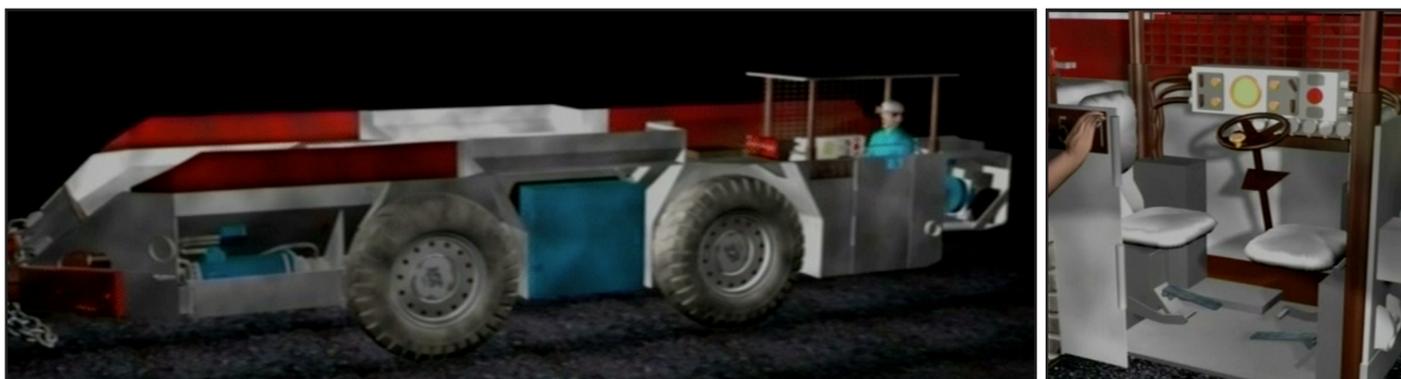


Figure 1: Shuttle car general arrangement (<https://www.youtube.com/watch?v=4DBVX2GJFr4>)

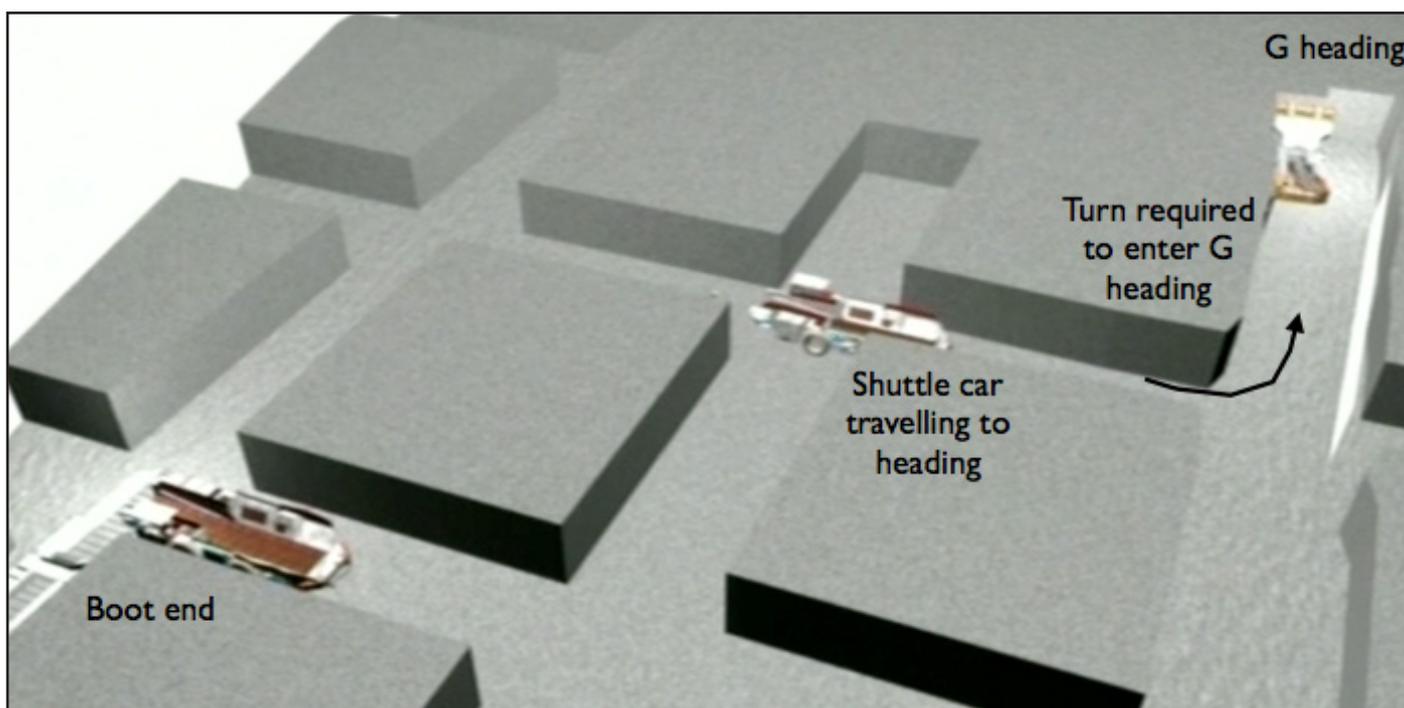


Figure 2: Layout of mine. (<https://www.youtube.com/watch?v=4DBVX2GJFr4>)

The shuttle car was then driven to the rear of the continuous miner. The continuous mining machine operator and the cable hand were located on the left rib, behind the continuous miner, adjacent to the loading end of the shuttle car. The continuous mining machine operator commenced cutting coal and filling the shuttle car. A loud clanging sound was then heard coming from the continuous mining machine. The continuous mining machine operator turned off the continuous mining machine and yelled out that the track was broken. He walked towards the shuttle car cab to talk to the shuttle car driver sitting in his cab. The cable hand was standing nearby. The continuous mining machine operator instructed the shuttle car driver to take the shuttle car out of the heading to the conveyer boot end.

The shuttle car driver then moved to the in-by seat of the shuttle car, facing out-by, and commenced driving the shuttle car out-by, intending to turn right to return to the boot end. Negotiating the corner from the starting position of the shuttle car close to the rib required the shuttle car driver to turn the steering wheel to steer the out-by end of the shuttle car away from the right rib (Figure 3).

Shuttle cars are designed with four-wheel steering and considerable overhang at each end to allow the vehicle to negotiate underground roadway corners. The consequence is that the extremities of the car move laterally as the car changes heading.

As the shuttle car driver was driving out-by, he heard a yell from the continuous mining machine operator and the shuttle car driver stopped the shuttle car. He stood up and looked around and saw the continuous mining machine operator leaning against the rib at the tail end of the car, facing him. The area where the continuous mining machine operator was trapped was near a protrusion in the left rib.

The evidence of the forensic pathologist was that at this point the continuous mining machine operator was pinned by the shoulders, but was not seriously injured.

The continuous mining machine operator yelled at the shuttle car driver to get the car off him, and indicated to the shuttle car driver that he should move the shuttle car in-by. The shuttle car driver sat in the out-by seat of the shuttle car, facing in-by, touched the tram (accelerator) and (by his account) turned the steering wheel, intending to move the shuttle car away from the left rib. The shuttle car moved in-by and the continuous mining machine operator yelled out. The continuous mining machine operator was now placed with his back to the rib, facing toward the shuttle car body (Figure 3). The evidence of the forensic pathologist was that the continuous mining machine operator had by then suffered crush injuries to the pelvis that would have been fatal regardless of any medical attention available.

Shuttle cars used in Australia have a peculiar steering arrangement with the steering wheel located transversely (perpendicular to conventional vehicles). When the shuttle car is driven out-by towards the coal conveyor, the operator faces the direction of travel, a clockwise rotation of the steering wheel causes the vehicle heading to change to the driver's right, and vice-versa. This is a compatible steering arrangement which is executed without difficulty. However the steering effect on the wheels remains the same in both directions; consequently, when driving in-by (and facing the direction of travel) a clockwise rotation of the steering wheel causes the vehicle heading to change to the driver's left. This is an example of an incompatible directional control-response relationship. Alternating between compatible and incompatible steering relationship with each change of direction of travel has been demonstrated to increase the probability of directional steering errors [8-10].

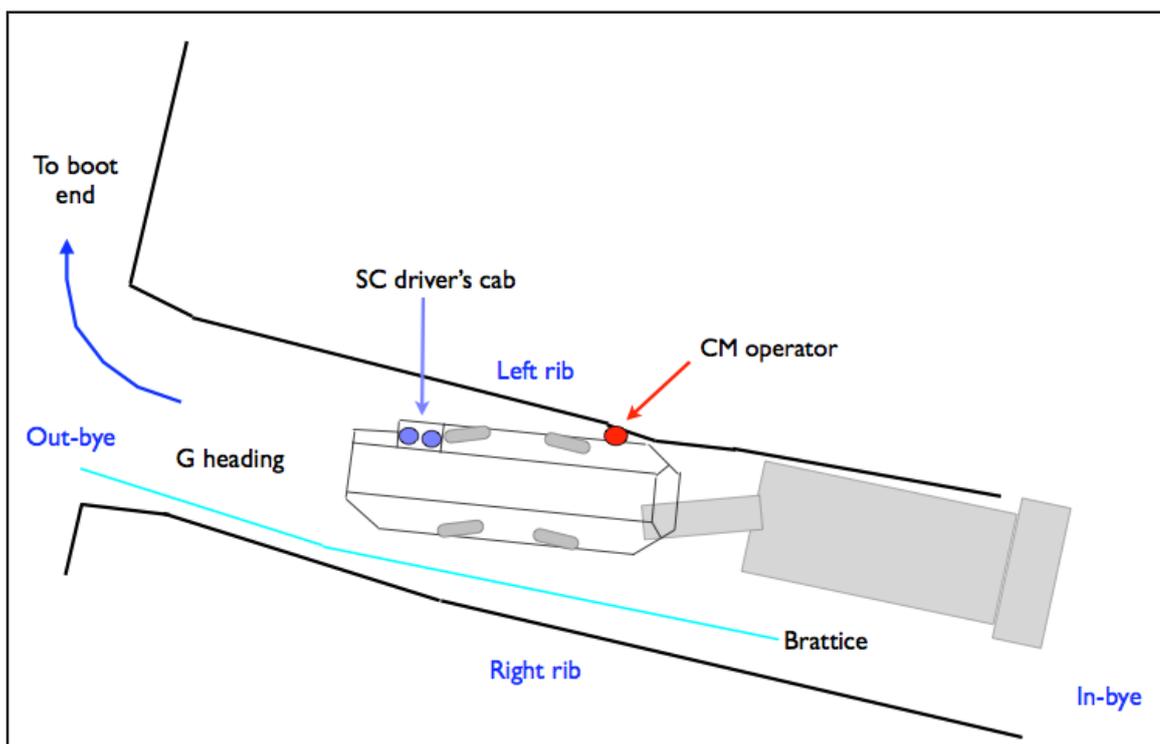


Figure 3: Drawing of situation post-accident

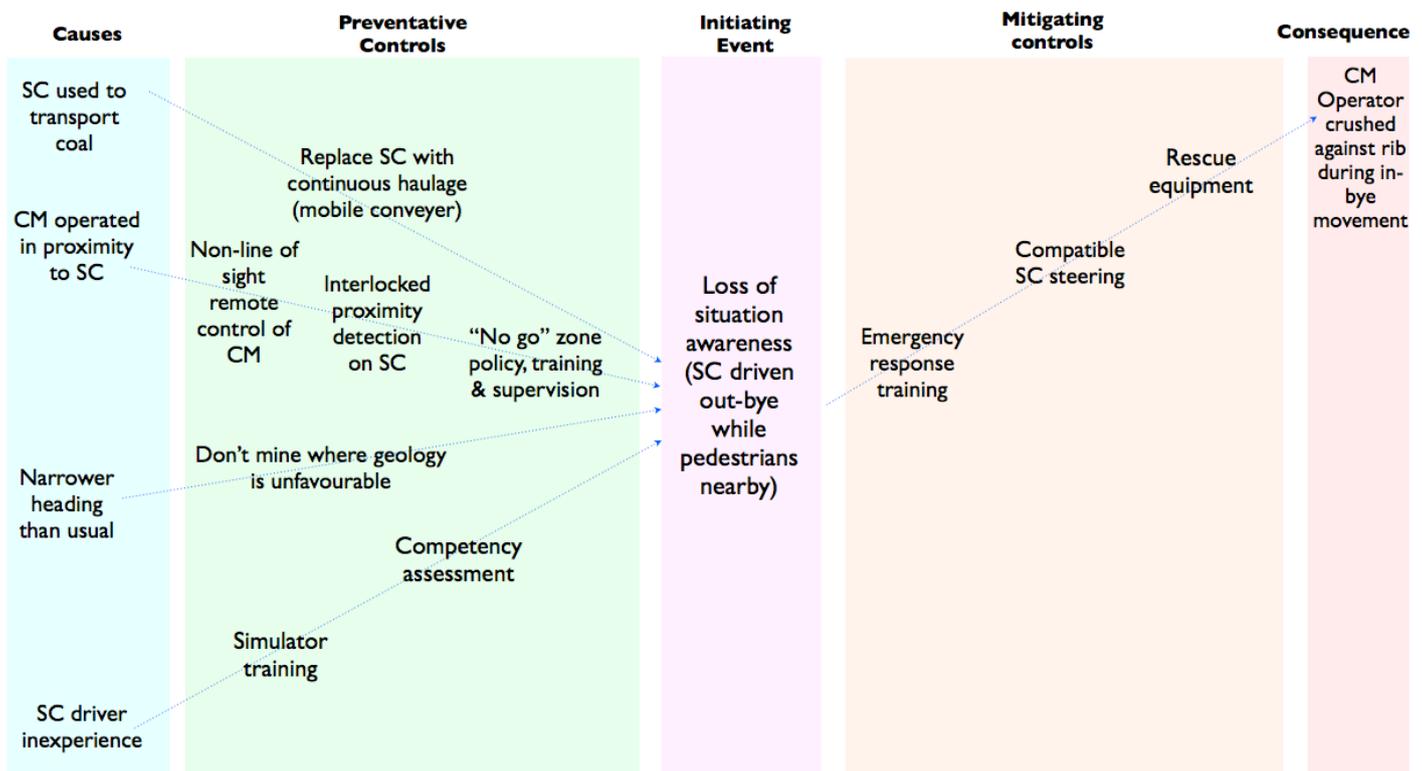


Figure 4: Bow-tie representation of the causes, consequence, and potential preventative and mitigating control measures for the case study.

The shuttle car driver was an inexperienced operator placed in an extremely error provocative situation. He was in a state of panic. He had just run into his supervisor who was now yelling at him to move the shuttle car. To drive the shuttle car away from the left rib, he needed to turn the steering wheel anti-clockwise, a movement that in any other vehicle would have moved the car closer to the rib. While the witness statements are unclear, it is likely that when attempting to drive the shuttle car away from the rib to release the continuous mining machine operator, the shuttle car driver instead turned the steering wheel clockwise as he drove the shuttle car in-by, causing the in-by end of the shuttle car to move towards, rather than away from the rib, with fatal injuries arising as a consequence.

Results

Figure 4 provides a bow-tie representation of the incident.

The victim was the operator of a continuous mining machine who had instructed the shuttle car driver to take the shuttle car out of the heading to allow repairs to the continuous mining machine to be undertaken. The top event, or initiating event, was determined to be a lack of awareness by the shuttle car driver that driving the shuttle car out-by, and turning it as he did so, would endanger the continuous miner operator. The causes of the top event were the use of shuttle cars to transport coal from a continuous mining machine that was operated by line-of-sight remote control, and a relatively inexperienced driver operating the shuttle car in a heading that was narrower than he was accustomed to. An inappropriate decision to move the shuttle car in-by after the initial pinning of the victim, and a directional control-response incompatibility inherent in the steering design of the shuttle car, contributed to the severity of the consequence.

A range of potential control measures were identified during the analysis, including: (i) replacing shuttle cars with continuous haulage such as a mobile conveyer; (ii) non-line-of-sight remote control of continuous miners; (iii) proximity detection of pedestrians interlocked with shuttle car controls; (iv) "always-compatible" shuttle car steering design.

Discussion

A bow-tie representation provides a useful way of systematically examining and communicating the causes, consequences, and potential preventative and mitigating control measures or barriers associated with the fatality. In the short-term, the installation of sensors interlocked with shuttle car control systems which detect the proximity of pedestrians and stop or prevent the car from moving is a technically feasible control measure which should be considered by all mines where shuttle cars are used [11,12].

Similar measures may also be taken to reduce the risk of collisions between continuous mining machines and pedestrians [13] and these devices are being mandated in some international jurisdictions. Non-line-of-sight remote control of continuous mining machines (or automation) would remove operators from both hazards. The use of continuous haulage in the form of flexible conveyer trains to replace shuttle cars is also technically feasible, however the capital cost is large, and a risk of collision between the continuous haulage and the continuous miner operator may be introduced. Achieving an "always-compatible" steering design is not difficult from an engineering point of view, however the change management process is not trivial if the existing steering arrangement is maintained. Introducing a completely different steering mechanism may be preferable although careful investigation of the human factors aspects is justified [e.g. 14-16].

Clearly there is considerable scope for improvements in the design of shuttle cars. Unfortunately, despite Coroner Hennessey's recommendation in 2009:

"That a working party comprising the Department, coal mine operators, workers, Union representatives and other interested organisations form to meet with manufacturers of shuttle cars to review and discuss, with the intention of designing out or improving the design of some of the concerns related to the ergonomic and/or safety factors and control surfaces of shuttle cars." [7] (p. 95)

no such working party has been formed.

More broadly, the incident analysis presented here has shown that a bow-tie representation can be an effective risk communication tool to link together events with their causes, controls and consequences. The human factors and ergonomics community may find the use of the technique to be a useful tool to identify and evaluate potential design control measures for the prevention of injuries and fatalities. Further work is underway by the authors to undertake bow-tie analyses of a larger number of fatal incidents in mining that will be collated to identify priority counter-measures for further investigation and research.

References

1. Chevreau F.R. Wybo J.L. Chauchois D. Organizing learning processes on risks by using the bow-tie representation. *Journal of Hazardous Materials*. 2006 130: 276-283.
2. De Dianous V. Fievez, C. ARAMIS project: a more explicit demonstration of risk control through the use of bow-tie diagrams and the evaluation of safety barrier performance. *Journal of Hazardous Materials*. 2006 130: 220-33.
3. Duijim, N. J. Safety-barrier diagrams as a safety management tool. *Reliability Engineering and System Safety*. 2009 94: 332-341
4. Pitblado R. Weijand, P. Barrier diagram (Bow Tie) quality issues for operating managers. *Process Safety Progress*. 2014 DOI:10.1002/prs.11666
5. Kirsch P. Goater S. Harris J. Sprott D. Joy J. RISKGATE: Promoting and redefining best practice for risk management in the Australian coal industry, *Proceedings of the 12th Coal Operators' Conference*, University of Wollongong & The Australasian Institute of Mining and Metallurgy. 2012 315-325.
6. Kirsch P. Harris J. Sprott D. Cliff D. RISKGATE and Australian coal operations. *Proceedings of the 2014 Coal Operators' Conference*. Coal 2014: Australian Coal Operators' Conference 2014, Wollongong, NSW, Australia, 2014 389-398.
7. Hennessey 2009 Findings of inquest File No. ROCK-COR-42/2007 (http://www.courts.qld.gov.au/__data/assets/pdf_file/0007/86848/cif-blee-jge-20090910.pdf)
8. Zupanc C. Burgess-Limerick R. Wallis G. Performance as a consequence of alternating Control-Response compatibility: Evidence from a coal mine shuttle car simulator. *Human Factors*. 2007 49: 628-636.
9. Zupanc C. Burgess-Limerick R Wallis G. Effect of Age on Learning to Drive a Virtual Coal Mine Shuttle Car. *The Ergonomics Open Journal*. 2011 4;(Suppl. 2-M1): 112-124.
10. Zupanc C. Burgess-Limerick R. Wallis G. Strategy affects compatibility: Evidence from an underground coal mine shuttle car simulator. *Theoretical Issues in Ergonomics Science*. 2014 DOI: 10.1080/1463922X.2013.857738.
11. Burgess-Limerick R. Avoiding collisions in underground mines. *Ergonomics Australia*. HFESA 2011 Conference Edition. 2011 11:44
12. Schiffbauer W.H. Active proximity warning system for surface and underground mining applications. *Mining Engineering*. 2002 54: 25-33
13. Jobs C.C. Carr J. Ducarme, J.P. Evaluation of an advanced proximity detection system for continuous mining machines. *International Journal of Applied Engineering Research*. 2012 7: 649-671.
14. Burgess-Limerick R. Zupanc C. Wallis G. Directional control-response compatibility of joystick steered shuttle cars. *Ergonomics*. 2012 55: 1278-1283.
15. Burgess-Limerick R. Zupanc C. Wallis G. Effect of control order on steering a simulated underground coal shuttle car. *Applied Ergonomics*. 2013 44: 225-229.
16. Cloete S. Burgess-Limerick R. Zupanc C. Wallis G. Control order and visuomotor strategy development for joystick-steered underground shuttle cars. *Human Factors*. 2014 56:1177-1188.