BOWTIE ANALYSIS OF MINING FATALITIES TO IDENTIFY PRIORITY CONTROL TECHNOLOGIES

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Executive Summary

A bow-tie analysis of 517 mining fatalities occurring over a ten year period (2005-2014) was undertaken with the aim of identifying and prioritizing potential technological control measures. The priority technologies identified for further investigation based on the number of fatalities are:

1. Interlocked pedestrian proximity detection on mobile equipment (incorporating proximity warning) (46 fatalities)
2. Interlocked seat restraints on mobile plant, particularly haul-trucks (39)
3. Video cameras on mobile plant (37)
4. Remote operation of mobile plant (37)
5. Non-contact methods of assessing underground strata condition (36)
6. Fire suppression on fixed and mobile plant (33)
7. Remote methane monitors in gob interlocked with longwall shearer (29 fatalities)
8. Methane extraction from longwall block in advance of mining (29)
9. Remote operation of longwall (29)
10. Stone dust monitoring (29)
11. Active explosion barrier (29)
12. Interlocked proximity detection on fixed plant (27)
13. Non-line-of-sight remote control of continuous mining machine (26)
14. Usable SCSR / CABA (19)
15. Refuge chamber (19)
16. Inertisation sealed areas (17)
17. Remote monitoring sealed areas (17)
18. Live electrical warning device (16)
19. Remote bolting (14)
20. Automatic brake testing at pre-start (13)
21. Outburst prediction (12)

Recommendation 1 - Systematically investigate the current state of development, and adoption, of the priority technologies identified.

Recommendation 2 - Investigate the potential barrier decay mechanisms, and the human-centered design issues associated with control technologies selected for further development.

Introduction

Bow-tie analysis (sometime called "cause-consequence" analysis) is a risk analysis and communication technique widely used in high hazard industries (eg., aviation, chemical, petro-chemical)[1] and more recently in mining[2]. The technique combines elements of fault-tree analysis and event-tree analysis. Pitblado and Weijand[3] 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 web site 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[4] .

At the centre of each bow-tie is an initiating 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[5] or barriers which can reduce the probability of the initiating event occurring (preventive controls), and the control 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.

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[1] **Chevreau, F.R., J.L. Wybo, JL and D. Chauchois**, D. (2006). Organizing learning processes on risks by using the bow-tie representation. *Journal of Hazardous Materials, 130*, 276-283; **De Dianous, V. and C. Fievez, C**. (2006). 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, 130*, 220–33; **Duijim, N. J.** (2009). Safety-barrier diagrams as a safety management tool. *Reliability Engineering and System Safety, 94*, 332-341

[2] **Burgess-Limerick, R., Horberry, T., & Steiner, L.** (2014) Bow-tie analysis of a fatal underground coal mine collision. *Ergonomics Australia. 10:2*

[3] **Pitblado R. Weijand, P.** (2014). Barrier diagram (Bow Tie) quality issues for operating managers. *Process Safety Progress*, 33, 355-361. DOI:10.1002/prs.11666

[4] **Kirsch P. Goater S. Harris J. Sprott D. Joy J.** (2012) 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. 315-325. **Kirsch P. Harris J. Sprott D. Cliff D.** (2014) 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.

[5] A control is defined as an act, object or system which prevents or mitigates an unwanted event. The performance of the control should be specified, observable, measurable and auditable. **ICMM** (2015). Health and Safety Critical Control Management. http://www.icmm.com/document/8570

The aim of this project was to undertake an analysis of the investigations of all fatal mine accidents occurring in the USA over a ten year period. Bow-tie representations of each event were created as a means of identifying both existing and potential control measures which may have prevented the initiating event from occurring (preventive controls), or reduced the severity of the consequences of the initiating event (mitigating controls).

The focus of the research was on technological controls rather than administrative controls such as procedures and training. The frequency with which different control technologies were included in the bow-tie representations, and the number of fatalities in which each may have potentially had a beneficial effect, is examined as one means of prioritizing potential technological control measures for further investigation.

Method

The US Mine Safety and Health Agency (MSHA) undertakes investigations of all fatalities which occur on mine leases in the USA. The reports of these investigations are made publicly available via the MSHA website (http://www.msha.gov/fatals/). The investigation reports for the 451 incidents occurring from 2005 to 2014 were retrieved. Single fatalities resulted from 433 of the incidents. Thirteen incidents involved dual fatalities and one involved a triple fatality. Four major incidents occurred during the period in which five (Darby, 2006), nine (Crandell Canyon, 2007), twelve (Sago, 2006) and twenty-nine (Upper Big Branch, 2010) fatalities occurred. The total number of fatalities over the 10 year period was 517.

The investigation reports were analyzed to identify the initiating event for each incident. The principle causes which contributed to the initiating event occurring were then determined. While the outcome of each incident was a fatality or multiple fatality, the outcomes were coded to capture information regarding the mechanism by which the fatalities occurred.

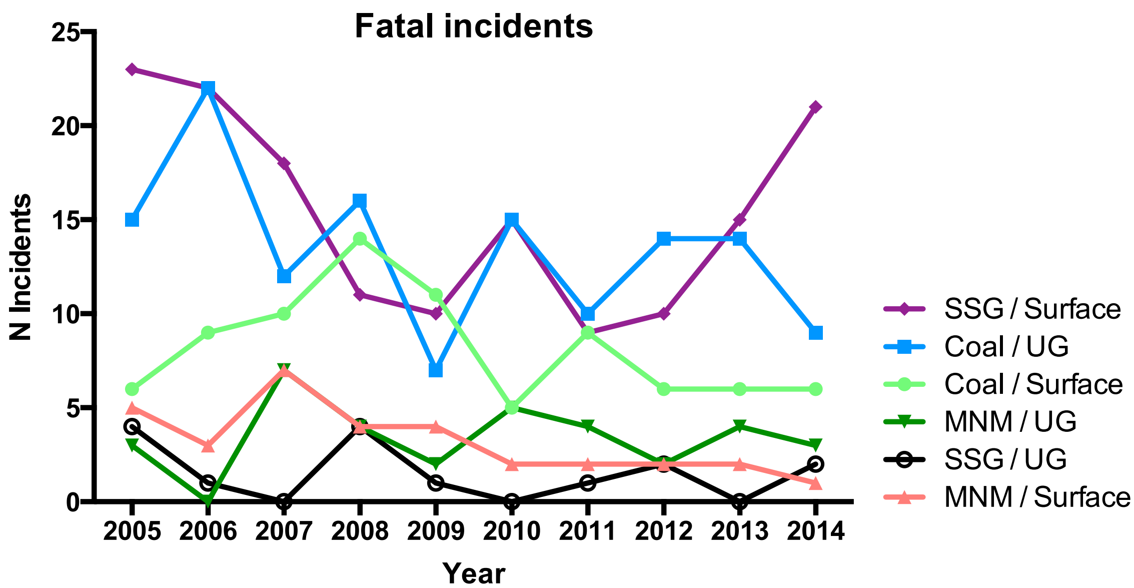
As a means of refining the coding categories, a subset of 59 incidents were independently reviewed by a second researcher and the resulting draft bow-ties compared and discussed. A bow-tie representation was then constructed for each of 451 events using the revised coding categories. Both the existing and potential preventative and mitigating control measures were identified for each incident and included in the bow-ties. Appendix A includes examples of bow-tie representations constructed for each incident. Generic bow-tie representations were then constructed for each initiating event category. The outcomes, causes, and technology control measures are also tabulated by industry sector (coal, metal/non-metal, stone/sand/gravel) and mine type (surface or underground). Finally, the control technologies were prioritized based on fatality frequency.

Results

Table 1 provides a break down of the annual number of incidents and number of fatalities as a function of sector and mine type. These data are also illustrated in Figure 1.

Table 1: Number of incident (N) and fatality numbers (F) by year, sector & mine type

Year	**Coal / Surface**		**Coal / UG**		**MNM / Surface**		**MNM / UG**		**SSG / Surface**		**SSG / UG**		**Total**	
	N	F	N	F	N	F	N	F	N	F	N	F	**N**	**F**
2005	6	7	15	16	5	5	3	3	23	23	4	4	**56**	**58**
2006	9	9	22	38	3	3	0	0	22	22	1	1	**57**	**73**
2007	10	11	12	23	7	8	7	7	18	19	0	0	**54**	**68**
2008	14	14	16	16	4	4	4	4	11	11	4	4	**53**	**53**
2009	11	11	7	7	4	4	2	2	10	10	1	1	**35**	**35**
2010	5	5	15	44	2	2	5	6	15	15	0	0	**42**	**72**
2011	9	10	10	10	2	2	4	4	9	9	1	1	**35**	**36**
2012	6	6	14	14	2	2	2	2	10	10	2	2	**36**	**36**
2013	6	6	14	14	2	2	4	5	15	15	0	0	**41**	**42**
2014	6	6	9	10	1	1	3	3	21	21	2	3	**42**	**44**
Total	**82**	**85**	**134**	**192**	**32**	**33**	**34**	**36**	**154**	**155**	**15**	**16**	**451**	**517**



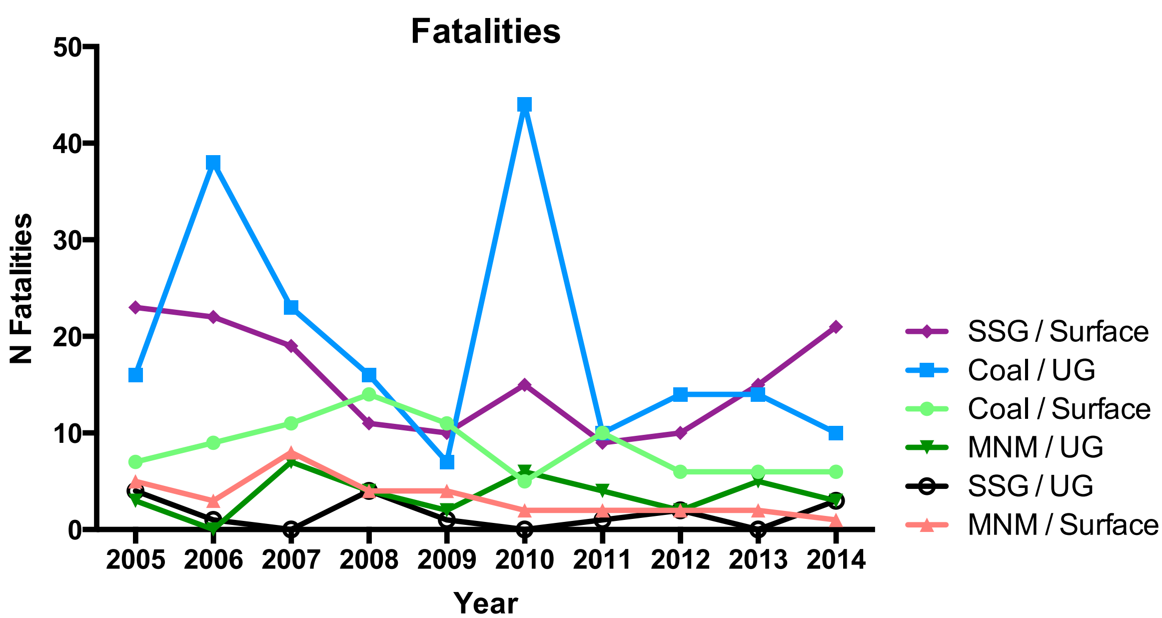


Figure 1: Annual number of fatal incidents and number of fatalities as a function of industry sector and mine type.

Outcomes

The outcome of each incident was coded to capture information regarding the mechanism by which the fatal injuries occurred. Table 2 provides a summary of the outcomes as function of sector and mine type.

Table 2: Incident outcomes by industry sector and mine type

Outcome (fatality mechanism)	Coal / Surface	Coal / UG	MNM / Surface	MNM / UG	SSG / Surface	SSG / UG	Total
Struck by rock	7	54		11	6	2	**80**
Mobile plant - environment interaction	27	4	7	5	27	5	**75**
Mobile plant - pedestrian interaction	10	37	2	3	12	4	**68**
Struck by other	5	40	3	3	10		**61**
Fall	9	10	8	2	22	4	**55**
Struck by falling object	5	4	4		22	1	**36**
Fixed plant - pedestrian interaction		5	2		18		**25**
Poisoning	1	19	2	2			**24**
Crushed	6	10		1	5		**22**
Electrocution	3	5	2	2	10		**22**
Engulfed	2			4	8		**14**
Drowning	4				10		**14**
Mobile plant - vehicle interaction	4	2	1		1		**8**
Burns	2		1	2	1		**6**
Entangled				1	3		**4**
Heat stroke		1					**1**
Other		1	1				**2**
Total	**85**	**192**	**33**	**36**	**155**	**16**	**517**

Initiating Events

The initiating events identified during the analysis of the 451 incident reports were:

- loss of control of equipment, materials or mechanical energy (121 incidents/125 fatalities)
- loss of situation awareness (123 incidents/124 fatalities)
- loss of control of strata or ground (91 incidents/106 fatalities)
- unintended explosion or fire (9 incidents/53 fatalities)
- equipment malfunction (48 incidents/49 fatalities)
- loss of balance (47 incidents/47 fatalities)
- loss of control of an explosion (6 incidents/6 fatalities)
- exposure to health hazard (5 incidents/6 fatalities)
- overexertion (1 incident/1 fatality)

Table 3 provides a breakdown of the initiating events by industry sector and mine type.

Table 3: Initiating event fatality numbers for industry sector and mine type

Initiating Event	Coal / Surface	Coal / UG	MNM / Surface	MNM / UG	SSG / Surface	SSG / UG	Total
Loss of control of equipment, materials or mechanical energy	23	28	14	4	53	3	**125**
Loss of situation awareness	20	39	9	8	46	2	**124**
Loss of control of strata or ground	12	59	0	14	17	4	**106**
Unintended explosion or fire	3	48	0	0	2	0	**53**
Equipment malfunction	13	9	4	6	12	5	**49**
Loss of balance	12	7	3	0	23	2	**47**
Loss of control of an explosion	1	1	0	2	2	0	**6**
Exposure to health hazard	1	1	2	2	0	0	**6**
Overexertion	0	0	1	0	0	0	**1**
TOTAL	**85**	**192**	**33**	**36**	**155**	**16**	**517**

The initiating events which resulted in more than 6 fatalities over the ten year period are considered in greater detail below.

Loss of control of equipment, materials or mechanical energy implies that the incident occurred due to a failure to control gravitational potential energy (typically a suspended load) or mechanical energy (typically associated with a vehicle or other equipment). Alcohol and/or other drugs were implicated in several incidents, as was inexperience. The fatality outcomes most frequently arising from this initiating event were: mobile plant - environment interaction (32); struck by falling load (29); mobile plant - pedestrian interaction (22); struck by other (15) and crushed (10). Figure 2 provides a generic bow-tie representation for this initiating event. Each incident may have multiple principle causes. Preventative and mitigating control technologies are represented on the bow-tie between the relevant cause and the initiating event, although this does not imply that the control measure was necessarily applicable to all of these incidents.

In some cases, particularly those related to equipment maintenance, physical isolation would have been an effective non-technological control measure.

Preventative control technology relevant to these incidents includes:

- Automatic park brake (9 fatalities)
- Automated haul truck (7)
- Speed limiter (5)
- Interlocked electrical warning (4)
- Interlocked guarding on fixed plant (3)
- Video cameras (2)

Mitigating control technology relevant to these incidents includes:

- Seat belt interlock (21 fatalities)
- Remote operation of mobile plant (9)
- Interlocked pedestrian proximity detection on mobile equipment (7)
- Interlocked pedestrian proximity detection on fixed equipment (6)
- Active edge detection (3)

Table B.1, Appendix B, provides a detailed breakdown of the causes, outcomes and potential control technologies identified for these incidents as a function of industry sector and type.

Loss of situation awareness implies that the incident occurred while all aspects of the incident were under control, but that the awareness of the situation held by the person or persons in control was inaccurate in some critical respect.

For example, a person energized equipment (typically a conveyer) while unaware that another person was conducting maintenance; or an electrician worked on a circuit mistakenly believed to be isolated; or a vehicle operator collided with an unseen pedestrian or vehicle or object (particularly underground); or a person drove or walked over an unseen edge; or an equipment operator or maintainer unintentionally placed themselves "in the line of fire". The fatality outcomes most frequently arising from this initiating event were: mobile plant - pedestrian interaction (38 fatalities); electrocution (20); mobile plant - environment interaction (19); fixed plant - person interaction (14); and fall (10).

In each case the energy sources were under control - the incident was initiated when the operator lost awareness of the situation. Potential preventative control measures for such events are broadly those which convey additional information about the situation to the person in control (who may have been the victim). Potentially effective mitigating control measures are generally those which prevent the operator from taking the action which resulted in the fatality, even though the operator's awareness of the situation was lost, or separate the energy source and the victim. Figure 3 provides a generic bow-tie representation of fatal incidents in which the initiating event was coded as loss of situation awareness.

Preventative control technology relevant to these incidents includes:

- Video cameras (35 fatalities)
- Pedestrian proximity warning device on mobile equipment (39)
- Live electrical warning technology (15)
- Vehicle proximity alarm (5)
- Edge detection warning (3)
- Fatigue monitoring warning device (4)

Mitigating control technology relevant to these incidents includes:

- Interlocked pedestrian proximity detection on mobile equipment (39 fatalities)
- Interlocked pedestrian proximity alarm on fixed plant (14)
- Remote operation mobile plant (8)
- Non-line of sight remote control for continuous mining machines (6)
- Interlocked edge detection (6)
- Light warning system installed on underground equipment (5)
- Interlocked seat restraint (5)
- Interlocked vehicle proximity detection (4)
- Crane electrical proximity alarm (1)

Table B.2, Appendix B, provides a detailed breakdown of the causes, outcomes and potential control technologies identified for these initiating events as a function of industry sector and type.

Loss of control of strata incidents included 54 underground coal incidents involving roof or rib fall, 11 falls in underground metal or non-metal mines, and 7 incidents in which material fell from a highwall at a surface mine. Failure of a supporting surface or ground occurred in a further 8 events. Figure 4 provides a generic bow-tie representation for this initiating event.

Preventative control technology relevant to these incidents includes:

- Non-contact methods of assessing underground strata condition (36 fatalities)
- Ground penetrating radar or stability monitoring (9)
- Non-invasive / non-contact methods of assessing highwall stability (7)

Mitigating control technology relevant to these incidents includes:

- Non-line-of-sight remote control of continuous mining machine (18 fatalities)
- Remote operation of mobile equipment (17)
- Remote bolting (14)
- Interlocked proximity detection on fixed equipment (2)

Table B.3, Appendix B, provides a detailed breakdown of the causes, outcomes and potential control technologies identified for these incidents as a function of industry sector and type.

Unintended explosion or fire incidents were few in number (9 incidents) but accounted for 53 fatalities. Figure 5 provides a generic bow-tie representation for this initiating event.

Preventative control technology relevant to these incidents includes:

- Remote methane monitors in gob (goaf) interlocked with longwall shearer (29 fatalities)
- Methane extraction from longwall block in advance of mining (29)
- Stone dust monitoring (29)
- Inertisation of sealed areas (17)
- Remote monitoring sealed areas (17)

Mitigating control technology relevant to these incidents includes:

- Fire suppression on fixed and mobile plant (33)
- Remote operation of longwall (29 fatalities)
- Active explosion barrier (29)
- Usable SCSR / CABA (19)
- Refuge chamber (19)

Table B.4, Appendix B, provides a detailed breakdown of the causes, outcomes and potential control technologies identified for these incidents as a function of industry sector and type.

Equipment malfunction incidents included brake failures; failures of crane, hoists, blocks, or chains during lifting or pulling loads; hydraulic cylinder, valve or hose failure; failure of platforms and other supporting surfaces. Figure 6 provides a generic bow-tie representation for this initiating event.

Preventative control technology relevant to these incidents includes:

- Automatic pre-start brake test (13 fatalities)
- Interlocked truck overload prevention (3)
- Fatigue assessment (1)
- Non-intrusive testing of hoist cable (1)

Mitigating control technology relevant to these incidents includes:

- Seat belt interlock (13 fatalities)
- Interlocked pedestrian proximity detection on fixed equipment (2)
- Interlocked pedestrian proximity detection on continuous mining machine (1)
- Non-line-of-sight remote control of continuous mining machine (1)

Table A.5, Appendix A, provides a detailed breakdown of the causes, outcomes and potential control technologies identified for these incidents as a function of industry sector and type.

Loss of balance incidents typically occurred during construction/demolition or maintenance and lead to falls from height, or into operating equipment such as a crusher or conveyer. Seven fatalities involved drowning. Figure 7 provides a generic bow-tie representation for this initiating event.

Mitigating control technology relevant to these incidents includes:

- Interlocked pedestrian proximity detection on mobile plant (2 fatalities)
- Interlocked pedestrian proximity detection on fixed equipment eg., conveyor/crusher (5)

Table B.6, Appendix B, provides a detailed breakdown of the causes, outcomes and potential control technologies identified for these incidents as a function of industry sector and type.

Causes

Regardless of initiating event, the causes most commonly associated with fatalities over the ten year period, and the number of fatalities to which each was relevant, were:

- Inexperienced or untrained operators (61 fatalities)
- Working on energized equipment (53)
- Pedestrians near mobile equipment (52)
- Restricted visibility from mobile equipment (51)
- Unstable roof / rib (51)
- Methane concentration in explosive range (46)
- Working at height / ladder (43)
- Working under suspended load (40)
- Ignition source (36)
- Coal dust (29)
- Drugs / Alcohol (26)
- Operating or parking on slope (22)
- Brake condition (15)
- Unstable ground / highwall (15)
- Roadway design or condition (15)
- Working under unsupported roof / face (15)
- Fatigue (14)

Table 4 provides a breakdown by sector and mine type of the most common causes identified across all initiating events. While some causes (eg., methane) are specific to specific sectors and mine type, particularly underground coal mines, others such as “working on energised equipment” “restricted visibility from mobile plant” and “inexperience or lack of task specific training” were common across sectors and mine types.

Table 4: Common causes by industry sector and mine type

Causes	Coal / Surface	Coal / UG	MNM / Surface	MNM / UG	SSG / Surface	SSG / UG	Total
Inexperience / untrained	11	16	3	2	25	4	**61**
Working on energised equipment	8	9	4	4	28		**53**
Pedestrians near mobile plant	5	26	3		15	3	**52**
Unstable roof or rib		43		5		3	**51**
Restricted visibility from mobile plant	9	24	2	2	12	2	**51**
Methane in explosive range		46					**46**
Working at height / on ladder	9	8	6	2	16	2	**43**
Working under suspended load	4	5	4		26	1	**40**
Ignition source		36					**36**
Coal dust		29					**29**
Drugs/Alcohol	13	4	2		7		**26**
Operating or parking on slope	8	1	2	1	9	1	**22**
Roadway design or condition	4	3	1		5	2	**15**
Brake condition	7			2	3	3	**15**
Unstable ground / highwall	6				9		**15**
Working under unsupported roof / face	1	10		3		1	**15**
Fatigue	6	3	1		4		**14**

Preventive and mitigating technology controls

Regardless of initiating event, the preventive and mitigating technology controls which may have reduced the probability or severity of more than 10 fatalities in the US mining industry over the ten year period examined were:

Preventive control technology

- Pedestrian proximity warning device on mobile equipment (39 fatalities)
- Video cameras on mobile plant (37)
- Non-contact methods of assessing underground strata condition (36)
- Methane extraction from longwall block in advance of mining (29)
- Remote methane monitors in goaf interlocked with longwall shearer (29 fatalities)
- Inertisation sealed area (17)
- Live electrical warning technology (16)
- Automatic pre-start brake test (13)
- Outburst prediction technology (12)

Mitigating control technology

- Interlocked pedestrian proximity detection on mobile equipment (46)
- Seat restraint interlock (39)
- Fire suppression on mobile plant / conveyor / longwall (33)
- Active explosion barrier (29 fatalities)
- Remote operation mobile plant (37)
- Remote operation of longwall (29)
- Interlocked pedestrian proximity detection on fixed equipment (27)
- Non-line-of-sight remote control of continuous mining machine (26)
- Usable SCSR / CABA (19)
- Refuge chamber (19)
- Remote bolting (14)

The breakdown of these control technologies across sector and mine type is provided in Table 5 and 6. Again, a number of the control technologies are specific to underground coal mines, while others have more generic application.

Table 5: Preventative control technologies associated with more than 10 fatalities over the 10 year period by industry sector and mine type

Preventive control technology	Coal / Surface	Coal / UG	MNM / Surface	MNM / UG	SSG / Surface	SSG / UG	Total
Pedestrian proximity warning on mobile plant	4	23	1	3	7	1	**39**
Video camera on mobile plant	8	14	2	2	11		**37**
Non-contact assessment of underground strata condition		27		9			**36**
Methane extraction		29					**29**
Remote methane monitoring interlocked with longwall shearer		29					**29**
Stone dust monitoring		29					**29**
Inertisation sealed areas		17					**17**
Remote monitoring sealed areas		17					**17**
Live electrical warning device	1	2	3	1	9		**16**
Auto-brake test at pre-start	7			2	3	1	**13**
Outburst prediction technology		12					**12**

Table 6: Mitigating control technologies associated with more than 10 fatalities over the 10 year period.

Mitigating control technology	Coal / Surface	Coal / UG	MNM / Surface	MNM / UG	SSG / Surface	SSG / UG	Total
Interlocked pedestrian proximity detection on mobile plant	5	29	1	3	7	1	**46**
Interlocked seat restraint	16	2	3	2	14	2	**39**
Fire suppression on mobile plant / conveyer / longwall	2	31					**33**
Remote operation mobile plant	12	6		5	10	4	**37**
Remote longwall operation		29					**29**
Active explosion barrier		29					**29**
Interlocked pedestrian proximity detection on fixed plant	1	6	2		18		**27**
Non-line-of-sight remote control of CM		26					**26**
Usable SCSR / CABA		19					**19**
Refuge chamber		19					**19**
Remote bolting		12		2			**14**

Discussion

The focus of this project is on technological controls rather than administrative controls such as procedures and training. The frequency with which different control technologies are represented in the bow-tie representations, and the number of fatalities in which each may have potentially had a beneficial effect, provides one view of prioritization. This analysis does not provide any information about the likely effectiveness of any control measure, nor has the feasibility or cost-effectiveness of any technology been addressed. It is also possible that the analysis has not comprehensively captured all potential control technologies. It should also be noted that some of the technologies highlighted below (non-contact methods of assessing underground strata condition, stone dust monitoring, and outburst prediction) are not strictly control measures in that the performance of these activities alone does not prevent or mitigate the unwanted event. However, they have been included here because the information obtained via these technologies, combined with appropriate policies and procedures (eg., Trigger Action Response Plans), has potential to mitigate the consequences of strata failure, unintended explosions, and outbursts respectively.

Based on the number of fatalities over the ten year period in which each of the control technologies identified may have been beneficial, the priority technologies for further investigation are:

1. Interlocked pedestrian proximity detection on mobile equipment - incorporating proximity warning (46)
2. Interlocked seat restraints on mobile plant, particularly trucks (39)
3. Video cameras on mobile plant (37)
4. Remote operation of mobile plant (37)
5. Non-contact methods of assessing underground strata condition (36)
6. Fire suppression on fixed and mobile plant (33)
7. Remote methane monitors in gob interlocked with longwall shearer (29 fatalities)
8. Methane extraction from longwall block in advance of mining (29)
9. Remote operation of longwall (29)
10. Active explosion barrier (29)
11. Stone dust monitoring (29)
12. Interlocked proximity detection on fixed plant (27)
13. Non-line-of-sight remote control of continuous mining machine (26)
14. Usable SCSR / CABA (19)
15. Refuge chamber (19)
16. Inertisation sealed areas (17)
17. Remote monitoring sealed areas (17)
18. Live electrical warning device (16)
19. Remote bolting (14)
20. Automatic brake testing at pre-start (13)
21. Outburst prediction (12)

Many of these control technologies are specific to underground coal mining, a consequence of nearly 40% of the fatalities occurring in this group of mines. The highest priority control measures for surface coal mines are interlocked seat restraints and the remote operation of mobile plant. Theses controls are also relevant for surface stone/sand/gravel sites, however interlocked pedestrian detection for fixed plant such as crushers and conveyors is the highest priority for this group.

Next steps

Many of the technologies identified are currently under development or investigation. For example, remote methane monitoring and non-contact methods of assessing strata condition are topics identified in calls for proposals by NIOSH under a Broad Agency Announcement solicitations for Development and Demonstration of Mine Safety and Health Technology, and investigations of strata failure is ongoing (eg., ACARP project C23008). Stone dust measurement techniques have also been recently developed[6] and research is being conducted on alternatives to stone dusting (ACARP project C12016).

Other technologies have been in development for some time. For example, considerable work has been undertaken towards automation and remote operation of longwall equipment[7] and towards demonstrating the feasibility of active explosion barriers[8]. The assessment of outburst risk has also been the subject of a recent review[9]. Considerable work has also been undertaken in the area of interlocked pedestrian proximity detection for underground coal mining mobile equipment and this technology is commercially available[10] (and required by legislation) for continuous-mining machines, and work is underway for other underground coal mobile plant (ACARP project C24010). Other technologies such as video cameras for mobile equipment (infra-red[11] or visible spectrum), remote operation of dozers[12], and methane drainage are also available; although the extent to which such technologies are deployed has not been systematically assessed. Advanced methane draining techniques using water jets are also under investigation by CRC mining (ACARP project C24008), and it has been suggested that methane from in-seam gas drainage may be used to achieve inertisation of a longwall goaf (gob)[13]. Other technologies are less well developed, for example, interlocked pedestrian proximity detection for fixed equipment, and non-line-of-sight remote control for continuous-mining machines, although substantial efforts have been undertaken by NIOSH towards remotely supervised continuous mining machine operation in the past, and research is currently underway (ACARP project C22015). Non-line of sight remote operation of continuous-mining machines has also been previously achieved for temporary use in outburst conditions.

Recommendation 1 - Systematically investigate the current state of development, and adoption, of the priority technologies identified.

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[6] **Barone, T.L. et al** (2015) Sampling and Analysis Method for Measuring Airborne Coal Dust Mass in Mixtures with Limestone (Rock) Dust, *Journal of Occupational and Environmental Hygiene*, DOI: 10.1080/15459624.2015.1116694

[7] http://www.acarp.com.au/Media/ACARPMatters_7_LA.pdf

[8] ACARP projects C14027 & C22007, see also **du Plessis & Spath** (2014) Active barrier performance preventing methane explosion propagation. Coal Operator's Conference, Wollongong. http://ro.uow.edu.au/cgi/viewcontent.cgi?article=2192&context=coal

[9] **Gray, I., & Wood, J**. (2015). Outburst risk determination and associated factors. ACARP project C23014 final report.

[10] http://mstglobal.com/solutions/proximity-detection/underground-coal-mining/

[11] http://qrc.org.au/conference/wp-content/uploads/2015/09/Peabody-Energy-Infra-Red-Thermal-Camera-on-Underground-Mobile-Equipment-WINNER.pdf

[12] eg., http://www.rct.net.au/solutions/automation/remote-dozer-solutions/

[13] **Claasen, C**. (2011). Goaf inertisation and sealing utilising methane from in-seam gas drainage system. 11th Underground Coal Operators' Conference, University of Wolongong p. 369-374. http://ro.uow.edu.au/cgi/viewcontent.cgi?article=2041&context=coal

Determining the priority of different control technologies also requires consideration of potential effectiveness. However, estimation of the likely effectiveness of any particular control technology in a given situation is not trivial. The potential effectiveness of control technologies, and implementation success, will be dependent to a large degree on the effort undertaken during design and implementation to ensure that human capabilities and limitations are considered[14].

For example, installation of video cameras is a potential control technology to reduce the probability of loss of situation awareness caused by restricted visibility from mobile equipment. However, in any given situation the probability of loss of situation awareness will not be reduced to zero. The effectiveness of the technology depends on it's design with respect to human limitations and capabilities. For example, the location of video displays within the cab will influence an operator's ability to assimilate and utilize the visual information. The technology is also subject to barrier decay mechanisms, such as the need to maintain the technology in good working order.

Another example is the potential for interlocked pedestrian proximity detection technology to be installed on mobile haulage such as shuttle cars, RAM cars, and Load-Haul-Dump in underground coal mines. The argument for pursuing such a technology is strong, in that such equipment was involved in 16 fatalities involving interactions with pedestrians in underground coal mines in the ten year period examined here. (In contrast, only 9 fatalities were associated with continuous-mining machine - pedestrian interactions in the same time period). However, while there may be technical issues to overcome, there are also substantial human factors issues which may prevent the effective deployment of the technology. For instance, any detection technology will not be perfect and there will be false positives. The implementation of the control measure will fail if the false positive rate is not acceptable to equipment operators,. Consequently, investigation of what false-positive rate would be acceptable to users, and what influences this, will be an important part of developing the technological control. Similarly, the installation of interlocked pedestrian proximity detection technology on mobile haulage has the potential to alter the behavior of both the drivers of mobile plant and pedestrians working in the vicinity of mobile plant in ways which are likely to decrease the effectiveness of the control measure. These behavioral changes also require consideration during the development of the control measure. Similar considerations will apply to each of the other control technologies identified and require further exploration.

Recommendation 2 - Investigate the potential barrier decay mechanisms, and the human-centered design issues associated with control technologies selected for further development.

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[14] **Burgess-Limerick**, R., Cotea, C., Pietrzak, E., & Fleming, P. (2011). Human Systems Integration in Defence and civilian industries. *Australian Defence Force Journal, 186*, 51-60.

Example bow-tie representations constructed for individual incidents

Example 1: MAI-2011-16. Wesley Sherwood (Age 22) was killed when he fell into an operating jaw crusher. He was last seen standing on the viewing platform. He apparently climbed over the railing of the platform to clear jammed material.

Causes	Preventive controls	Initiating event	Mitigating controls	Consequence
Clearing blockage required climbing into crusher	Remote operation rock breaker	Loss of balance	Interlocked pedestrian proximity detection on crusher	Fixed plant - person interaction
Working on energised equipment	Isolation lockout procedure, training & supervision			
Inexperience	Task training & supervision			
Drug impaired	Random drug testing			

Example 2: MAI-2012-10. Peter Faust (Age 49) was greasing the head pulley on the discharge end of a stacker conveyor when the conveyor was started by a co-worker. The electrical panel of the conveyor had been modified to bypass it's stop/start switches.

Causes

- Routine maintenance requires working at height
- Working on energised equipment
- Modified control system

Preventive controls

- Remote greasing
- Use man-lift
- Isolation lockout procedure, training & supervision
- Change management process including risk assessment

Initiating event

Loss of situation awareness (by co-worker)

Mitigating controls

- Pre-start alarm
- Fall arrest harness
- Interlocked pedestrian proximity detection on conveyor

Consequence

Fall

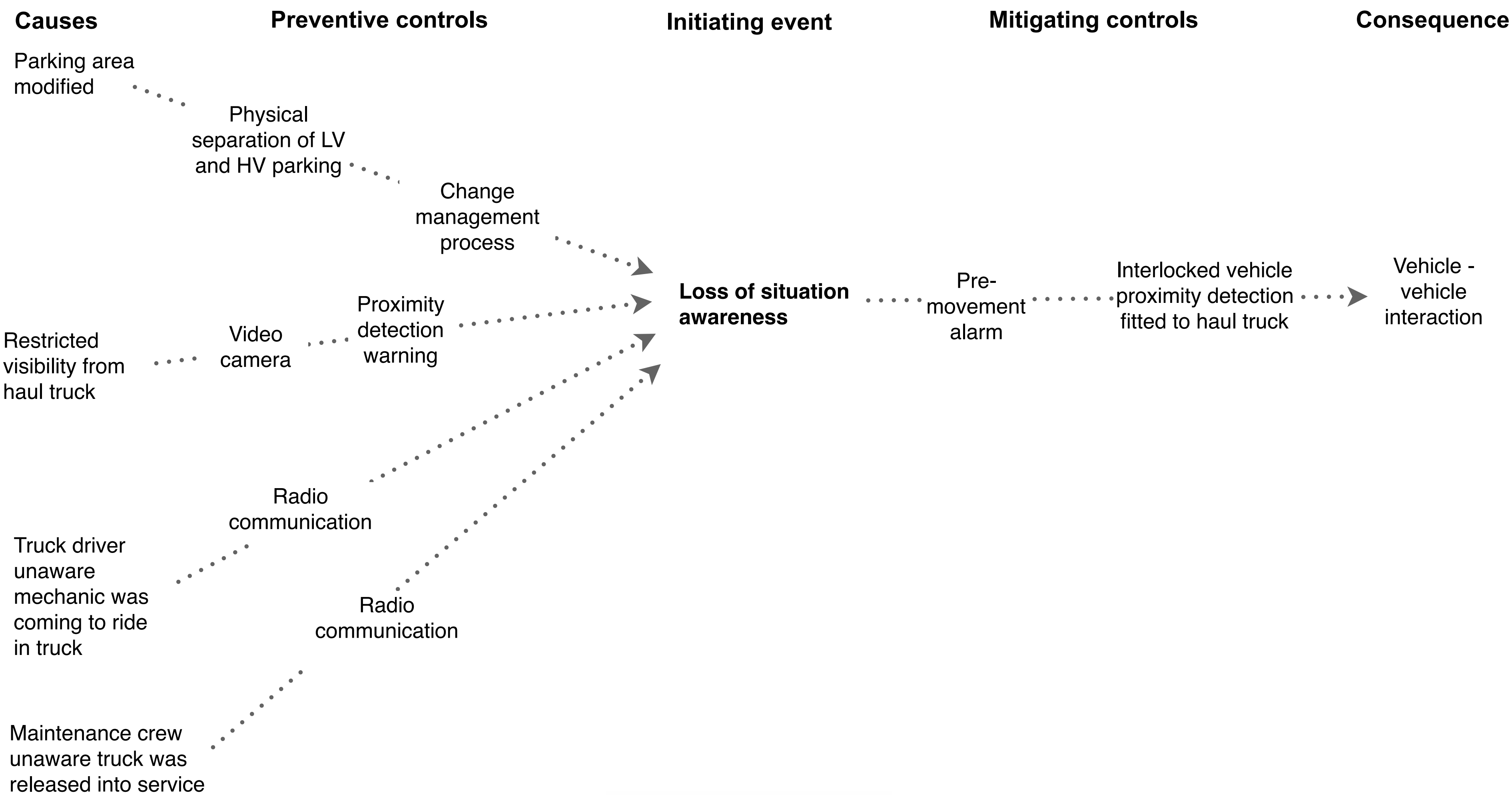
Routine maintenance requires working at height → Remote greasing; Use man-lift → Loss of situation awareness (by co-worker)

Working on energised equipment → Isolation lockout procedure, training & supervision → Loss of situation awareness (by co-worker)

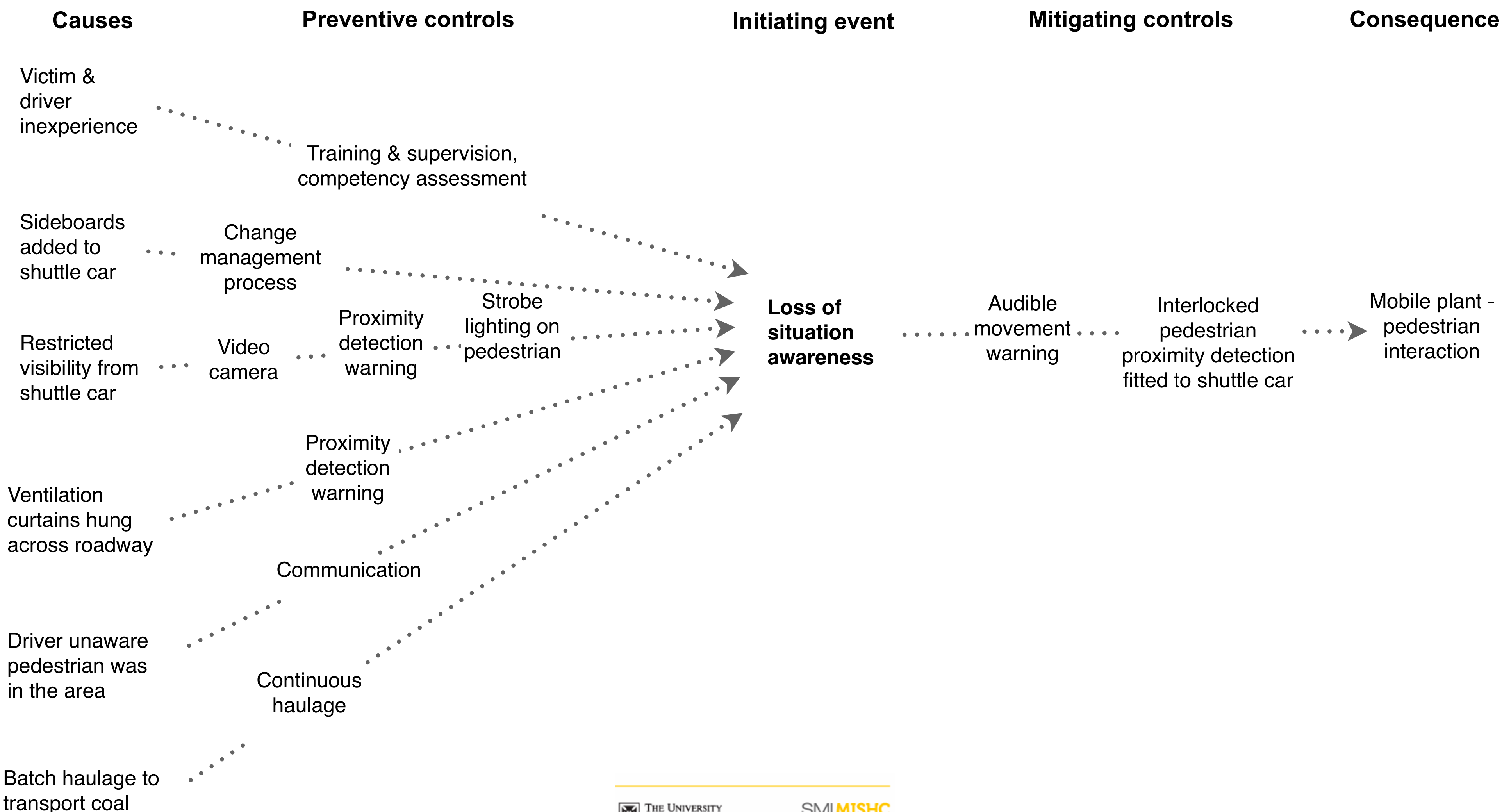
Modified control system → Change management process including risk assessment → Loss of situation awareness (by co-worker)

Loss of situation awareness (by co-worker) → Pre-start alarm; Fall arrest harness; Interlocked pedestrian proximity detection on conveyor → Fall

Example 3: MAI-2010-12. Thomas Benavidez (aged 52) died which the light vehicle he was operating was struck by a haul truck. The light vehicle was parked in front of the haul truck. The parking area was modified 4 days previously.



Example 4: CAI-2010-40. Wilbert (Ray) Starcher (aged 60) was walking towards the continuous mining machine when he was run over from behind by a shuttle car. The shuttle car operator's visibility was obscured by the addition of sideboards, and potentially by ventilation curtains hung across the roadway.



Example 5: CAI-2009-17. Stevie Johnson (Age 52) was driving an overloaded coal truck down a slope when the brakes failed. The victim attempted to leave the truck cab and was struck by the trailer.

Causes

- Truck overloaded
- Maintenance error (steering pressure seals installed backwards)
- Brakes worn
- Batch haulage to transport coal

Preventive controls

- Procedure, training, supervision
- Interlocked load measurement
- Design to reduce errors
- Training, supervision
- Automatic pre-start brake testing
- Pre-start inspection
- Proactive maintenance
- Continuous haulage

Initiating event

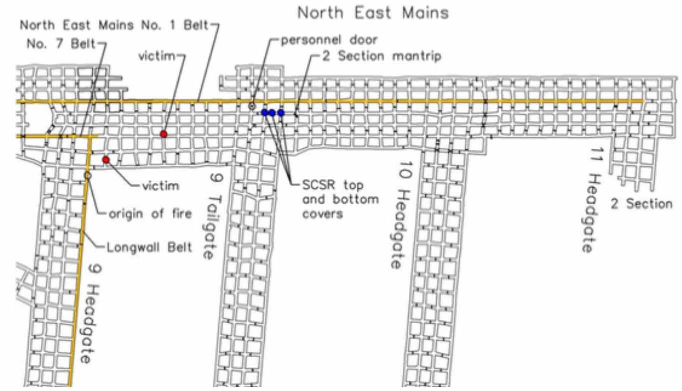
Equipment malfunction

Mitigating controls

- Seat-belt training and supervision, seat-belt interlock

Consequence

- Mobile plant - environment interaction



Example 6: CAI-2006-14-15. A fire occurred at the longwall belt takeup storage unit. Attempts to extinguish the fire were unsuccessful and evacuation was delayed. Two-miners failed to evacuate.

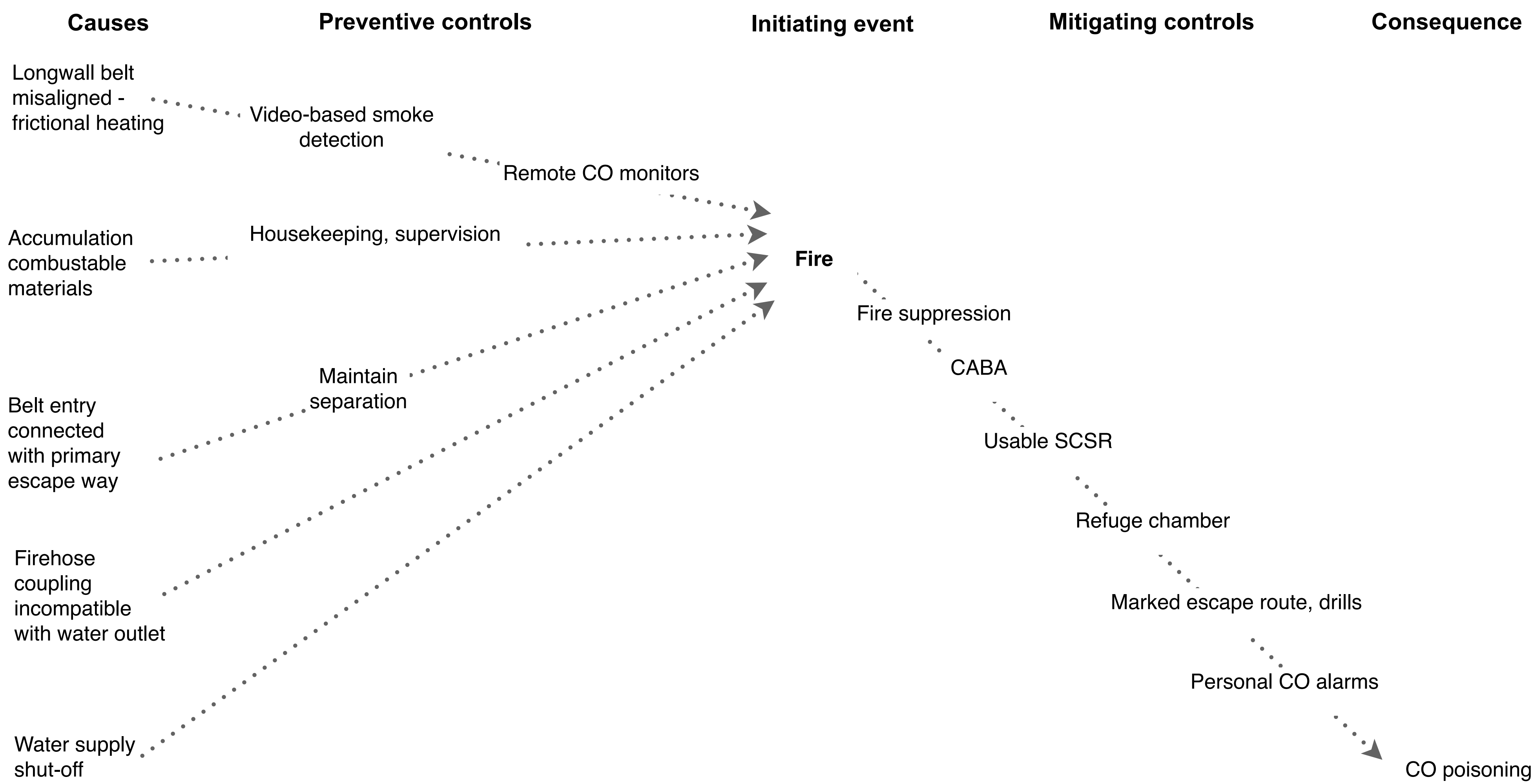


Table B.1 Outcomes, Causes, & Control Technologies by sector and mine type for "Loss of control of equipment, materials or mechanical energy" initiating event.

Outcome	C / S	C / U	MNM / S	MNM / U	SSG / S	SSG /U	Total
Mobile plant - environment interaction	9		5	1	14	3	**32**
Mobile plant - pedestrian interaction	4	11	1	2	4		**22**
Mobile plant - vehicle interaction							
Fixed plant - pedestrian interaction			1		2		**3**
Engulfed					2		**2**
Crushed	3	4			3		**10**
Fall		5			1		**6**
Struck by falling load	4	4	4		17		**29**
Struck by other	2	4	3		6		**15**
Electrocution	1				1		**2**
Drowning					2		**2**
Entangled				1	1		**2**
Total fatalities	**23**	**28**	**14**	**4**	**53**	**3**	**125**

Cause	C / S	C / U	MNM / S	MNM / U	SSG / S	SSG /U	Total
Working near unstable or suspended load	3	5	4		20		**32**
Restricted visibility		1	1		3		**5**
Speeding	1			1	3	1	**6**
Fatigue	2	1	1		2		**6**
Working near plant		5			4		**9**
Drugs/Alcohol	7	1	2		3		**13**
Working on energised equipment	1	4	1	1	6		**13**
Roadway design or condition	2	1			1	2	**6**
Operating or parking on slope	5	1	2	1	4	1	**14**
Inexperience	4	4	1		12	3	**24**
Steering design	1	3					**4**
Working at height		4			1		**5**
Confined space	1	1			1		**3**
Other	13	22	12	5	39	1	**92**

Control technology	C / S	C / U	MNM / S	MNM / U	SSG / S	SSG /U	Total
Preventive							
Video camera		1			1		**2**
Speed limiter	1			1	2	1	**5**
Automated Haul Truck	3				4		**7**
Fatigue interlock					1		**1**
Live electrical indication					1		**1**
Interlocked guarding			1		2		**3**
Mitigating							
Interlocked proximity detection on fixed plant		2	1		3		**6**
Non-line-of-sight remote control of CM		2					**2**
Interlocked proximity detection on mobile plant		5			2		**7**
Remote operation	2	3		1	2	1	**9**
Interlocked seat restraint	5	2	3		10	1	**21**
Active lane control / edge detection			2		1		**3**
Interlocked electrical warning	3				1		**4**
Automatic park brake	3	2		1	3		**9**

Table B.2 Outcomes, Causes, & Control Technologies by sector and mine type for "Loss of Situation Awareness" initiating event.

Outcome	C / S	C / U	MNM / S	MNM / U	SSG / S	SSG /U	Total
Mobile plant - environment interaction	8	4	1	1	5		**19**
Mobile plant - pedestrian interaction	4	23	1	1	7	2	**38**
Mobile plant - vehicle interaction	3	2	1		1		**7**
Fixed plant - pedestrian interaction		1	1		12		**14**
Struck by rock					1		**1**
Crushed	1	2			1		**4**
Fall	1	1	3	1	4		**10**
Struck by falling load					1		**1**
Struck by other	1	1		3	2		**7**
Electrocution	2	5	2	2	9		**20**
Drowning					1		**1**
Entangled					2		**2**
Total fatalities	**20**	**39**	**9**	**8**	**46**	**2**	**124**

Cause	C / S	C / U	MNM / S	MNM / U	SSG / S	SSG /U	Total
Restricted visibility from mobile plant	9	24	2	2	12	2	**51**
Pedestrians near mobile plant	4	18	2		8	2	**34**
Fatigue	2	1			1		**4**
Working at height				1	1		**2**
Drugs/Alcohol	2	2			1		**5**
Working on energised equipment	4	4	3	3	18		**32**
Working near suspended load					2		**2**
Inexperience / untrained	2	7			6		**15**
Roadway design / condition	2	2	1		4		**9**
Environment	1	1	1				**3**
Multiple vehicles	3	2	1		1		**7**
Other	10	19	5	5	28	2	**69**

Control technology	C / S	C / U	MNM / S	MNM / U	SSG / S	SSG /U	Total
Preventive							
Video camera	8	13	2	2	10		**35**
Pedestrian proximity warning	4	23	1	3	7	1	**39**
Vehicle proximity warning	3	2					**5**
Edge warning	3						**3**
Fatigue monitoring	2	1			1		**4**
Live electrical warning device	1	2	3	1	8		**15**
Mitigating							
Interlocked proximity detection on fixed plant	1	2	1		10		**14**
Non-line-of-sight remote control of CM		6					**6**
Interlocked proximity detection on mobile plant	4	23	1	3	7	1	**39**
Remote operation	3	1		1	3		**8**
Interlocked seat restraint	3				2		**5**
Light warning on ug mobile plant		5					**5**
Interlocked edge detection	3			1	2		**6**
Crane electrical proximity alarm	1						**1**
Interlocked vehicle-vehicle PD	3	1					**4**

Table B.3 Outcomes, Causes, & Control Technologies by sector and mine type for "Loss of control of strata or ground" initiating event.

Outcome	C / S	C / U	MNM / S	MNM / U	SSG / S	SSG /U	Total
Mobile plant - environment interaction	2			1	5		**8**
Engulfed	2			2	5		**9**
Crushed		4					**4**
Fall	1					2	**3**
Struck by other		1					**1**
Drowning	1				3		**4**
Struck by rock	6	54		11	4	2	**77**
Total fatalities	**12**	**59**		**14**	**17**	**4**	**106**

Cause	C / S	C / U	MNM / S	MNM / U	SSG / S	SSG /U	Total
Unstable roof		33		3		2	**38**
Unstable rib		10		2		1	**13**
Unstable ground	1				7		**8**
Unstable highwall	5				2		**7**
Outburst conditions		5					**5**

Cause	C / S	C / U	MNM / S	MNM / U	SSG / S	SSG /U	Total
Standing in hopper / bin					3		**3**
Inexperience		1		1	1	1	**4**
Fatigue		1					**1**
Operating on slope/edge	3				5		**8**
Working under highwall	5				2		**7**
Working under unsupported roof / face	1	10		3		1	**15**
Drugs / Alcohol		1			1		**2**
Flawed engineering analysis		9					**9**
Retreat mining		5					**5**
Other	4	18		11	8	2	**43**

Control technology	C / S	C / U	MNM / S	MNM / U	SSG / S	SSG /U	Total
Preventive							
Outburst prediction technology		12					**12**
Non-contact assessment of underground strata condition		27		9			**36**
Ground stability monitoring	1			1	7		**9**

Control technology	C / S	C / U	MNM / S	MNM / U	SSG / S	SSG /U	Total
Slope / highwall stability monitoring	5				2		**7**
Mitigating							
Remote bolting		12		2			**14**
Non-line-of-sight control CM		18					**18**
Remote operation mobile plant	7	2		3	5	2	**17**
Interlocked pedestrian proximity detection on fixed plant		1			1		**2**
Interlocked seat restraint					1		**1**

Table B.4 Outcomes, Causes, & Control Technologies by sector and mine type for "Unintended fire or explosion" initiating event.

Outcome	C / S	C / U	MNM / S	MNM / U	SSG / S	SSG /U	Total
Burns	2						**2**
Poisioning		19					**19**
Struck by other	1	29			2		**32**
Total fatalities	**3**	**48**	**0**	**0**	**2**	**0**	**53**

Cause	C / S	C / U	MNM / S	MNM / U	SSG / S	SSG /U	Total
Methane in explosive range		46					**46**
Ignition source		36					**36**
Coal dust		29					**29**
Inexperience	1				1		**2**
Lightning		12					**12**
Combustable materials on conveyer		2					**2**
Frictional ignition on conveyer		2					**2**
Other	3				2		**5**

Control technology	C / S	C / U	MNM / S	MNM / U	SSG / S	SSG / U	Total
Preventive							
Methane extraction		29					**29**
Remote methane monitoring interlocked with longwall shearer		29					**29**
Stone dust monitoring		29					**29**
Video based fire detection		2					**2**
Remote CO monitoring		2					**2**
Inertisation sealed areas		17					**17**
Remote monitoring sealed areas		17					**17**
Gas line detection on dozer	1						
Mitigating							
Remote longwall operation		29					**29**
Active explosion barrier		29					**29**
Fire suppression on mobile plant / conveyer / longwall	2	31					**33**
usable SCSR / CABA		19					**19**
Refuge chamber		19					**19**

Table B.5 Outcomes, Causes, & Control Technologies by sector and mine type for "Equipment malfunction" initiating event.

Outcome	C / S	C / U	MNM / S	MNM / U	SSG / S	SSG /U	Total
Mobile plant - environment interaction	8		1	2	3	2	**16**
Mobile plant - pedestrian interaction	1	3				2	**6**
Mobile plant - vehicle interaction	1						**1**
Fixed plant - pedestrian interaction		2					**2**
Engulfed				2	1		**3**
Crushed	1			1	1		**3**
Fall			2	1	3		**6**
Struck by falling load	1				4	1	**6**
Struck by other	1	4					**5**
Burns			1				**1**
Total fatalities	**13**	**9**	**4**	**6**	**12**	**5**	**49**

Cause	C / S	C / U	MNM / S	MNM / U	SSG / S	SSG /U	Total
Brake condition	7			2	3	3	**15**
Overloaded truck	3						**3**
Steering condition	2			1		1	**4**
Fatigue interlock	1						**1**
Hoist cable condition		1					**1**
Overloaded crane					1		**1**
Lifting equipment condition					2		**2**
Working under suspended load	1				4	1	**6**
Roadway design or condition	6		1	1	1		**9**
Inexperience	4				2		**6**
Working at height			1	1	2		**4**
Drugs/Alcohol	1				1		**2**
Working near plant	1	2				1	**4**
Other	7	10	4	6	11	4	**42**

Control technology	C / S	C / U	MNM / S	MNM / U	SSG / S	SSG /U	Total
Preventive							
Auto-brake at pre-start	7			2	3	1	**13**
Interlocked overload protection	3						**3**
Non-destructive testing hoist cable		1					**1**
Park brake interlock	1						**1**
Fatigue interlock	1						**1**
Authority to drive interlock						1	**1**
Mitigating							
Interlocked seat restraint	8			2	2	1	**13**
Non-line-of-sight remote control of CM		1					**1**
Interlocked proximity detection on CM		1					**1**
Remote longwall operation		1					**1**
Interlocked proximity detection on fixed plant		2					**2**

Table B.6 Outcomes, Causes, & Control Technologies by sector and mine type for "Loss of balance" initiating event.

Outcome	C / S	C / U	MNM / S	MNM / U	SSG / S	SSG /U	Total
Mobile plant - environment interaction							
Mobile plant - pedestrian interaction	1				1		**2**
Mobile plant - vehicle interaction							
Fixed plant - pedestrian interaction		2			4		**6**
Engulfed							
Crushed	1						**1**
Fall	7	5	3		14	2	**31**
Struck by falling load							
Struck by other							
Burns							
Drowning	3				4		**7**
Total fatalities	**12**	**7**	**3**	**0**	**23**	**2**	**47**

Cause	C / S	C / U	MNM / S	MNM / U	SSG / S	SSG /U	Total
Working on energised equipment	2	1			4		**7**
Drugs / Alcohol	3				1		**4**
Inexperience		3	1		3		**7**
Working at height	2	2	2		6	1	**13**
Working on ladder	5		1		2		**8**
Access / egress mobile plant	1		1		2		**4**
Fatigue	1				1		**2**
Weather	2	2	1		1	1	**7**
Other	7	1	1		17	1	**27**

Control technology	C / S	C / U	MNM / S	MNM / U	SSG / S	SSG /U	Total
Preventive							
Automated haul truck	1						**1**
Remote control rock breaker					2		**2**
Mitigating							
Interlocked proximity detection on fixed plant		1			4		**5**
Interlocked proximity detection on mobile plant	1	1					**2**