Using Bow-Tie analyses to enhance incident investigation activities

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Practitioner Summary:
The Bow-Tie Analysis (BTA) technique is a risk analysis tool that combines features from both fault-tree analysis and event-tree analysis to identify an incidents initiating event, the causes of that initiating event, both the preventative and mitigatory controls that could potentially have prevented it or reduced the severity of the event, and the consequences. The aim of the research was to determine whether incident investigation activities could generate additional risk controls by applying the BTA technique to fatal incident reports generated by the Mine Safety & Health Administration. Between the period 2008 and 2014, 66 fatal collisions occurred that involved unwanted interactions between mobile equipment and mining employees, other mobile equipment, infrastructure and voids. Comparisons were made between the risk controls identified by the original investigators and those identified by UQ researchers specialised in Ergonomics and Human Factors. Application of the BTA technique was found to be a useful tool for eliciting additional information when identifying preventative and mitigatory controls. A higher number of risk controls were identified by the UQ researchers than the original investigation team. It would appear that the application of BTA to identifying risk controls from incident reports in the mining industry would uncover a larger number of different and relevant preventative and mitigation risk controls. Further work is required to understand why.

Keywords: Bow-Tie analysis (BTA), incident investigation, mining

1. Introduction
In the United States of America, the Mine Safety and Health Administration (MSHA) conducts investigations of fatal mining incidents and publishes the report for the purposes of enhancing safety awareness so that the reoccurrence of similar incidents may be prevented in the future. The reports identify the root cause(s) of the incident and recommended corrective actions. This project forms part of a larger project designed to better understand fatal incidents in the mining industry. The current article contains research specifically focusing on enhancing our understanding of collisions between mining equipment and employees, other mining equipment, infrastructure and voids.

The BTA technique is used as a risk analysis tool that combines the use of fault tree analysis and event tree analysis to identify, graphically illustrate and communicate the causes, consequences, prevention and mitigation controls that underlie unwanted events. The BTA has been used within the oil and gas, petrochemical, aviation and mining domains (Achield & Weaver, 2012; Burgess-Limerick, Horberry, & Steiner, 2014; Pitblado & Weijand, 2014; Saud, Israni, & Goddard, 2014). In Australia, the use of bow ties is an accepted way to graphically demonstrate whether organisation controls have reduced the risk of a major incident so far as is reasonably practicable (Safe Work Australia, 2012).

The BTA analysis was applied to the MSHA fatal report information to determine if it could help investigators identify those risk controls that could have prevented or lessoned the severity of the event outcomes to an acceptable level of risk.
1.1 Mine Safety and Health Administration (MSHA) data

The primary objective of MSHA reports is to identify the root cause(s) of mining incidents in order to share this information with those in a position to prevent similar events occurring in the future. Fatality reports available cover both coal mines and metal/non-metal fatalities. The MSHA database categorises events against 21 classifications which include powered haulage, machinery, slips trips and falls, ignition or explosion of gas or dust etc.

Unwanted vehicular interactions or collisions represent an event type currently requiring greater understanding in the Australian mining environment. Consequently that event subset was the focus of the current project. Collision events were identified primarily in ‘Powered haulage’ events and to a lesser extent in ‘Machinery’ and ‘Hoisting’ events. Powered haulage events are caused by the motion of the haulage unit (e.g., shuttle cars, haulage trucks, load-haul-dumps, etc). Machinery events include those that result from the action or motion of machinery or from failure of components. Hoisting events involve those in which an individual is fatally injured by hoisting equipment. Please see MSHA website for full definitions.

1.1 The Bow-Tie Analysis (BTA) technique

The BTA technique has been identified as a particularly useful analysis tool as it helps to visually represent the controls either present or necessary to prevent and or mitigate unwanted incidents and events. The final product generates a visual representation that can be readily communicated, understood and evaluated.

Although there is no formal standard or accepted methodology for applying the BTA technique the approach undertaken here was based on RISKGATE, which is a project strongly supported by the Australian Coal Association Research Program (ACARP). RISKGATE is an on-line body of knowledge that uses the BTA technique to assist the coal industry understand and control specific major incidents and links them to information regards specific event controls. It can also assist identify gaps in existing control measures.

There are five overall components of a bow tie – initiating event, causes, consequences, preventative controls and mitigatory controls. The first, initiating event, is the knot or centre of the bow tie. The initiating event is the event that can result in an undesired outcome. In other words the loss of control of a hazard. The next components involve identifying the causes of the initiating event and the potential outcomes of that event. The next step requires the identification of those control measures (preventative controls or barriers) that can reduce the likelihood of the initiating event occurring, and those control measures (mitigatory or recovery controls) that can reduce the severity of the consequences of each initiating event, for each of the identified causes.

Although the BTA technique can be extended to assess the effectiveness of control measures in place, it was not a feature of this study.

2. Method

The BTA study of the MSHA fatal information involved analysing 66 fatal incidents that occurred between 2006 and 2014 in the coal and metal/non-metal mine sites in the USA. The incidents were limited to those that involved an unwanted vehicle interaction scenario which included heavy mining vehicle to heavy mining vehicle (e.g., haul truck colliding with excavator or another haul truck), heavy mining vehicle to light vehicle (e.g., haul truck contacting a people carrying utility or bus), heavy mining vehicle to pedestrian, light vehicle to light vehicle, light vehicle to pedestrian, and heavy or light vehicle to void (e.g., vehicle over the edge). Although there was no collision with an object, the final interaction scenario, vehicle and void, was included on the grounds that a vehicle entered a high risk zone without authorisation. The total number of fatalities in the American mining industry between 2006 and 2014 was 264, indicating that 25% of incidents involved some form of unwanted vehicular interaction. Only those incidents that had a final report at the time of the research were included in the analysis.

A bow tie representation was created for each fatality event. See Figure 1 as an example.
Figure 1: Example bow tie analysis of an incident in a coal mine.

NB: A – absent control at time of incident; P – present control at time of incident; and italicized – controls identified by UQ researchers.
Each bow tie contained the following components of an incident: cause(s), preventative risk controls (also known as barriers), initiating events (when control was lost), mitigation risk controls (also known as recovery controls) and the outcome. The preventative and mitigation risk controls were further separated in two regards. Firstly, distinction was made between risk controls identified by the MSHA investigators and/or mine site personnel and those identified by the UQ researchers. Distinction was also made between those risk controls present at the time of the incident and those that were not. An assessment of control effectiveness or quality was not included in this analysis. The two researchers coded the reports separately and then discussed each incident BTA until agreement was reached.

Examples of each of the elements of the BTA can be found in Table 1.

### Table 1. Typical examples of elements from the bow-tie model

<table>
<thead>
<tr>
<th>Causes</th>
<th>Preventative Risk Control</th>
<th>Initiating event</th>
<th>Mitigatory Risk Control</th>
<th>Outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design of shuttle car obstructed view of helper</td>
<td>Mechanical interlock</td>
<td>Loss of situation awareness</td>
<td>Collision avoidance system</td>
<td>Driver thrown from vehicle</td>
</tr>
<tr>
<td>Truck overloaded</td>
<td>Proximity detection system</td>
<td>Loss of control</td>
<td>Seatbelt interlock</td>
<td>Driver struck by vehicle</td>
</tr>
<tr>
<td>Operator was standing in a Red-Zone (exclusion-zone)</td>
<td>Equipment design</td>
<td>Engineering failure</td>
<td>Confidential reporting system</td>
<td></td>
</tr>
<tr>
<td>Visibility - opaque fly pads obstructed view of pedestrian</td>
<td>Mine design</td>
<td></td>
<td>Emergency training</td>
<td></td>
</tr>
<tr>
<td>Brake failure on truck</td>
<td>Non line of sight remote control</td>
<td></td>
<td>Regulatory oversight</td>
<td></td>
</tr>
<tr>
<td>Pedestrians shared same path as mobile equipment</td>
<td>Fatigue management system</td>
<td></td>
<td>Barriers</td>
<td></td>
</tr>
</tbody>
</table>

The types of vehicular and pedestrian interactions can be seen in Table 2.

### Table 2: Frequency of interaction types and examples.

<table>
<thead>
<tr>
<th>Interaction type</th>
<th>Number</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vehicle to Person</td>
<td>35</td>
<td>Miner crushed between a large power centre (being relocated by forklifts) and the coal rib; Scoop operator crushed between coal rib and a battery-powered scoop; Driver reversed over by front end loader</td>
</tr>
<tr>
<td>Vehicle to Vehicle</td>
<td>5</td>
<td>Dump truck operator struck back of stationary dump truck; Utility miner crushed when shovel lost traction and travelled backwards down the slope crushing his truck; Scraper struck combination fuel/service truck on a 2-way haulroad</td>
</tr>
<tr>
<td>Vehicle to Infrastructure / Void</td>
<td>26</td>
<td>Truck went out of control on a downhill slope and struck a rib causing it to overturn; Bobcat travelled into the impoundments waters; Operator of rock truck travelled over the edge of the spoil dump</td>
</tr>
</tbody>
</table>
3. Results

Results from the BTA indicated that it is a useful tool for eliciting further information to identify preventative and mitigatory risk controls. A considerable number of risk controls were identified by the UQ researchers that were not made by either the MSHA investigators or the mine site personnel. Almost double the number of preventative risk controls were identified by the UQ researchers (n=453) than those identified by the MSHA investigators and/or the mine site personnel (n=263). A similar finding arose for the identification of mitigatory risk controls (UQ researchers, n=191; MSHA and mine, n=82).

3.1 Descriptives – Preventative Risk Controls

3.1.1 MSHA and Mine Owners

The most frequently identified preventative risk control made by the MSHA and Mine Owners was training (n=52; e.g., operator had not received new miner training), followed distantly by procedures (n=19; e.g., management to provide written procedure that ensures adequate pre-operational checks are conducted), maintenance (n=15; adequate maintenance to prevent and identify safety defects), lighting (n=13; vehicle makers and hazard lights to be used under all low light conditions), and supervision (n=13; mine operator did not ensure compliance with roof control plan). See Figure 2 for details.

![Most frequently identified Preventative Risk Controls identified by MSHA & Mine Owners](image)

Figure 2: Most frequent preventative risk controls identified by MSHA and Mine Owners
3.1.2 UQ Researchers

The most frequently identified preventative risk control made by the UQ Researchers was risk management (n=33; risk assessment not undertaken to identify risks), proximity detection systems (n=32; operator unaware of approaching vehicle), implementation of previously identified risk controls (n=27; controls identified in previous similar incident had not been implemented), safety culture (n=22; routine use of bulldozer to assist shovel ascend grades), auditing (n=22; ensure procedures being correctly followed), and supervision (n=20; maintenance supervision – main brake line rusted through). See Figure 3 for details.

Proximity detection systems in this context referred to those technologies that provided information to the operator of the location of people, equipment, infrastructure or voids when they were in a range in which the operator needed to act, however the system did not take action itself. The implementation of previously identified risk controls refers to instances in which the MSHA report discussed previous incidents, either at that mine or another, that the organisation would most likely have been aware of and hence aware of the potential risk controls. In this instance they had not implemented the controls and had they the likelihood of the current incident may have been reduced.

![Most frequently identified Preventative Risk Controls identified by UQ Researchers](image)

Figure 3: Most frequent preventative risk controls identified by UQ Researchers
3.2 Descriptives – Mitigatory Risk Controls

3.2.2 MSHA and Mine Owners.

The most frequently identified mitigatory risk control was berms / barriers and escape ramps (n=15; berm did not prevent overtravel), followed by emergency response (n=14; driver extricated from vehicle immediately after incident), crashworthiness (n=12; rollover protection system in bulldozer), and seatbelts (n=12; truck did not have seatbelt). See Figure 4 below.

![Most frequently identified Mitigatory Risk Control identified by MSHA and Mine Owners](image)

Figure 4: Most frequent mitigatory risk controls identified by MSHA and Mine Owners.

3.2.3 UQ Researchers.

The most frequently identified mitigatory risk controls by the UQ researchers was as follows: collision avoidance system (n=39; operator made aware of void however proceeded unintentionally over edge), regulatory oversight (n=20; non-fatal days lost for mine 5.56, compared to national rate of 1.37), personal alert system (n=19; delay between incident and time operator discovered), and seatbelt interlock (n=17; vehicle prevented from moving until seatbelt fixed). See Figure 5.

Collision avoidance system, in this context, refers to a system that actively influences the movement of the mobile equipment to prevent a collision. In the majority of fatality reports statistics were provided that compared the non-fatal days lost (NFDL) of the mine to the national rate. This was considered a potential opportunity for closer examination to be made of activities at the mine for the purposes of enhancing safety / education. When the NFDL rate for the mine was considerably higher than the national rate it was listed as a potential mitigatory control. It was also listed when the NFDL rate for the nation was above 2.0 and the mine reported no NFDL’s which may be an indicator of non-reporting. Personal alert systems refers to a potential system that could notify mine site personnel to an employee in distress and was identified when there was a delay between the incident and discovery of the injured / deceased. The seatbelt interlock is a system that stops the vehicle from moving unless the seatbelt has been fastened.
Figure 5: Most frequent mitigatory risk controls identified by UQ Researchers

4 Conclusions
The application of BTA to identifying risk controls from incident reports in the mining industry would appear to uncover a larger number of different and relevant preventative and mitigation risk controls. Further work is required to understand why. This work was restricted to analysing the presence of controls based on the published MSHA data. The original evidence was not accessed for this research. We conclude that further benefits may be gathered by assessing the effectiveness of risk controls however the current nature of the data doesn’t allow for the benefits to be fully realised. It is hoped that the insights gained from further work will lead to improvements in the identification of risk controls during incident investigation activities.

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References