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Design of intelligent proximity detection zones to prevent striking and pinning fatalities around continuous mining machines

P.T. Bissert, **J.L. Carr**, **J.P. DuCarme**, and **A.K. Smith**

Mechanical engineer, mining engineer, mechanical engineer and mechanical engineer, respectively, Pittsburgh Mining Research Division, National Institute for Occupational Safety and Health (NIOSH PMRD), Pittsburgh, PA, USA

Abstract

The continuous mining machine is a key piece of equipment used in underground coal mining operations. Over the past several decades these machines have been involved in a number of mine worker fatalities. Proximity detection systems have been developed to avert hazards associated with operating continuous mining machines. Incorporating intelligent design into proximity detection systems allows workers greater freedom to position themselves to see visual cues or avoid other hazards such as haulage equipment or unsupported roof or ribs. However, intelligent systems must be as safe as conventional proximity detection systems. An evaluation of the 39 fatal accidents for which the Mine Safety and Health Administration has published fatality investigation reports was conducted to determine whether the accident may have been prevented by conventional or intelligent proximity. Multiple zone configurations for the intelligent systems were studied to determine how system performance might be affected by the zone configuration. Researchers found that 32 of the 39 fatalities, or 82 percent, may have been prevented by both conventional and intelligent proximity systems. These results indicate that, by properly configuring the zones of an intelligent proximity detection system, equivalent protection to a conventional system is possible.

Keywords

Proximity detection systems; Intelligent proximity detection; Continuous mining machines; NIOSH

Introduction

Underground coal miners are exposed to a variety of hazards on a daily basis. Among coal and rock dust exposure, high noise levels, roof and rib falls, and the potential for fires and explosions, operating and working with heavy machinery poses a significant risk to miner safety. One of the most hazardous jobs is operating or working nearby a continuous mining

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machine. According to U.S. Mine Safety and Health Administration (MSHA) statistics, 40 miners have been fatally struck or pinned by a continuous mining machine since 1984. (At the time of this writing, an investigation report is not available for the most recent occurrence in January 2016.) In an effort to prevent future striking and pinning fatalities from occurring, proximity detection systems have been developed and are now required on all operating continuous mining machines in underground coal mines with the exception of full-face continuous mining machines (MSHA, 2015).

Commercially available proximity detection (cPD) systems are based on the principle of magnetic flux density (B-field). Typically, four magnetic field generators are positioned on a continuous mining machine, and personal alarm devices are worn by the miners that detect magnetic flux density difference. As a miner wearing a personal alarm device gets closer to the machine, the flux density increases. Zones can be constructed around the machine so that an alarm will trigger on the personal alarm device based on the flux density.

Zone sizes and boundaries are based on predefined distances from the machine, and can be configured by software. The proximity detection system provides both a visual and audible warning to alert the miner of zone incursions. The continuous mining machine slows down for a “warning zone” incursion, and completely halts for a “stop zone” incursion. An example set of warning and stop zones is shown in Fig. 1. Proximity detection systems are static in nature, with zone boundaries are fixed relative to the machine chassis, except when the continuous mining machine is cutting coal. This feature is known as “mining mode” and reduces the zones toward the rear of the machine to allow the operator to get out of the way of oncoming shuttle cars. It should be noted that machine motions that could harm the operator, such as a conveyor boom swing, are not prevented during mining mode.

Researchers at the U.S. National Institute for Occupational Safety and Health (NIOSH) have developed an intelligent proximity detection (iPD) system. Both iPD and cPD systems function on the same hardware and vary in terms of software. The iPD differs from the cPD in that it creates multiple zones to selectively disable only machine motions that could be hazardous to the miner while allowing safe actions to be performed uninterrupted. The iPD system is based on utilizing all of the magnetic generators to measure the magnetic flux density and localize the miner relative to the machine using trilateration methods. The cPD system does not localize the miner relative to the machine, and simply identifies zone incursions based on any magnetic flux density reading that is associated with a miner being too close to the machine. The iPD system provides the operators with more freedom to position themselves to best perform their work by defining specific zones where only selected machine actions are prevented. This could lead to safer, more efficient continuous mining machine operation, and could also prevent unintentional machine shutdowns associated with cPD systems when a miner enters the stop zone. Ultimately, these advantages also help to build miner acceptance of proximity detection systems (Haas and Rost, 2015).

While the functionality of iPD systems has not been adopted by cPD system manufacturers, the iPD is designed to provide worker protection at least equivalent to cPD while giving miners greater flexibility to more safely carry out their work.

Intelligent proximity zone configurations

Three different iPD zone designs are presented in this paper. None of these designs are intended to be recommendations, but rather are presented as examples for comparing the factors associated with establishing zone definitions. The first zone layout, iPD 1, is shown in Fig. 2. In this configuration, both zones 9 and 10 are dynamic in that they move with the conveyor boom as it pivots laterally to load coal onto haulage equipment. Zones 1 through 8 are static zones and are based on the continuous mining machine chassis.

When a miner is detected, continuous mining machine motions associated with the zone are disabled. Continuous mining machine motions are grouped by their function: tramming, conveyor boom, cutter head, gathering pan, cutter motor, conveyor motor, and high speed tram. The logic governing which functions are disabled in each zone is shown in Table 1. This particular configuration was developed by NIOSH researchers as a proof-of-concept for selective machine function shutdown (Jobes et al., 2011; Jobes, Carr and DuCarme, 2012; Carr and DuCarme, 2013; DuCarme, Carr and Reyes, 2013; Carr et al., 2015).

The second zone layout, iPD 2, is shown in Fig. 3. Similar to iPD 1, iPD 2 features dynamic zones 9, 10, 11 and 12 that follow the position of the conveyor boom. The remainder of the zones, 1 to 8 and 13, are static and are based on the continuous mining machine chassis. The logic for each zone and the corresponding functions that are disabled are described in Table 2. Variations from iPD 1 to iPD 2 include:

- Zones 1 to 10 cover only the perimeter.
- Zone 11 was added as a buffer between zones 9 and 10 to prevent unsafe conveyor boom motions when an operator is near the tail.
- Zones 12, on the conveyor boom, and 13, on the machine frame, were added to prevent accidents when a miner is on the continuous mining machine.
- Zones 9 and 10 will have different zones disabled based on the conveyor boom swing position. Disabled functions are less restrictive for a centered conveyor compared with a conveyor swung left or right.
- Zones 2 to 8 will disable forward (TUU) and reverse (TDD) tram to prevent accidents when a miner is beside the continuous mining machine.

All tram functions in iPD 2 are blocked for zones 4 and 5 to prevent any unsafe pivoting motions.

The third zone layout, iPD 3, is shown in Fig. 4. iPD 3 is designed to simplify the zone logic while maintaining safety. As such, iPD 3 utilizes fewer zones such that the simplified zone logic could benefit adoption of the iPD system by continuous mining machine operators. All of the zones in this configuration are based on the continuous mining machine chassis and are static. There are no dynamic zones in this configuration as there is no approved method for measuring the position of the conveyor boom. At the time of this writing, there is no hardware that can measure the position of the conveyor boom that has been approved as permissible underground equipment. The governing logic that selectively disables continuous mining machine functions for different zones is described in Table 3. Variations from iPD 2 to iPD 3 include:

- Only five zones are used to consolidate logic and maintain safety.
- All tram functions (forward, reverse, pivot) are blocked for zones 2 and 3 to prevent accidents when a miner is beside the continuous mining machine.
- All pivoting tram functions are blocked to account for uncertainty in pivoting radius.
- The dynamic zone from iPD 2 was replaced with a static zone that accounts for the conveyor boom swing radius.
- The only allowable function in zone 1 is both crawlers down (TDD).
- The only allowable function in zone 5 is both crawlers up (TUU).

Continuous mining machine fatalities analysis

NIOSH researchers conducted an analysis of 39 fatalities involving continuous mining machines from the years 1984 to 2015 in order to gain insight into the potential for proximity detection systems to enhance miner safety. All of the cases included in this study involve a miner being struck or pinned by a continuous mining machine in an underground U.S. mine. (Although 40 continuous mining machine striking/pinning fatalities had occurred since 1984, at the time of this writing, an investigation report is not available for the most recent occurrence in January 2016.) The primary objectives of this analysis include:

- Identify where, relative to the continuous mining machine, the miners were struck or pinned
- Estimate the number of cases in which a proximity detection system could have prevented the fatality.
- Compare safety benefits between the cPD and iPD systems.

MSHA investigation reports were reviewed and analyzed for each accident to determine whether a cPD or iPD system could have prevented the fatality. Eyewitness accounts were not always available, and as such clear specific information regarding which zone the victim may have been in is not available in all of the investigation reports. For these particular reports, multiple zones are identified as *possible* locations where the victim may have been. Additionally, all possible machine motions that may have been the cause of the accident were considered.

As an example, on Nov. 17, 2012, a continuous mining machine operator was pinned while backing the machine out of the first cut of a crosscut that was being developed. The MSHA investigation report indicates that the operator was pinned between the left side of the continuous mining machine’s cutting drum and rib (Fig. 5). Based on this information, it was most likely a pivoting action (TDU) performed by the operator that resulted in the accident. NIOSH analysis concluded that a cPD system could have prevented this accident because the machine would have shut down once the operator entered the stop zone. In regard to the iPD systems discussed in this paper, the operator would have been in zone 2 for all three zone configurations. Based on the pre -scribed zone logic tables, all three of the iPD layouts could have prevented the accident as the pivoting actions would have been disabled (TDx or TDU).

The fatality accident analyses that were conducted on the 39 cases are based on the information provided by the MSHA investigation reports and the NIOSH research team's knowledge of mining environments and proximity detection systems. While sufficient accident data are not available to draw statistically significant conclusions, the analyses provide insight toward the ability of proximity detection systems to prevent striking and pinning accidents.

It is mandated that a proximity detection system prevents a continuous mining machine that is tramming or repositioning from contacting a miner by stopping the machine (MSHA, 2015). For the purpose of this analysis, it was assumed that all machine motions would be blocked when a miner entered the stop zone for cPD systems. For the three iPD systems, if the governing zone logic configurations would have blocked the machine motions that were identified as potentially causing the accident, it was assumed that the system would have prevented the fatality. A summary of these analyses is shown in Table 4 with the detailed results shown in Table 5.

Results

NIOSH researchers developed a prototype intelligent proximity detection, iPD, system that could improve upon the operational efficiency of cPD systems while providing equivalent safety. This is achieved by selectively disabling only the continuous mining machine motions that could harm operators and allowing them more freedom to safely position themselves around the machine to accomplish their work. The research team quantified the safety performances of cPD and iPD by reviewing and analyzing 39 fatal accidents involving continuous mining machines since 1984.

This study showed that 82 percent of the fatalities could have been prevented by cPD systems. Three different iPD zone layouts were presented to demonstrate how performance is affected by zone and logic definitions. These iPD systems were analyzed over the same set of 39 accidents. The results showed that both iPD 2 and iPD 3 could have prevented 82 percent of the accidents, equivalent to cPD, while iPD 1 could have only prevented 61 percent of the accidents.

This analysis indicates that by implementing iPD into commercially available proximity detection systems, miners could have the safety benefits of proximity detection systems while having more freedom to move around the machine and work more efficiently, thus potentially enhancing acceptance of the systems. Again, only MSHA investigation reports were used to perform these analyses. While sufficient accident data are not available to yield statistically validated conclusions, the analyses performed provide insight into the effectiveness of proximity detection systems.

In this particular study, iPD 2 and iPD 3 provided higher levels of safety compared with iPD 1, due to the iPD 1 zone logic definitions that allowed for tramming motions when a miner is detected on the side of the continuous mining machine. More importantly, the comparison between the three different iPD zone layouts illustrates that the zone definitions are critical to proximity detection system effectiveness. None of the three iPD systems should be considered absolute or should be considered as recommended designs. The purpose of the three iPD layouts is to provide examples of how the zones for an iPD system could be designed, and also to demonstrate how different zone definitions affect the ability to prevent fatalities. It should also be noted that there are a number of other factors that can influence the performance of proximity detection systems, such as conveyor elevation, cutting drum elevation, tramming, and mining mode (Carr et al., 2015). These factors should also be taken into consideration when designing zone configurations for intelligent proximity systems.

Conclusion

Intelligent proximity detection systems could provide equivalent safety to commercially available proximity detection systems and could improve upon operational efficiency and miner acceptance. Zone designs must be carefully considered prior to installation, as the zone layouts and logic definitions can have a significant effect on performance. Researchers at NIOSH intend to continue working with proximity detection manufacturers to further improve miner safety by demonstrating the performance of iPD systems.

Acknowledgments

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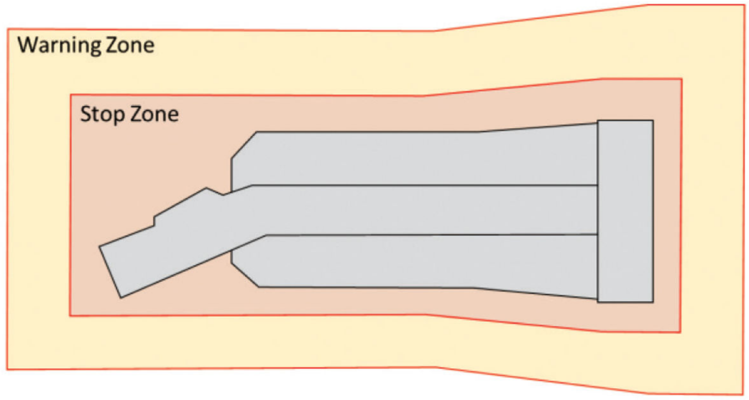

Figure 1.
Representation of a cPD system.

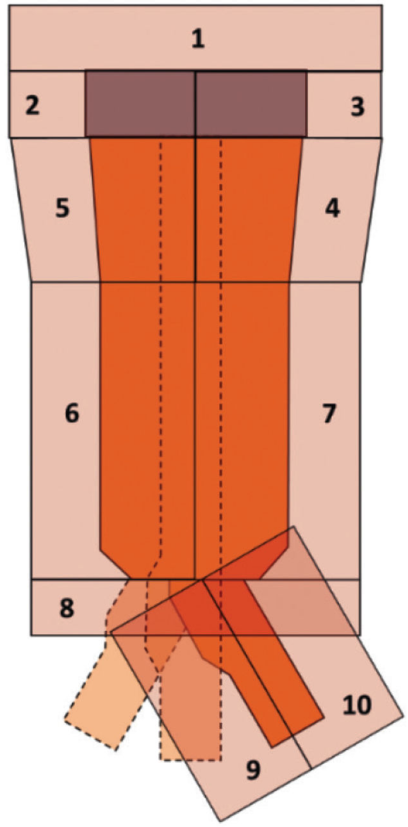

Figure 2.
iPD 1 zone layout.

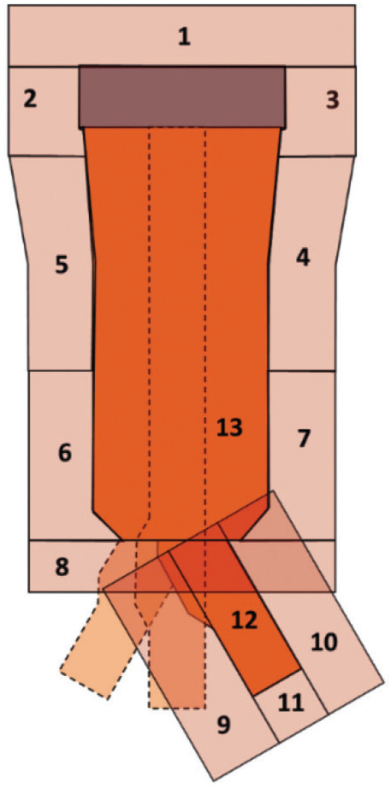

Figure 3.
iPD 2 zone layout.

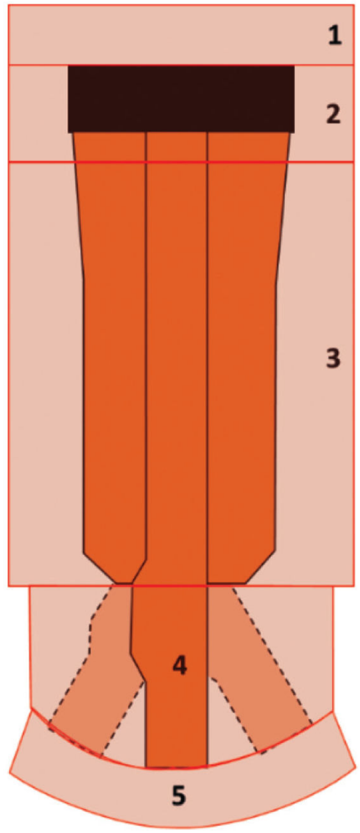

Figure 4.
iPD 3 zone layout.

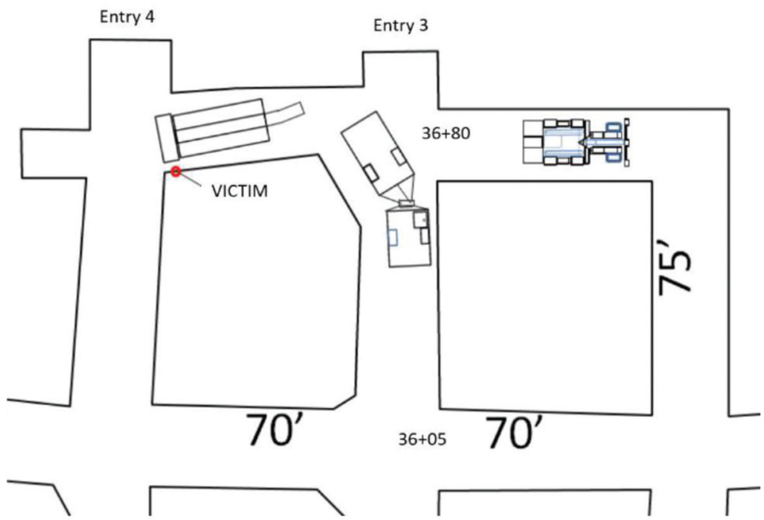

Figure 5.

Fatality location of CMM operator on Nov. 17, 2012 (Mine Safety and Health Administration, 2013).

Table 1

Logic table for iPD 1 zone layout.

Group	Machine motion		Code	1	2	3	4	5	6	7	8	9	10
	+	**Allowed**											
	−	**Disabled**		**Zone**									
Tram (left crawler, right crawler).	Up	Up	TUU	−	+	+	+	+	+	+	+	+	+
	-	Up	TxU	−	−	+	+	−	+	−	+	+	−
	Up	-	TUx	−	+	−	−	+	−	+	+	−	+
	Down	Down	TDD	+	+	+	+	+	+	+	−	−	−
	-	Down	TxD	+	+	−	−	+	−	+	−	−	−
	Down	-	TDx	+	−	+	+	−	+	−	−	−	−
	Down	Up	TDU	−	−	+	+	−	+	−	−	+	−
	Up	Down	TUD	−	+	+	−	+	−	+	−	−	+
Conveyor.	Up.		CU	+	+	+	+	+	+	+	+	−	−
	Down.		CD	+	+	+	+	+	+	+	+	+	+
	Swing right.		CR	+	+	+	+	+	+	+	+	+	−
	Swing left.		CL	+	+	+	+	+	+	+	+	−	+
Cutter head.	Up.		HU	−	−	−	+	+	+	+	+	+	+
	Down.		HD	−	−	−	+	+	+	+	+	+	+
Gathering pan.	Up.		PU	−	−	−	+	+	+	+	+	+	+
	Down.		PD	−	−	−	+	+	+	+	+	+	+
Cutter motor.			H	−	−	−	+	+	+	+	+	+	+
Conveyor motor.			C	+	+	+	+	+	+	+	−	−	−

+ **Allowed**

– **Disabled**

Group	**Machine motion**	**Code**	**Zone 1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
	High speed tram.	HST	–	–	–	–	–	–	–	–	–	–

Table 2

Logic table for iPD 2 zone layout.

	+	Allowed		Zones																
	−	Disabled										Tail center		Tail left		Tail right				
Group	Machine	motion	Code	1	2	3	4	5	6	7	8	9	10	9	10	9	10	11	12	13
Tram (left crawler, right crawler).	Up	Up	TUU	−	−	−	−	−	−	−	+	+	+	−	+	+	−	+	−	−
	--	Up	TxU	−	−	−	−	−	−	−	−	+	−	−	−	+	−	−	−	−
	Up	-	TUx	−	−	−	−	−	−	−	−	−	+	−	+	−	−	−	−	−
	Dn	Dn	TDD	+	−	−	−	−	−	−	−	+	+	+	−	−	+	−	−	−
	--	Dn	TxD	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−
	Dn	-	TDx	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−
	Dn	Up	TDU	−	−	+	−	−	+	−	−	+	−	−	−	−	−	−	−	−
	Up	Dn	TUD	−	+	−	−	−	−	+	−	−	+	−	−	−	−	−	−	−
Conveyor.	Raise.		CU	+	+	+	+	+	+	+	+	+	+	+	+	+	+	−	−	+
	Lower.		CD	+	+	+	+	+	+	+	+	+	+	+	+	+	+	−	−	+
	Swing right.		CR	+	+	+	+	+	+	+	+	+	−	+	−	+	−	−	−	+
	Swing left.		CL	+	+	+	+	+	+	+	+	−	+	−	+	−	+	−	−	+
Cutter head.	Raise.		HU	−	−	−	+	+	+	+	+	+	+	+	+	+	+	+	+	−
	Lower.		HD	−	−	−	+	+	+	+	+	+	+	+	+	+	+	+	+	−
Gathering pan.	Raise.		PU	−	−	−	+	+	+	+	+	+	+	+	+	+	+	+	+	−
	Lower.		PD	−	−	−	+	+	+	+	+	+	+	+	+	+	+	+	+	−
Cutter motor.			H	−	−	−	+	+	+	+	+	+	+	+	+	+	+	+	+	+

				Zones																
	+	Allowed																		
	−	Disabled										Tail center		Tail left		Tail right				
Group	Machine	motion	Code	1	2	3	4	5	6	7	8	9	10	9	10	9	10	11	12	13
Conveyor motor.			C	+	+	+	+	+	+	+	+	+	+	+	+	+	+	−	−	−
High speed tram.			HST	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−

Table 3

Logic table for iPD 3 zone layout.

Group	Machine motion		Code	Zone				
	+		Allowed					
	−		Disabled					
Group	**Machine motion**		**Code**	**1**	**2**	**3**	**4**	**5**
Tram (left crawler, right crawler).	Up	Up	TUU	−	−	−	−	+
	--	Up	TxU	−	−	−	−	−
	Up	--	TUx	−	−	−	−	−
	Down	Down	TDD	+	−	−	−	−
	--	Down	TxD	−	−	−	−	−
	Down	--	TDx	−	−	−	−	−
	Down	Up	TDU	−	−	−	−	−
	Up	Down	TUD	−	−	−	−	−
Conveyor.	Raise.		CU	+	+	+	−	+
	Lower.		CD	+	+	+	−	+
	Swing right.		CR	+	+	+	−	+
	Swing left.		CL	+	+	+	−	+
Cutter head.	Raise.		HU	−	−	+	+	+
	Lower.		HD	−	−	+	+	+
Gathering pan.	Raise.		PU	−	−	+	+	+
	Lower.		PD	−	−	+	+	+
Cutter motor.			H	−	−	+	+	+
Conveyor motor.			C	+	+	+	−	+

		+ Allowed	**Zone**				
		− Disabled					
Group	**Machine motion**	**Code**	**1**	**2**	**3**	**4**	**5**
High speed tram.		HST	−	−	−	−	−

Table 4

Summary indicating whether proximity detection could have been a preventative factor.

	cPD	iPD 1	iPD 2	iPD 3
Percent of fatalities that could have been prevented by proximity detection.	82%	61%	82%	82%

Table 5

Comparison of different proximity zone layouts for accidents based on 1984–2014 MSHA data.

Legend: + = Fatality could have been prevented by proximity; − = Fatality could not have been prevented by proximity

Fatality	Date (Y-M-D)	Possible zone(s) that victim was in: iPD 1	iPD 2	iPD 3	Possible CMM function(s) leading to fatality	Proximity detection preventable?: cPD	iPD 1	iPD 2	iPD 3
1	1984-10-15	7	7	3	TUU,TxU,TUx	+	−	+	+
2	1988-06-22	10	10	4, 5	TxU,TDU	+	+	+	+
3	1988-12-12	7	7	3	TxU,TDx,TDU	+	+	+	+
4	1990-02-01	7	7	3	TxU,TDx,TDU	+	+	+	+
5	1990-03-29	7	7	3	TUU,TxU,TUx	+	−	+	+
6[a]	1990-11-12	6, 7	13	3	C	−	−	−	−
7	1990-12-17	7	7	3	TxU,TDx,TDU	+	+	+	+
8	1991-09-25	10	10	4, 5	TDx,TDU	+	+	+	+
9	1992-09-02	7	7	3	TDD,TxD,TDx,TDU	−	−	−	−
10	1993-07-19	1, 3	1, 3	2	TUU,TUx,TxU,TUD	+	−	+	+
11[a]	1993-11-05	1, 2, 3	1, 13	1, 2	H	−	−	−	−
12	1993-12-27	10	10	4	TxU,TDx,TDU	+	+	+	+
13	1995-03-24	10	10	4, 5	TxU,TDU	+	+	+	+
14[a]	1995-04-18	8, 9, 10	12	4	C	−	−	−	−
15	1996-10-21	7	7	3	TDx	+	+	+	+
16	1997-03-28	6	6	3	TUx,TxD,TUD	+	+	+	+
17	1997-07-26	10	10	4, 5	TUU,TxU,TUx	+	−	+	+

	+	Fatality could have been prevented by proximity						
	–	Fatality could not have been prevented by proximity						

Fatality	Date (Y-M-D)	Possible zone(s) that victim was in: iPD 1	iPD 2	iPD 3	Possible CMM function(s) leading to fatality	Proximity detection preventable?: cPD	iPD 1	iPD 2	iPD 3
18	2000-01-21	1, 2, 3	1, 13	1, 2	TUU,TUx,TxD,TUD, H	+	–	+	+
19	2000-05-12	7	7	3	TxU	+	+	+	+
20	2000-08-15	7	7	3	TxU,TDx,TDU	+	+	+	+
21[b]	2001-04-12	10	10	4, 5	-	–	–	–	–
22	2001-11-21	3	3	2	TUx,TxD,TUD	+	+	+	+
23	2002-03-22	10	10	4, 5	TxU,TDx,TDU	+	+	+	+
24	2002-08-12	10	10	4, 5	F,TxU,TUx	+	–	+	+
25	2003-04-15	6	6	3	TUx,TxD,TUD	+	+	+	+
26	2003-10-22	3, 4	3	2	TUx,TxD	+	+	+	+
27[c]	2004-02-01	9	9	4, 5	TUD	–	–	–	–
28	2004-04-03	3	3	2	TUx,TUD	+	+	+	+
29	2004-05-18	10	10	4	TxU,TDx,TDU	+	+	+	+
30[d]	2008-04-18	9, 10	9, 10, 11	4	-	–	–	–	–
31	2008-10-16	7	7	3	TDD,TDx,TDU	+	–	+	+
32	2010-04-22	9	9	4	TUU	+	–	+	+
33	2010-06-24	7	7	3	TDU	+	+	+	+
34	2011-03-25	10	10	4	TxU,TDx,TDU	+	+	+	+
35	2012-07-27	10	10	4	TDx,TDU	+	+	+	+

		+	Fatality could have been prevented by proximity						
		−	Fatality could not have been prevented by proximity						
Fatality	Date (Y-M-D)	Possible zone(s) that victim was in			Possible CMM function(s) leading to fatality	Proximity detection preventable?			
		iPD 1	iPD 2	iPD 3		cPD	iPD 1	iPD 2	iPD 3
36	2012-11-17	2	2	2	TxD,TDx,TDU	+	+	+	+
37	2013-02-13	10	10	4	CR	+	+	+	+
38	2014-02-21	10	10	4	TDU	+	+	+	+
39	2015-01-28	10	10	4	TDU	+	+	+	+

[a] Proximity systems as designed are not likely to be used during maintenance.

[b] Accident was a result of one continuous mining machine being struck by another continuous mining machine.

[c] The bolter operator on a full-face continuous mining machine with an integrated bolter (non-metal mine) was pinned when he exited the onboard cab. Proximity detection systems with silent zones (designated zones where a mine worker is allowed) may have prevented this fatality.

[d] This accident occurred on a continuous mining machine with a mobile bridge conveyor system. Special design considerations would be necessary to prevent accidents related to continuous haulage.