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A Rapid Review of Collision Avoidance and Warning Technologies for Mining Haul Trucks

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Abstract

Given the recent focus on powered haulage incidents within the US mining sector, an appraisal of collision avoidance/warning systems (CXSs) through the lens of the available research literature is timely. This paper describes a rapid review that identifies, characterizes, and classifies the research literature to evaluate the maturity of CXS technology through the application of a Technology Readiness Assessment. Systematic search methods were applied to three electronic databases, and relevant articles were identified through the application of inclusion and exclusion criteria. Sixty-four articles from 2000 to 2020 met these criteria and were categorized into seven CXS technology categories. Review and assessment of the articles indicates that much of the literature-based evidence for CXS technology lies within lower levels of maturity (i.e., components and prototypes tested under laboratory conditions and in relevant environments). However, less evidence exists for CXS technology at higher levels of maturity (i.e., complete systems evaluated within operational environments) despite the existence of commercial products in the marketplace. This lack of evidence at higher maturity levels within the scientific literature highlights the need for systematic peer-reviewed research to evaluate the performance of CXS technologies and demonstrate the efficacy of prototypes or commercial products, which could be fostered by more collaboration between academia, research institutions, manufacturers, and mining companies. Additionally, results of the review reveal that most of the literature relevant to CXS technologies is focused on vehicle-to-vehicle interactions. However, this contrasts with haul truck fatal accident statistics that indicate that most haul truck fatal accidents are due to vehicle-to-environment interactions (e.g., traveling through a berm). Lastly, the relatively small amount of literature and segmented nature of the included studies suggests that there is a need for incremental progress or more stepwise research that would facilitate the improvement of CXS technologies over time. This progression over time could be achieved through continued long-term interest and support for CXS technology research.

Keywords Collision avoidance · Collision warning · Technology · Mining · Haul trucks

1 Introduction

Within the US mining sector, accidents involving powered haulage continue to be one of the leading safety concerns for mineworkers, and powered haulage regularly accounts for the greatest number of fatalities each year. In fact, powered-haulage-related incidents accounted for 50% (14 of 28) of the fatalities in 2017 and 48% (13 of 27) of the fatalities in 2018 [1]. Powered haulage is one of 21 accident classifications defined by the US Mine Safety and Health Administration (MSHA) and includes haulage units of all types such as rail cars, conveyor belts, belt feeders, service trucks, and haulage trucks [2]. However, when looking closer at the equipment type, mobile equipment, such as service trucks, haul trucks, and front-end-loaders, account for most of the incidents. Nearly 40% (10) of the 28 overall fatalities in 2017 involved mobile equipment [3]. Following the high number of incidents in 2017, MSHA identified powered haulage as a special safety initiative in 2018 that provided additional resources for technical assistance and conducting awareness

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campaigns. Additionally, MSHA issued a request for information (RFI, Docket No. MSHA-2018–0016) in June of 2018 from mining industry stakeholders and community members on developing best practices, training materials, policy and procedures, technological improvements, and any other information for improving miner safety in and around mobile equipment. In particular, MSHA sought information on the role of engineering controls, such as CXS technologies, that would "enhance equipment operators' ability to see all areas near the machine, warn equipment operators of potential collision hazards, [or] prevent equipment operators from driving over a high wall or dump point" [3].

In response to MSHA's RFI, mining sector stakeholders shared their own site-specific advancements, success stories, and methods for reducing collisions. These ranged from basic devices, such as mirrors, flashing lights, and high-visibility flags, to highly advanced collision avoidance systems that actively take control and stop a haul truck if an imminent collision is detected. Stakeholders also emphasized the need for increasing operator situational awareness, improving training, and improving communication between operators and other workers [4]. As a result of this stakeholder feedback, MSHA published additional guidance on powered haulage collision prevention and provided access to newly developed training materials, including safety flyers and best practices [5]. Additionally, MSHA highlighted CXS technologies as a potential solution to reduce the risk of powered haulage collisions at mine sites after analyzing fatal accidents at US surface operations from 2003 to 2018. The analysis concluded that 21 accidents resulting in 23 fatalities could have been prevented by CXS technology [6].

While there is evidence to suggest that CXS technologies can help to prevent haul-truck-related collisions, less is known about the current state of the technology: what type of testing and evaluation has been done, what type of interactions is the technology focused on preventing, and what is the overall direction of CXS technology research. To help characterize the current state of CXS technologies, this paper will provide a literature-based review of the work that has been done from 2000 to 2020 to evaluate the performance of CXS technologies in the surface mining environment through the application of a Technology Readiness Assessment (TRA).

1.1 Technology Readiness Assessment (TRA)

A TRA provides a framework that can be used to assess the maturity of technologies in terms of the degree to which those technologies have been demonstrated to successfully operate under the range of conditions encountered during use. By providing an objective measure of the maturity of a technology, such an assessment gives a basis for making decisions about acquisition, product development, and research priorities. To perform a TRA, a clearly defined measure of maturity is needed. A frequently used scale for these assessments is the Technology Readiness Level (TRL), a nine-point scale that defines maturity from conceptualization to a fully mature, field-deployed technology.

The TRL scale was developed by the National Aeronautics and Space Administration (NASA) in the 1980s [7, 8] and has been subsequently modified and adopted by several other organizations, including the United States Department of Defense (DOD), the US Department of Energy (DOE), and the European Space Agency [9–11]. The TRL metric was used for this study because it provides an independent assessment regardless of a product's development stage. Other methods, such as development lifecycle management and product lifecycle management, depend on tracked progress that is not conducive for a snapshot assessment [12–14].

Another key advantage of the TRL metric is that it provides a common language with which the technology status can be clearly communicated. By allowing technology developers, users, industry regulators, and researchers to easily see the degree to which a specific technology has been proven, the TRL metric gives a means of better recognizing the risks associated with technology transition. In this case, the TRL gives a consistent and objective means of presenting whether a technology has been successfully evaluated through laboratory tests, field tests, or deployments of commercialized systems.

1.2 Collision Avoidance/Warning Systems (CXSs)

CXSs are technological systems designed to detect objects, warn operators, and/or automatically take action to prevent and mitigate collision accidents involving mobile equipment. For surface mining operations, CXSs are typically installed on powered haulage equipment, such as haul trucks, where their operation carries a significant risk of collision with something in the environment, another vehicle, or a person on the ground. Most commercially available CXSs are designed to detect objects around the vehicle, especially in blind spots, and inform the vehicle operator and other involved persons at risk. Some CXSs are stand-alone and rely solely on information obtained through sensors installed on the host vehicle, while other CXSs communicate information between the host vehicle and other connected devices, vehicles, and infrastructure. Systems that communicate with other devices in ad hoc networks are more generally described as vehicle-to-everything (V2X).

CXSs employed at surface mining operations are available as standard and optional equipment from original equipment manufacturers (OEMs). Systems can also be added to existing equipment by OEMs and aftermarket integrators. These CXSs may include one or more technologies.

Technologies include single-, multiple-, and 360-degree-view cameras for detection and viewing blind areas surrounding equipment. Global Navigation Satellite System (GNSS) receivers can be integrated for tracking vehicle and hazard positions, path prediction, and enforcing geofenced exclusion zones. Radio Detection and Ranging (RADAR) and Light Detection and Ranging (LiDAR) sensors are also commonly employed to detect and discern the presence of personnel and objects near the equipment. CXSs may also include electromagnetic or radio frequency tags for detecting and tracking object positions. Tag-based CXSs utilize received signal strength or time of flight to determine the distance between a transmitter and a receiver or between a pair of transceivers, which are mounted on the vehicles or worn by people. Therefore, tag-based CSXs are only able to track objects with an appropriate tag.

Whatever the underlying technologies, CXSs are intended to prevent and mitigate mobile equipment accidents. CXSs are typically intended to prevent accidents involving a loss of situational awareness or failure to recognize hazards that can result in a loss of control and potentially harmful vehicle interactions with personnel, other equipment, and the environment [15]. However, there currently is not a single system or technology suitable for all operations and conditions [16]. A robust integration of CXS technology can afford a greater level of protection for people, equipment, and infrastructure from unwanted interactions. However, technology cannot completely defeat the risk for collisions [17].

2 Objective

The objective of this study is to provide a review of the published scientific literature related to collision avoidance and warning systems (CXSs) and technologies in the surface mining environment and assess their current level of maturity. This review specifically focuses on CXSs designed to prevent or mitigate collisions related to haul trucks.

3 Methodology

A rapid review methodology was selected for the search and appraisal of existing research on CXSs and technologies. By using elements of a full systematic review, a rapid review provides a rigorous method for assessing existing literature while reducing the overall scope of the review process by allowing concessions such as focusing the research question, limiting search strategies, and/or performing less sophisticated analysis [18]. This study utilized a rapid review strategy using a Search, Appraisal, Synthesis, and Analysis (SALSA) framework [19]. The steps for the rapid review included the following: (1) Search, a systematic search of three databases; (2) Appraisal, selection of relevant studies using inclusion and exclusion criteria and grouping by technology category; (3) Synthesis, extraction of relevant data from articles including variables such as study type, testing methods, and metrics tested; and (4) Analysis, an analysis of the progression and state of CXS technology maturity through the application of a Technology Readiness Assessment (TRA).

3.1 Search (Systematic Search of Electronic Databases)

Three electronic databases (i.e., Compendex, Scopus, and OneMine) were searched using a keyword search strategy with Boolean logic. The strategy predominantly consisted of three groups of keywords connected by "AND" Boolean operators with keywords within each group combined by "OR" Boolean operators. The first group included the terms "collision" OR "proximity" to identify articles related to collision concerns. The second group of keywords consisted of terms specific to the mining domain to limit the results to mining-related work (e.g., "mining equipment," "haul truck," "mine truck," "mine," "mining"). The third group consisted of terms related to CXS technologies and/or sensors (e.g., "collision avoidance," "collision warning," "object detection," "radar," "GPS," "camera," "tag"). Certain keywords, such as "data mining" and "landmine," were excluded from the search strategy using "NOT" operators to reduce the number of nonrelevant articles returned.

The specific keywords chosen to be included or excluded in the search strategy were first selected by the authorship team and then refined through several iterations and tests of the search that included a brief review of the search results. For example, early search strategies returned many articles related to military landmines. Further refinement in strategy led to the exclusion of the term "landmine." In another example, variants of keywords such as "GPS" were also discovered through iterative testing, which led to the inclusion of terms such as "global positioning" and "global navigation."

The search tools and capabilities for each database varied slightly (e.g., allowing the use of certain Boolean operators, truncation, wildcard operators, or other parameters). Therefore, the search string and operators were customized for each database as shown in Table 1. Parameters were also set to extract articles written in English between 2000 and 2020 and articles identified as peer-reviewed articles, conference proceedings, and government agency publications. Additionally, the search was limited to the title, abstract, and keyword registry of each article. In the case of the OneMine database, the search strategy did not include mining domain keywords such as "mine" or "mine truck" because the database itself is specific to the mining sector.

Table 1 Search strategy and record of returned articles

Database	Strategy	Records
Scopus	(TITLE-ABS-KEY ("collision*") OR TITLE-ABS-KEY ("proximity")) AND (TITLE-ABS-KEY ("mining equipment") OR TITLE-ABS-KEY ("mine equipment") OR TITLE-ABS-KEY ("haul truck*") OR TITLE-ABS-KEY ("mine truck*") OR TITLE-ABS-KEY ("mine") OR TITLE-ABS-KEY ("mines") OR TITLE-ABS-KEY ("mining") OR TITLE-ABS-KEY ("miner")) AND (TITLE-ABS-KEY ("collision avoidance") OR TITLE-ABS-KEY ("collision warning*") OR TITLE-ABS-KEY ("proximity detection") OR TITLE-ABS-KEY ("object detection") OR TITLE-ABS-KEY ("radar") OR TITLE-ABS-KEY ("gps") OR TITLE-ABS-KEY ("global positioning") OR TITLE-ABS-KEY ("gnss") OR TITLE-ABS-KEY ("global navigation system*") OR TITLE-ABS-KEY ("detection and ranging") OR TITLE-ABS-KEY ("lidar") OR TITLE-ABS-KEY ("ladar") OR TITLE-ABS-KEY ("electromagnetic") OR TITLE-ABS-KEY ("camera*") OR TITLE-ABS-KEY ("vision") OR TITLE-ABS-KEY ("ultra-wideband") OR TITLE-ABS-KEY ("v2x") OR TITLE-ABS-KEY ("v2v") OR TITLE-ABS-KEY ("rfid") OR TITLE-ABS-KEY ("tag") OR TITLE-ABS-KEY ("ad-hoc")) AND NOT INDEXTERMS ("data mining") AND NOT TITLE-ABS-KEY ("landmine*") AND PUBYEAR > 1999 AND (LIMIT-TO (DOCTYPE, "cp") OR LIMIT-TO (DOCTYPE, "ar") OR LIMIT-TO (DOCTYPE, "re") OR LIMIT-TO (DOCTYPE, "ch") OR LIMIT-TO (DOCTYPE, "sh") OR LIMIT-TO (DOCTYPE, "bk") OR LIMIT-TO (DOCTYPE, "no")) AND (LIMIT-TO (LANGUAGE, "English"))	379 articles -13 internal duplicates (identical articles returned within Scopus)
Compendex	(((collision*) OR (proximity)) WN KY) AND (((mining equipment) OR (mine equipment) OR (haul truck*) OR (mine truck*) OR (mining) OR (mine) OR (mines) OR (miner)) WN KY) AND (((collision avoidance) OR (collision warning*) OR (proximity detection) OR (object detection) OR (radar) OR (gps) OR (gnss) OR (global navigation satellite system*) OR (global positioning) OR (detection and ranging) OR (lidar) OR (ladar) OR (electromagnetic) OR (camera*) OR (vision) OR (ultra-wideband) OR (V2X) OR (V2V) OR (RFID) OR (tag) OR (ad hoc)) WN KY) NOT ({data mining} WN CV) NOT ((landmine*) WN KY) AND ((2020 OR 2019 OR 2018 OR 2017 OR 2016 OR 2015 OR 2014 OR 2013 OR 2012 OR 2011 OR 2010 OR 2009 OR 2008 OR 2007 OR 2006 OR 2005 OR 2004 OR 2003 OR 2002 OR 2001 OR 2000) WN YR) AND (({ca} OR {ja} OR {bk} OR {ch} OR {ds} OR {ip} OR {st}) WN DT) AND ({english} WN LA)	317 articles - 10 internal duplicates (identical articles returned within Compendex) - 248 duplicate articles with Scopus results
OneMine	(("collision") | ("proximity")) + (("collision avoidance") | ("collision warning") | ("proximity detection") | ("object detection") | ("radar") | ("gps") | ("gnss") | ("global navigation satellite system") | ("global positioning") | ("detection and ranging ") | ("lidar") | ("ladar") | ("electromagnetic") | ("camera") | ("vision") | ("ultra-wideband") | ("V2X") | ("V2V") | ("RFID") | ("Tag") | ("ad hoc")) From 2000 to 2020 [entered in a separate field]	86 articles - 1 internal duplicate (identical articles returned within OneMine) - 29 duplicate articles with Scopus and Compendex results
	De-duplicated articles in EndNote	**481**
	Remove older than 2000	**448**
	Remove magazine articles and presentations	**432**

The database search was done in series starting with Scopus, then Compendex, and, lastly, OneMine. All searches were run in the time span of March through April 2020. Records of the articles returned in each search were imported into EndNote X9 reference management software. The software was used to merge the citation records from each database and remove any duplicate articles. After this process, a total of 432 articles remained for further review.

3.2 Appraisal (Selection of Relevant Studies)

Inclusion and exclusion criteria were developed by the authorship team to remove nonrelevant articles from further analysis. The team first defined a general set of inclusion criteria using the population, intervention, comparison, outcome (PICO) framework [20]. The population/domain of interest for this study was defined as surface mining equipment at an operating mine site or at field/laboratory test locations, with a focus on off-road haul trucks. The intervention was defined as CXS ideation, implementation, performance testing, or evaluation of effectiveness, including any type of CXS-related technology such as cameras, GNSS, LiDAR, RADAR, tag-based, and/or V2X. The comparison was defined as none (i.e., operating without the CXS technology) or an alternative technology within the domain of CXS. Lastly, the outcome was defined as a measurable (i.e., quantitative or qualitative) reduction in surface mining equipment collisions or characterization of CXS or technology functionality, performance, reliability, or usability (e.g., false alarm rate).

Additional inclusion and exclusion criteria were created to further refine the selection of studies. The inclusion criteria were set to include articles related to other heavy equipment domains (e.g., construction), any articles using sensors to avoid collision, and any articles related to traffic control or interface design. However, to be included, all articles were required to mention mining as an example or potential use case. Exclusion criteria were set to exclude other types of mining (e.g., data mining, underwater mining, mine fields), on-road trucking, and any articles outside of the original search parameters (e.g., date range, year, publication type) that may have been included in the search results.

The inclusion and exclusion criteria were applied to the 432 articles from the search results to identify articles for further review. Using EndNote X9 reference software, the titles and abstracts of each article were independently screened and coded by two reviewers. Articles that did not relate to CXS or otherwise fell out of the scope of the inclusion criteria were coded and placed into a grouping titled N/A (excluded). Articles that met the inclusion criteria were grouped by CXS technology category using a defined set of codes including CAMERA, GNSS, RADAR, LiDAR, TAG, V2X, OTHER, UNDERGROUND, and N/A as shown in Table 2.

3.3 Synthesis (Extraction of Relevant Data from Articles)

In some cases, articles were assigned more than one code. Once all articles were independently coded, the reviewers met to resolve any disagreements about inclusion. A third reviewer

Table 2 Included articles grouped by CXS technology

Code	Definition	**Total**
CAMERA	Camera used as sensor (any spectrum, e.g., Infrared, Ultraviolet) or as viewing device (e.g., backup camera and 360 view)	13
GNSS	Includes Global Navigation Satellite System (GNSS) and Global Positioning System (GPS)	25
RADAR	Radio Detection and Ranging (any spectrum, e.g., ultra-wideband)	23
LiDAR	Light Detection and Ranging (LiDAR) and Laser Detection and Ranging (LADAR)	4
TAG	All tag-based systems. Radio-frequency identification (RFID), Electromagnetic Field, Bluetooth, ZigBee	18
V2X	All networking, Ad Hoc, Vehicle-to-Vehicle (V2V), Centralized Networking	21
OTHER	Work that is chiefly focused on improvements to CXS related algorithms, software, simulations, modeling, or underlying capabilities	27
UNDERGROUND (excluded)	Study takes place underground or on underground mining equipment. Does not specify surface mining as a use case	81
N/A (excluded)	Any paper that does not relate to CXS or otherwise falls outside the scope of the inclusion	268
	Total from search	**432**
	Total excluded	**349**
	Total included	**83**

In some cases, articles were assigned more than one code. Total included reflects the number of articles from the search results minus the number coded as UNDERGROUND and N/A (excluded) was utilized to ensure the application of inclusion and exclusion criteria was consistent between researchers and to serve as a tiebreaker if consensus could not be reached. After the initial coding, the review team decided to exclude all articles coded as UNDERGROUND. In many cases, it was unclear if the underground technologies could be applied to the surface mining environment and review team did not want to mischaracterize the findings of these articles since the focus of this effort was surface mining only. After the meetings and removal of the underground articles, 83 articles remained for the review.

After the selection process was complete, a second review was conducted to extract and classify relevant data from the articles for further consideration under the TRA phase. A member of the authorship team was assigned as primary reviewer for each of the coded technology groups (e.g., CAMERA, GNSS, LiDAR). This review, by the primary reviewer, included reading the full text of each article in detail, providing a narrative summary for each article, and identifying variables of interest including the testing type (Table 3), CXS type (Table 4), interaction

Table 3 Coding definitions used for test type

Code	Definition
Functional Testing	The technology is tested against basic design requirements or specifications (i.e., does it work? does it do what it is supposed to do?)
Analytical Testing	The technology is evaluated or analyzed using analytical techniques (e.g., simulation testing) to forecast potential outcomes based on possible variations of project or environmental variables and their relationships with other variables
Performance Testing	The technology is tested to determine performance characteristics (i.e., accuracy, detection rate, and range). The technology is tested to evaluate the degree to which a test item accomplishes designated functions within given constraints of time and other resources
Reliability Testing	The technology is tested to determine ruggedness or performance over time in the intended environment
Usability Testing	The technology is evaluated to determine the ease of use through observation or feedback from users

Table 4 Coding definitions used for CXS type

Code	Definition
Component	Sensor or components that attempt to aggregate raw data, delineate objects of interest, and generate context of information relative to vehicle [This definition is used to code papers that are not testing full systems with overall control types/objectives.]
Awareness	Technologies that provide information to enhance the operator's ability to observe and understand potential hazards in the vicinity of the equipment: • Provides enhanced situational awareness • Provides context of the situation to the operator • Where is it? • What is it? • How far away is it? • What is its heading? • How fast is it going? • Supports visual confirmation for the operator
Warning	Technologies that provide alarms and/or instruction to enhance the operator's ability to predict a potential unsafe interaction and the corrective action required: • Determines an imminent threat of collision • Provides a specific instruction to the operator to intervene
Avoidance	Technologies that automatically intervene and take some form of equipment control to prevent or mitigate an unsafe interaction: • Provides a specific instruction to the machine to intervene • Machine assesses the instruction in relation to other contributing factors, then intervenes

Table 5 Coding definitions used for interaction type

Code	Definition
Vehicle-environment interaction	Operator loses control or otherwise drives vehicle into an environmental hazard (e.g., large rock, berm, into pond, tips over)
Vehicle-person interaction	Vehicle has a collision with a pedestrian
Vehicle-vehicle interaction	Vehicle has a collision with another vehicle

Table 6 Coding definitions used for metrics tested

Code	Definition
None	No testing or metrics measured
Measurement accuracy	Comparison of reported position values to known or ground truth values
Sensor/network performance	Determining maximum range of sensor. Evaluation or testing of network performance or radio signal propagation
System function	Pass or fail of system design specifications or expected outcomes
Detection reliability	False alarm rates, nuisance alarms, missed events. Evaluation of system ability to detect object or report events
Qualitative assessment	Operator impressions or feedback from subject matter experts
Classification accuracy	Ability to identify types of objects, shapes, or equipment
Component reliability	Evaluation of the ruggedness or dependability of components under specified conditions over time

type (Table 5), and metrics tested (Table 6). The extracted data were entered into an Excel spreadsheet accessible by all review team members. For each article, the primary reviewer also assigned a TRL rating (as described in the next section of this paper). Once the review of all articles was complete, the team met through a series of teleconferences to discuss the primary reviewer's findings and ensure consistency in the team's interpretation of and application of the inclusion and exclusion criteria and the TRL definitions. In some cases, the full text review revealed additional details that led to the exclusion of the article (e.g., not applicable to CXS or mining). In cases where the full text was not available, the article was excluded from further review. After these additional exclusions, 64 articles remained for the final analysis.

3.4 Analysis (Application of Technology Readiness Assessment)

The extracted data from each article were used as evidence during the TRA and for the assignment of a final TRL to the CXS technologies described in each article. Mining-specific TRL definitions developed by Carr [21], as shown in Table 7, were utilized to ensure that the CXS technologies were being evaluated with respect to the mining domain. The mining-specific TRL definitions take into consideration factors such as the progression of technology (i.e., concept, component, prototype, operational system) and the environment in which testing occurred (i.e., analytical, laboratory, relevant environment, operating mine site). To assign final TRL ratings to each article, all team members met via a series of teleconferences to discuss pertinent information regarding each article and to ensure consistency in the reading and interpretation of the TRL definitions. The preliminary TRLs assigned in the data extraction phase were then either confirmed or modified based on the team's teleconference review. A final TRL rating required consensus by a minimum of three of the review team members.

4 Results

4.1 Articles Selected for Inclusion

As shown in Fig. 1, the initial search of the three electronic databases (Compendex, Scopus, and OneMine) resulted in 432 articles once all duplicate articles were excluded. After applying inclusion/exclusion criteria, title and abstract reviews, and full-text reviews, the number of articles remaining was reduced to 64—or approximately 14.8% of the initial search results. However, several articles were assigned to two or more technology groups in cases where multiple CXS technologies were discussed within the article. This resulted in a total of 97 cases included for analysis.

4.2 General Characteristics of CXS Found Within Included Articles

As shown in Table 8, a relatively large portion consisting of 38 (39%) of the 97 articles were solely focused on CXS designed to prevent vehicle-vehicle interactions. Another large portion consisting of 21 (22%) sought to provide solutions for "All" types of interactions between the vehicle, environment, and person. Notably, vehicle-vehicle interactions are represented in 83 (85%) of the cases (i.e., all technology categories except vehicle-person and vehicle-environment). In contrast, a relatively small portion consisting of 11 (11%) of the CXS were solely focused on vehicle-person interactions. An even smaller portion consisting of 3 (3%) of the CXS were solely focused on vehicle-environment interactions. All CXS technology categories (e.g., CAMERA, GNSS, LiDAR) were

Table 7 NASA, DOD, and mining-specific TRL definitions [21]

	NASA Definition	DOD Definition	Mining-specific Definition
TRL 9	Actual system "flight proven" through successful mission operations	Actual system proven through successful mission operations	Actual system proven through successful use in active mining operations under the range of conditions expected to be encountered in use
TRL 8	Actual system completed and "flight qualified" through test and demonstration (ground or space)	Actual system completed and qualified through test and demonstration	Actual system completed and demonstrated through field tests
TRL 7	System prototype demonstration in a space environment	System prototype demonstration in an operational environment	System prototype demonstration in a representative operating mine
TRL 6	System/subsystem model or prototype demonstration in a relevant environment (ground or space)	System/subsystem model or prototype demonstration in a relevant environment	System/subsystem model or prototype demonstrated in a relevant environment
TRL 5	Component and/or breadboard validation in relevant environment	Component and/or breadboard validation in relevant environment	Component and/or breadboard validation in relevant environment
TRL 4	Component and/or breadboard validation in laboratory environment	Component and/or breadboard validation in laboratory environment	Component and/or breadboard validation in laboratory environment
TRL 3	Analytical and experimental critical function and/or characteristic proof of concept	Analytical and experimental critical function and/or characteristic proof of concept	Proof of concept established through analytical or experimental means
TRL 2	Technology concept and/or application formulated	Technology concept and/or application formulated	Technology concept and/or application formulated
TRL 1	Basic principles observed and reported	Basic principles observed and reported	Basic principles observed and reported

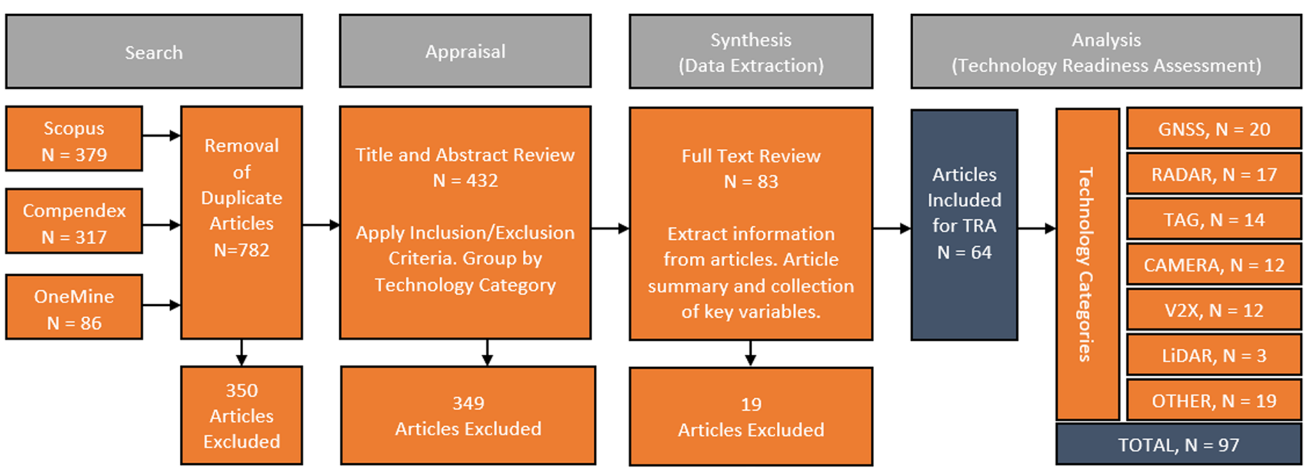


Fig. 1 Flow diagram showing number of articles at each stage of the review. Note: The total of 97 final cases includes articles that were coded into two or more technology categories

represented in the vehicle-vehicle interaction category. In comparison, vehicle-environment interactions were only associated with "Other" and "RADAR" technologies.

Table 9 shows CXS system type. A large portion consisting of 47 (48%) of the articles involved testing or evaluation of CXS component-level technology (e.g., sensors, data aggregation, algorithm optimization) rather than fully developed systems. After that, the most common type of CXS within the articles was "Warning" systems (i.e., technologies that provide alarms and/or instruction to enhance the operator's ability to predict a potentially unsafe interaction and the corrective action required). Warning type systems accounted for 36 (37%) of the CXS within the articles, while Avoidance and Awareness type systems accounted for only 10 (10%) and 4 (4%) of the CXS, respectively.

When looking at the type of testing done on the CXS, Table 10 shows that a large portion consisting of 33 (34%) of the articles were focused on "Performance" testing (i.e., where the technology is tested to evaluate the degree to which it accomplishes designated functions within given constraints of time or other resources). Another large portion consisting of 26 (27%) of the articles were focused on "Functional" testing (i.e., Does it work? Does it do what it is supposed to do?). However, 27 (28%) articles conducted "No testing." In these cases, the CXS were often discussed

Table 8 Collision interaction type cross-tabulated by technology category

	Technology category							
Interaction type	CAMERA	GNSS	LiDAR	OTHER	RADAR	TAG	V2X	Grand total
Vehicle-vehicle	6	7	2	10	4	2	7	38
All		10		2	2	6	1	21
Vehicle-vehicle and vehicle-environment	2	2	1	3	4	1	3	16
Vehicle-person	2	1		1	2	4	1	11
Vehicle-vehicle and vehicle-person	2			1	4	1		8
Vehicle-environment				2	1			3
Grand total	**12**	**20**	**3**	**19**	**17**	**14**	**12**	**97**

Table 9 CXS system type cross-tabulated by technology category

	Technology category							
CXS system type	CAMERA	GNSS	LiDAR	OTHER	RADAR	TAG	V2X	Grand total
Component	5	9	3	14	5	5	6	47
Warning	4	8		3	8	7	6	36
Avoidance	2	1		1	4	2		10
Awareness	1	2		1				4
Grand total	**12**	**20**	**3**	**19**	**17**	**14**	**12**	**97**

Table 10 Test type cross-tabulated by technology category

	Technology category							
Test type	CAMERA	GNSS	LiDAR	OTHER	RADAR	TAG	V2X	Grand total
Performance	2	10	2	6	2	7	4	33
No testing done	5	5		5	6	4	2	27
Functional	4	3	1	4	7	3	4	26
Analytical		1		2			2	5
Usability		1		2				3
Functional/reliability/usability	1				1			2
Usability/functional					1			1
Grand total	**12**	**20**	**3**	**19**	**17**	**14**	**12**	**97**

Table 11 Metrics collected and cross-tabulated by technology category

Metric tested	Technology category							
	CAMERA	GNSS	LiDAR	OTHER	RADAR	TAG	V2X	Grand total
None	5	5		5	6	4	2	27
Measurement accuracy	1	9	2	4		2	2	20
Sensor/network performance	1	2			2	5	4	14
System function	2	1	1	5	2		2	13
Detection reliability	1			2	7	2	1	13
Qualitative assessment		3		3	1		1	8
Classification accuracy	1					1		2
Component reliability	1					1		2
Grand total	**12**	**20**	**3**	**19**	**18**	**15**	**12**	**99***

*Two instances tested more than one metric type

conceptually, within technology frameworks, or for use in potential/future applications. In contrast to these first three categories of testing, a relatively small number of articles were focused on "Analytical," "Usability," and/or "Reliability" testing of CXS (see Table 3 for definitions of these test types).

In terms of the metrics collected (i.e., variables measured) during testing, Table 11 shows that many of the articles focused on "Measurement accuracy," "Sensor/network performance," "System function," and "Detection reliability." A smaller portion of the articles focused on "Qualitative assessment," while only two articles focused on "Classification accuracy," and two focused on "Component reliability." Note that "None" accounted for 27 articles, which coincides with the "No testing done" classification shown in Table 10.

4.3 Technology Readiness Assessment Results

The assigned TRLs for all articles are shown graphically in Fig. 2 by the publication date (year) of the article. A large portion of the coded articles were assigned TRLs in the range of 2 to 4, which are defined as early levels of technology maturity, such as *technology concept formulation* (level 2), *proof of concept* (level 3), or *component testing in a laboratory environment* (level 4). Another large portion of the articles were assigned TRLs ranging from 5 to 6, which are defined as moderate levels of technology maturity, such as *component validation in a relevant environment* (level 5) or *system/prototype validation in a relevant environment* (level 6). However, a relatively small portion of the articles were assigned TRLs ranging from 7 to 9, which are defined as high levels of technology maturity, such as *system/prototype*

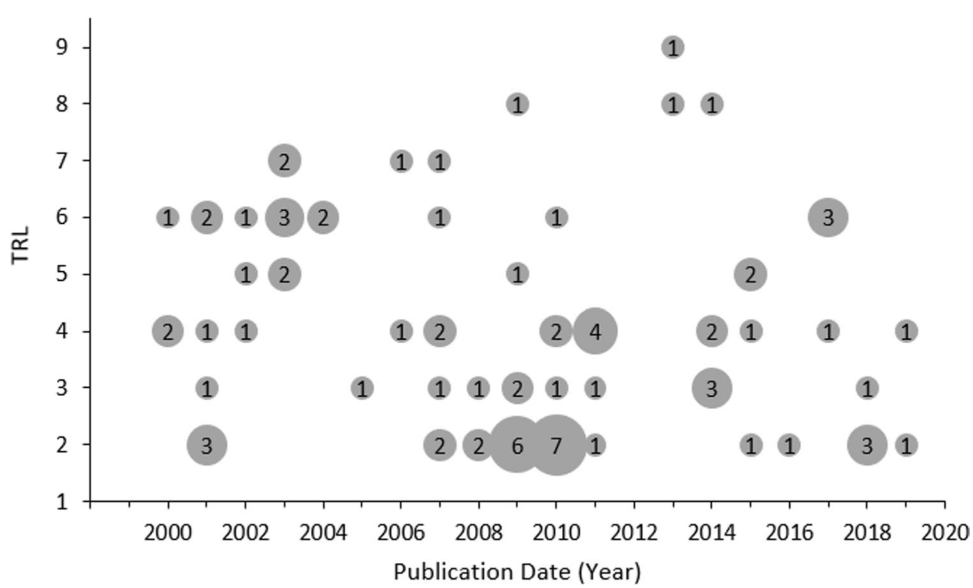


Fig. 2 TRLs assigned for all articles by publication date (year)

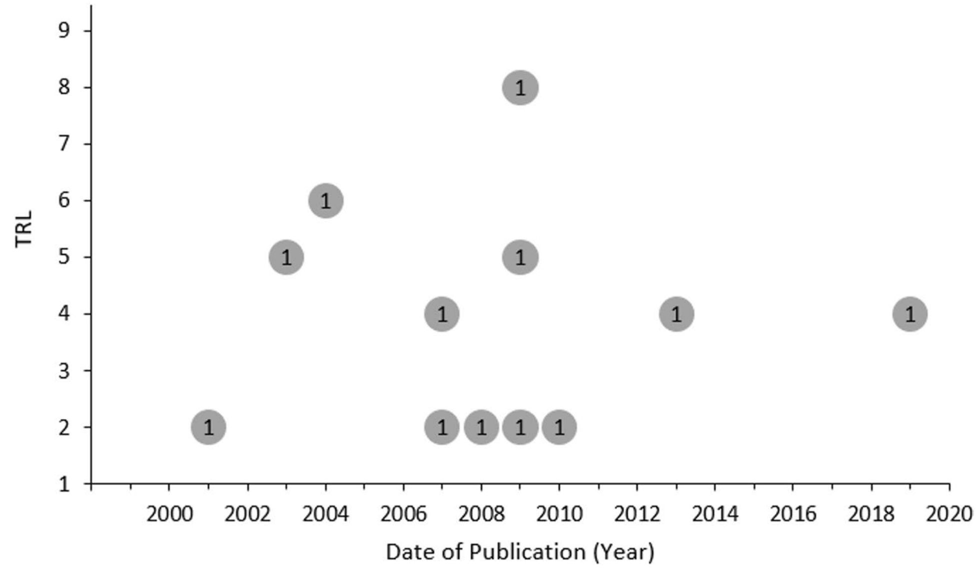


Fig. 3 TRLs assigned for camera-based technology articles by publication date (year)

demonstration in an operational environment (level 7), *actual system completed and qualified through test and demonstration* (level 8), or *actual system proven through successful mission operations* (level 9).

4.3.1 Camera-Based CXSs

The assigned TRLs for camera-based articles are shown in Fig. 3. Notably, none of the articles included within the review described operator awareness systems such as rear- and side-view video systems (e.g., backup cameras, side-view cameras, "360" cameras) installed on haul trucks. Rather, the majority of these articles described systems utilizing "computer vision" (e.g., pattern recognition, photogrammetry, videogrammetry, artificial intelligence) to detect persons entering a predefined zone near fixed machinery [22], recognize objects of various configurations [23], and detect persons near a working excavator [24]. Most of these camera-based "computer vision" technology articles were assigned a TRL of 2 to 4, indicating lower levels of maturity. However, in contrast, the highest TRL assigned to a camera-based technology article was an 8. This article described a commercially available operator awareness camera system for cable shovels that is used in conjunction with radar proximity sensors to aid the shovel operator in avoiding collisions with haul trucks [25]. Overall, these results may indicate lower levels of maturity for cameras used as sensors, while cameras used as operator aids are at higher levels of maturity.

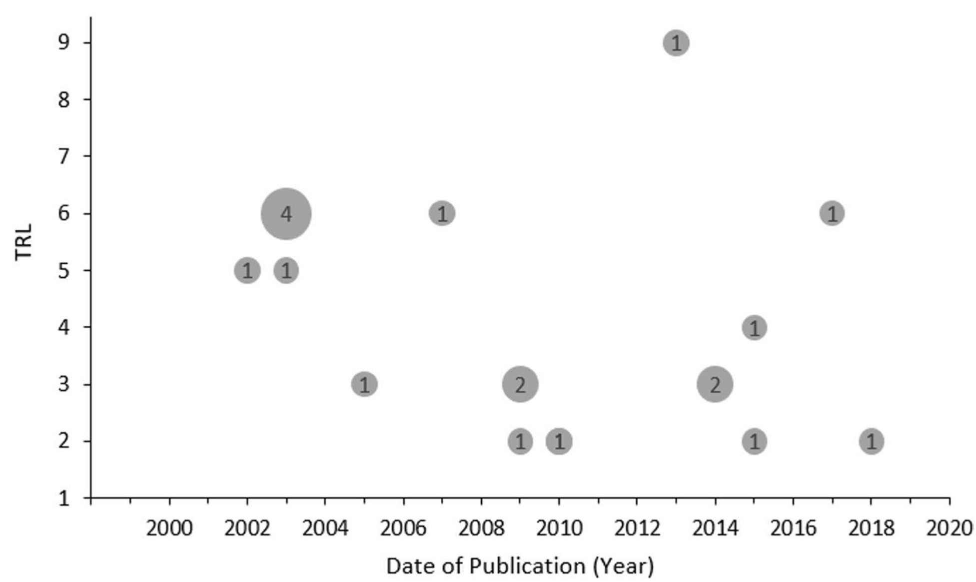


Fig. 4 TRLs assigned for GNSS-based technology articles by publication date (year)

4.3.2 GNSS-Based CXSs

As shown in Fig. 4, most GNSS-based articles were assigned a TRL within the range of 2 to 4, indicating that much of the research on GNSS-based technology is being done within laboratory conditions rather than in relevant or operating environments. Many of these articles focused on incremental improvements to GNSS technology, such as identifying the best location for antenna placement on large mining vehicles [26], reducing errors with the use of algorithms [27], or combining GNSS data with ground-based data for improved positioning [28, 29]. Most of the remaining articles were assigned TRLs of 5 to 6. These articles typically evaluated GNSS systems in relevant environments such as mine sites with only one article published recently [30]. However, none of the articles were assigned TRLs of 7 or 8, indicating that very little testing has been done or reported for complete GNSS systems in operational environments. However, one article received the highest TRL rating of a 9 for the evaluation of a commercially available system that is widely used at multiple mine sites [31]; this was the only 9 in the entire dataset.

4.3.3 RADAR-Based CXSs

As shown in Fig. 5, a series of RADAR-based articles were assigned TRLs of 2 from 2007 to 2011. Many of these articles offer descriptions of how radar-based technology could be applied to the mining environment. For example, one article described a framework for research in this area going forward [32], while another article described the design and limitations of radar-based systems but did not report any field testing [33]. In other cases, articles described radar-based technologies used in fundamentally different applications, such as on a stacking conveyor or ship loader, but still within the domain of mining and collision avoidance [34]. A large portion of the radar-based articles represented progressive work completed by Todd Ruff of the NIOSH Mining Program. These articles were published between 2000 and 2007 and span from a TRL of 2 to 7. The work began as conceptual and prototype testing in a laboratory and completed with the testing of commercially available and prototype systems at an operating mine site [35–42]. The highest assigned TRL for a RADAR-based article is an 8; this article describes a commercially available RADAR-based collision avoidance system for electric rope shovels designed to reduce impacts of the rope shovel with itself, haul trucks, and the environment [43]. No additional publications about RADAR-based CSXs were identified after 2014.

4.3.4 LiDAR-Based CXSs

The assigned TRLs for LiDAR-based articles are shown in Fig. 6. A relatively small amount of literature was found by this study's search strategy related to LiDAR-based collision avoidance technologies within the mining sector. Only three articles were selected for inclusion. None of these articles described applications of LiDAR technology onboard haul trucks but rather on other equipment found within the mining environment such as electric rope shovels [44], bucketwheel excavators [45],

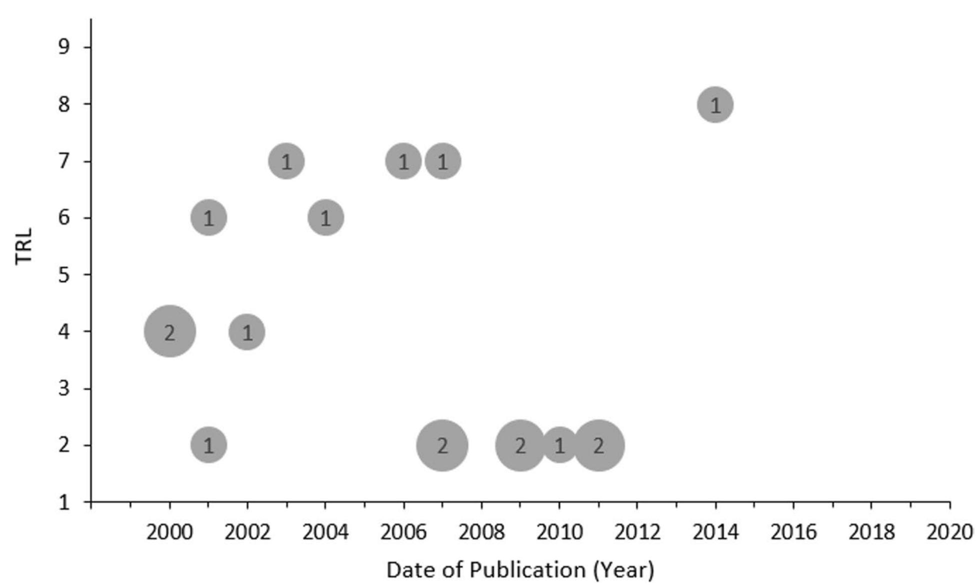


Fig. 5 TRLs assigned for RADAR-based technology articles by publication date (year)

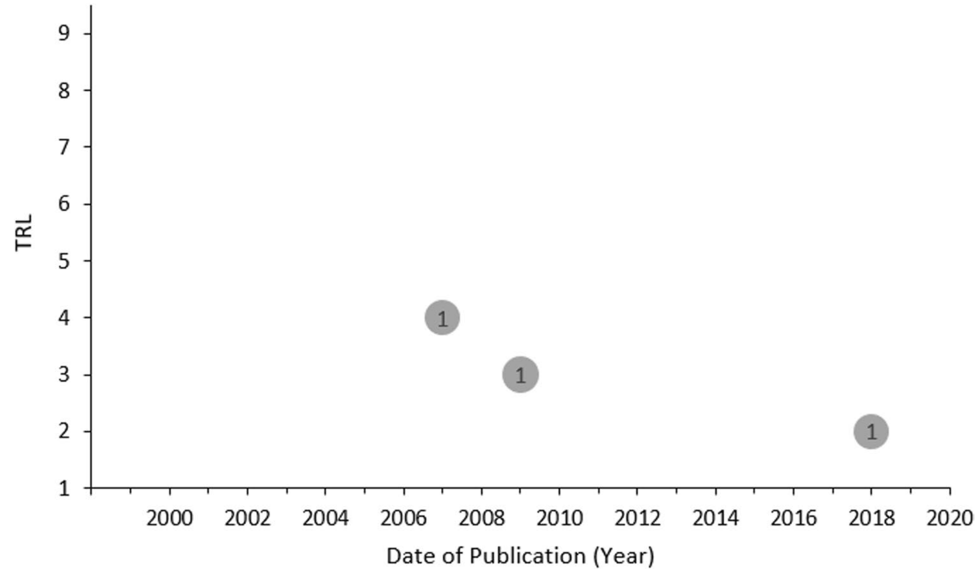


Fig. 6 TRLs assigned for LiDAR-based technology articles by publication ate (year)

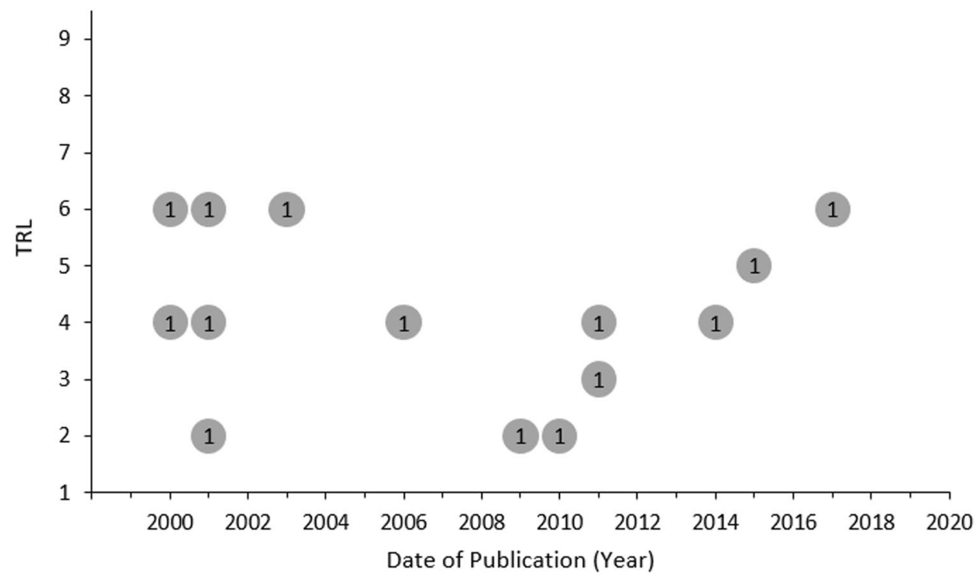


Fig. 7 TRLs assigned for tag-based technology articles by publication date

and front-end loaders [46]. The highest TRL assigned to a LiDAR-based technology article was 4, indicating a lower level of technology maturity.

4.3.5 TAG-Based CXSs

As shown in Fig. 7, all included tag-based articles were assigned a TRL of 6 or below. These articles appear to fall into two groups. The first set of articles, from 2000 to 2006, have TRLs from 2 to 6 and capture much of the early CXS development for the mining industry. Some articles are more focused on tag-based technology specifically for surface mining applications [39], while others are focused on underground systems that may be adapted for surface mining [47]. The second group of articles appear to progress in maturity from 2009 to 2017 but are generally produced by different authors and describe different systems. However, in general, these articles tend to describe more integrated multi-sensor systems that appear to be progressing in complexity over time [30, 48].

4.3.6 V2X-Based CXSs

As shown in Fig. 8, an early wave of V2X-based articles was published between 2002 and 2003. These articles involved the development and testing of prototype proximity warning systems utilizing V2X technology with GPS data to provide peer-to-peer positioning information

Fig. 8 TRLs assigned for V2X-based technology articles by publication date

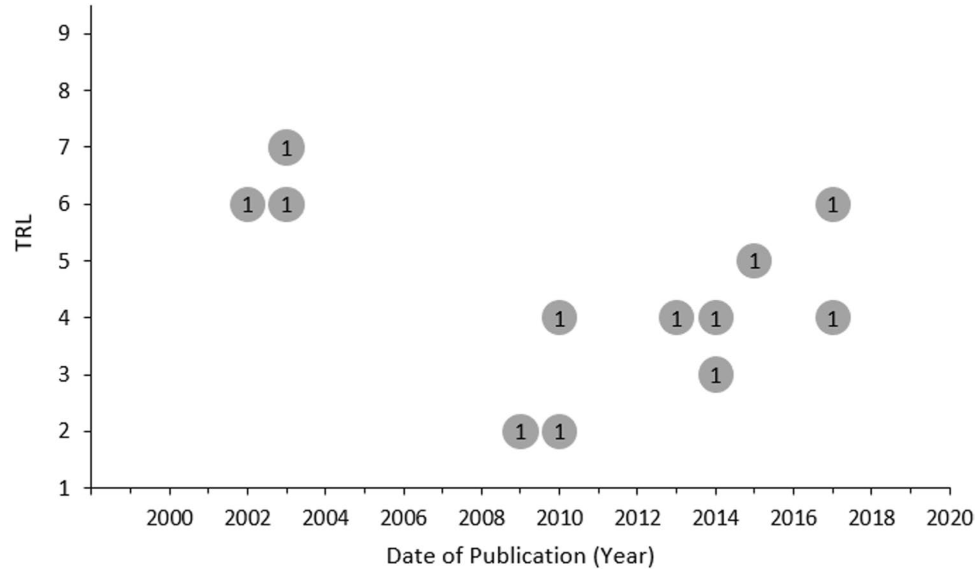
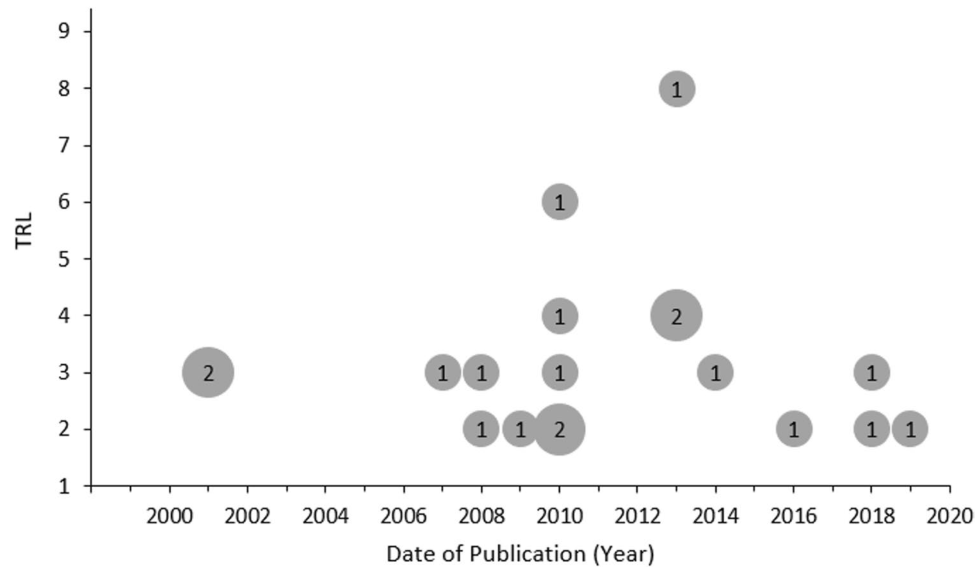


Fig. 9 TRLs assigned for "Other" technology articles by publication date



between mining vehicles to avoid collisions and hazards with known coordinates, such as dump edges [49–51]. These articles provided functional demonstrations of the technology and concluded that these types of systems could work within the mining environment. However, based on the available literature, it is unclear if these systems were further refined or adopted by mine operators, OEMs, or equipment suppliers. Following this initial grouping of articles, there appears to be a gap in the literature from 2003 to 2009. However, a second wave of articles was published between 2009 and 2017. These articles focus on making improvements to various aspects of V2X-based systems and describing progress in maturity through the time period. For example, Sabniveesu et al. [48] describe making improvements to network reliability, Kaufman et al. [26] investigate the effect of haul truck metallic frames on radio antenna propagation, and Virtanen and Jankkari [52] describe using V2X technology to aid in positioning vehicles in GPS-denied environments.

4.3.7 Other CXSs

As shown in Fig. 9, most of the articles within the "Other" category were assigned TRLs of 2 to 4. The topics covered within these articles include improvements to

CXS-related algorithms, software, simulations, modeling, or underlying capabilities. For example, articles provided a concept or framework for how CXS capabilities could be improved [53, 54], an overview of CXS technologies used in robotics applications [55], or a probabilistic method for predicting vehicle movements [56]. More examples include improvements to guidance algorithms for obstacle avoidance [57], computer modeling of navigation strategies [58], and an evaluation of a CXS user interface for a proximity and terrain modeling system [59]. Two of the "Other" technology articles were assigned TRLs in the range of 6 to 8. Both articles provided a qualitative assessment of CXS efficacy by field observations, gathering operator/user feedback, and identifying potential human factors challenges associated with CXSs [60, 61].

5 Discussion

The rapid review assessed the current state of CXS research through the application of systematic search methods and a Technology Readiness Assessment. Coding and categorization of relevant data from selected articles revealed insights into the focus areas and potential gaps in current CXS research from 2000 to 2020. However, it is important to note that this review only included publicly available scientific sources, including peer-reviewed journal articles, conference proceedings, and government reports, primarily from academic or government institutions, and does not include a good representation of research done by private organizations or commercial enterprises as this research is not generally published in the literature. The following sections will discuss the findings and limitations of the review.

5.1 Focus Areas of CXS Research

The results of this literature review indicate that the focus of CXS research has been on preventing vehicle-to-vehicle collisions. While this indeed accounts for many of the fatalities in the mining industry, vehicle-environment and vehicle-person collisions are more prevalent [62, 63]. In an analysis of truck-related fatalities from 1995 through 2002, vehicle collisions accounted for 11% of the 89 fatalities, while pedestrian collisions were 28% and environmental interactions (i.e., utility collisions, rollovers) accounted for 50% [62]. A newer analysis looking at fatalities from 2005 through 2018 found a similar trend in accidents. Again, vehicle-vehicle collisions were prevalent, but not the majority, accounting for only 9% of the 91 haul-truck-related fatal accidents; pedestrian collisions and environmental interactions (e.g., drove off of a high wall) accounted for 15% and 54%, respectively [63]. Interestingly, motor vehicle fatalities follow an opposite trend, but there is a possible explanation for this. The National Safety Council reported that in 2018, vehicle-vehicle collisions accounted for 42% of all traffic deaths and 72% of all motor vehicle accidents, while pedestrian collisions only accounted for 19.5% of all motor vehicle deaths [64]. But, similar to the mining-specific data, single-vehicle automotive crashes with fixed objects, pedestrians, and non-collisions (e.g., rollovers) accounted for a greater proportion of fatalities (55%) and fatal crashes (57%) [65]. With a larger market share and higher overall mortality and mobility impact, automotive research and advances may drive some of the off-road mining-specific technology availability. Nevertheless, the accident statistics for the mining sector suggest that there is an opportunity for CXS research to address a potentially larger need in pedestrian collisions and other single-vehicle accidents.

MSHA also identified the need to address vehicle-environment interactions. Besides inadequate seatbelts and vehicle-vehicle collisions, MSHA identified vehicle-environment interactions as one of the top 3 contributing factors to mobile equipment accidents. It found that 61 fatal accidents have occurred in the USA since 2007 that involved mobile equipment, and 20 of those accidents specifically involved bulldozer operators and haul truck drivers falling over the edge of a high wall or dump point at surface mines [3]. In the literature review, only 3% of the articles were solely focused on vehicle-environment interactions, 16% were focused on both vehicle-vehicle and vehicle-environment interactions, and 22% were related to "All" types of interactions between the vehicle, environment, and person. Moving forward, more dedicated research is needed on CXSs that detect vehicle-environment interactions.

The results of this study also suggest that a larger focus is being taken on warning systems as opposed to awareness or avoidance. The lack of research on avoidance systems may be due, in part, to the lack of regulatory action taken to mandate collision avoidance systems (i.e., automated control) at surface mine sites. As an example, underground mines in the USA adopted collision avoidance systems (i.e., proximity detection systems) on continuous mining machines after MSHA regulations passed; however, in the absence of regulation, many mine operators chose not to implement avoidance systems on other mobile equipment within their mines [63]. Additionally, development and testing of collision avoidance systems in the mining sector may also have been limited due to the uncertainties surrounding the technology implementation in other sectors such as the automotive market. There still is significant uncertainty over the appropriateness of intermediate automation (e.g., automated systems that require a driver at the wheel) [65], as well as concerns related to trust in these systems for motor vehicles [66] and other mining vehicles [67]. As more avoidance features become standard in the automotive market, these problems may begin to resolve. However, one major barrier to adoption of avoidance systems in mining may be terminology. The mining industry uses the idea of avoidance or complete prevention of collision, whereas the automotive industry uses the idea of limited mitigatory control in "collision-imminent braking" [66]. As evidenced by the limited studies and validation data, collision avoidance systems still require additional development and testing.

The limited amount of collision awareness research is far less clear. Situational awareness has been discussed in the mining context for at least a decade [68]. Furthermore, warning and design principles suggest that context can greatly improve an operator's decision-making [69]. New research in automation and control also supports the importance of awareness before warnings in the fact that two-stage warnings are proving to be more effective than just one-stage warnings [70]. However, given that research on the importance of awareness technologies and two-stage warnings is relatively new, it is possible that research on awareness systems has not reached the mining sector yet. Future work could be done to explicitly look at the awareness aspects of systems, how well they improve operator situational awareness, and their performance and maturity levels.

The results of this study also highlight the research focus on component testing rather than full systems. While component testing is appropriate and makes sense for low technology maturity, as researchers explore the development of specific sensors or applications, the industry also has a strong need for independent system validation. It is essential that CXSs are not only tested for effectiveness in the laboratory, but also for effectiveness in field implementation. The mining environment is far less controlled and forgiving than a parking lot or empty field. Something that may work well on pavement with controlled boundaries and equipment may fail to perform on a dirt roadway leaving the pit. It is imperative that the limits of safety–critical systems such as CXSs are well-understood to ensure that performance meets expectations and other controls are implemented as necessary. More validation testing to characterize the performance and reliability of these systems is critical. Though testing is likely done by the manufacturers outside of the scientific literature, independent validation can provide a better understanding of true performance and limitations.

5.2 Technology Readiness

Although full systems exist on the market and some are in use at operational mine sites, this literature review does not generally reflect that, as there is a lack of TRLs above 7 or 8. In fact, only 8% of the articles yielded a TRL above 7, indicating a need for more robust testing and reporting on complete system implementations in the scientific literature. This gap may be due to limited systematic research on full systems, a lack of collaboration(s) between research institutions and private companies, or the proprietary nature of the work which prevents publishing of results in peer-reviewed publications. Testing complete systems in relevant or operational environments is critical to understanding how a technology will work, helps to identify any unintended consequences, and allows for improvements in human-centered design [71]. However, the literature that is available on technology implementation at operational mine sites is often presented within non-peer-reviewed sources, such as trade publications (e.g., magazines) or white papers. These sources were excluded from this review as they tend to serve more as product advertisements rather than objective evaluations of system effectiveness and performance. However, some known work also failed to appear in the literature searches such as the Australian Coal Industry's Research Program (ACARP) project C26028 [72]. Increased promotion and publication of work done by industry groups could improve industry knowledge.

Another possible explanation for the gap in higher level TRLs is that industry may be waiting for a jump to full automation rather than investing in operator aids. Fully autonomous mining equipment and automated mines are already deployed and progressively becoming more available. For example, several mines in Australia's Pilbara region operate fleets of autonomous surface mining haul trucks [73–75]. Though a move to full automation could limit mine workers' exposure to dangerous situations and thus potentially decrease injuries and fatalities, there is uncertainty about how long it will take for full automation to be adopted by the mining industry and the extent to which it will be adopted. As the mining industry navigates the automation revolution, continued CXS research would ensure improved safety of mine workers and provide a valuable safety solution for situations that are not suitable for full automation.

Lastly, the results of the TRA indicate that there appears to be a lack of a significant upward trend or stepwise progression of the research and TRLs over time. Though a small trend was noted in the tag-based technologies, this was generally not observed for CXSs as a whole or within the other technologies. This lack of research progression could be due to several different issues. As mentioned previously, with respect to avoidance systems, there has been limited regulatory pressure, which could correspond to a lack of funding in the area. This could also be due to leaps in technology, where systems become obsolete during testing and are abandoned. In addition, it is possible that the technology was already integrated into mines and either no further improvements were made or improvements were made but kept proprietary. In general, for stepwise progression, there needs to be a continued long-term interest and monitory support in the area from technology develops, researchers, implementers, and regulators.

5.3 Limitations

With several iterations, including the refinement of keyword terms and search strategy, the authorship team attempted to capture as much relevant literature as possible. However, it is still possible that the authors' chosen keywords and search strategy did not capture all relevant articles. For example, if an article only described a technology as a "backup alarm," it is possible that terms like "collision avoidance" or "proximity detection" would not detect the article in this case. However, given the large set of keywords used and the number of duplicate articles returned from the three databases, the authors feel confident that a representative amount of literature was captured through the search strategy described in Section 3.1.

The search was limited to peer-reviewed articles from three electronic databases. Research or work documented in other sources such as trade publications (e.g., magazines), white papers, unpublished reports, dissertations, and other "grey literature" were not included. However, after a cursory review of the non-peer-reviewed literature excluded from this review, the authors believe that these sources likely would not have substantially influenced the conclusions of this review.

No assessment of the research article quality was done (e.g., quality of literature, rigorousness of methodology, consistency of results, confounding factors, potential biases, repeatability). However, it is likely that the addition of a quality assessment of the literature would have resulted in the exclusion of even more articles from the original search results. Given that the number of included articles in this study is relatively small, the authors believe that the application of a quality assessment would only narrow the results of the review and would not change the overall conclusion that more research in this topic area is needed.

6 Conclusion

This review and search strategy yielded a relatively small amount of peer-reviewed literature relevant to CXS technologies for surface mining haul trucks. This result is not surprising given the relatively small size of the mining sector and that CXS technologies remain to be proven within the mining sector. However, the appraisal of articles included within the review, through the application of the Technology Readiness Assessment (TRA), identifies several gaps where additional research is needed. First, the focus of CXS technologies on vehicle-vehicle interactions may be misguided given that most haul-truck-related fatalities are due to vehicle-environment interactions (i.e., loss of control, rollover, or going over a high wall). It may be beneficial for future research to focus on vehicle-to-environment interactions to align with the fatality and injury data. Secondly, the absence of technology articles rated in the higher levels of maturity indicate that there may be a need for more systematic research on mature systems which is published in the peer-reviewed literature and collaboration between academia, government research institutions, and industry to evaluate the performance of CXS technologies. Lastly, the segmented nature of the research studies indicates that there is a need for more stepwise research in which research can progressively improve over time. In several cases, the technology reached a moderate level of maturity (i.e., TRLs around 5 to 6), but it was unclear if the technology was adopted by industry or if research continued. Overall, the mining sector may benefit from more peer reviewed published work to evaluate CXS technologies, possibly through collaboration between the industry and academia or research agencies.

Appendix A

Table 12

Table 12 Table of included articles

Group	Authors	Year	Title	Test type	CXS type	Interaction type	TRL
CAMERA	Borthwick, James R.: Lawrence, Peter D.: Hall, Robert H	2009	Mining Haul Truck Localization Using Stereo Vision	Performance	Component	Vehicle-Vehicle	5
CAMERA	Ferreira, N; McElman, C	2010	Proximity Cameras and Global Positioning Systems—An Integrated Approach	No testing done	Warning	Vehicle-Vehicle	2
CAMERA	Frimpong, S.: Li, Y.: Agarwal, S	2007	Frontier Research in Dynamic Control, Vision And Collision Avoidance For Truck Haulage	No testing done	Avoidance	Vehicle-Vehicle and Vehicle-Environment	2
CAMERA	Frimpong, S.: Li, Y.: Aouad, N	2009	Intelligent machine monitoring and sensing for safe surface mining operations	No testing done	Avoidance	Vehicle-Vehicle and Vehicle-Environment	2
CAMERA	Ishimoto, H.: Tsubouchi, T	2013	Stereo vision-based worker detection system for excavator	Functional	Component	Vehicle-Person	4
CAMERA	Nabavi, Nima	2009	Integrating Radar Proximity Sensing and Camera Vision to Improve Mining Equipment Safety with Minimal Distraction	No testing done	Warning	Vehicle-Vehicle	8
CAMERA	National Institute for Occupational Safety and Health	2001	Technology News—No. 484—Devices to Monitor Blind Spots Near Large Haulage Equipment	No testing done	Warning	Vehicle-Vehicle	2

Table 12 (continued)

Group	Authors	Year	Title	Test type	CXS type	Interaction type	TRL
CAMERA	Ruff, T	2007	RI 9672—Recommendations for Evaluating and Implementing Proximity Warning Systems on Surface Mining Equipment	Functional	Component	Vehicle-Vehicle	4
CAMERA	Ruff, Todd M	2003	New Technology to Monitor Blind Areas Near Surface Mining Equipment	Functional	Component	Vehicle-Vehicle and Vehicle-Person	5
CAMERA	Ruff, Todd M	2004	RI 9660—Evaluation of Systems to Monitor Blind Areas Behind Trucks Used in Road Construction And Maintenance: Phase 1	Functional/Reliability/Usability	Awareness	Vehicle-Vehicle and Vehicle-Person	6
CAMERA	Ruff, Todd M	2008	Feasibility of using intelligent video for machine safety applications	Functional	Warning	Vehicle-Person	2
CAMERA	Somua-Gyimah, G.: Frimpong, S.: Nyaaba, W.: Gbadam, E	2019	A computer vision system for terrain recognition and object detection tasks in mining and construction environments	Performance	Component	Vehicle-Vehicle	4
GNSS	Agamennoni, G.: Nieto, J.: Nebot, E	2009	Mining GPS data for extracting significant places	Functional	Component	All	3
GNSS	Ferreira, N; McElman, C	2010	Proximity Cameras and Global Positioning Systems—An Integrated Approach	No testing done	Component	All	2
GNSS	Gao, Yang: Meng, Xiaolin: Hancock, Craig M.: Stephenson, Scott: Zhang, Qiuzhao	2014	UWB/GNSS-based cooperative positioning method for V2X applications	Performance	Component	All	3

Table 12 (continued)

Group	Authors	Year	Title	Test type	CXS type	Interaction type	TRL
GNSS	Gioia, Ciro: Borio, Daniele	2015	Stand-alone and hybrid positioning using asynchronous pseudolites	Performance	Component	All	4
GNSS	Kapica, Roman: Vrublova, Dana: Korandova, Beata: Krupa, Martin	2018	The application of terrestrial laser scanning for the management of mining in real time	Performance	Component	Vehicle-Vehicle and Vehicle-Environment	2
GNSS	Kaufmann, Thomas: Maeder, Urban: Fumeaux, Nchristophe	2014	Antenna placement on a large mining vehicle	Analytical	Awareness	All	3
GNSS	Kavuri, Ajay: Prakash, Bisleshana: Sabniveesu, Venkataraghavasivanagashashank: Nimbarte, Ashish: Kulathumani, Vinod: Kecojevic, Vladislav	2017	An adaptive, run-time navigation system for haul trucks in surface mines	Functional	Warning	Vehicle-Vehicle	6
GNSS	Nienhaus, Karl: Hahn, Martin: Winkel, Reik	2009	Wireless sensing applications in the mining and minerals industry	No testing done	Component	Vehicle-Person	2
GNSS	Nieto, A.: Dagdelen, K	2002	Development of Dump Edge And Vehicle Proximity Warning System Using GPS And Wireless Network Communications To Improve Safety In Open Pit Mines	Functional	Warning	All	5
GNSS	Nieto, A.: Dagdelen, K	2003	Development and testing of a vehicle collision avoidance system based on GPS and wireless networks for open-pit mines	Performance	Warning	Vehicle-Vehicle	6

Table 12 (continued)

Group	Authors	Year	Title	Test type	CXS type	Interaction type	TRL
GNSS	Nieto, A.: Dagdelen, K	2003	Reliability Testing of a Vehicle Proximity Warning System Based on GPS and Wireless Networks	Performance	Component	Vehicle-Vehicle	5
GNSS	Nieto, A.: Miller, S.: Miller, R	2005	GPS proximity warning system for at-rest large mobile equipment	No testing done	Avoidance	All	3
GNSS	Nieto, Antonio: Dagdelen, Kadri	2003	Accuracy testing of a vehicle proximity warning system based on GPS and wireless networks	Performance	Component	All	6
GNSS	Ruff, T	2007	RI 9672—Recommendations for Evaluating and Implementing Proximity Warning Systems on Surface Mining Equipment	Performance	Warning	Vehicle-Vehicle	6
GNSS	Ruff, T. M	2013	Improving Traffic Awareness on Mine Access and Haul Roads	Usability	Warning	All	9
GNSS	Ruff, Todd M	2003	New Technology to Monitor Blind Areas Near Surface Mining Equipment	Performance	Warning	Vehicle-Vehicle	6
GNSS	Ruff, Todd M.: Holden, Thomas P	2003	Preventing collisions involving surface mining equipment: A GPS-based approach	Performance	Warning	Vehicle-Vehicle and Vehicle-Environment	6
GNSS	Saravia, Esteban Chumpitaz: Condori, Magno Huamani: Ccoa, Miguel Angel Pacoticona	2015	Management support system for a fleet of vehicles in an open pit mine	No testing done	Awareness	Vehicle-Vehicle	2

Table 12 (continued)

Group	Authors	Year	Title	Test type	CXS type	Interaction type	TRL
GNSS	Sun, Enji: Nieto, Antonio: Li, Zhongxue: Kecojevic, Vladislav	2010	An integrated information technology assisted driving system to improve mine trucks-related safety	No testing done	Warning	All	2
GNSS	Wei, Wang: Runjing, Zhou	2009	Research on the anti-collision system of surface coal mine based on the highly accurate GPS location technology	Performance	Component	Vehicle-Vehicle	3
LiDAR	Himmelman. Nicholas, P.: Borthwick, J. R.: Kashani, Ali H.: Lin, Li-Heng: Poon, Alan: Hall, Robert A.: Lawrence, P. D.: Salcudean, Septimiu E.: Owen, William S	2009	Rope Shovel Collision Avoidance System	Performance	Component	Vehicle-Vehicle	3
LiDAR	Kapica, Roman: Vrublova, Dana: Korandova, Beata: Krupa, Martin	2018	The application of terrestrial laser scanning for the management of mining in real time	Performance	Component	Vehicle-Vehicle and Vehicle-Environment	2
LiDAR	Sarata, S.: Koyachi, N.: Kuniyoshi, H.: Tsubouchi, T.: Sugawara, K	2007	Detection of dump truck for loading operation by wheel loader	Functional	Component	Vehicle-Vehicle	4
OTHER	Cloete, Steven: Horberry, Tim	2013	Collision avoidance and semi-automation in electric rope shovel operation	Usability	Avoidance	Vehicle-Vehicle	8
OTHER	Gu, Rong: Marinescu, Raluca: Seceleanu, Cristina: Lundqvist, Kristina	2018	Formal Verification of an Autonomous Wheel Loader by Model Checking	Performance	Component	All	3

Table 12 (continued)

Group	Authors	Year	Title	Test type	CXS type	Interaction type	TRL
OTHER	Himmelman. Nicholas, P.: Borthwick, J. R.: Kashani, Ali H.: Lin, Li-Heng: Poon, Alan: Hall, Robert A.: Lawrence, P. D.: Salcudean, Septimiu E.: Owen, William S	2009	Rope Shovel Collision Avoidance System	No testing done	Component	Vehicle-Vehicle	2
OTHER	Kapica, Roman: Vrublova, Dana: Korandova, Beata: Krupa, Martin	2018	The application of terrestrial laser scanning for the management of mining in real time	Performance	Component	Vehicle-Vehicle and Vehicle-Environment	2
OTHER	King, J.: Hale, R.: Hwang, F.: Seshadri, J.: Rokonuzzaman, M.: Gosine, R	2001	A general framework for group robotics with applications in mining	Functional	Component	Vehicle-Vehicle	3
OTHER	Lynas, Danellie: Horberry, Tim	2010	Exploring the human factors challenges of automated mining equipment	Usability	Component	Vehicle-Vehicle	6
OTHER	Marks, Eric D.: Wetherford, J. E.: Teizer, J.: Yabuki, N	2013	Potential of Leading Indicator Data Collection and Analysis for Proximity Detection and Alert Technology in Construction	Performance	Component	Vehicle-Person	4
OTHER	Mayton, Alan G.: Pollard, Jonisha P.: Nasarwanji, Mahiyar F.: Kim, Brian Y	2019	Advancing strategies to reduce worker injury risk on mobile mining equipment	No testing done	Warning	Vehicle-Vehicle and Vehicle-Person	2
OTHER	Moczulski, Wojciech: Przystalka, Piotr: Sikora, Marek: Zimroz, Radoslaw	2016	Modern ICT and mechatronic systems in contemporary mining industry	No testing done	Awareness	Vehicle-Vehicle	2

Table 12 (continued)

Group	Authors	Year	Title	Test type	CXS type	Interaction type	TRL
OTHER	Nieto, A.: Peng, S. L	2010	Proximity warning and terrain modelling system based on Delaunay triangulation and surface spline interpolation	Functional	Warning	Vehicle-Vehicle	4
OTHER	Pandey, Anish: Sonkar, Rakesh Kumar: Pandey, Krishna Kant: Parhi, D. R	2014	Path planning navigation of mobile robot with obstacles avoidance using fuzzy logic controller	Analytical	Component	Vehicle-Environment	3
OTHER	Park, H.: Le, S.: Chu, B.: Hong, D	2008	Obstacle avoidance for robotic excavators using a recurrent neural network	Analytical	Component	Vehicle-Vehicle	2
OTHER	Rathnayake, M. P. N.: Samarasekera, K. J.: Rajapakshe, S. C.: Wikramasinghe, E. W. M. P. W. D. C. B.: Mahagedara, H. B. M. U. L. B.: Samaranayake, M. G. C. R.: Narampanawe, K. M. M. W. N. B	2010	Design and implementation of autonomous robot with solid object identification algorithm	Functional	Component	Vehicle-Environment	2
OTHER	Stentz, Anthony	2001	Robotic technologies for outdoor industrial vehicles	No testing done	Component	Vehicle-Vehicle	3
OTHER	Sun, Enji: Nieto, Antonio: Li, Zhongxue: Kecojevic, Vladislav	2010	An integrated information technology assisted driving system to improve mine trucks-related safety	No testing done	Warning	All	2
OTHER	Talmaki, Sanat: Kamat, Vineet R	2013	Multi-sensor monitoring for real-time 3D visualization of construction equipment	Performance	Component	Vehicle-Vehicle	4

Table 12 (continued)

Group	Authors	Year	Title	Test type	CXS type	Interaction type	TRL
OTHER	Worrall, S.: Orchansky, D.: Masson, F.: Nieto, J.: Nebot, E	2010	Determining high safety risk scenarios by applying context information	Functional	Component	Vehicle-Vehicle and Vehicle-Environment	3
OTHER	Worrall, Stewart: Nebot, Eduardo	2007	Automated process for generating digitised maps through GPS data compression	Performance	Component	Vehicle-Vehicle and Vehicle-Environment	3
OTHER	Worrall, Stewart: Nebot, Eduardo	2008	A probabilistic method for detecting impending vehicle interactions	Performance	Component	Vehicle-Vehicle	3
RADAR	Augustin, Christian: Nienhaus, Karl: Winkel, Reik	2011	Advanced 2D radar for rough environments: Positioning, volumetric measurement and collision avoidance	No testing done	Avoidance	Vehicle-Vehicle and Vehicle-Environment	2
RADAR	Ferreira, N; McElman, C	2010	Proximity Cameras and Global Positioning Systems—An Integrated Approach	No testing done	Avoidance	All	2
RADAR	Frimpong, S.: Li, Y.: Agarwal, S	2007	Frontier Research In Dynamic Control, Vision And Collision Avoidance For Truck Haulage	No testing done	Avoidance	Vehicle-Vehicle and Vehicle-Environment	2
RADAR	Hargrave, Chad O.: Bialkowski, Marek	2011	Scanning radar system for machine guidance	Functional	Component	Vehicle-Vehicle	2
RADAR	Hsieh, E.: DeWitt, P.: Taylor, W	2014	Using proximity/object detection to increase shovel productivity in the open pit mine	Performance	Avoidance	Vehicle-Vehicle	8
RADAR	Nabavi, Nima	2009	Integrating Radar Proximity Sensing and Camera Vision to Improve Mining Equipment Safety with Minimal Distraction	No testing done	Warning	Vehicle-Vehicle	2

Table 12 (continued)

Group	Authors	Year	Title	Test type	CXS type	Interaction type	TRL
RADAR	National Institute for Occupational Safety and Health	2001	Technology News—No. 484—Devices to Monitor Blind Spots Near Large Haulage Equipment	No testing done	Warning	Vehicle-Vehicle	2
RADAR	Nienhaus, K.: Winkel, R	2007	Enabling Mining Safety & Automation By Electronically Scanning Microwave Radar Systems On Surface Mining Machines	Functional	Warning	Vehicle-Vehicle and Vehicle-Environment	2
RADAR	Nienhaus, Karl: Hahn, Martin: Winkel, Reik	2009	Wireless sensing applications in the mining and minerals industry	No testing done	Component	Vehicle-Vehicle and Vehicle-Environment	2
RADAR	Ruff, T	2007	RI 9672—Recommendations For Evaluating And Implementing Proximity Warning Systems On Surface Mining Equipment	Functional	Warning	Vehicle-Environment	7
RADAR	Ruff, T. M	2001	Application of radar to detect pedestrian workers near mining equipment	Functional	Warning	Vehicle-Person	6
RADAR	Ruff, Todd	2006	Evaluation of a radar-based proximity warning system for off-highway dump trucks	Performance	Warning	Vehicle-Vehicle and Vehicle-Person	7
RADAR	Ruff, Todd M	2000	RI 9652—Test Results of Collision Warning Systems For Surface Mining Dump Trucks	Functional	Component	Vehicle-Vehicle and Vehicle-Person	4
RADAR	Ruff, Todd M	2000	RI 9654—Test Results of Collision Warning Systems For Surface Mining Dump Trucks: Phase 2	Functional	Component	Vehicle-Vehicle and Vehicle-Person	4

Table 12 (continued)

Group	Authors	Year	Title	Test type	CXS type	Interaction type	TRL
RADAR	Ruff, Todd M	2002	RI 9657—Recommendations for Testing Radar-Based Collision Warning Systems On Heavy Equipment	Functional	Component	Vehicle-Person	4
RADAR	Ruff, Todd M	2003	New Technology to Monitor Blind Areas Near Surface Mining Equipment	Usability/Functional	Warning	All	7
RADAR	Ruff, Todd M	2004	RI 9660—Evaluation of Systems To Monitor Blind Areas Behind Trucks Used In Road Construction And Maintenance: Phase 1	Functional/Reliability/Usability	Warning	Vehicle-Vehicle and Vehicle-Person	6
TAG	Ferreira, N; McElman, C	2010	Proximity Cameras and Global Positioning Systems—An Integrated Approach	No testing done	Warning	All	2
TAG	Gao, Yang: Meng, Xiaolin: Hancock, Craig M.: Stephenson, Scott: Zhang, Qiuzhao	2014	UWB/GNSS-based cooperative positioning method for V2X applications	Performance	Component	All	4
TAG	Kavuri, Ajay: Prakash, Bisleshana: Sabniveesu, Venkataraghavasivanagashashank: Nimbarte, Ashish: Kulathumani, Vinod: Kecojevic, Vladislav	2017	An adaptive, run-time navigation system for haul trucks in surface mines	Performance	Warning	Vehicle-Vehicle	6
TAG	Kloos, Gerold: Guivant, Jose E.: Nebot, Eduardo M.: Masson, Favio	2006	Range based localisation using RF and the application to mining safety	Performance	Component	All	4

Table 12 (continued)

Group	Authors	Year	Title	Test type	CXS type	Interaction type	TRL
TAG	National Institute for Occupational Safety and Health	2001	Technology News—No. 484—Devices to Monitor Blind Spots Near Large Haulage Equipment	No testing done	Warning	All	2
TAG	Nienhaus, Karl: Hahn, Martin: Winkel, Reik	2009	Wireless sensing applications in the mining and minerals industry	No testing done	Component	Vehicle-Person	2
TAG	Ruff, Todd M	2000	RI 9652—Test Results of Collision Warning Systems For Surface Mining Dump Trucks	Functional	Warning	All	4
TAG	Ruff, Todd M	2000	RI 9654—Test Results of Collision Warning Systems For Surface Mining Dump Trucks: Phase 2	Functional	Warning	Vehicle-Person	6
TAG	Ruff, Todd M	2003	New Technology to Monitor Blind Areas Near Surface Mining Equipment	Functional	Warning	Vehicle-Vehicle and Vehicle-Person	6
TAG	Ruff, Todd M.: Hession-Kunz, Drew	2001	Application of radio-frequency identification systems to collision avoidance in metal/nonmetal mines	Performance	Component	Vehicle-Person	6
TAG	Sabniveesu, Venkataraghavasivanagashashank: Kavuri, Ajay: Kavi, Rahul: Kulathumani, Vinod: Kecojevic, Vladislav: Nimbarte, Ashish	2015	Use of wireless, ad-hoc networks for proximity warning and collision avoidance in surface mines	Performance	Component	Vehicle-Vehicle	5
TAG	Schiffbauer, W. H	2011	Mine wide protection for miners, equipment and infrastructure	No testing done	Avoidance	All	3

Table 12 (continued)

Group	Authors	Year	Title	Test type	CXS type	Interaction type	TRL
TAG	Schiffbauer, W. H.: Mowrey, G. L	2001	An environmentally robust proximity warning system for hazardous areas	Performance	Avoidance	Vehicle-Vehicle and Vehicle-Environment	4
TAG	Thomas, Stewart: Teizer, Jochen: Reynolds, Matthew	2011	SmartHat: A battery-free worker safety device employing passive UHF RFID technology	Performance	Warning	Vehicle-Person	4
V2X	Gao, Yang: Meng, Xiaolin: Hancock, Craig M.: Stephenson, Scott: Zhang, Qiuzhao	2014	UWB/GNSS-based cooperative positioning method for V2X applications	Performance	Component	Vehicle-Vehicle	4
V2X	Kaufmann, Thomas: Maeder, Urban: Fumeaux, Nchristophe	2014	Antenna placement on a large mining vehicle	Analytical	Component	Vehicle-Vehicle	3
V2X	Kavuri, Ajay: Prakash, Bisleshana: Sabniveesu, Venkataraghavasivanagashashank: Nimbarte, Ashish: Kulathumani, Vinod: Kecojevic, Vladislav	2017	An adaptive, run-time navigation system for haul trucks in surface mines	Functional	Warning	Vehicle-Vehicle	6
V2X	Nienhaus, Karl: Hahn, Martin: Winkel, Reik	2009	Wireless sensing applications in the mining and minerals industry	No testing done	Component	Vehicle-Person	2
V2X	Nieto, A.: Dagdelen, K	2002	Development of Dump Edge And Vehicle Proximity Warning System Using GPS And Wireless Network Communications To Improve Safety In Open Pit Mines	Functional	Warning	Vehicle-Vehicle and Vehicle-Environment	6

Table 12 (continued)

Group	Authors	Year	Title	Test type	CXS type	Interaction type	TRL
V2X	Nieto, A.: Peng, S. L	2010	Proximity warning and terrain modelling system based on Delaunay triangulation and surface spline interpolation	Functional	Warning	Vehicle-Vehicle	4
V2X	Nieto, Antonio: Dagdelen, Kadri	2003	Accuracy testing of a vehicle proximity warning system based on GPS and wireless networks	Performance	Warning	Vehicle-Vehicle and Vehicle-Environment	6
V2X	Nishimura, Yusuke: Osafune, Tatsuaki: Kato, Seiya: Hiromori, Akihito: Yamaguchi, Hirozumi: Higashino, Teruo	2017	Vehicle Proximity Awareness by Inter-Vehicle Communication for Surface Mine Operation Safety	Analytical	Component	Vehicle-Vehicle	4
V2X	Ruff, Todd M.: Holden, Thomas P	2003	Preventing collisions involving surface mining equipment: A GPS-based approach	Functional	Warning	Vehicle-Vehicle and Vehicle-Environment	7
V2X	Sabniveesu, Venkataraghavasivanagashashank: Kavuri, Ajay: Kavi, Rahul: Kulathumani, Vinod: Kecojevic, Vladislav: Nimbarte, Ashish	2015	Use of wireless, ad-hoc networks for proximity warning and collision avoidance in surface mines	Performance	Component	Vehicle-Vehicle	5
V2X	Sun, Enji: Nieto, Antonio: Li, Zhongxue: Kecojevic, Vladislav	2010	An integrated information technology assisted driving system to improve mine trucks-related safety	No testing done	Warning	All	2
V2X	Virtanen, Ari: Jankkari, Jari	2013	V2X in industrial site safety applications	Performance	Component	Vehicle-Vehicle	4

Declarations

Conflict of Interest The authors declare no competing interests.

Disclaimer The findings and conclusions in this paper are those of the authors and do not necessarily represent the official position of the National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention. Mention of any company name or product does not constitute endorsement by NIOSH.

References

1. NIOSH Mining. (2021). Number and percentage of occupational fatalities by accident class. Retrieved April 16, 2021, from https://wwwn.cdc.gov/NIOSH-Mining/MMWC/Fatality/Count?StartYear=2018&EndYear=2019&SelectedMineType≡
2. U.S. DOL (2011) United States Department of Labor, Mine Safety and Health Administration, MSHA Handbook Series: Accident/illness investigations procedures, Handbook Number: PH11-I-1, June 2011
3. Mine Safety and Health Administration (2018a) Safety improvement technologies for mobile equipment at surface mines, and for belt conveyors at surface and underground mines. Retrieved July 28, 2020, from https://www.federalregister.gov/documents/2018/06/26/2018-13603/safety-improvement-technologies-for-mobile-equipment-at-surface-mines-and-for-belt-conveyors-at
4. Mine Safety and Health Administration (2018b) Powered haulage safety – stakeholder feedback. Retrieved April 18, 2021, from https://www.msha.gov/powered-haulage-safety-%E2%80%93-stakeholder-feedback
5. Mine Safety and Health Administration (2018c) Safety topic: mobile equipment at surface mines. Retrieved April 16, 2021, from https://www.msha.gov/training-education/safety-and-health-materials/safety-topic-mobile-equipment-surface-mines
6. Wharry M (2018) Collision avoidance systems and collision warning systems reducing surface mobile equipment accidents through technology. Retrieved April 16, 2021, from https://www.msha.gov/sites/default/files/events/Collision%20Warning%20TRAM%2010_3_2018.pdf
7. Mankins JC (1995) "Technology readiness levels: a white paper," NASA, Office of Space Access and Technology
8. SR. Sadin, FP. Povinelli R. Rosen (1988) "The NASA technology push towards future space mission systems,"
9. United States Department of Defense (2011) "Technology Readiness Assessment (TRA) Guidance,"
10. Sanchez R (2011) "Technology Readiness Assessment Guide," United States Department of Energy
11. European Space Agency, "Technology readiness level," (2016) [Online]. Available: http://sci.esa.int/sre-ft/50124-technology-readiness-level/
12. Bergsjö D (2009) Product lifecycle management. Chalmers University of Technology, Gothenburg
13. Grieves M (2005) Product lifecycle management: driving the next generation of lean thinking. McGraw-Hill
14. Sääksvuori A, Immonen A (2008) Product lifecycle management. Springer, Berlin
15. EMESRT – Earth Moving Equipment Safety Round Table (2019) PR-5A, Vehicle Interaction Systems. August
16. E&MJ – Engineering and Mining Journal (2014) Proximity detection aids minesite awareness. November
17. IM – International Mining (2019) Wabtec on the evolution of collision awareness systems in mining. October 2019
18. Grant MJ, Booth A (2009) A typology of reviews: an analysis of 14 review types and Associated methodologies. Health Info Libr J 26(2):91–108. https://doi.org/10.1111/j.1471-1842.2009.00848.x
19. Booth A, Sutton A, Papaioannou D (2016) Introducing the SALSA framework. Systematic approaches to a successful literature review. Sage, Thousand Oaks, CA, pp 23–26
20. Huang X, Lin J, Demner-Fushman D (2006) Evaluation of PICO as a knowledge representation for clinical questions. AMIA … Annual Symposium proceedings. AMIA Symposium 2006:359–363
21. Carr JL (2019) An investigation into the factors that govern success for new safety and health technologies in the mining industry and the efficacy of those factors to predict the likelihood of success for emerging technologies (doctoral dissertation). The Pennsylvania State University. Retrieved February 02, 2021, from https://etda.libraries.psu.edu/catalog/17229jlc645
22. Ruff TM (2008) Feasibility of using intelligent video for machine safety applications. 2008 IEEE Industry Applications Society Annual Meeting. https://doi.org/10.1109/08ias.2008.342
23. Somua-Gyimah GF, S.: Nyaaba, W.: Gbadam E (2019) A computer vision system for terrain recognition and object detection tasks in mining and construction environments. Paper presented at the 2019 SME Annual Conference and Expo and CMA 121st National Western Mining Conference, February 24, 2019 - February 27, 2019, 700 14th Street, Denver, CO, United States
24. Ishimoto H, Tsubouchi T (2013) Stereo vision based worker detection system for excavator. Proceedings of the 30th International Symposium on Automation and Robotics in Construction and Mining (ISARC 2013): Building the Future in Automation and Robotics. https://doi.org/10.22260/isarc2013/0110
25. Nabavi N (2009) Integrating radar proximity sensing and camera vision to improve mining equipment safety with minimal distraction
26. Kaufmann T, Maeder U, Fumeaux C (2014) Antenna placement on a large mining vehicle. Paper presented at the 2014 International Workshop on Antenna Technology: Small Antennas, Novel EM Structures and Materials, and Applications, iWAT 2014, March 4, 2014 - March 6, 2014, Sydney, NSW, Australia
27. Wang W, Zhou R (2009) Research on the anti-collision system of surface coal mine based on the highly accurate GPS location technology. Paper presented at the 9th International Conference on Electronic Measurement and Instruments, ICEMI 2009, August 16, 2009 - August 19, 2009, Beijing, China
28. Gao YM, Xiaolin: Hancock, Craig M.: Stephenson, Scott: Zhang, Qiuzhao (2014) UWB/GNSS-based cooperative positioning method for V2X applications. Paper presented at the 27th International Technical Meeting of the Satellite Division of the Institute of Navigation, ION GNSS 2014, September 8, 2014 - September 12, 2014, Tampa, FL, United States
29. Gioia CB, Daniele (2015) Stand-alone and hybrid positioning using asynchronous pseudolites. Sensors (Switzerland) 15(1):166–193. https://doi.org/10.3390/s150100166
30. Kavuri A, Prakash B, Sabniveesu V, Nimbarte A, Kulathumani V, Kecojevic V (2017) An adaptive, run-time navigation system for haul trucks in surface mines. Int J Min Reclam Environ 31(5):364–374. https://doi.org/10.1080/17480930.2016.1148566
31. Ruff TM (2013) Improving traffic awareness on mine access and haul roads. Paper presented at the 23rd World Mining Congress and Expo 2013, Montreal, Quebec, Canada
32. Frimpong S, Li Y, Agarwal S (2007) Frontier research in dynamic control, vision and collision avoidance for truck haulage. Paper presented at the SME Annual Meeting, Denver, CO
33. Ferreira NMC (2010) Proximity cameras and global positioning systems - an integrated approach

34. Hargrave CO, Marek B (2011) Scanning radar system for machine guidance. Paper presented at the 18th Annual International Conference on Mechatronics and Machine Vision in Practice 2011, M2VIP 2011, December 6, 2011 - December 7, 2011, Brisbane, QLD, Australia
35. Ruff TM (2000) RI 9652 - Test results of collision warning systems for surface mining dump trucks. The National Institute for Occupational Safety and Health (NIOSH)
36. Ruff TM (2000) RI 9654 - Test results of collision warning systems on off-highway dump trucks: phase 2. The National Institute for Occupational Safety and Health (NIOSH)
37. Ruff TM (2001) Application of radar to detect pedestrian workers near mining equipment. Appl Occup Environ Hyg 16(8):798–808. https://doi.org/10.1080/10473220118943
38. Ruff TM (2002) RI 9657 - Recommendations for testing radar-based collision warning systems on heavy equipment. The National Institute for Occupational Safety and Health (NIOSH)
39. Ruff TM (2003) New technology to monitor blind areas near surface mining equipment. Paper presented at the 2003 IEEE Industry Applications Conference; 38th Annual Meeting: Crossroads to Innovation, October 12, 2003 - October 16, 2003, Salt Lake City, UT, United States
40. Ruff TM (2004). RI 9660 - Evaluation of systems to monitor blind areas behind trucks used in road construction and maintenance: phase 1. The National Institute for Occupational Safety and Health (NIOSH)
41. Ruff T (2006) Evaluation of a radar-based proximity warning system for off-highway dump trucks. Accid Anal Prev 38(1):92–98. https://doi.org/10.1016/j.aap.2005.07.006
42. Ruff T (2007) RI 9672 - Recommendations for evaluating and implementing proximity warning systems on surface mining equipment. The National Institute for Occupational Safety and Health (NIOSH)
43. Hsieh EDP.: Taylor W (2014) Using proximity/object detection to increase shovel productivity in the open pit mine. Paper presented at the 2014 SME Annual Meeting and Exhibit: Leadership in Uncertain Times, SME 2014, February 23, 2014 - February 26, 2014, Salt Lake City, UT, United States
44. Himmelman. Nicholas, PB., JR.: Kashani, Ali H.: Lin, Li-Heng: Poon, Alan: Hall, Robert A.: Lawrence, PD.: Salcudean, Septimiu E.: Owen, William S (2009) Rope shovel collision avoidance system
45. Kapica RV, Dana: Korandova, Beata: Krupa, Martin (2018) The application of terrestrial laser scanning for the management of mining in real time. Paper presented at the 18th International Multidisciplinary Scientific Geoconference, SGEM 2018, July 2, 2018 - July 8, 2018, Albena, Bulgaria
46. Sarata, SKN.: Kuniyoshi, H.: Tsubouchi, T.: Sugawara K (2007) Detection of dump truck for loading operation by wheel loader. Paper presented at the 24th International Symposium on Automation and Robotics in Construction, ISARC 2007, September 19, 2007 - September 21, 2007, Kochi, India
47. Schiffbauer WH, Mowrey GL (2001) An environmentally robust proximity warning system for hazardous areas. Paper presented at the Emerging Technologies Update, September 10, 2001 - September 12, 2001, Houston, TX, United States
48. Sabniveesu VK, Ajay, Kavi Rahul, Kulathumani Vinod, Kecojevic Vladislav, Nimbarte Ashish (2015) Use of wireless, ad-hoc networks for proximity warning and collision avoidance in surface mines. Int J Min Reclam Environ 29(5):331–346. https://doi.org/10.1080/17480930.2015.1086550
49. Nieto ADK (2002) Development of dump edge and vehicle proximity warning system using GPS and wireless network communications to improve safety in open pit mines. Paper presented at the SME 2002 Annual Meeting, Phoenix, AZ
50. Nieto A, Kadri D (2003) Accuracy testing of a vehicle proximity warning system based on GPS and wireless networks. Int J Surf Min Reclam Environ 17(3):156–170. https://doi.org/10.1076/ijsm.17.3.156.14772
51. Ruff TM, Holden TP (2003) Preventing collisions involving surface mining equipment: a GPS-based approach. J Safety Res 34(2):175–181. https://doi.org/10.1016/S0022-4375(02)00074-9
52. Virtanen A, Jankkari J (2013) V2X in industrial site safety applications. Paper presented at the 20th Intelligent Transport Systems World Congress, ITS 2013, October 14, 2013 - October 18, 2013, Tokyo, Japan
53. JHR King F Hwang J Seshadri M Rokonuzzaman R Gosine 2001 A general framework for group robotics with applications in mining. Paper presented at the Mobile Robots XV and Telemanipulator and Telepresence Technology VII, November 5, 2000 November 6, 2000 MA, United states Boston
54. Talmaki SK, Vineet R (2013) Multi-sensor monitoring for real-time 3D visualization of construction equipment. Paper presented at the 30th International Symposium on Automation and Robotics in Construction and Mining, ISARC 2013, Held in conjunction with the 23rd World Mining Congress, August 11, 2013 - August 15, 2013, Montreal, QC, Canada
55. Stentz A (2001) Robotic technologies for outdoor industrial vehicles. Paper presented at the Unmanned Ground Vehicle Technology, April 16, 2001 - April 17, 2001, Orlando, FL, United States
56. Worrall SN, Eduardo (2008) A probabilistic method for detecting impending vehicle interactions. Paper presented at the 2008 IEEE International Conference on Robotics and Automation, ICRA 2008, May 19, 2008 - May 23, 2008, Pasadena, CA, United States
57. Pandey AS, Rakesh Kumar: Pandey, Krishna Kant: Parhi DR (2014) Path planning navigation of mobile robot with obstacles avoidance using fuzzy logic controller. Paper presented at the 2014 8th IEEE International Conference on Intelligent Systems and Control, ISCO 2014, January 10, 2014 - January 11, 2014, Coimbatore, India
58. Park HLS, Chu B.: Hong D (2008) Obstacle avoidance for robotic excavators using a recurrent neural network. Paper presented at the International Conference on Smart Manufacturing Application
59. Nieto AP, L S (2010) Proximity warning and terrain modelling system based on Delaunay triangulation and surface spline interpolation. Trans Institutions Mining Metallurgy, Section A: Mining Technol 119(1):1–7. https://doi.org/10.1179/037178409X12596677450045
60. Lynas DH, Tim (2010) Exploring the human factors challenges of automated mining equipment. Paper presented at the 46th Annual Human Factors and Ergonomics Society of Australia Conference 2010, HFESA 2010, October 31, 2010 - November 3, 2010, Sunshine Coast, QLD, Australia
61. Cloete SH, Tim (2013) Collision avoidance and semi-automation in electric rope shovel operation. Paper presented at the 49th Annual Human Factors and Ergonomics Society of Australia Conference 2013, HFESA 2013, December 2, 2013 - December 4, 2013, Perth, WA, Australia
62. Kecojevic V, Radomsky M (2004) The causes and control of loader- and truck-related fatalities in surface mining operations. Inj Control Saf Promot 11(4):239–251
63. Bellanca JL, Ryan ME, Orr TJ et al (2021) Why do haul truck fatal accidents keep occurring? Mining, Metallurgy & Exploration 38:1019–1029. https://doi.org/10.1007/s42461-021-00410-1
64. National Safety Council (2020) Type of crash. Retrieved April 18, 2021, from https://injuryfacts.nsc.org/motor-vehicle/overview/type-of-crash/
65. Seppelt BD, Victor TW (2016) Potential solutions to human factors challenges in road vehicle automation. In Road vehicle automation 3 (pp. 131–148). Springer, Cham

66. Trimble TE, Bishop R, Morgan JF, Blanco M (2014) Human factors evaluation of level 2 and level 3 automated driving concepts: past research, state of automation technology, and emerging system concepts
67. Swanson LR, Bellanca JL (2019) Mineworkers' trust in proximity detection systems for mobile machines. Saf Health Work 10(4):461–469
68. Horberry T, Burgess-Limerick R, Steiner LJ (2010) Human factors for the design, operation, and maintenance of mining equipment. CRC Press
69. Endsley MR (1995) Toward a theory of situation awareness in dynamic systems. Hum Factors 37(1):32–64
70. Ma S, Zhang W, Yang Z, Kang C, Changxu Wu, Chai C, Shi J, Li YZH (2021) Take over gradually in conditional automated driving: the effect of two-stage warning systems on situation awareness, driving stress, takeover performance, and acceptance. Int J Human-Computer Interaction 37(4):352–362. https://doi.org/10.1080/10447318.2020.1860514
71. Horberry T, Burgess-Limerick R, Steiner L (2015, August) Human centered design for mining equipment and new technology. In Proceedings of the 19th Triennial Congress of the IEA (Vol. 9, p. 14)
72. Grandone S, Gunasinghe D, Greyvensteyn I (2021) ACARP C26028 PDS validation framework: phase 3. Mining3. Queensland, Australia
73. Rio Tinto to expand autonomous truck operations to fifth Pilbara mine site. Retrieved May 13, 2021, from https://www.riotinto.com/en/news/releases/Automated-truck-expansion-Pilbara
74. Fortescue completes autonomous haul truck fleet conversion in Western Australia. (2020, October 28). Retrieved May 13, 2021, from https://im-mining.com/2020/10/28/fortescue-completes-autonomous-haul-truck-fleet-conversion-in-western-australia/.
75. Bellamy D, Pravica L (2011) Assessing the impact of driverless haul trucks in Australian surface mining. Resour Policy 36(2):149–158. https://doi.org/10.1016/j.resourpol.2010.09.002