COLLISION PREVENTION SYSTEMS

INTEROPERABILITY REPORT

(I.E., WORK PACKAGE 9)

INDUSTRY ALIGNMENT ON TMM REGULATIONS; SPECIAL PROJECT OF THE MINERALS COUNCIL SOUTH AFRICA

REV 4

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CPS Interoperability Report Acceptance			
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1. Purpose of this document

This document deals with the challenges related to interoperability of Collision Prevention Systems for Trackless Mobile Machines (TMM) in the SA Mining Industry (SAMI).

The document is a deliverable of Work Package 9 of the CAS Readiness Phase work of the INDUSTRY ALIGNMENT ON TMM REGULATIONS; SPECIAL PROJECT OF THE MINERALS COUNCIL SOUTH AFRICA.

2. Definitions and abbreviations

The following definitions and abbreviations will be used to create a common approach for all deliverables: (Note: The rationale for some of the terms and definitions is set out in the CMS Technical Specification Guideline Review Report)

CMS	Collision Management System – The overall combination of preventative controls, mitigation, recovery and supporting controls implemented by a mine site to prevent TMM collisions
CPS	Collision Prevention System: A Product System that comprises the functionality and characteristics that comply with the RSA TMM collision prevention regulations. (Regulations 8.10.1 and 8.10.2 and user requirements)
CWAS/(CxD)*	Collision Warning and Avoidance System device (CxD) - Device with sensors providing collision warning and avoidance functions to detect objects in the vicinity of the machine, assess the collision risk level, effectively warn the operator of the presence of object(s), and/or provide signals to the machine control system to initiate the appropriate interventional collision avoidance action on the machine to prevent the collision. Note to entry: Proximity Detection System (PDS) is a colloquial industry term for a physical device providing effective warning or collision avoidance functionality.
CxDMI	CxD Machine Interface: The module providing integration of the CxD and the TMM CPS Products
CxDC	CxD Controller: The module providing decision making, data logging, supervisory control functionality
Contractor	Contractor means EMPLOYEE" which means any person who is employed or working at a mine.
Driver or operator reaction time (also known as perception response time)	The time that elapses from the instant that the driver recognises the existence of a hazard in the road, to the instant that the driver takes appropriate action, for instance, applying the brakes. The response time can be broken down into four separate components: detection, identification, decision and response. When a person responds to

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	something s/he hears, sees, or feels, the total reaction time can be decomposed into a sequence of components namely: • Mental processing time (sensation, perception / recognition, situational awareness, response selection and programming) • Movement time, and • Driver response time. Driver reaction time is also affected by several issues such as visibility, operator state of mind (fatigue), direction or position of perceived danger.
DMRE	Department of Mineral Resources and Energy.
Drive past data acquisition point	An installation that facilitates data to be transferred from a TMM to the installation and then communicated from the installation to a database.
EW (Surface)	Effective Warning: The expected outcome of the operator action is that the potential collision is prevented, therefore an effective warning must inform the operators of both TMMs what the appropriate action(s) are to prevent the potential collision.
EW (Underground)	Effective Warning: The expected outcome of the operator and pedestrian action is that the potential collision is prevented, therefore an effective warning must inform the operators of TMMs what the appropriate action(s) are to prevent the potential collision and must alert the pedestrian to potential collisions or interactions with TMMs in the vicinity.
Emergency stopping	In the case of an emergency situation, the machine needs to slow down and stop as quickly as possible, without losing control (meaning directional stability) and without any immediate negative health and safety impact on the operator.
EMC	Electromagnetic Compatibility
EMI	Electromagnetic Interference
EMESRT	Earth Moving Equipment Safety Round Table
Employee	EMPLOYEE" means any person who is employed or working at a mine.
Functional Specification:	Specifications that define the function, duty, or role of the product. Functional specifications define the task or desired result by focusing on what is to be achieved rather than how it is to be done.
Homologation	Homologation means to sanction or "allow." Homologation refers to the process taken to certify that a TMM fitted with a CPS is manufactured, certified and tested to meet the standards specified for critical safety related devices fitted to TMMs.
ICASA	*Independent Communications Authority of South Africa*

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ICMM	International Council on Mining and Metals.
Interface	A boundary across which two independent systems meet and act on or communicate with each other. Four highly relevant examples: 1. CxD-machine interface – the interface between a Collision Warning and Avoidance System Device (CxD) and the machine. This interface is described in ISO/TS 21815-2, 2. The user interface – Also sometimes referred to as the Graphic User Interface (GUI) if an information display is used. This is the interface between the user (TMM operator or pedestrian) and the CxD or pedestrian warning system, 3. V2X interface – the interface between different CxD devices. V2X is a catch-all term for vehicle-to-everything. It may refer to vehicle-to-vehicle (V-V), vehicle-to-pedestrian (V-P) or vehicle-to-infrastructure (V-E), 4. CxD-peripheral interface – This is an interface between the CxD and other peripheral systems that may be present on the TMM. Examples include a fleet management system, machine condition monitoring system, fatigue management system. Note: An interface implies that two separate parties (independent systems) are interacting with each other, which may present interoperability and/or EMI and EMC challenges.
Loss of control	The uncontrolled movement of a TMM due to operator, machine or environmental reasons. Note: Section 8.10.3 of MHS Act. Loss of control may result from several scenarios: • Machine failure – park brake or service brake, tyre blowout, • Operator disabled – fatigue, medical condition, inattention, distraction, non-compliance with TMP rules (e.g., over speeding on decline, overloading)
MBS	Machine Braking System: The CPS module providing CPS braking functionality.
MC	Machine Controller: The TMM CPS module that provides the control functions to a non-intelligent TMM
MCSA	Minerals Council South Africa.
MCxDI	Machine Controller CxD Interface: The TMM CPS Product module providing integration between the TMM Product and The CxD
MHS Act	Mine Health and Safety Act No. 29 of 1996 and Regulations.
MHSC	Mine Health and Safety Council
MOSH	Mining Industry Occupational Safety and Health.
MRAC	Mining Regulations Advisory Committee

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PDS*	Proximity Detection System – see CxD. *
Pedestrian	A person lying, sitting, or walking rather than travelling in a vehicle.
Project	Industry Alignment on TMM Collision Management Systems Project: CAS READINESS PHASE.
Quality Assurance	Verifying a process, product, or service; usually conducted by a person experienced in the specific field.
Reasonably practicable measure	Reasonably practicable means practicable having regard to: (a) the severity and scope of the hazard or risk concerned, (b) the state of knowledge reasonably available concerning that hazard or risk and of any means of removing or mitigating that hazard or risk, © the availability and suitability of means to remove or mitigate that hazard or risk, and (d) the costs and the benefits of removing or mitigating that hazard or risk.
SAMI	South African Mining Industry
Safe speed	The speed that will ensure the controlled stopping of a TMM without any immediate negative impact on the operator or machine. Note: This is a conditional variable value, depending on multiple input variables.
SE	Systems Engineering: Systems engineering is an interdisciplinary field of engineering and engineering management that focuses on how to design, integrate, and manage complex systems over their life cycles.
Significant risk (of collision)	The reasonable possibility of a TMM collision given all the controls that a mine has put in place to prevent a TMM collision.
Slow down*	ISO/TS 21815-2 defines slow down as: The SLOW_DOWN action is sent by the CxD to reduce the speed of the machine in a controlled / conventional manner as defined by the machine control system. The intent of this command is to slow down the machine when the CxD logic determines that a collision / interaction can be avoided by reducing speed.
Stop*	ISO/TS 21815-2 provides for two definitions, an emergency stop, and a controlled stop, both of which are a 'Stop'. The definitions are: 1. The EMERGENCY_STOP action is sent by CxD to instruct the machine to implement the emergency stop sequence defined by the machine control system. The intent of this command is to stop the machine motion as rapidly as possible to reduce the consequence level, if the CxD logic determines that a collision is imminent. The equivalent of an emergency stop is the operator slamming on the brakes in an emergency. 2. The CONTROLLED_STOP action is sent by CxD to instruct the machine to implement the controlled stop sequence defined by the machine control system. The intent of this command is to stop the

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	machine motion in a controlled / conventional manner when the CxD logic determines that a collision / interaction can be avoided by slowing down and stopping. The equivalent of a controlled stop is slowing down and stopping when approaching a red traffic light.
System	A combination of interacting elements organized to achieve one or more stated purposes (ISO/IEC/IEEE 2015)
Technical specification	Specifications that define the technical and physical characteristics and/or measurements of a product, such as physical aspects (e.g., dimensions, colour, and surface finish), design details, material properties, energy requirements, processes, maintenance requirements and operational requirements.
This document	Integrated CPS Testing Regime. A document that defines the proposed integrated testing of CPS, its elements and modules.
TMM	Trackless Mobile Machine. (Machine, vehicle, etc.)
TMM OEM	Original Equipment Manufacturer of TMMs. Original Equipment Manufacturer of a TMM may be the organisation which originally supplied, or last rebuilt or modified the TMM or the supplier per section 21 of the Mine Health and Safety Act, 1996 (Act No. 29 of 1996)
TMM CPS Product	The product that will make a non-intelligent TMM intelligent and CxD ready
TMP	Traffic Management Plan. A document that defines the traffic management system that a mine employs to ensure the safe movement of TMMs and pedestrians on the mine.
TRL	Technology Readiness Level. A technology maturity framework for measuring and monitoring technology maturity in 9 increasing levels from TRL 1 to TRL 9.
URS	User Requirements Specification: A document that defines the requirements for products or systems from the perspective of the user. (for this project the user is mines)
VD	Vicinity Detection: The element responsible for detecting TMMs and Pedestrians to prevent TMM collisions as per TMM regulations.
Vicinity (Surface TMMs)	The distance/time/ of two TMMs from the point of a potential collision, such that if the operators of both machines are instructed to take action to prevent a potential collision, then and one or both does not act then the CPS will be able to prevent the potential collision. Note: Vicinity is a conditional, variable value, depending on multiple input variables. It is smaller than any value that is within the range of normal operation

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Vicinity (Underground TMM and pedestrians)	The distance of a TMM from a pedestrian, such that if the operator of the TMM and the pedestrian do not take action to prevent a potential collision then an emergency slow down and stopping of the TMM can be successfully executed to prevent a potential collision between the TMM and the pedestrian. Note: Vicinity is a conditional, variable value, depending on multiple input variables. It is smaller than any value that is within the range of normal operation.
V2X	Vehicle to Anything
V2XI	Vehicle to Anything Interface
V-V	Vehicle to Vehicle
V-P	Vehicle to pedestrian
Walking speed	In the absence of significant external factors, humans tend to walk at about 1.4 metres per second or 5 km per hour. This is included to help define the crawl speed of vehicles.
WP 9	Work Package 9. One of the work packages of the Industry Alignment on TMM Collision Management Systems Project: CAS READINESS PHASE.

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3. Executive Summary

Interoperability is a challenge wherever there isn't homogeneity. In the context of Collision Prevention Systems, the following heterogenic realities exist:

- Multiple Types of mining operations, each with some unique processes and TMMs
- Multiple mines of similar types of operations yet with some unique processes and with different operating regimes, standards and procedures.
- Multiple types of TMMs on any mine.
- Multiple brands of TMMs on any mine.
- Multiple models of specific brands of TMMs on a mine. Some brands and models are intelligent TMMs and many are not.
- Multiple serial numbers of specific models of the same brand and type of TMM on the same mine
- Multiple suppliers of CxD products suppliers each using its own technology
- Multiple 3rd party CPS providers each using its own technology
- Multi skilled TMM operators operating multiple types of TMMs.
- TMM movement between mines in the same mining company
- TMM movement of contract mining companies between mines
- TMMs of different contract mining companies on the same mine and interacting with the mine's own TMMs

The heterogenic elements related to CPS in the SAMI is unparalleled. Over and above that, CPS interoperability is also a multi-faceted technical challenge that requires a holistic focus.

Technical Interoperability must be a focus wherever there is an interface within the CPS as well as the CPS and its immediate environment.

Figure 1 identifies 6 key CPS interfaces that require consideration. These are:

- Vicinity Detection
- The CXD Machine Interface
- The CXD Human interface
- The CXD and peripheral systems interface
- The Maintenance and Repair interface

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INTEROPERABILITY:

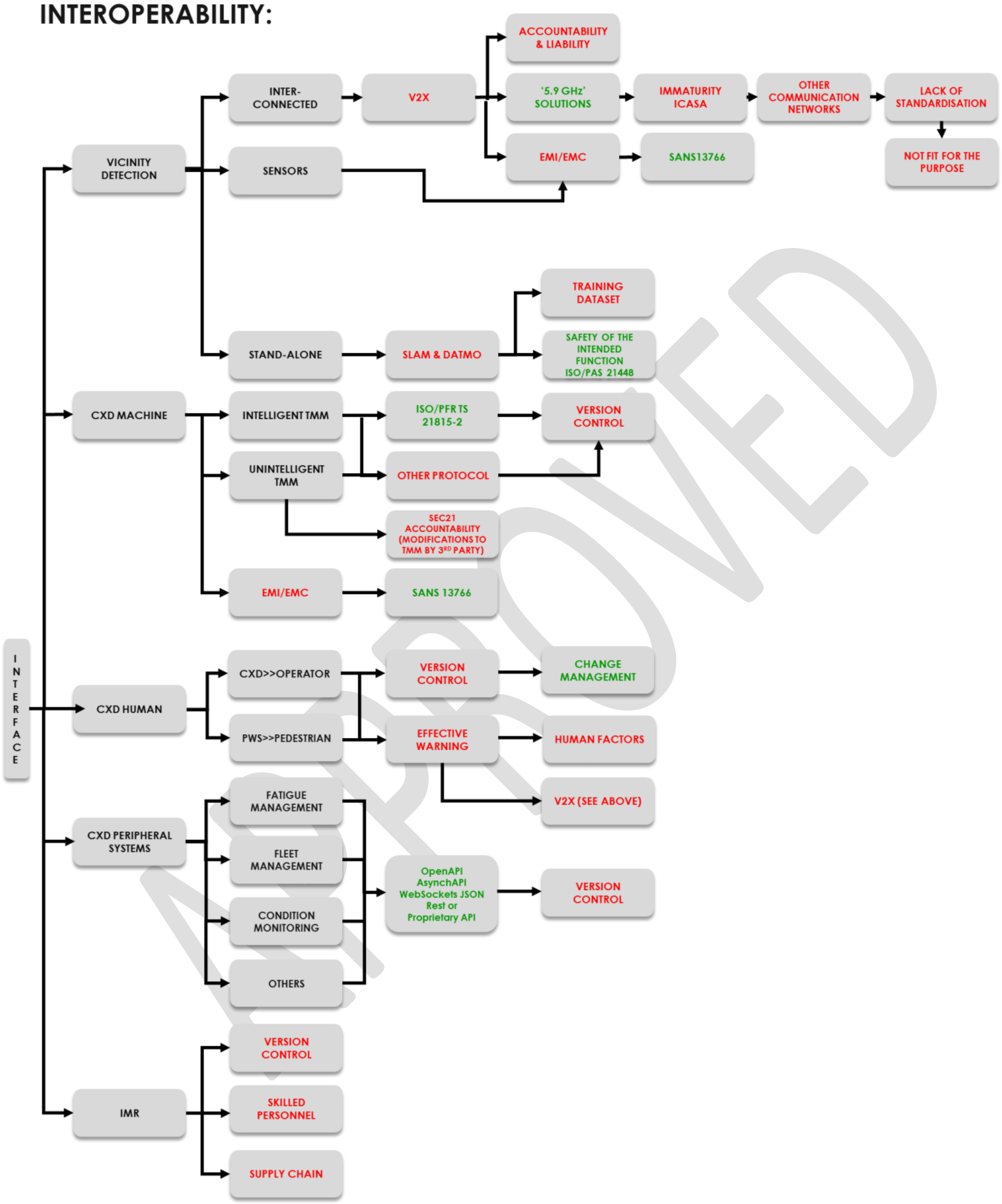

Fig 1: Interoperability schematic: Challenges and potential solutions

Each of these are discussed specifically in the detail report.
At a high level, for CPS products to be interoperable the following must be achieved:

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Vicinity **detection** modules from one CPS must be able to detect all TMMs or pedestrians (as appropriate) in its operating environment, process the data and give an **effective warning** to all other TMMs or pedestrians (as appropriate), irrespective of the CPS products (brands) installed on other TMMs or pedestrians. Detection is currently mostly achieved with sensors. Sensors from one TMM detect other TMMs by communicating with the sensors of the other TMM. Internationally, the communication between sensors is defined as V2X communication. Interoperable V2X communication is also needed for effective warning from a CPS from one TMM to a CPS from another CPS.

Currently (July 2021) CPS providers use different communication standards - of their own choice - for their V2"X" communication. It is these **differing specifications** that result in CPSs not being interoperable. Given the current reality where some TMM OEMs are only willing to work with one specific CxD provider, a mine that has a fleet of different brands of TMMs, all of whom the TMM OEM is only working with one CxD provider, will not be able to introduce CPS on the mine.

The accelerated CPS development initiative is a CPS provider driven approach that will either require V2X communication standards or every CxD provider will have to have a specific product for every TMM brand, model and serial number.

Mature International standards for V2X communication do **not** currently exist that can be specified for CPS products. There are standards emerging, however they are still very immature and are changing frequently. The development of international standards for Intelligent Transportation Systems (ITS) is a key enabler of V2X communication globally. The associated research to specify the "correct" standards are receiving multibillion-dollar investments in the ITS sector.

The SAMI TMM regulations are forcing the SAMI to be ahead of the **global** ITS developments. **The potential risk of failure of the entire CPS initiative due to the lack of CPS interoperability is something that must be considered at the highest level.** It is noteworthy that the ICMM ICSV initiative's strategy is to piggyback on the ITS developments and use the ITS standards **once approved**. With no regulatory sword over its head the ICMM can afford to wait until the enabling standards are approved.

Indications are, that, for surface CPSs the foundation of the future V2X standards will be the 5.9 GHz frequency band that has been approved for the ITS in the US and Europe as its foundation. Although there is no guarantee, the probability that the rest of the world will follow is high.

As a minimum the SAMI with agreement from TMM OEMs and CPS providers should follow this trend and specify 5.9 GHz as a requirement for V2X communication.

Another complication not to be overlooked is that the SAMI uses commercial LDVs that will in future be factory fitted with "CPS" products, developed by the LDV OEMs. Likewise, when the global TMM OEMs (as they have decided to do) will follow suit, future TMMs will be fitted with integrated CPS products. This means that with differing V2X

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communication standards, CPS fitted TMMs will not be interoperable with new LDVs and new TMMs. If SAMI's CPS solutions are not interoperable with new LDVs or TMMs it will require significant investment and operational disruption to correct, since local regulations require CPSs to be fail to safe, meaning TMMs must not operate when CPSs are unable to communicate correctly. Being part of a global world, it will suit local decision makers well to follow the global trend.

Being an enabler of interoperable CPS product development, the 5.9 GHz frequency - that is currently not regulated in South Africa - needs to be regulated in South Africa for the ITS (and thus for CPS products). The time that this will take as well as the time it will take ICASA to establish certification capability must be considered in the schedule of the accelerated CPS development initiative.

Whilst workaround options are possible or alternative standards can be selected, these will come with significant risk. SECDI is not in a position to recommend any such, due to the potential consequences if the CPS initiative fails on the bases of such workarounds or recommendation of alternative communication standards.

Mature Standards for V2X communication are not the only challenge for CPS interoperability. Communication between the CxD and the TMM controller (MC) is another area of standardisation required for CPS interoperability. Fortunately, the recent (July 2021) publishing of ISO/ TS 21815-2 [2] resolved most of this challenge and if the handshake protocol example in ISO/TS 21815-2 [2] is specified for CPS development (as SECDI intends to do) CxD – MC interoperability will be ensured.

The **reality of the upgrading of all existing CPS products** with CxD-MC interfaces that conform to ISO/ TS 21815-2 [2] must be recognised and accounted for in development and commissioning timelines.

The CPS – human interface is yet another CPS interoperability challenge since the CPS of one TMM must provide an effective warning to an operator of another TMM that could be fitted with a CPS from another CPS provider. A human centric design process is required to ensure effective warning of operators and pedestrians (as appropriate) and to ensure that such warnings are interoperable between CPS products from different providers.

4. Conclusions

The following conclusions with regards CPS interoperability can be made:

- The TMM regulatory requirements are a major, but not the only driver of the CPS interoperability requirement.
- Interoperability is an absolute requirement for the successful introduction of CPS into the SAMI.
- Mature International interoperability standards for CPS products does not currently exist.
- CPS interoperability is a multi-faceted challenge that requires a holistic approach.
- V2X communication standards are globally still very immature.

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- Local V2X communication standards that does not conform to future V2X communication standards will have major future repercussions for the SAMI.
- Availability of reliable sensors if a local standard is selected is a major consideration for such selection.
- Human interoperability of CPS products is a highly specialised field with limited local expertise available.

5. Recommendations

It is recommended that:

1) The SAMI adopt physical separation standards for TMM collision prevention and in doing so control the risk of TMM collisions in as much of operations as possible. (The TMM regulations allows for other effective controls to be used to manage TMM collision risk and therefore not requiring CPS where such controls are effective.
2) Based on the SAMI, s physical separation of TMMs standards, the SAMI define the significantly reduced CPS needs and follow a safety and technology risk informed CPS development process.
3) The SAMI establish a V2X task team under auspices of one or more tertiary and research institutions to get actively involved with the global V2X developments. This task team must include as many as possible TMM OEMs.
4) All CPS development partners (ICASA, Mines, CXD developers, TMM OEMs and 3rd party providers) decide/agree on a specification for V2X communication that will govern the local CPS development for:
    a. Surface CPS products
    b. Underground CPS products
5) If the 5.9 GHz frequency band is chosen for surface CPS products it must be ICASA regulated and certification facilities must be established.
6) If 5.9 GHz is chosen, the availability of 5.9 GHz frequency sensors that will be backwards compatible with the ever-evolving newer versions must be considered.
7) Resolution of the aspects of EMI/EMC that is recommended in the EMI/EMC report be considered holistically with the interoperability aspects.
8) Since the human interface is so critical and specialised serious consideration be given to initiate one collaborative effort to analyse the CPS human interface, apply the necessary human factors expertise and specify a CPS human interface that is the result of a people centric design process.

6. Background

TMM regulations for the SAMI were promulgated in 2015. Some of the clauses related to diesel powered TMMs were suspended as a result of non-availability of technology to provide the functionality that is required to auto slowdown and stop the TMMs. A CPS is a complex Product System comprising multiple elements (sub systems), some comprising components that are still in technology development. Furthermore, the range of TMM

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types, brands and models in the mining industry is vast. This adds to the complexity and the challenge faced by the SAMI.

In 2019 the MRAC of the MHSC (the committee responsible for facilitation of the TMM regulations) assembled a team of experts to advise it on the readiness of technology with a view to uplift the suspended clauses of the TMM regulations.

The task team concluded that the technology is not yet ready and that a few, but significant technology challenges are still to be overcome. Interoperability was one of the aspects highlighted. The Minerals Council South Africa initiated a project to facilitate the technology development of the CPS technology and the associated ecosystem (Life Cycle System).

7. CPS Interoperability in context

CPS interoperability is probably the biggest challenge for the SAMI's ability to comply with the TMM regulatory requirements and remain at optimal operational productivity. The question may be asked "Why is interoperability necessary?"

CPS interoperability must be viewed in the context of:

CPS Functionality

The TMM regulatory requirement is, amongst others, that **both** operators of TMMs (or the **operator of a TMM and a pedestrian**) are given an **effective warning** to prevent a potential collision. This requirement implies that the CxD of one TMM must be able to communicate an effective warning to the CXD of another

TMM (or to a pedestrian as applicable) and the CxD from that TMM must communicate back to the CxD from the sending TMM that appropriate action has been taken to prevent a potential collision or that such action has not been taken. This can only happen if the two CxDs from different TMMs can communicate with each other.

An illustrative example explaining the concept of interoperability from the telecommunications industry is that of a smartphone. All smartphones can phone each other via a cellular network. It does not matter if the smartphone used is a Samsung or an Apple iPhone, or whether the network used is MTN or Vodacom. The caller can phone any receiver. In a similar fashion, any CxD on any TMM should be able to communicate with any other CxD on any other TMM (or pedestrian).

It is important to note that an effective warning to **both TMM operators or the TMM operator and the pedestrian** is not a requirement in the EMESRT initiative.

In the EMESRT case it is possible to "allow" only one TMM operator to receive an advisory to take action. This is technically a much easier scenario to develop as there is no need for inter CPS communication to achieve the advisory.

TMM collision risk

The DMRE has made it very clear that it expects the SAMI to introduce CPS products to **prevent** TMM collisions and has hence regulated such. This necessitates the availability of CPS products that can be timeously introduced in the SAMI in order to ensure

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compliance to the regulations at the time of the upliftment of the suspended TMM regulations. The regulations have limited its focus to TMM to TMM collisions for surface operations and to TMM and pedestrian collisions for underground trackless mining operations.

Whilst mines have full autonomy to manage TMM collision risk with any effective control, the regulation states that where significant risk of TMM collisions exist a mine must as a minimum introduce CPS products as a control to prevent such risk. A mine that has not introduced controls to **effectively physically separate** TMMs from other TMMs on surface operations and TMMs from pedestrians in underground trackless operations will find it difficult to justify that a significant risk of TMM collisions does not exist.

Furthermore, the MHSA expects mines to execute extreme diligence in conducting its risk analysis. For TMM collision risk, a mine therefore must consider at least its own and that of all other mines' historic fatality and serious injury scenarios related to TMMs and introduce controls that will **prevent** such collisions to be repeated.

More importantly a mine's TMM collision risk must include identification of all **potential** TMM collisions. **TMM collisions can happen wherever interaction is possible** and therefore the mine's traffic flow and risk analysis must include the identification of all TMM places and points of interaction.

Recent work done by the SAMI, facilitated by the Minerals Council South Africa, showed significantly more LDV TMMs than any other type of TMM. It also showed that LDVs are involved in almost all surface operational processes.

The sheer number of **LDVs** means they are the most exposed type of TMM on surface mines. Hence a proper traffic flow and risk analysis is needed to highlight all operational processes and aspects where HMEs can **interact** with an LDV as a scenario of significant risk of TMM collisions. Similarly, in underground mines, pedestrians are able to freely move around in all areas of the mine and will be exposed to all the TMMs working underground

In the absence of a formal regulatory relaxation it will be irresponsible for the accelerated CPS development initiative not to deal extensively with ensuring the availability of CPS products for all types, brands and models of TMMs. This heightens the requirement for CPS products that are interoperable with different TMMs (including different TMM types, models, and model versions).

As the Minerals Council South Africa high-level TMM collision risk analysis takes shape, and the regulator agrees on specific TMM exclusions, some types and models of TMMs might be excluded. However, the need for interoperability, although with a smaller scope, will remain.

SAMI TMM dynamics

South Africa is an importer of almost all of its fleet of "yellow" earth moving machines, including TMMs. Naturally as a price taker these machines come at a significant relative cost.

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Each mine has its own operating strategy and policies on TMM usage and procurement, having a direct bearing on their approach to TMM life cycle management

Add to this the rand-dollar exchange rate and it is obvious why only a few of the top tier mining companies (probably product exporters) can afford modern fleets. Overlay a slow industry growth rate and the reality of significant numbers of "legacy" (old, unintelligent) TMMs becomes apparent.

A further TMM dynamic that must be considered is the initiatives of mines to facilitate new previously disadvantaged operators into the market. These small operators operate with legacy equipment on specific mining processes. Their fleets operate in-between the mine's own TMMs.

Finally, the significant size of contract mining where a contract miner uses its own fleet of TMMs on multiple mining sites must be considered.

All of these TMM dynamics contribute to the need for interoperable CPSs. It is highly likely that any CPS initiative will fail to reduce significant risk of TMM collisions without interoperability.

As reported in the CMS Technical Specification Guideline Review Report, the current CMS development approach is mine driven. Most mines have identified haul trucks as the only TMMs that are so called "significant collision risk vehicles" and most do not consider the regulatory requirement that both TMMs need to take action to prevent a potential collision. Even such an approach reduces but does not eliminates the need for V2X communication.

The difficulty to justify such an approach was discussed above. A further complication is that current CPS solutions to auto slowdown and stop fully loaded haul trucks at speeds above 30 km/h has not been demonstrated for typical haul roads in the SAMI. This while most mines' hauling speeds are up to 40 km/h. The TMM regulations does not provide any leeway with regard to the speed of TMMs. It is further obvious that the higher the speed of approaching haul trucks the more difficult it is to auto slow and stop them in order to prevent a potential collision.

Detail Report

8. Defining interoperability

Since Interoperability can have multiple different definitions, it is important to clearly define what is meant by interoperability of CPS within the SAMI. Kosanke [1] provides several definitions for interoperability. The definitions vary based on the context within which they are used. Some of the definitions with technical relevance (all are valid) to the SAMI and CPS products include:

1. The ability of two or more systems or elements to exchange information and to use the information that has been exchanged [2].

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2. The capability promoted but not guaranteed, by joint conformance with a given set of standards, that enables heterogeneous equipment, generally built by various vendors, to work together in a network environment [2].
3. The ability of two or more systems or components to exchange information in a heterogeneous network and use that information [2].
4. Compatibility of modules with each other or with the system into which they are inserted [2]. When a pair of such units is said to interoperate,
    a. they cannot suffer damage as a consequence of being powered and functioning in the same system [2];
    b. the modules and the system will each be able to perform the basic function for which they were designed [2].

The SAMI approved CPS product system definition as per the CPS Requirements Document shows where different systems or elements have to exchange information to ensure functionality. Information must be exchanged across a boundary, also known as in interface. The IEEE defines an interface as [2]:

1. A shared boundary (general definition).
2. A shared electrical boundary between parts of a computer system, through which information is conveyed.
3. A shared boundary between two layers or modules of software.

It is thus concluded that interoperability needs to be ensured wherever information is shared across an interface. Interoperability is also an important topic of the ICMM ICSV initiative. a CPS has different functionality and therefore requires that interoperability is more extensive than what is discussed at initiatives such as the ICMM ICSV. Fortunately, ISO/PRF TS 21815-2 technical specification addresses a portion of the CPS challenge.

Considering interoperability, the interfaces involved in CPS technology include:

1. The **vicinity detection** interface – this is the ability of CxDs to detect the presence of all other TMMs (irrespective of type, brand or model) and pedestrians within its vicinity. This is one of the aspects of interoperability receiving a lot of attention from the ICMM ICSV.

2. The **CxD to machine interface** – this is described in ISO/TS 21815-2, however the it does not cover all aspects of the interface. A CxD developer may therefore deviate from ISO/TS 21815-2 in certain cases (to be discussed in the relevant section).
3. The **CxD to human interface** – this is the interface providing effective warnings to TMM operators and to pedestrians.
4. The interface between a **CxD and peripheral systems**, such as fatigue monitoring, condition monitoring or fleet management, etc.
5. The interface between the **CPS and its supporting activities**, such as installation, maintenance and repair (IMR)

Error! Reference source not found. provides a model of the challenges (indicated in red) t hat need to be addressed to ensure CPS interoperability across all the interfaces. Green blocks indicate potential solutions to the identified challenges.

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9. The SAMI CPS interoperability challenge

The current nature of CPS offerings is considered to be an interim state, with third party CxD developers supplying devices that interface with a range of TMM OEMs.

This has presented some challenges, with many TMMs not equipped with standardised CxD>>Machine interfaces (some are not equipped with CxD>>Machine interfaces at all). This has resulted in partial rollout of CPS to portions of TMM fleets that are CPS compatible/ready. Additionally, this has allowed third party interface suppliers to enter the market to modernise 'unintelligent' TMMs.

The introduction of third-party technology providers has improved the maturity and interoperability of the TMMs in the SAMI, but this has heightened the requirement for skilled supporting staff to install, maintain and repair the technology. Furthermore, the use of third-party technology providers introduces risk from a liability and accountability perspective.

Different site requirements may also influence the efficacy of different CPS technologies. TMMs are often moved from one site to another or sold to another mine. It is possible that mines with significantly different traffic management plans may require different CPS approaches, and hence **inter-mine interoperability** is required.

It is anticipated that interoperability will remain a challenge, even as 'end-state' solutions enter the market (end-state solutions are where the CxD is integrated as a factory fitted option by the TMM OEM). The concern is that TMMs from multiple OEMs (constituting a mixed fleet, as is the case in virtually all mines in SA) will not be able to interoperate.

This document addresses the understanding of the CPS interoperability challenges facing the SAMI by:

1. Defining the CPS interoperability challenge (see Section 8).
2. Providing a CPS interoperability model to highlight potential challenges that need to be addressed (see **Error! Reference source not found.**).
3. Investigating existing approaches in the global mining industry (see Section 10).
4. The challenges identified in the CPS interoperability model are then discussed in detail and recommendations are made for each (see Sections 11 to 15).

10. Existing approaches in the global mining industry

CPS interoperability is receiving attention on a global scale. As part of their Initiative for Cleaner, Safer Vehicles (ICSV), the International Council on Mining and Metals (ICMM) has discussed interoperability at length[1] [3]. The ICMM recognises that currently, CPS technology is provided by a single (often third party) supplier for an **entire site** – this is currently the case in the SAMI too. The ICMM mentions that the development of the ISO/TS 21815-2 technical specification [4] has provided some clarity to the CxD>>Machine interface and increased the interoperability, but the need still exists for

[1] The contents of the ICMM's discussions are not freely available. UP has been involved with the ICMM ICSV Vehicle Interaction working group and has been privy to these discussions. This is a summary of what has been discussed and should not be considered a comprehensive account of the ICMM's interoperability related effort.

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interoperability between CPSs from different OEMs. Some key points featuring in the ICMM discussions include:

1. The mining industry is ahead of the automotive industry in adopting collision awareness technology. This adoption is driven by safety standards set by the automotive industry and the global mining industry's drive to eliminate fatalities.
2. The automotive industry is investing heavily in developing safety technology, partially driven by the development of sensor technology.
3. Mine machines have a longer lifespan than that of automobiles (at least in the United States). Machines have an average lifespan of 20 years vs. 10.5 years for automobiles. Mines thus need a solution that can be retrofitted to older equipment.
4. While modern passenger cars have been fitted with technologies such as Adaptive Cruise Control, Automatic Emergency Braking, Lane Departure Warning and Blind Spot Detection, automotive OEMs have been slow in moving this technology to pickup trucks and other light commercial vehicles often found on mines.
5. There is an extremely wide range of equipment types present on mines (e.g. haul trucks, loading tools, and support equipment such as graders, light vehicles and buses). The equipment has many different OEMs with significantly different ages and specifications.

The ICMM has the following vision for **future** technology in the TMM interaction space:

1. TMM OEMs will adopt an approach that is very similar to that of the automotive industry. This will allow the mining industry to leverage the investment of billions of dollars by the automotive industry to the benefit of the mining industry.
2. Each TMM OEM will develop and manage vicinity detection, effective warning and automatic stopping. This development and management will be complemented by industry standards.
3. Light vehicles will have the latest technologies enabling automatic emergency braking, developed by automotive OEMs.
4. Legacy machines will be managed by third party technology providers and/or OEMs. This implies that third party providers will have to move to **global** industry interoperability standards.

The first step toward interoperability is in the process of being taken, in the form of the ISO/TS 21815-2 technical specification [4]. ISO/TS 21815-2 describes the on-board communication interface between a connected device and mobile machines for use in earthmoving, mining and road construction applications to enable interventional collision avoidance actions. The interface is intended for use by a collision avoidance system device integrated **independently** from the machine.

It should be noted that the ISO/TS 21815-2 is not intended to provide plug-and-play implementation. Several details are not fully described by the technical specification and should be negotiated between the CxD provider and the TMM OEM [4].

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The ISO/TS 21815-2 technical specification development was facilitated by the Earth Moving Equipment Safety Round Table (EMESRT) and involved a community made up of individuals representing mining companies, TMM OEMs, third party CPS providers and other stakeholders [5]. The technical specification has been published in July 2021 [4].

One significant difference between the global initiatives and activities addressing interoperability from the SAMI requirement, is that the global approach has been led by an industry drive to reduce fatalities and injuries due to vehicle interaction. This contrasts with the legislation driven requirements in the SAMI. The global industry can thus afford to adopt a 'sit-and-wait' approach, following the lead of the automotive industry. The reality is that the SAMI does not have that luxury and needs to address the interoperability challenges (amongst other CPS technical challenges) urgently.

11. Vicinity detection

Vicinity detection systems can broadly be divided into interconnected and stand-alone systems:

1. Interconnected systems require the sharing of information between different devices. This is often referred to as vehicle-to-everything (V2X) communication. These types of systems are extensively used for CPS in the SAMI. Vicinity detection systems in this category typically make use of global navigation satellite systems (GNSS) and/or radio-frequency time-of-flight (RF ToF).
2. Stand-alone systems do not require the sharing of information between devices. These vicinity detection systems make use of active sensors – sensors that are able to perceive the environment and detect the presence of obstacles without establishing communication with the obstacles. Examples include radar, camera and lidar-based systems. CPS relying solely on these types of sensors are not abundant in the SAMI at the time of writing [July 2021].

Active sensors are often used in conjunction with other sensors requiring interconnectivity and sensor fusion.

V2X networking and communication

Interconnected vicinity detection systems rely on communication between devices installed on machines and issued to pedestrians with devices potentially supplied by different CPS developers. Communication with infrastructure and other networks (such as cellular networks) to improve CPS performance is also possible. Ensuring interoperability between different devices, potentially from different suppliers, in the CPS product system is essential. Efficient V2X communication (low latency) is needed to maximize the time available to the operator/pedestrian to take evasive action, or for the machine to slow down and stop safely. The regulatory requirement that both operators or the operator and pedestrian, as applicable) should be effectively warned implies that V2X are needed for all CPS systems.

V2X communication is a hot topic in the world of Intelligent Transportation Systems (ITS) and has been subject of extensive research and standardisation in the automotive and communications industries over the past few decades. The ICMM ICSV Vehicle

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Interaction working group is monitoring these standards and developments in the automotive industry and aims to follow their lead. This will leverage the billions of dollars invested by the automotive industry to the benefit of the mining industry.

Different standardization bodies have led efforts to specify V2X technologies, especially after the 5.9 GHz spectrum was allocated for ITS in the US and Europe. Three families of standards have emerged, notably the IEEE 1609.x set in the US [6], the ETSI/CEN Cooperative-ITS and the 3GPP Cellular-V2X (C-V2X) approach in Europe. The IEEE and ETSI/CEN approaches use the IEEE 802.11p standard for the physical and data link layers for short-range V2V communication (often referred to as Dedicated Short-Range Communication, or DSRC) [7]. The 3GPP specifications include both short-range specifications for direct communication between vehicles (known as sidelink/LTE-PC5) and for wide area vehicle to network (V2N) communication that allows vehicles to communicate with cellular networks (known as uplink/downlink or LTE-Uu) [8]. The sidelink operates in the 5.9 GHz band, but uplink and downlink bands vary and are based on LTE bands [9].

The 802.11p-based family of standards (known as WAVE in the US and ITS-G5 in Europe) do not rely on communication infrastructure (in contrast to C-V2X) and are thus suited to remote areas. The data volume of 802.11p messages is very low, ensuring low latency [7].

Studies have shown that the 3GPP C-V2X approach provides superior performance to IEEE 802.11p [8, 10], but this is disputed by others [9, 11, 12]. Systems making use of IEEE 802.11p can co-exist with C-V2X systems if they use **different channels in the 5.9 GHz band**. Hybrid ITS network architecture, with the different approaches performing different functions (e.g. safety critical and fleet management) are becoming prevalent. This is discussed at length by Kiela, et al. [9].

C-V2X has the significant benefit that it provides for vehicle to network (V2N) communication in addition to V2V and V2P. This is part of the development of Fifth Generation (5G) technologies that are closely associated with the Fourth Industrial Revolution (4IR) and Internet of Things (IoT) emerging technologies. 5G integration may unlock further benefits through the integration with other peripheral systems, such as fleet management, autonomous hauling, remote operation, condition monitoring and so on [13-15].

Another concerning fact is that ICASA does not make provision for communication in the 5.9 GHz band at the moment [16]. Even though there are products on the international market that support both DSRC and C-V2X [9], it is uncertain if they will be able to obtain ICASA Type Approval.

In summary, the V2X technology currently available on the market is still in an evolution phase with very little industry convergence. Standards are still being developed and new releases/amendments are made before technology complying with the existing version is available in the market. Matters are complicated further with a lack of backwards compatibility as technical issues are addressed in new versions (this is especially true for the C-V2X technologies) [9]. The automotive and telecommunications industries are

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hard at work, developing new technology, but there is very little convergence (for now) [11]. It is thus premature to specify V2X-related interoperability standards for adoption in the SAMI.

However, there are some lessons to be learnt from the rapidly evolving V2X technology, namely:

- V2X communication is vastly different from regular internet protocol (IP), TCP/UDP-based communication. V2X consists of point-to-point ad hoc networks; this is in contrast to typical IP networks with multiple nodes between the source and the endpoint. Several necessary features can thus be removed from typical IP communication because it is unnecessary in a V2X environment [7] and causes unwanted latency.
- V2X communication relies on low latency (typically 1-10 ms, always below 20 ms for safety critical applications) and requires techniques to prevent channel congestion. The strictest latency requirement is for fully autonomous vehicles, limited to 3 ms with up to 1000Mbps data rates [9]. Performance requirements of V2X communication may be specified (as done by SAE J2945/X [17]).
- A standardized message set dictionary must be used to ensure interoperability. A message set dictionary defines the content of messages and their formats. The message set dictionary (such as SAE J2735 [18]) contains a basic safety message (BSM) that is essential to ensure unambiguous communication between different devices (interoperability).

The content of the BSM described by SAE J2735 is given in Table 1. A personal safety message (PSM) is also under development that is intended to be broadcast to vulnerable road users such as pedestrians and cyclists.

Its critical contents are very similar to Part I of the BSM, but it includes information on the user too (such as size and behaviour).

Table 1 – Basic safety message content described by SAE J2735 (adapted from [7] and [19])

BSM Part I – Critical state information	**BSM Part II – Optional information**	**PSM critical content**
Message identifier Message counter Temporary ID Current time Latitude and longitude Elevation Positional accuracy Transmission (gear setting) and Velocity Heading Steering wheel angle Tri-axial accelerations and yaw rate Brake system status (whether braking is active)	Event flags (e.g. hard brake, hazard lights, etc.) Path history Path prediction (expected/intended) GNSS correction information (RTCM format)	Message identifier Message counter Current time 3D position (latitude, longitude and elevation) Positional accuracy Velocity Heading Device type

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Vehicle size (resolution of 1cm)		

Performance testing of V2X is another important aspect of V2X communication that needs to be considered, especially for the case where off-the-shelf components conforming to the discussed DSRC and C-V2X standards are **not** readily available. There are two approaches available, both with relevance, namely the SAE J2945/X family (addressing the system engineering principles, including performance requirements [17]) and the 5GAA P1-180092 [20].

SAE J2945/1 [21] provides the functional and performance requirements for V2V safety and SAE J2945/9 focuses on V2P requirements [22]. The SAE J2945/X family focuses on DSRC communication, with a specific emphasis on the basic safety message (BSM) described by SAE J2735 [18]. The SAE J2945/1 includes requirements for channel and data rates, device start-up, data element accuracy and persistency, congestion control, RF performance requirements, etc. [21].

5GAA P1-180092 [20] includes performance measures for DSRC and C-V2X. 5GAA P-180092 specifies SAE J2735 as the message set dictionary and SAE J2945/1 for the performance requirements for both DSRC and C-V2X. The performance measures are [20]:

1. Packet error rate – the number of missed packets at the receiver from a particular transmitter
2. Inter packet gap - the time between successive successful packet receptions
3. Channel busy percentage – the time during which the wireless channel is busy (this is specific to DSRC)
4. Channel busy ratio – similar to channel busy percentage, but applicable to C-V2X
5. Information age – the time interval between the current time at the receiver and the timestamp applied by the transmitter and contained in the BSM
6. Application end-to-end latency – the time interval between the time instant the transmitter delivers the packet (BSM) to the lower layers (specifically the MAC and PHY layers)
7. Other relevant measures:
    a. Communication properties
        i. Received signal strength indicator (DSRC)
        ii. Reference signal received power (C-V2X)
        iii. Over-the-air message size
    b. V2V kinematic properties such as range, speed, elevation and heading
    c. Device performance (latency)

In conclusion, the V2X technology is not mature yet. It seems likely that future developments in the V2X field will make use of the 5.9 GHz band. This development will be led by the ITS sector, specifically by the automotive industry. TMM OEMs will likely adopt automotive V2X technology for CPS applications and in the process ensure vicinity detection and effective warning interoperability through V2X communication. However, currently, it is unsure if this will be the case. Before V2X communication

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technology has matured, it is impossible to specify standards for V2X communication to ensure interoperability.

SLAM & DATMO

Stand-alone vicinity detection systems are required to perform several tasks to effectively prevent collisions:

1. In the absence of a GNSS, the sensors need to locate the machine within its environment. In some cases, the sensors also map the environment. This is known as Simultaneous Localization and Mapping (SLAM). SLAM is focused on the performance in a static environment and the outputs of SLAM are the location of the machine and a map of the static environment (such as berms, buildings, road signs, power lines, etc.) [23].
2. Once the static environment has been identified, the sensors need to detect dynamic objects that need to be avoided (other TMMs and pedestrians). These moving objects are then tracked. This is known as Detection And Tracking of Moving Objects (DATMO). DATMO includes detecting new objects and assigning them to tracks, modelling dynamic object trajectories, performing data association, omitting objects that are outside of the sensor's field of view, accounting for occluded objects; all while operating robustly [23].

SLAM and DATMO require several techniques to function effectively. A plethora of SLAM and DATMO techniques are available and new and improved approaches are frequently published in the scientific literature [23].

The majority of SLAM and DATMO techniques are based on artificial intelligence (AI) techniques. The fundamental steps of DATMO include:

1. Ground removal (separating the static environment and the dynamic objects).
2. Clustering measurement points (grouping a set of measurement points together to form an object) and classifying the object (i.e. a haul truck as opposed to a pedestrian).
3. Estimating the pose of detected objects (determining where the detected objects are pointing and heading, etc.).
4. Assigning objects to tracks and managing these tracks (i.e. realising that measured data belongs to a single object and identifying that object as a single object, not multiple different objects).

As a result, many SLAM and DATMO techniques require some form of machine learning (ML). This inherently means that vicinity detection systems that utilizes ML are **nondeterministic** – in other words, the same inputs to the system may produce different outcomes. This means that CPSs that use SLAM and DATMO for vicinity detection will need to be trained with data that represents the environment within which they will be used. Some of the consequences are:

1. It is possible that a CPS that has been trained and deployed successfully on Mine A may not function on Mine B, because of the change in environment (such as colour of the roads, shape of the berms, type, size, shape and colour of TMMs,

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colour of the overalls worn by pedestrians, etc.). Such a system will have to undergo a period of retraining so that it can perform according to specification.
2. A generic training data set does not exist and may be impossible to obtain (too many variables).

A further complication is the requirement of effective warning for pedestrians in underground mines and for both TMMs in surface mines. This implies that V2X communication is necessary even for SLAM and DATMO based CPS.

The mining industry is accustomed to systems that are predominantly deterministic, meaning that they respond predictably to known and understood states, failure modes, and conditions. In contrast, nondeterministic systems respond to conditions based on probability and hence their behaviour is not easily quantified [24].

Of serious concern is the functional safety of CPS, especially for the case of nondeterministic systems. This concern is shared by the ICMM ICSV vehicle interaction working group, EMESRT, the Construction and Mining Equipment Industry Group (CMEIG) and the Global Mining Guidelines Group (GMG) [24, 25]. These institutions offer the following guidance:

1. In the interim, a risk-based evaluation approach that combines traditional and evolving risk management techniques including extensive testing. This interim approach will require strong engagement and collaboration between stakeholders – see [25] for details.
2. Following the lead of the automotive industry. The ISO/PAS 21448:2019 standard evaluates the intended functionality of nondeterministic safety systems [26]. This is through extensive validations over a series of use/misuse cases.
3. Adopting new standards as they emerge, notably from the ISO/TC 127 earthmoving machinery committee.

EMI/EMC

Electromagnetic interference (EMI) and compatibility (EMC) are important considerations for interoperability. EMC is needed for both **sensing and communications (V2X)** [27, 28]. This can be illustrated with two examples:

1. **Sensor** – Automotive radars typically operate in the 76-81 GHz band. It is entirely possible that multiple vehicles (say Car A and Car B), within close proximity to each other, will be equipped with radars operating in similar frequency ranges (bands). The radar signal by Car B can be "detected" by Car A. This may mask true targets that Car A would otherwise have been able to detect. Radar congestion is a serious concern and was the subject of an extensive study by the National Highway and Traffic Administration (NHTSA) in the US [28]. Proper **filtering** at the signal processing level can circumvent this masking (interference).
2. **V2X** – As discussed extensively in the V2X section, interference is possible due to the existence of **multiple standards** in the 5.9 GHz band (IEEE 802.11p vs. 3GPP C-V2X). Careful channel management is necessary to avoid this.

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Fortunately, EMI/EMC is a mature field and detailed considerations have been given to ensure EMC in the relevant section. Please refer to the EMI/EMC report of this project for detailed discussions and recommendations.

Implications for industry

The implications for the SAMI are:

1. Due to the effective warning requirement, V2X communication is required by all CPS systems in the SA market.
2. The V2X communication industry is undergoing rapid development and there is little standardization. Off-the-shelf components are not readily available in large quantities (at least not before they are replaced by newer, better components).
3. V2X communication is built on a common dictionary (the message that is shared between CxDs) and a standardized communication protocol. A common dictionary is already available (the SAE J2735 standard), but the protocol is the part undergoing rapid development. While the protocol is evolving, the CPS vendors in the SA market may adopt other communication protocols. These communication protocols will not be fit for purpose and will be subject to latency. Latency is to be avoided at all costs. Such communication protocols will also lack standardization and limit interoperability.
4. The status quo in the current SAMI is that a third party CxD provider commissions all machines on a specific site, hence ensuring interoperability of V2X communication. This is expected to be an interim condition and will change once factory fitted CxDs become available from large TMM OEMs.
5. The overwhelming majority of CxDs in the SAMI currently make use of interconnected sensors, with little to no adoption of camera or lidar technology for collision prevention purposes. Radars are becoming prevalent on surface TMMs, but as a short-range sensor used for pedestrian and other obstacle (such as infrastructure, boulders, etc.) detection. Very little machine learning-based vicinity detection is currently available in the SA market. This implies that adopting a 'safety of the intended function' approach as described by ISO/PAS 21448 is not yet necessary and it will have very little short-term impact on the SAMI. As CxDs utilizing machine-learning techniques become available on the market, adherence to ISO/PAS 21448 is required.
6. EMI/EMC testing is needed to ensure compatibility of sensors and V2X communications. This is addressed extensively in the EMI/EMC document.

12. CxD>>Machine interface

The CxD to machine interface establishes information transfer between the machine and the CxD. Information is transferred in both directions. There are three examples illustrating the majority of current and expected configurations:

1. **End-state intelligent machine with factory fitted CPS.** In this case, the CxD is completely integrated with the TMM by the TMM OEM during factory assembly. Information shared between the CxD and TMM is completely internal and under the control of the TMM OEM. *Any* interface may be used in this case.

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2. **Current, legacy machines with no (or limited) on-board electronics.** This is a typical example in the SAMI at the time of writing [June 2021]. Typically, a third party retrofits an electronic interface to the TMM. This interface element provides communication to the CxD based on measurements taken from the TMM (such as brake line pressure, wheel speed, etc.) and implements automatic slowdown and stop by actuating valves and other mechanical components fitted to the TMM. Two interfaces thus exist in this configuration:
    a. The coupling between the interface element and the TMM, typically an array of relays and other mechanical components.
    b. The coupling between the interface element and the CxD. The interface element may be provided by the CxD supplier or by an additional third party. These two parties need to agree on an interface protocol. It is recommended that the latest version of ISO/TS 21815-2 [4] be used
3. **Intelligent TMMs with OEM fitted CxD>>Machine interfaces.** This is a scenario that is becoming more prevalent in the SAMI, especially with ADTs. The TMM is fitted with a CxD>>Machine interface by the TMM OEM (either factory fitted or retrofitted). The TMM OEM typically specifies the ISO/TS 21815-2 interface protocol [4]. Any CxD developer that complies with the requirements of ISO/TS 21815-2 should then be able to interface with the TMM. It is highly unlikely that the TMM OEM in such a scenario will specify a different protocol.

It is important to understand the information shared in the CxD>>Machine interface as specified in ISO/TS 21815-2. The information sharing protocol described in ISO/TS 21815-2 [4] is an excellent example of what information should be shared and how it should be done:

1. Information is shared via a Controller Area Network (CAN) bus.
2. ISO/TS 21815-2 specifies the connectors and makes provision for CAN HI and LO, power supply and grounding, and override switches.
3. ISO/TS 21815-2 makes provision for information sharing with four logical groups (messages). Provision has been made for further messages in future revisions of the specification. The four logical groups are:
    a. CxD>>machine status – actions and enquiries sent by the CxD to the machine that modify the machine configuration (such as loading new speed set points).
    b. CxD>>machine command – actions and enquiries sent by the CxD to the machine that affect the machine state (such as slowing down, limiting speed, preventing movement, or stopping).
    c. Machine>>CxD reply – the response of the machine to CxD actions or enquiries (such as confirming that a speed limit controller is available and that the machine is acting on instructions from the CxD).
    d. Machine>>CxD data – data provided by the machine to the CxD (such as speed, direction, gear position, payload status, pitch, and roll).

The final version ISO/TS 21815-2 was published in July 2021 – CxD developers and TMM OEMs will need time to implement the finalized protocol. The current challenges with ISO/TS 21815-2 include:

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1. The technical specification was published in July 2021, and thus no adoption of the published version is currently available.
2. Several draft versions have been in circulation for many years. There are significant changes between draft versions. Currently, many CPS developers active in the SAMI will claim ‘ISO21815 compliance’, but without specifying which version (not even specifying part 2 of the specification) and whether the entire communication protocol has actually been implemented, verified and validated.
3. The technical specification does not make provision for unintelligent TMMs (i.e. without controllers and CAN-bus features).
4. The technical specification specifically states that it is not intended to be used in a plug-and-play manner. Details, such as negotiation and handshaking between CxD and machine, are not specified. These details need to be agreed upon by the various parties and are a serious cause for concern.

EMI/EMC

Already addressed in EMI/EMC document, specifically IEC 61000-4-6, potentially IEC 61000-4-5 too. The EMI/EMC requirements have been discussed in detail in the section on EMI/EMC.

Implications for industry

It is recommended that ISO/TS 21815-2 is specified for all TMMs (including unintelligent TMMs that need to be retrofitted with a suitable interface). This is the current trajectory of the industry and aligns with earlier work supported by the Minerals Council SA.

13. CxD>>Human interface

The importance of the human as an element in the CPS product system must be emphasised. The Mine Health and Safety Act’s (MHSA) requirement that operators and pedestrians be given ‘effective warnings’ before the CxD intervenes (auto slowdown and stop) [29], the interface between the CxD providing the effective warning to the TMM operator and the interface between the pedestrian warning system (PWS) and the pedestrian is of crucial importance. It is entirely plausible that different CxD>>Human interfaces will be in use on a particular site, hence ensuring that the interfaces are standardized is critical to achieving interoperability.

The MHSA requires an effective warning, but the regulation does not provide an explicit definition of an effective warning. A detail regulatory analysis was done as part of the CMS Technical Requirements Guideline review and documented in the review report.

Two key points were confirmed:

1. The operators of both TMMs must be warned (for the case of a potential collision on a surface mine between two or more TMMs).
2. If the operators are expected to take action after being warned to avoid the potential collision, they must be granted reasonable opportunity to take the action. An effective warning therefore also includes the time that an operator is given to respond to the effective warning in order to avoid a potential collision.

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These key points describe the functional requirements of an effective warning, but they do not address the technical requirements. In general, it is expected that an effective warning will consist of a combination of visual, audible and haptic instruction:

1. A visual instruction may be a warning light or a graphic user interface.
2. An audible instruction may be a buzzer, alarm or voice command.
3. Haptic instruction may be a vibrating element drawing the human's attention.

One of the fundamentals of the CPS product system is to warn the relevant parties of a potential collision. The MHSA clearly states that the warning shall be effective, however no definition is provided. Wagner, et al. [30] defines a CPS warning as effective if its presence increases the probability that the concerning parties are able to locate and identify the potential collision. This implies that the operator will have to be given enough time to perceive the warning, attend to the CxD human interface, interpret the information to understand the situation, and to decide on a course of action to rectify the situation [31]. An effective warning will maximize the time available to the operator to take the correct evasive action.

Two case studies provide context to be considered.

Surface case study: Horberry, et al. [31] details a case study in which fatalities involving dump trucks were examined and presents important findings of the effectiveness of the CxD human interface. The vast majority of dump truck fatalities were found to have resulted from the operator not having an accurate understanding of the location and movements of other vehicles and pedestrians in his/her vicinity. The findings of this study concluded that, unsurprisingly, a CPS product system had a noticeable effect on reducing collisions, regardless of the type of interface. However, it was also found that a descriptive schematic interface showing a mini map of the vicinity reduced the potential for collision more so than a simpler interface displaying only basic information of the surrounding area to the operator. Driver experience significantly affected the role CPS played in avoiding collisions, with novice drivers more reliant on the support and guidance of the CPS interface.

Underground case study: Cooke and Horberry [32] analysed an incident where a LHD struck a LDV in an underground gold mine. The LHD had only a collision warning system installed, and the system could not auto retard and stop. Following the incident, it was found that the operators had negative opinions on the CPS system that lead to them disregarding the information displayed to them. A few basic changes were made to the CxD human interface and the acceptance of the interface was re-evaluated. It was found that by shortening the audible warning, flashing a visual warning only once, and clearly showing the most recent detected vehicle in the vicinity, improved the overall acceptance of the CPS by the operators. The authors concluded that the effectiveness of the CPS system is difficult to quantify, but that the acceptance of the technology will be a good indicator of its effectiveness.

Achieving an effective warning

Achieving an effective warning by applying human factors during design is an established field of research. Following established guidelines when designing a human

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interface is the first step to achieving intuitive, easy to understand interfaces that will aid in addressing the interoperability challenge. Table 2 discusses ergonomics standards and guidelines with relevance to human interface design.

Table 2 – Standards and guidelines relevant to achieving effective warning

Standard/Guides	Description
SANS 1610 (ISO 6011)	**Earth-moving machinery - Visual display of machine operation**. The machine operation functional information to be presented by the visual displays of earth-moving machinery for a seated operator are specified. Visual display of information specified (readable, colour related specifics, operator sector of vision).
SANS 6405	**Earth-moving machinery — Symbols for operator controls and other displays** Describes common symbols and symbols specific to types of earth moving equipment.
SANS 259	**Earth-moving machinery — Operator's field of view — Test method and performance criteria** Describes a static test method for determining and evaluating the operator's visibility. Not applicable to "effective warning" since the operator has already not seen the hazard but may be useful in determining limitations to operator visibility.
Dover/Vienna testing [33]	The **Dover/Vienna test** is a psychomotor test that includes: • multiple stimuli reaction test • attention and spatial perception • visual structuring, glare recovery and visual perceptual field identification • measures the ability to co-ordinate movement and determine practical learning ability through speed-accuracy variables • measurement of time, movement and distance estimation
Human factor design guideline [30]	Extensive information on visuals, audible warning, font sizes, control interfaces, colours, etc. • Visual o Alerting and warning displays shall result in a greater probability of a maintainer's detecting the triggering condition than would be the case in their absence.

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	o The limits that initiate an alarm or warning display should be set so that the alarm gives maintainers adequate time to respond to the condition. o If multiple systems can issue an alarm at the same time, the operator must be able to differentiate priority. o Visual alarms should be singular in purpose yet comprehensive in meaning. o Automatic clearing of alarms. The equipment or system that triggers an alarm shall clear the alarm automatically when the triggering condition no longer exists. • Audible; o Audio warning signals should consist of two elements, an alerting signal and an identifying or action signal. o Audible alarms used in conjunction with a visual display, an audio warning device shall be supplementary or supportive. o Alarms shall exceed the prevailing ambient noise level by at least 10 dB(A) or any maximum sound level with a duration of 30 sec. by at least 5 dB(A), whichever is louder.

In summary, the standards and guidelines highlight the following important aspects:

1. **Training:** For the warning to be effective, the person that receives the warning must be able to interpret and react to the warning in the shortest possible time. Thus, training of the person on the specific human interface that he/she will be using is important and should be included as part of the TMM training that the operator receives. Simulators, if used, should include the human interface. The duration and extent of training for operators on the CxD human interface needs to be addressed.

   It is at least expected that the operator receives formal training with the CPS product that is fitted to his or her machine, and therefore will have to undergo re-training if there has been an update or change to the human interface.

2. **Standardised display:** Since there are only guides and no standardised way of displaying information to the operator, it can be expected that human interfaces between CPS systems will vary and cause confusion in operators.

   CPS vendors should follow sound human-equipment interface design practises and should at least include the basics as recommended in this document. The test regime of the CPS product system should include an evaluation of the effectiveness on the interface as well.

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3. **Excessive information**: In a complex environment with multiple interactors, the CPS interface may provide an excessive amount of information to the operator and will lead to the warning being ineffective.
   If multiple potential collisions can be displayed to the operator simultaneously, they must be prioritised to allow the operator to determine which is the most probable collision.

4. **False-alarm rate:** False alarms are encountered in the form of false positives and false negatives. False negative means that a potential collision was not detected, and a collision occurred. False positive means that a potential collision was detected when there was no potential collision.
   Achieving zero false positives and negatives is virtually impossible. Typically, CxD developers will err on the side of caution, preventing all false negatives but allowing for a small number of false positives. Naturally, the number of false alarms should be as few as possible; however, it will also be impossible to have it completely eliminated.

   An acceptable number of false alarms has to be defined (such as zero false negatives, one false positive per machine per shift). This number may vary significantly between surface and underground mining operations.

5. **Evaluation of the system's effectiveness**: objectively evaluating the effectiveness of the human interface is a specialist field and should be conducted by an expert.

   Since collisions are relatively rare on South African mine sites, analysing number of fatalities to determine the effectiveness of the human interface may be a slow process. A survey of the operators' acceptance of the CPS product system could be a better approach to evaluate the human interface (be it in a qualitative manner).

Recommendations and implications for industry

To achieve interoperability of CPS human interfaces, the following is recommended:

1. **Ergonomic guidelines should be followed when designing the human interface**. Horberry, et al. [31] lists several design guidelines for the human interface design, and the most relevant are listed below;
   - CPS interface should make use of both visual and auditory displays.
   - Visual displays should be placed within the operator's field of view, as defined by SANS 1610 (or ISO 6011).
   - CPS interface should provide identity, position and velocity information of a nearby vehicle to the operator.
   - Auditory warnings should be used only if there is a potential collision and should not be repeated more than three times per incident.

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- Speech based auditory warnings, if used, should be limited to a single word, for example "Move left!"
- Auditory warnings should be directional to orientate the driver's attention to the location of the collision.
- If multiple potential collisions are present, the auditory warning should only address the highest priority collision, while the other potential collisions should be displayed visually.

Several other recommendations in [30] and [31] address specifics such as levels, intensity, duration, etc. with regard to visual and audible warnings. CPS developers should consult these guides.

2. **The effectiveness of the human interface must be evaluated**, either by consulting an expert, or by conducting surveys on the operators. The effectiveness of the human interface is of the highest importance to ensure that the system is accepted and trusted.

14. CxD>>Peripheral systems

Moore [13] discusses some core mining truck issues, with a specific focus on autonomy and provides examples from mines and TMM OEMs around the world. He states that the benefits of autonomy are finding wider applications and are not limited to large OEMs any longer. One specific benefit that is being leveraged is the integration of Autonomous Hauling Systems (AHS) with Fleet Management Systems (FMS). FMS is being integrated with safety layers, traffic control systems and so on. Integration of the CxD with peripheral systems is typically done via an Application Programming Interface (API). Several open source APIs are available (such as OpenAPI, AsynchAPI, etc.) or they may be proprietary (developed through collaboration between CxD developers and peripheral system developers).

The integration of CPS with peripheral systems such as FMS, fatigue management and condition monitoring is anticipated and expected to be part of the ongoing fourth industrial revolution. CPS provides information that should be leveraged by the SAMI to improve safety, increase productivity and reduce operational costs by making informed decisions.

15. Installation, maintenance and repair

The success of a CPS will rely on the technical support during its operational life. As mentioned earlier, mining machines have extended operational lifespans, on the other hand, computer technologies are often obsolete (written off) within three years. It is thus entirely feasible that multiple different CPS technologies will be fitted to various machines at different stages of their operating life. The procurement of second hand TMMs from other mine sites will also introduce different versions of CPS technologies to a single mine site. All of these versions of CPS will need to be installed, maintained and repaired by skilled artisans; they will need efficient supply chains to provide the components needed for maintenance and repair. Upgrading of CPS technologies (as is the norm for software-based technologies) will need strict version control to ensure their continued operation.

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16. References

[1] K. Kosanke, "ISO Standards for Interoperability: a Comparison," London, 2006, pp. 55-64: Springer London.

[2] IEEE., *The Authoritative Dictionary of IEEE Standards Terms, Seventh Edition* (IEEE Std 100-2000). New York, NY: The Institute of Electrical and Electronics Engineers, Inc., 2000, pp. 1-1362.

[3] Global Mining Guidelines Group. (2019, 31 May 2021). *ICMM Innovation for Cleaner, Safer Vehicles Initiative (ICSV) – Vehicle Interaction (VI) workstream*. Available: https://gmggroup.org/interoperability/icmm-innovation-for-cleaner-safer-vehicles-initiative-icsv-vehicle-interaction-vi-workstream/

[4] *ISO/TS 21815-2 Earth-moving machinery - Collision warning and avoidance - Part 2: On-board J1939 communication interface*, 2021.

[5] Earth Moving Equipment Safety Round Table. (2021, 31 May 2021). *Vehicle Interaction*. Available: https://emesrt.org/vehicle-interaction/

[6] *IEEE Guide for Wireless Access in Vehicular Environments (WAVE) Architecture*, 2019.

[7] J. B. Kenney, "Dedicated short-range communications (DSRC) standards in the United States," *Proceedings of the IEEE,* vol. 99, no. 7, pp. 1162-1182, 2011.

[8] V. Vukadinovic *et al.*, "3GPP C-V2X and IEEE 802.11p for Vehicle-to-Vehicle communications in highway platooning scenarios," *Ad Hoc Networks,* vol. 74, pp. 17-29, 2018/05/15/ 2018.

[9] K. Kiela *et al.*, "Review of V2X–IoT standards and frameworks for ITS applications," *Applied Sciences,* vol. 10, no. 12, p. 4314, 2020.

[10] 5GAA. (2017, 10 June 2021). *An essessment of LTE-V2X (PC5) and 802.11p direct communications technologies for improved road safety in the EU*. Available: https://5gaa.org/wp-content/uploads/2017/12/5GAA-Road-safety-FINAL2017-12-05.pdf

[11] A. Filippi, K. Moerman, V. Martinez, A. Turley, O. Haran, and R. Toledano, "IEEE802. 11p ahead of LTE-V2V for safety applications," *Autotalks NXP,* pp. 1-19, 2017.

[12] A. Turley, K. Moerman, A. Filippi, and V. Martinez. (2018, 10 June 2021). *C-ITS: Three observations on LTE-V2X and ETSI-ITS G5*. Available: https://www.nxp.com/docs/en/white-paper/CITSCOMPWP.pdf

[13] P. Moore. (2021) All knowledge is fleeting. *International Mining*. 26-33.

[14] N. Odendaal. (2020) Full 5G adoption in mining still years away. *Mining Weekly*. Available: https://www.miningweekly.com/article/full-5g-adoption-in-mining-still-years-away-2020-08-24

[15] Epiroc Makina A.S. (2021, 10 June 2021). *5G moves mining forward*. Available: https://www.epiroc.com/en-ge/customer-stories/2019/5g-moves-mining-forward

[16] Independent Communications Authority of South Africa, "The Radio Frequency Spectrum Regulations 2015," *Government Gazette (Notice 279 of 2015),* vol. No. 38641:3-104, 30 Mar 2015, 2015.

[17] SAE international. (2017, 3 June 2021). *Dedicated short range communication (DSRC) systems engineering process guidance for J2945/X documents and common design concepts*. Available: https://www.sae.org/standards/content/j2945_201712/

[18] SAE international. (2020, 3 June 2021). *V2X communications message set dictionary J2735*. Available: https://www.sae.org/standards/content/j2735_202007/

[19] Tome Software. (2019, 11 June 2021). *Updating the Basic Safety Message to communicateVulnerable Road User (VRU) information using Bluetooth 5*. Available: https://www.tomesoftware.com/wp-content/uploads/2019/10/B2V-Whitepaper-VRU-BSMs-over-BT5-October-28-2019.pdf

[20] 5GAA. (2018, 11 June 2021). *V2X Functional and Performance Test Procedures – Selected Assessment of Device to Device Communication Aspects*. Available: https://5gaa.org/wp-content/uploads/2018/10/5GAA_P-180092_TR_V2X_FP_Test_Procedures_v1.1.pdf

APPROVED

Permission to use information presented herein to be granted by **Minerals Council South Africa** prior to use.

[21] SAE international. (2020, 3 June 2021). *Vehicle Level Validation Test Procedures for V2V Safety Communications J2945/1A_202007*. Available: https://www.sae.org/standards/content/j2945/1a_202007/
[22] SAE international. (2017, 11 June 2021). *Vulnerable Road User Safety Message Minimum Performance Requirements J2945/9_201703*. Available: https://www.sae.org/standards/content/j2945/9_201703/
[23] A. Pancham, N. Tlale, and G. Bright, "Literature review of SLAM and DATMO," in *4th Robotics and Mechatronics Conference of South Africa (RobMech 2011)*, CSIR International Conference Centre, Pretoria, 23-25 November 2011, 2011.
[24] C. Sathe and G. Topham. (2020, 14 June 2021). *Guideline for applying functional safety to autonomous systems in mining*. Available: https://gmggroup.org/wp-content/uploads/2020/08/20200709_Guideline_for_Applying_Functional_Safety_to_Autonomous_Mining_Systems-GMG-AM-FS-v01-r01.pdf
[25] CMEIG. (2020, 14 June 2021). *White paper and guiding principals - Functional safety for earthmoving machinery*. Available: https://www.cmeig.com.au/wp-content/uploads/CMEIG-EMESRT-ICMM-White-Paper-and-Guiding-Principles-for-Functional-Safety-on-Earthmoving-Machinery-Ver.-0.5.pdf
[26] *ISO/PAS 21448 Road vehicles - Safety of the inteded functionality*, 2019.
[27] A. Bajwa. (2020, 11 June 2021). *EMC/EMI challenges for the connected car*. Available: https://interferencetechnology.com/wp-content/uploads/2020/05/2020_Automotive_EMC_Guide.pdf#page=12
[28] Z. Peterson. (2020, 11 June 2021). *Overcoming 76-81 GHz automotive radar EMC challenges*. Available: https://interferencetechnology.com/wp-content/uploads/2020/05/2020_Automotive_EMC_Guide.pdf#page=12
[29] *Mine Health and Safety Act 29 of 1996 and Regulations,* Mine Health and Safety Council, 2018.
[30] D. Wagner, J. A. Birt, M. D. Snyder, and J. P. Duncanson, "Human factors design guide for acquisition of commercial-off-the-shelf subsystems, non-developmental items, and developmental systems," 1996.
[31] T. Horberry, R. Burgess-Limerick, and L. Steiner, "Human centred design for mining equipment and new technology," in *Proceedings 19th Triennial Congress of the IEA*, 2015, vol. 9, p. 14: Citeseer.
[32] T. Cooke and T. Horberry, "Driver satisfaction with a modified proximity detection system in mine haul trucks following an accident investigation," *Ergonomics Australia,* vol. 2011, pp. 1-6, 2011.
[33] N. Christodoulou. (2021, 28 June 2021). *Dover Systems Testing*. Available: https://doversystems.co.za/

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Permission to use information presented herein to be granted by **Minerals Council South Africa** prior to use.