Collision Prevention System Test Verification Project

Final Report

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Executive summary

This document represents the final deliverable resulting from the Service Level Agreement (SLA) established between the Minerals Council South Africa (referred to as the Minerals Council) and the University of Pretoria (UP). The purpose of this agreement was to verify the Collision Prevention System (CPS) Test Specification. UP developed CPS testing instrumentation to this end and carried out trial runs of the various test protocols as outlined in the SLA.

The primary objectives of this document are to assess and report on several key aspects:

1. **Clarity and Feasibility:** The document evaluates the clarity of each test instruction and the feasibility of executing them consistently. While most instructions are clear, some updates are necessary to enhance clarity and consistency.

2. **Definition and Consistency:** It highlights the need for revisions and additions to definitions in all the CPS documents. Ensuring consistent terminology usage across documents will reduce uncertainty among CPS product developers and may expedite and enhance CPS product maturity.

3. **CPS User Requirements (URS):** The CPS URS, especially in interaction scenarios, requires review. This review should include defining significant risks associated with each scenario to refine the CPS user requirements.

4. **CPS Test Regime:** Currently, the CPS Test Regime does not explicitly list brake performance testing, ICASA type approval and electromagnetic compatibility testing. The CPS Test Regime needs to be updated to clearly indicate where these tests fit in. Additionally, the test regime needs to be adjusted to accommodate current test capabilities and resources.

5. **Alignment:** Closer alignment between the CPS Functional and Technical Performance Requirements (FTPR) and the CPS Test Specification is recommended. This will facilitate and expedite adoption and alignment within the South African Mining Industry (SAMI).

6. **Resource Considerations:** Resource availability, including suitable proving grounds, human resources, and test vehicles, poses challenges to testing surface CPS products. Modifications to the CPS Test Specification are recommended to accommodate current constraints, with an emphasis on allowing off-site testing. Funding for a dedicated CPS-focused proving ground is essential for the long-term sustainability of CPS in the SAMI.

7. **Reporting Structure:** A reporting structure has been developed to communicate the outcomes of CPS product verification and validation tests effectively. This structure aims to provide detailed technical feedback to CPS product developers and concise, high-level overviews to CPS end-users.

8. **International Engagement:** Further engagement with international bodies, such as the ISO Technical Committee TC 0082, is necessary to enhance the ISO/TS 21815-2:2021 protocol. Anticipated additions to the ISO/TS 21815 family of standards in the near future should be considered for inclusion in future CPS document reviews/updates. The involvement of individuals with profound knowledge of SAMI's technical challenges pertaining to CPS is crucial in this process.

This final report encapsulates the key findings and recommendations from the comprehensive evaluation of the CPS Test Specification and related documents. The outcomes of this evaluation contribute to the refinement and improvement of CPS testing processes and specifications within the SAMI.

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Nomenclature

Table 1: Nomenclature

Acronym	Description
CM&EE	Consulting Mechanical and Electrical Engineers
CPS	Collision Prevention System
CxD	Collision Warning and Avoidance System Device
EMC	Electromagnetic compatibility
EMESRT	Earth Moving Equipment Safety Round Table
EMI	Electromagnetic interference
FTPR	Functional and Technical Performance Requirements
GNSS	Global Navigation Satellite System
GSS	Ground Speed Sensor
GTF	Gerotek Test Facilities
ICASA	Independent Communications Authority of South Africa
IMU	Inertial Measurement Unit
ISO	International Organisation for Standardization
LDV	Light Duty Vehicle
MMP	Mandela Mining Precinct
MOSH	Mining Occupational Safety and Health
OEM	Original Equipment Manufacturer
RFI	Radio Frequency Interference
SABS	South African Bureau of Standards
SAMI	South African Mining Industry
SECDI	Safety Engineering Competency Development Institute (Pty) Ltd
TA	Type approval
TMM	Trackless Mobile Machine
TRL	Technology Readiness Level
UG	Underground
UP	University of Pretoria
URS	User requirements
VPRS	VBOX Precision Ranging System

1 Introduction

The Minerals Council South Africa (referred to henceforth as the Minerals Council) contracted the University of Pretoria (UP) to conduct the verification of the Collision Prevention System (CPS) testing protocols as contained in the CPS Test Specification[1]. The aim of the verification project is to ensure that the CPS testing protocols are fit for purpose prior to being implemented and executed. The verification project consists of the following key objectives:

1. Test capability development
2. Test protocol verification
3. Reporting key learnings

This document is the final report, summarizing the work completed and the key findings for dissemination by all the relevant stakeholders. Additionally, work outside of the scope of this project but key to the CPS ecosystem readiness in South Africa, has been completed and is documented here. Finally, next steps are recommended.

[1] Available from https://www.mosh.co.za/transport-and-machinery/documents

2 CPS test capability development

2.1 Background

Verification of the test protocols in the CPS Test Specification is a significant task and requires the development of emulators and measurement systems. The CPS Test Specification is novel; no other test regime contains such a complex set of test instructions. In the automotive world, the industry standard is to use a simulation environment for complex tests such as these. There is no independent institution in South Africa with sufficient capability and expertise to verify CPS products against the CPS specifications (neither through simulation, nor testing).

TMM and CxD emulators have to be developed and commissioned to conduct Technology Readiness Level (TRL) 4 verification testing. An emulator is a piece (or pieces) of hardware and software that behaves similar to another product without actually being that product. The emulator allows another system to interface with it, without affecting the performance of the other system. The intent is that a CPS product, such as a Collision Warning and Avoidance System Device (CxD), can be seamlessly integrated with a TMM emulator. The TMM emulator is then used to test the CxD functionalities against the CPS FTPR at TRL4. Similarly, a CxD emulator is integrated with a TMM to verify the TMM's performance against the CPS FTPR. Figure 1 and Figure 2 respectively show the system architecture of the CxD and TMM emulators and how they are integrated with the equipment under test during TRL4 verification testing.

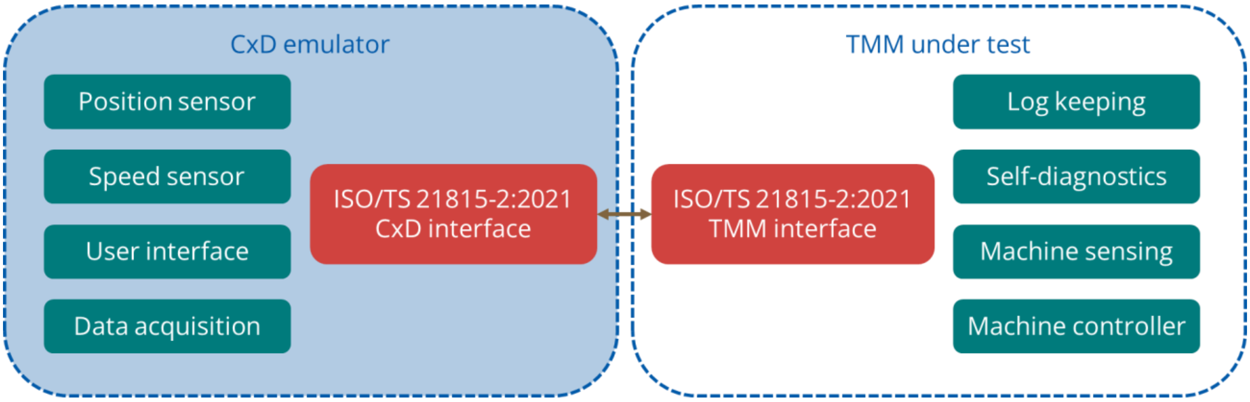

Figure 1: CxD emulator used to conduct TRL4 verification tests of TMMs

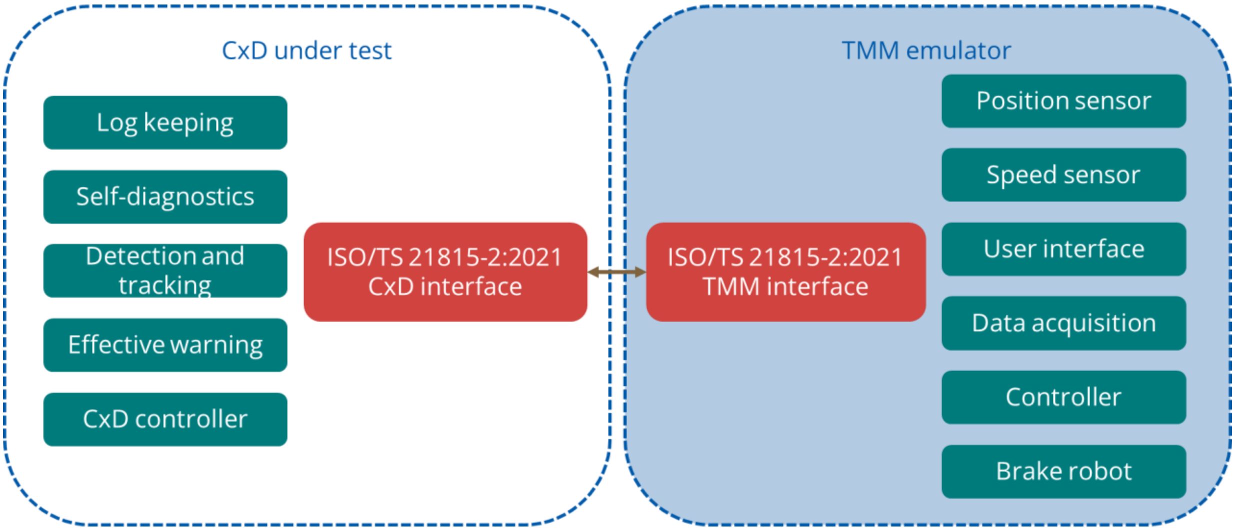

Figure 2: TMM emulator used to conduct TRL4 verification tests of CxDs

Once TRL4 testing is complete, CxD and TMM products are integrated with one another to form the CPS. TRL6 and higher testing does not require an emulator; it requires a CPS test kit. Figure 3 shows the system architecture of the CPS along with the CPS measurement kit.

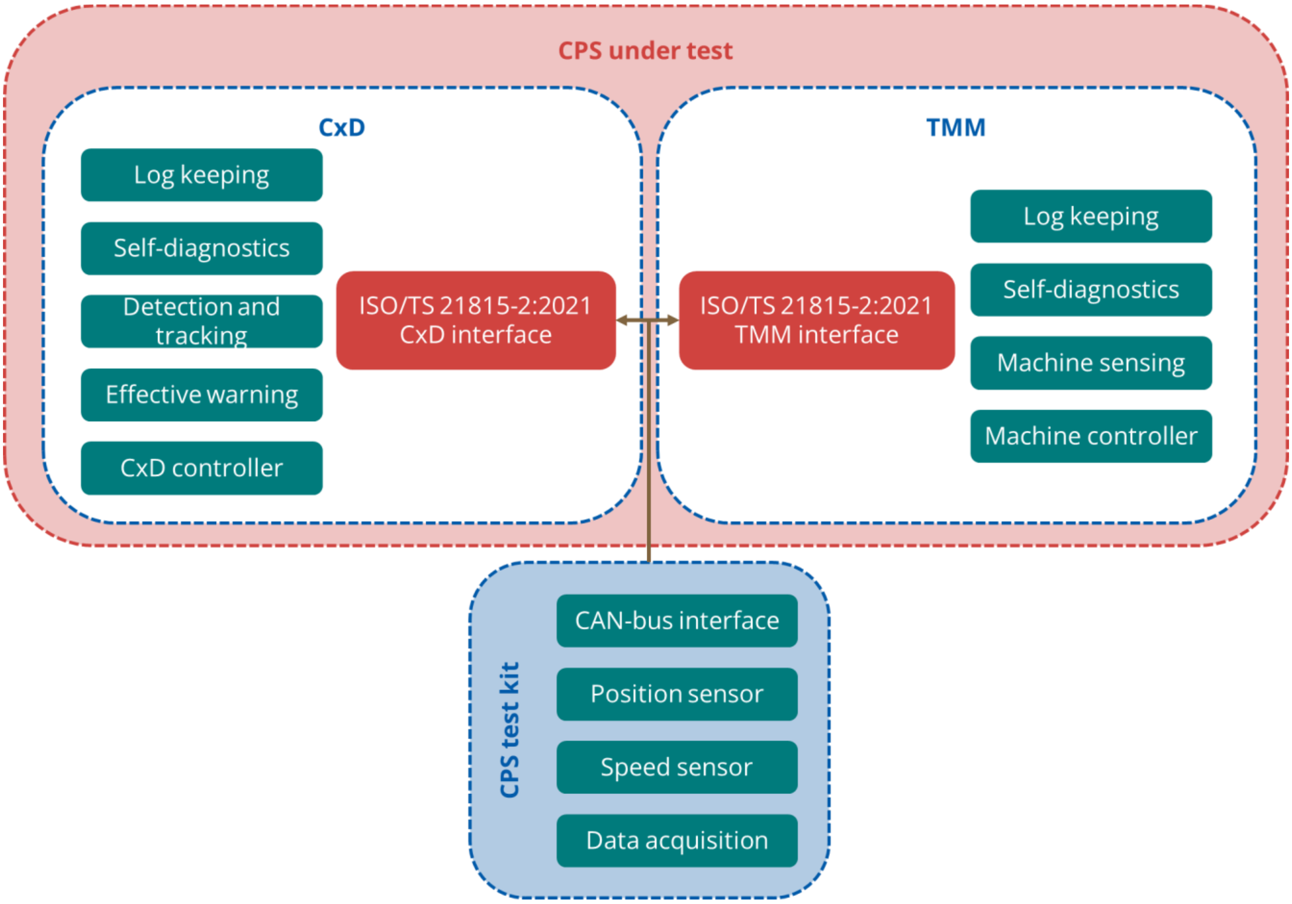

Figure 3: CPS test kit used for TRL6 and higher testing

2.2 Test instruments

The emulators and measurement kit have very similar functions, but the environment in which they will be used differ significantly. While all of the TRL4 CxD tests are conducted on surface, TRL4 TMM tests may be necessary wherever the TMM under test is located. This necessitates test instruments that can operate in various environments, ranging from a proving ground such as Gerotek Test Facilities (GTF), UP's vehicle laboratory, to both surface and underground mines. TRL6 and TRL7 testing will also typically take place in challenging environments. Although the states measured are very similar at all TRLs, the environment (and thus the measurement principle) will change. Test instruments that are robust and effective in these environments are needed. This section provides an overview of the instruments procured to achieve these objectives.

Table 2 summarizes the test instruments procured to develop the emulators and CPS test kits. A brief description of each instrument, the states it measures and its intended use are provided. Additionally, Figure 4 to Figure 8 show examples of these instruments.

Table 2: Summary of test instruments

Instrument	Description	Measured states	Use
Racelogic VBOX VB3i differential GNSS with dual antenna and IMU	High precision GNSS	Position Heading Speed Accelerations Rotational velocities	• TRL4 CxD testing • TRL4 TMM testing • TRL6 surface CPS testing • TRL7 surface TMM testing
Racelogic VBOX Sigma	Standard precision GNSS	Position Heading Speed	• TRL4 surface CxD testing
Racelogic VBOX Precision Ranging System (VPRS)	Ranging system for use when there is no satellite coverage	Position	• TRL4 underground TMM (if test is underground) • TRL4 underground CxD robustness testing • TRL6 underground CPS (if test is underground)
DICKEY-john Ground Speed Sensor (GSS)	Speed measurement sensor when there is no satellite coverage	Speed	• TRL4 underground TMM (if test is underground) • TRL4 underground CxD robustness testing • TRL6 underground CPS (if test is underground)
Logitech Webcam C310 HD	USB webcam	Video	• TRL4 CxD Effective Warning
Ewellix CASM-series linear actuators with Dunkermotoren drives	Actuators used to develop brake robot	None	• TRL4 CxD logic testing
dSPACE MicroAutoBox III	Real-time computer used to acquire data from sensors, interface with equipment under test and to control brake robots	None (records all sensor measurements)	All tests
Intrepid Control Systems neoVI PI	Alternative to dSPACE MicroAutoBox III with more limited functionality	None (records all sensor measurements)	• TRL4 CxD surface detection and tracking • TRL4 CxD surface logic testing
DJI Mavic 3 Enterprise	Unmanned aerial vehicle	Video	Used to film all tests with moving vehicles/TMMs

Figure 4: Racelogic VBOX VB3i differential GNSS with dual antenna and IMU (left); VBOX Sigma (right)

Figure 5: Racelogic VPRS (left and middle); DICKEY-john GSS (right)

Figure 6: Logitech Webcam C310 HD (left); Ewellix linear actuators with Dunkermotoren drives (right)

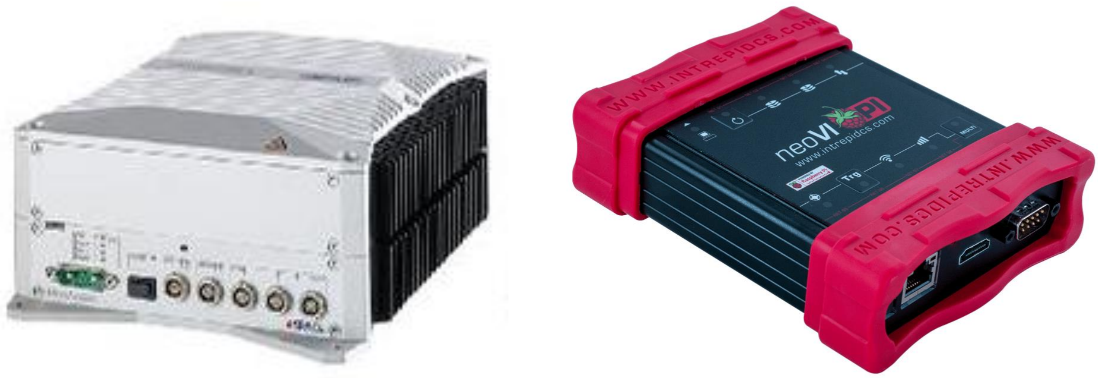

Figure 7: dSPACE MicroAutoBox III (left); Intrepid Control Systems neoVI PI (right)

Figure 8: DJI Mavic 3 Enterprise

Figure 9 shows a TMM emulator. The dSPACE MicroAutoBox III controller has been integrated with the VBOX VB3i high-precision GNSS. The brake robot used to slow and stop a test vehicle is also shown.

Figure 9: TMM emulator with dSPACE MicroAutoBox III, VBOX VB3i GNSS and brake robot

2.3 Next steps

Some refinements to the hardware are needed. This was anticipated, because new hardware was developed for this project. The refinements are aimed at expediting the testing process, and may be summarized as:

- It was noticed during the CPS Test Specification verification (see Section 3.2) that testing effective warning (for operators and pedestrians) needs more hardware and software development. This is especially true for the pedestrian warning system, because the test instruments used to record warnings given to the pedestrian are in harm's way should a failure occur during testing.
- Refinement of the brake robot control to allow for easy configuration to the test vehicle.
- The CPS Test Specification requires up to eight test vehicles for some of the test protocols. This represents a significant logistics challenge. Packaging and storage of the emulators, test kits and other peripheral equipment needed to conduct testing needs to be developed.
- A significant amount of data is recorded during testing. Developing a centralized data storage facility with automatic upload link from the test vehicles will ensure that recordings are organized and synchronized. This will expedite the analysis and dissemination of test results.
- Currently, the emulators and CPS test kit have a Graphic User Interface (GUI) aimed at development. The development of a test GUI is necessary.

3 CPS Test Specification verification

3.1 Background

In July 2022, the Minerals Council published the CPS Test Specification. It consists of 24 individual test protocols used to verify that CPS products comply with the CPS Functional and Technical Performance Requirements (FTPR). The test capability discussed in Section 2 was developed to execute the majority of these test protocols.

The test protocols are used to verify that CPS products comply with the CPS FTPR. Table 3 summarizes the test protocols. Note that protocol numbers 2, 8, and 21 to 24 were out of scope for this project. These protocols are indicated with an asterisk (*) in Table 3. However, during the course of the project, several opportunities to conduct the log keeping tests (nos. 2 and 8) presented themselves. The report thus includes the findings of these two test protocols too, even though they were originally not within this project's scope.

Table 3: Description of test protocols

No.	TRL	Test protocol	Test objective
1	4	TMM ISO 21815 Interface Test	Confirm that TMM can interface with CxD according to ISO 21815-2:2021.
2*	4	TMM Log keeping test	Logs needed to; • Conduct investigations should an incident occur • Maximize benefit derived from CPS – improved site control, production management, etc. • Record data at higher TRL testing
3	4	TMM Machine sensing test	TMM needs to share information with CxD to enhance CxD performance and avoid duplication. Information shared: • Speed • Direction • Gear selection • Payload status (empty, full, overloaded, fault) • Others
4	4	TMM Self–diagnostic test	TMM needs to be able to detect failure modes and fail to safe should a critical failure be present
5	4	Surface TMM Machine Controller Test	TMM needs to implement commands (such as SLOW_DOWN or CONTROLLED_STOP) sent by CxD. This test verifies that the TMM can implement these instructions.
6	4	Underground TMM Machine Controller Test	TMM needs to implement commands (such as SLOW_DOWN or CONTROLLED_STOP) sent by CxD. This test verifies that the TMM can implement these instructions.
7	4	CxD ISO 21815 Interface Test	Confirm that CxD can interface with TMM according to ISO 21815-2:2021
8*	4	CxD Log keeping Test	Logs needed to; Conduct investigations should an incident occur Maximize benefit derived from CPS – improved site control, production management, etc. Record data at higher TRL testing
9	4	Surface TMM CxD Self-diagnostic Test	CxD needs to be able to detect failure modes and fail to safe should a critical failure be present
10	4	Underground TMM CxD Self-diagnostic Test	CxD needs to be able to detect failure modes and fail to safe should a critical failure be present
11	4	Surface TMM Effective Warning Test	CxD must warn the operator effectively prior to initiating an automatic slow and stop event.

No.	TRL	Test protocol	Test objective
12	4	Underground TMM Effective Warning Test	CxD must warn the operator effectively prior to initiating an automatic slow and stop event.
13	4	Surface TMM CxD Basic Detection and Tracking Test	CxD must be able to detect TMMs within the specified detection range, and maintain this detection for the duration that the TMM is within the detection range. Logs essential to the successful performance of this test.
14	4	Underground TMM CxD Basic Detection and Tracking Test	CxD must be able to detect pedestrians within the specified detection range, and maintain this detection for the duration that the pedestrian is within the detection range. Logs essential to the successful performance of this test.
15	4	Surface TMM CxD Scenario Test	CxD algorithm tested by performing choreographed interaction scenarios.
16	4	Underground TMM CxD Scenario Test	CxD algorithm tested by performing choreographed interaction scenarios.
17	4	Underground CxD Robustness Test	CxD sensing functionality tested in a representative environment. * *Note that the original intention was to test this in mine mock-up on surface at the Engineering 4.0 test facility.
18	6	Surface TMM CPS Integration Test	Integration of CxD with TMM tested
19	6	Underground TMM CPS Integration Test	Integration of CxD with TMM tested
20	7	Surface TMM Advanced CxD Test	Sub-set of interaction scenarios tested in Test 15 repeated in representative environment to ensure robustness of CPS products
21*	8	Surface CPS Test	Limited roll-out of CPS to a dedicated portion of the mine. Logs monitored for a set period. Logs essential to conduct this test.
22*	8	Underground CPS Test	Limited roll-out of CPS to a dedicated portion of the mine. Logs monitored for a set period. Logs essential to conduct this test.
23*	9	Surface CPS Validation	Full-scale roll-out of CPS to entire mining operation where significant risk exists. Logs monitored for a set period. Logs essential to conduct this test.
24*	9	Underground CPS Validation	Full-scale roll-out of CPS to entire mining operation where significant risk exists. Logs monitored for a set period. Logs essential to conduct this test.

* out of project scope

3.2 Test protocol verification

All of the test protocols included in the scope of this project have now been trialled, either at the University of Pretoria's facilities, or at Gerotek Test Facilities (GTF). Minor updates to improve the clarity of test instructions and consistency of terminology need to be made to all the test protocols[2].

Table 4 to Table 7 documents the time and resources needed to setup and execute each test protocol. Note that these are estimates and they do not include data analysis and reporting times. Testing is often a highly unpredictable activity, and these time and resource estimates do not make provision for breakdowns, poor performance on the part of the CPS product supplier or other occurrences beyond the control of the UP team.

Figure 10 to Figure 15 document some of the tests during TRL4 interaction scenario testing. Key findings are discussed in Section 4.

[2] For the sake of brevity, these updates are not discussed in depth in this report. For more information, please contact the authors.

Table 4: TMM TRL4 verification tests

No.	Test protocol	Time [h]	Test personnel	Test location	Test validity	Comments
1	TMM ISO 21815 Interface Test	4	1	Ideal: UP laboratory Alternate: Where TMM is available	Adoption of standardized interface crucial to CPS product maturity. This test is instrumental in achieving that goal. CPS FTPR needs to be more specific.	The interface, log keeping and self-diagnostic tests are the fundamentals needed to conduct further testing. These tests are 'bench tests' and are ideally conducted on the same day. Tests can be done at a sub-system level and do not necessarily require a fully instrumented TMM. Tests can be pivoted to development tests to assist developer with accelerated readiness.
2*	TMM Log keeping test	2	1		Minor updates needed to test protocol, synchronization between CxD and TMM logs is important, especially to improve the CPS and to gain maximum value from it. Test instruction must reflect this.	
4	TMM Self–diagnostic test	2	1		Addition of more failure modes to test protocol necessary. Self-diagnostics implied in Regulations through mandated fail-to-safe functionality. Some failure modes for TMM cannot be tested in UP laboratory and need to be confirmed on site. Report to indicate next test where failure mode can be tested	
3	TMM Machine sensing test	2	2	Test area with sufficient space to accelerate TMM to maximum speed (or 40 km/h, whichever is smaller) and to slow down again.	Revisions to test scenarios necessary to ensure safety during testing. Population of data message a contentious issue with OEMs.	The machine sensing and controller tests require a fully instrumented TMM. The tests can be done in one day if good weather conditions prevail throughout. GTF is often suitable, especially for smaller TMMs. TMMs are often sent to GTF for SANS 1589-1 brake performance testing. This is an ideal opportunity to conduct
5	Surface TMM Machine Controller Test	3	2		Minor clarifications needed in test protocols. The use of a flowchart to explain the test procedure is recommended. Test highly valid; it determines if the OEM maintains control over	

No.	Test protocol	Time [h]	Test personnel	Test location	Test validity	Comments
6	Underground TMM Machine Controller Test	3	2	Area needs to be level and compacted. GTF is suitable for machines not exceeding an axle load of 15 ton and not exceeding a GVM of 40 ton.	the TMM during automatic slow and stop interventions.	the machine sensing and controller verification tests.

Table 5: CxD TRL4 verification tests

No.	Test protocol	Time [h]	Test personnel	Test location	Test validity	Comments
7	CxD ISO 21815 Interface Test	4	1	Ideal: UP laboratory Alternate: Where CxD is available	Adoption of standardized interface crucial to CPS product maturity. This test is instrumental in achieving that goal. CPS FTPR needs to be more specific.	The interface, log keeping and self-diagnostic tests are the fundamentals needed to conduct further testing. These tests are 'bench tests' and are ideally conducted on the same day. Tests can be done at a sub-system level, but require all electronic components of a CxD. Tests can be pivoted to development tests to assist developer with accelerated readiness.
8*	CxD Log keeping Test	2	1		Minor updates needed to test protocol, synchronization between CxD and TMM logs is important, especially to improve the CPS and to gain maximum value from it. Test instruction must reflect this.	
9	Surface TMM CxD Self-diagnostic Test	2	1		Test protocol to be updated: TMM not necessary during this test. Synchronization of CxD and TMM to be added as possible failure mode. Self-diagnostics implied in Regulations through mandated fail-to-safe functionality.	
10	Underground TMM CxD Self-diagnostic Test	2	1			
11	Surface TMM Effective Warning Test	2	4	GTF	Effective warning is mandated by the regulations. Clarification to test protocols needed, recommend to use a flowchart. More	The effectiveness of the warning is not explicitly tested, rather subjective notes and video footage is made available. The only quantifiable

No.	Test protocol	Time [h]	Test personnel	Test location	Test validity	Comments
12	Underground TMM Effective Warning Test	2	4	GTF	attention needs to be given to the Pedestrian Warning System. Different types of effective warnings to be discerned and definitions for each to be formulated.	metric is whether the operator (and pedestrian for UG) has sufficient time to react.
13	Surface TMM CxD Basic Detection and Tracking Test	8	9	GTF	Additions to test protocol necessary. Analysis of logs to be included. Consistency of test vehicle speed will improve quality of testing. CPS FTPR to be reviewed, confirm speeds. Improved schematic of test scenarios recommended.	The logs play a significant role to confirm that all the interactors are detected.
14	Underground TMM CxD Basic Detection and Tracking Test	2	4	GTF		The logs play a significant role to confirm that all the interactors are detected.
15	Surface TMM CxD Scenario Test	60	9	Some of the scenarios can be recreated at GTF. Remaining scenarios need to be tested at a suitable proving ground with a large open area.	Test highly relevant, but very complex. Test scenario schematic to be improved. Minor adjustments to terminology. Questions to be resolved: • Are the multiple interactor test scenarios (dump, pit, multiple object overtake, parking area, crossing, escorted vehicle) similar to what actually happens at surface mines? • The multiple object overtake has a lot of pushback from CxD developers. The significant risk in this scenario needs to be clearly defined in the URS and Test Specification to be updated accordingly. • Escorting scenario to be reviewed. Is it as done in real life?	The scenario test is the culmination of all the prior TRL4 tests. It is ground-breaking, no other test regime contains such a complex test. In the automotive world, the industry standard is to use a simulation environment for complex tests such as these. The organizational aspects of arranging, preparing and executing such a test in a scientific manner cannot be understated. It requires a highly professional test team. GTF is suitable for some of the simpler scenarios, specifically the straight-line scenarios such as head-on, passing, dove-tailing and overtaking. Intersections, curves and multiple interactor scenarios cannot be conducted at GTF. It is recommended that this test protocol be divided into scenarios that can be done at GTF and the remainder that need to be done elsewhere. Aerial video from drone valuable.

No.	Test protocol	Time [h]	Test personnel	Test location	Test validity	Comments
16	Underground TMM CxD Scenario Test	16	4	GTF	Minor updates needed to terminology. Uncertainty over scenario where TMM crawls past pedestrian. To be reviewed with Minerals Council TMM team.	The underground scenario test is often misinterpreted, because it seems illogical to test an underground CxD in perfect line-of-sight conditions.
17	Underground CxD Robustness Test	16	4	Suitable test location to be identified, must be a representative environment	Intention of the test is to determine whether CxD sensing is affected by environment. Representative environment necessary, otherwise test won't serve its purpose.	This test was intended to be conducted at the mine mock-up at Engineering 4.0. It is recommended that this test is moved from TRL4 to TRL7 testing.

Table 6: CPS TRL6 verification tests

No.	Test protocol	Time [h]	Test personnel	Test location	Test validity	Comments
18	Surface TMM CPS Integration Test	4	2	Availability of TMM will dictate. Possibilities include: • GTF • Mine site • OEM facility	Highly relevant tests, minor clarifications and refinements necessary. Adding the expected behaviour during auto slow and stop will be useful.	It is anticipated that the integration tests will continue for a long period of time. Limited interface standardization from the OEMs lead to CxD+TMM combinations and permutations that all need to be tested to ensure safe and efficient performance of the CPS.
19	Underground TMM CPS Integration Test	4	2			

Table 7: CPS TRL7 validation tests

No.	Test protocol	Time [h]	Test personnel	Test location	Test validity	Comments
20	Surface TMM Advanced CxD Test	16	5	Representative environment	Test is considered a validation test, confirms the result seen in Test no. 15. Concerns raised in Table 5 for Test no. 15 to be addressed here too, especially if Test no. 15 is adapted to current test site availability.	This test contains significant risk to test personnel if not conducted safely and only after all other verification tests have been completed.

Figure 10: TRL4 CxD Surface Interaction Scenario Test – Test configuration 6: T-junction

Figure 11: TRL4 CxD Surface Interaction Scenario Test – Test configuration 7: Multiple TMM crossing

Figure 12: TRL4 CxD Surface Interaction Scenario Test – Test configuration 12: Dump

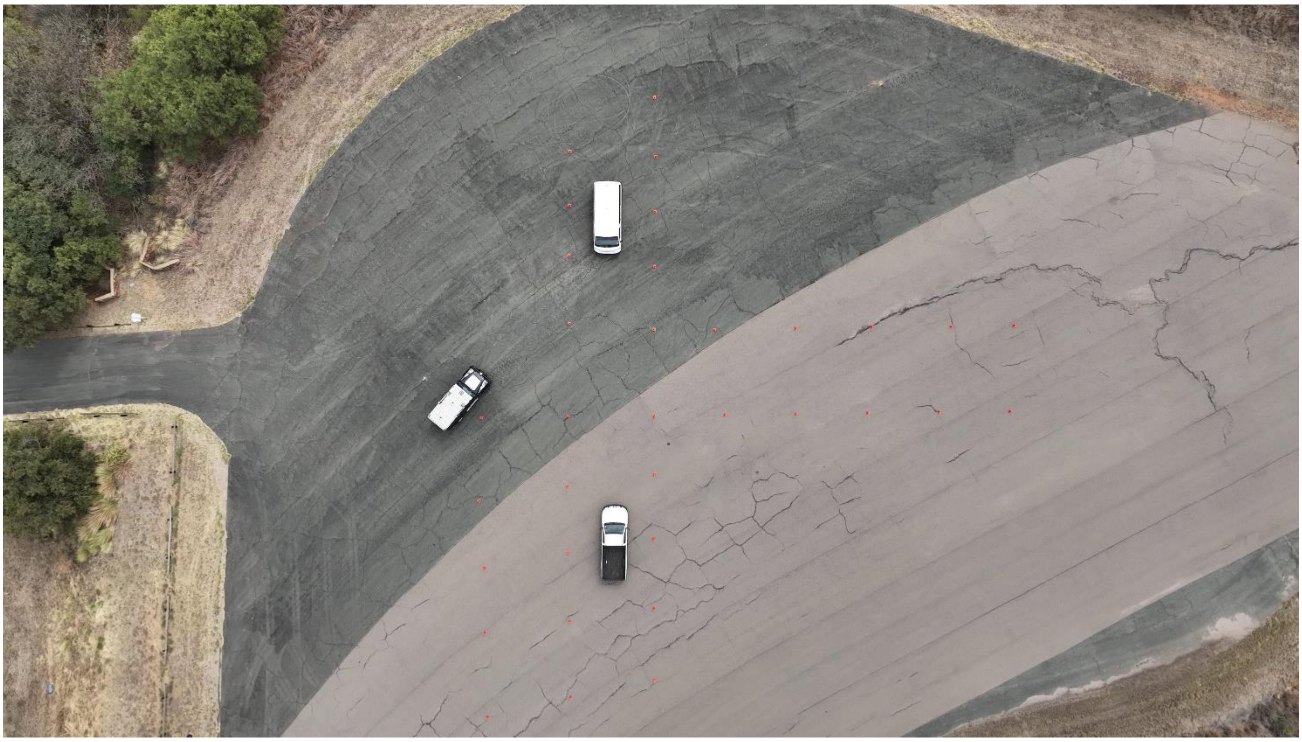

Figure 13: TRL4 CxD Surface Interaction Scenario Test – Test configuration 14: Parking area

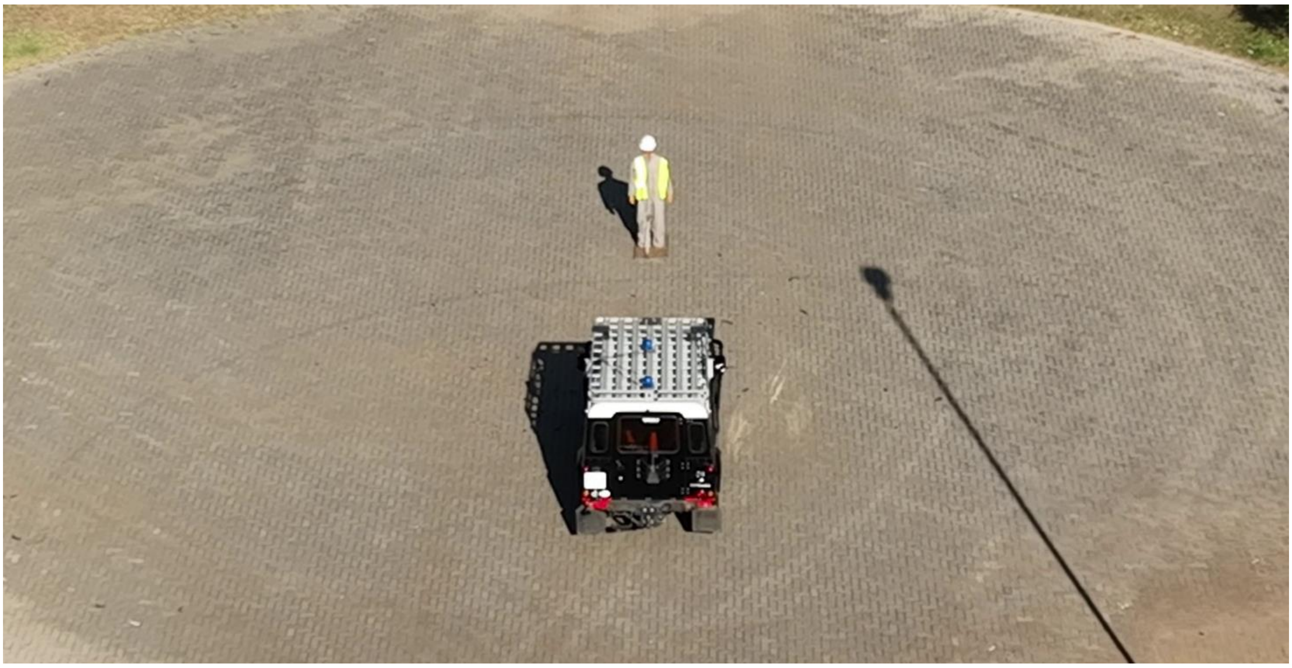

Figure 14: TRL4 CxD UG Interaction Scenario Test – Test configuration 2: Passengers

Figure 15: TRL4 CxD UG Interaction Scenario Test – Test configuration 7: TMM turning

4 Key learnings

One of the deliverables of this project is to report on key learnings attained during the course of conducting the CPS verification tests. This Section not only summarizes the key learnings attained during CPS verification testing, it includes key learnings attained through interaction with CPS product suppliers and other stakeholders. The key learnings may be summarized as:

1. The CPS Test Specification was devised with the development of a dedicated CPS proving ground in the not too distant future. However, lack of support of a CPS proving ground from the SAMI executives necessitated a modification of the CPS Test Regime to accommodate the available resources and capabilities.

   The need for a CPS test facility with sufficient space to allow for complete testing of CPS products remains. The lack of complete testing of CPS products may lead to limited performance of CPS products in operational environments, with the associated risk of collision and loss of production due to false positives.

2. The CPS Test Regime and CPS Test Specification only include tests newly developed by the Minerals Council. It is recommended that the CPS Test Regime be expanded to include at least the following:

   a. Brake performance testing such as SANS 1589-1:2022 and ISO 3450:2011
   b. ICASA Type Approval (TA)
   c. Electromagnetic compatibility (EMC) testing

   The abovementioned additions to the CPS Test Regime are not new test protocols. The intent is to create visibility of the need to conduct these tests and that they are conducted at the correct TRL. The intent is not that the CPS Test Team has to be involved with these tests in any way. Test reports should be available in case they are relevant to the CPS tests conducted by the CPS Test Team.

3. Improving the communication of test results with the wider industry. Currently, the test reports documenting findings and recommendations are highly technical. Highly technical reports are very useful to the CPS product developers, because it gives thorough feedback on the technical performance of their product. However, these reports are difficult to interpret for non-technical people and often lead to misinterpretations of a product’s maturity. A document structure was developed to give a clear indication of both technical feedback and product maturity. Additionally, preparing videos of the test scenarios in the various tests will make the CPS Test Specification more accessible to a wider, non-technical audience.

4.1 CPS Test Specification modification

Four modifications are recommended to the CPS Test Specification. These are:

1. **Dividing TRL4 Surface CxD Controller test into two separate tests:** GTF was not designed with CPS testing in mind. As a result, test tracks at GTF do not provide sufficient space needed for CPS testing. This was evident during the CxD Surface Interaction Scenario test (Appendix 15), because it cannot be fully executed at GTF. For the purpose of this project, the size needed was scaled down. However, this is inappropriate for actual CxD verification testing, because the dimensions of the scenario layout are critical to the performance of the CxD.

It is recommended to divide this test protocol into two tests, one test that can be conducted at GTF, and a new test that has to be done at a test facility (such as a mine) with LDVs. Anecdotal evidence from the project team's interaction with mines indicates that mines are hesitant to allow testing at their sites without prior testing at a facility such as GTF. However, the space constraints at GTF do not allow for effective testing of the CxD controller. Scenarios that are affected include:

- All intersection scenarios such as T-junctions and crossings
- Curved interaction scenarios
- All scenarios involving working areas such as a loading area and a dump

2. **Moving the TRL4 UG Robustness test to TRL7:** The intent of the TRL4 UG Robustness test (Appendix 17) is to verify that the CxD has acceptable performance in the challenging UG sensing environment. The original intent was to conduct this test in a mine mock-up on surface at Engineering 4.0. The mine mock-up would have allowed for repeatable, scientific testing of the UG CxD performance in a representative environment. However, the lack of support for such a facility necessitates that the test be moved to TRL7. The implication is that a CxD with an unproven sensing capability in an UG environment will have to be tested at a mine. It is recommended that this test protocol be revised to accommodate this fact to ensure safety of test personnel. Furthermore, the UG Robustness test will not be as repeatable as originally intended and will take significantly longer time to complete due to the organizational challenges of testing UG. Ideally, a dedicated test site should be considered. Two possibilities that should be considered include:

   - Funding the development of a mine mock-up on surface or,
   - Utilizing an existing mine such as the Mandela Mining Precinct's (MMP's) Maseve Test Mine

3. **Linking the CPS Test Specification closer to the CPS FTPR:** Although the CPS Test Specification was derived from the CPS FTPR, the CPS Test Specification does not always explicitly indicate which functionality contained in the CPS FTPR is being tested with a specific test protocol. It is recommended that the CPS Test Specification is updated to clearly indicate which functionality is under test with each test instruction. Clearly linking the test outcome in the test report to a specific functionality in the CPS FTPR is also recommended.

4. **Consistency of terminology:** Updating the CPS Test Specification (and possibly the CPS URS and CPS FTPR) to make consistent use of terminology is recommended[3].

5. **Amalgamation of the TRL4 ISO21815 FTPR, test specification, and reporting:** The functional requirements for the CxD and TMM interfaces are simply stated as "…documented in ISO TS 21815-2:2021" in the CPS FTPR, while the ISO21815 Appendix B documents contain the acceptance criteria and implied functionalities. This is not consistent with the rest of the CPS documents and it is recommended that the ISO21815 Appendix B documents be absorbed into the CPS FTPR and CPS Test Specification. This will also negate the need of the ISO21815 Appendix C document used for reporting the outcome of the test.

[3] For the sake of brevity, these updates are not discussed in depth in this report. For more information, please contact the authors

4.2 CPS Test Regime expansion

Figure 16 shows the proposed expansion of the CPS Test Regime. Expansion of the CPS Test Regime is needed to indicate the ideal position of tests that form part of CPS verification and certification. CPS products need to undergo brake performance testing, ICASA Type Approval and electromagnetic compatibility testing as part of the verification and certification process. It is recommended that:

1. The applicable brake performance test (SANS 1589-1:2022 or ISO 3450:2011) is included as one of the TRL4 TMM tests. These certification tests are already done regularly and their inclusion will not disrupt CPS products that are already in development or in operation.

2. The Electronic Communications Act 36 of 2005 requires that no product used or manufactured in South Africa may cause intentional or unintentional Radio Frequency Interference (RFI) or Electromagnetic Interference (EMI) to existing electrical/electronic equipment. All transmitters (above or below ground) must have either ICASA Type Approval or an ICASA Spectrum License. Testing to obtain the relevant certification is thus a legal requirement. CPS products thus need to undergo the relevant testing, at the correct point in the CPS Test Regime. The CPS Test Regime must thus be updated to indicate this. The project team will engage with an accredited EMC test laboratory to identify the correct point for the relevant tests and the correct standards to be specified. It is anticipated that tests will either be at the TRL4 or TRL6 Stage Gate. It is anticipated that existing CPS products, especially those used in UG mines, will be affected by this. A misconception exists that ICASA's authority does not extend below the surface of the Earth, and as a result many UG CPS products have not undergone the relevant certification. The impact that EMI/EMC testing and ICASA TA will have on existing CPS products is unknown at this stage.

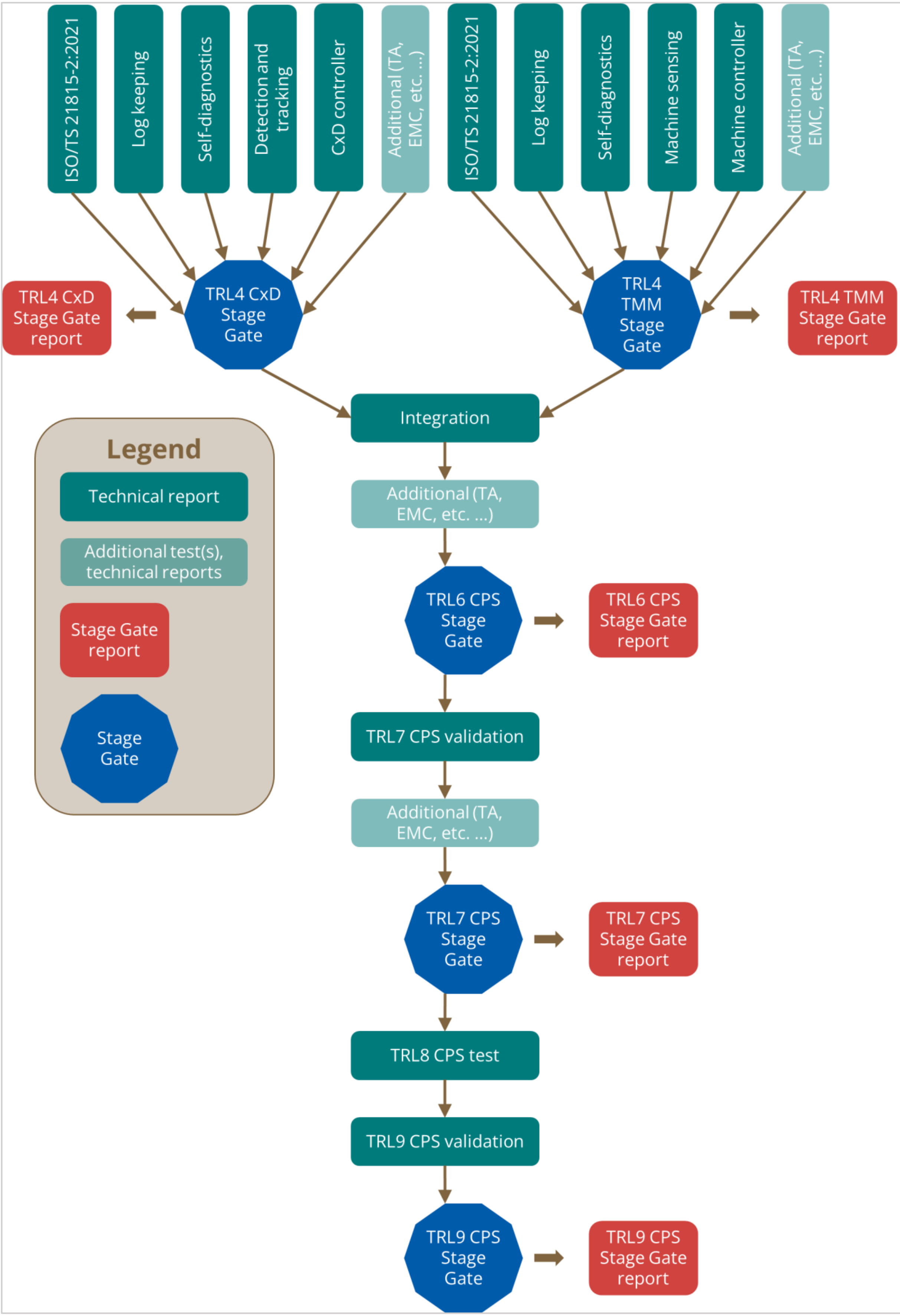

Figure 16: Proposed modifications to CPS Test Regime and document structure

4.3 Document structure

Figure 16 also indicates the proposed document structure that will improve communication with the relevant stakeholders. The objective of the communication structure is twofold:

1. **Providing evidence of CPS product maturity and readiness to the end user:** CPS end users need insight of the maturity of the CPS products at their operations or that they are considering to procure. Non-technical individuals often struggle to interpret the content of technical reports and consequently make unintended conclusions. Highly detailed technical reports are not needed to fulfil this objective. Stage Gate reports at the various TRLs are thus necessary to provide high-level insight into a CPS product's maturity. A Stage Gate report must thus indicate whether a product passes or fails the Stage Gate. Certain CPS products may have limitations, e.g. a TMM may opt not to provide all the data messages defined in ISO/TS 21815-2:2021. Consequently, the TMM may be able to implement an automatic slow and stop, but a CxD that plans to integrate with the TMM will have to rely on its own ability to measure states key to its performance. The Stage Gate report must indicate these limitations clearly to ensure that CPS products are used correctly and effectively. Table 8 shows an example of the feedback in a Stage Gate report.

2. **Providing technical feedback to CPS product developers**: CPS product testing has several technical objectives. The first is to verify that CPS products comply with the Mine Health and Safety Act and Regulations as interpreted by the Minerals Council CPS documents. The second is to provide technical feedback on observations made during CPS product testing with the aim of closing the gap between CPS products and the CPS FTPR. The technical report should clearly indicate whether a functionality required by the CPS FTPR is available or not. Technical recommendations should also be included; these recommendations should include next steps (such as continuing with subsequent TRL4 testing or redoing a TRL4 test). Table 9 shows an example of the feedback contained in a technical report. This example is a report on the outcome of the TRL4 log keeping test protocol. Note that a functionality is indicated as available or not available, and that a motivation is given if necessary.

   The technical feedback contained in these reports is often very complex and contains sensitive information. Sharing these reports with individuals/companies other than the CPS product developer is problematic due to confidentiality and reputational risks.

Table 8: Example of feedback in a Stage Gate report

Test	Outcome	Limitation
TMM ISO 21815 Interface Test	Pass	• TMM requires authentication during negotiation. • TMM only accepts certain Commands from CxD, see test report for details.
TMM Log keeping test	Pass	None
TMM Machine sensing test	Pass	None
TMM Self–diagnostic test	Pass	None
Surface TMM Machine Controller Test	Pass	TMM only responds to certain Commands from CxD, see test report for details.

Table 9: Example of feedback in a technical report

Test no. in Protocol	Log keeping Functionalities	Availability	Motivation for continuation of testing with non-availability	General observations
Test 1	Request time	Available		
	Provide time	Available		
	Record CxD time	Available		
	Record Machine time	Available		
Test 2	Record min. req. ISO/TS21815-2:2021 messages	Available		CxDLK Records all messages
	Record all commands and responses	Available		CxDLK Records all messages
	Record operator ID	Available		
	Record machine ID	Available		
	Record interacting pedestrian ID	Available		
	Record effective warning	Available		EW recorded separately on Ped. tag
	Record status of machine	Available		Drilling/Idle/Operational/Logged-off
	Record state of pedestrian	Available		Direction & distance
	Record faults of machine	Available		Interface missing/fault
	Record faults of CxD	Available		
	Record Machine override	Available		
	Record CxD override	Not Available	Relies on machine for override functionality	Communicated to Machine with J1939 message
	Record each entry with time stamp	Available		
	Record firmware configuration	Available		
	Record messages at 1Hz during normal operation	Available		Records all messages >1Hz
	Record messages at 10Hz during significant risk of collision	Available		Records all messages >10Hz
Test 3	Sufficient storage space for 7 days data	Available		File <100MB, Available space 500MB

Test no. in Protocol	Log keeping Functionalities	Availability	Motivation for continuation of testing with non-availability	General observations
	Provide periodic transfer of data	Available		Ethernet, <10s to download 7 days log file
Test 4	Store data redundantly	Available		2 mirrored storage units
	Provide protection against deletion	Available		ID, permission and certificate required
	Provide protection against alteration	Available		ID, permission and certificate required
	Fail to safe log keeping	Available		

5 Additional work

The full implementation of the CPS clauses in the Mine Health and Safety Act and Regulations on 21 December 2022, barely a month after the Minerals Council and UP entered into the SLA, placed the SAMI under severe regulatory pressure. In an effort to assist the SAMI, UP started conducting CPS product verification tests as the capability became available. This had the benefit of very quickly maturing the CPS test capability, but it resulted in the CPS Test Verification project taking longer than anticipated. The UP team has also engaged with an accredited EMC test laboratory in an effort to address the well-known EMI/EMC challenges faced by CPS products and end users. Lastly, the UP team has engaged with the technical committee responsible for the ISO/TS 21815 series of standards and the South African Bureau of Standards (SABS). This Section documents some of the key lessons learnt during the project team's engagement with CPS product developers and OEMs

5.1 TMM testing

Table 10 and Table 11 summarize the TMM OEMs and sub-system suppliers (mainly 3rd party interface providers) that have engaged with the project team or completed some of the TMM TRL4 verification tests. Considering the number of TMM OEMs with machines in the SAMI, the limited take-up and engagement experienced by mining personnel is evident. It should also be noted that Table 11 merely indicates the number of OEMs that have been tested, not the number of OEMs that have demonstrated compliance to the CPS FTPR.

Table 10: Application area of TMM OEMs & sub-system suppliers engaged with for TRL4 testing

Type	Number
Underground	8
Surface	5
Interface supplier	5
TMM OEM	7

Table 11: TRL4 verification testing progress of OEMs

TRL4 test	Engaged/Quoted	Tested	Total
TMM ISO 21815 Interface Test	7	4	11
TMM Log keeping test	5	1	6
TMM Self–diagnostic test	5	1	6
TMM Machine sensing test	6	0	6
TMM Machine Controller Test	6	0	6

5.2 CxD testing

Table 12 and Table 13 provide an overview of the CxD suppliers that have engaged with the project team or completed some TRL4 CxD verification tests. Sixteen (16) suppliers have engaged with the project team, which is estimated to represent a significant portion of the active suppliers in the SAMI. Uptake has generally been positive, but the clarification discussed in Section 4 will aid in their understanding of the CPS FTPR. Non-adoption by the TMM OEMs is also frustrating efforts on the part of the CxD suppliers to expedite roll-out. This is mainly due to the bespoke development necessary to accommodate each OEM's current functionality and non-standardized approach.

Table 12: Application area of CxD suppliers engaged with for TRL4 testing

Type	Number
UG	7
Surf	9

Table 13: TRL4 verification testing progress of CxD suppliers

TRL4 test	Engaged/Quoted	Tested	Total
CxD ISO 21815 Interface Test	10	6	16
CxD Log keeping Test	8	3	11
CxD Self-diagnostic Test	8	3	11
CxD Basic Detection and Tracking Test	8	0	8
CxD Effective Warning Test	8	0	8
CxD Scenario Test	8	0	8

5.3 EMI/EMC

Anecdotal evidence reported during various meetings, such as the monthly Multi-disciplinary Technical Expert Project Meeting: Industry Alignment on TMM Regulations Implementation Monitoring meeting and the Consulting Mechanical and Electrical Engineers (CM&EE) TMM Task Team meeting, shed light on the persistent EMI/EMC related challenges experienced by CPS products and CPS end users. The project team has engaged with an accredited EMC test laboratory, with the aim of addressing the EMI/EMC challenge. The engagement has led to the following two recommendations:

1. **The electromagnetic environment:** The electromagnetic environment in typical South African mines is largely unknown. The result is that CPS product developers do not have specifics of the electromagnetic environment within which their products have to operate. The electromagnetic environment may vary from site to site and may be influenced by various factors, such as mining method, geology, infrastructure, etc. The importance of understanding the electromagnetic environment and developing a database that gives CPS product developers guidance on the typical electromagnetic environment in the SAMI cannot be overstated.

2. **ICASA TA and EMC testing:** Giving more visibility to the ICASA TA and other EMC testing of CPS products to ensure that CPS products are certified and tested to be EMC within their operational environment is key. Existing EMC standards often do not make provision for CPS products, especially those operating at very low frequencies (often seen for UG CxDs). The result is that CPS products (both CxDs and TMMs) are often not tested for compatibility within the correct frequency bandwidths and to the correct exposure levels. Additionally, the development of a suitable test facility that can correctly test CPS products for EMC is needed. It is thus recommended that a guide to the regulatory requirements for the approval of CPS products is developed, along with a suitable test facility where CPS product EMC can be tested. Such a test facility may be integrated with the mine mock-up recommended in Section 4.1.

5.4 ISO/TS 21815-2:2021 review

During the development of the CxD and TMM emulators, the project team became aware of some discrepancies and inconsistencies in the ISO/TS 21815-2:2021 standard. Through an in-depth analysis, and because the project team developed both the CxD and TMM sides of the interface, the project team prepared a document identifying these discrepancies and inconsistencies, along with the project team's proposed remedies and interpretations[4].

Subsequently, the project team became aware of a questionnaire circulated at a recent Earth Moving Equipment Safety Round Table (EMESRT) meeting. The project team contacted the EMESRT representatives,

[4] Please contact the authors for details

and were eventually directed to Dr Chris Doran, the head of the ISO Technical Committee 0082 (the Technical Committee responsible for the ISO/TS 21815 series of standards). Dr Doran has also become aware of the possible need to review and update ISO/TS 21815-2:2021. The questionnaire that was circulated by EMESRT will serve as a motivation if a review is necessary or not.

It is of utmost importance that the concerns raised by the project team are addressed and resolved in future revisions of the ISO/TS 21815-2:2021 standard. The project team has started the process of joining the Technical Committee responsible for the ISO/TS 21815 series of standards through the SABS.

6 Recommendations

The following recommendations are made based on the insight this project provided:

1. **Update CPS documents with recommended changes:** Updates to the CPS User Requirements, Functional and Technical Performance Requirements, and the Test Specification are necessary. The objective of these updates is to improve the clarity of the documents, hopefully leading to wider and expedited adoption by CPS stakeholders. Key updates include:

    - Adding some definitions and improving on the consistency of terminology.
    - Adding more detail to the CPS FTPR and linking the CPS FTPR closer to the CPS Test Specification.
    - Revising some of the test instructions in the CPS Test Specification to improve the clarity of the test intention. Preparing videos that illustrate some of the test scenarios will aid all CPS stakeholders in their understanding of the highly technical documents.
    - Adapting the CPS Test Regime to accommodate current CPS test resources and to give more visibility to Brake Performance and EMC testing in the CPS Test Regime.
    - Adopting the reporting structure developed in this project.
    - Providing anonymized CPS testing feedback, as presented in Section 5 will give decisionmakers insight into CPS product maturity and may aid in their engagements with other stakeholders such as trade unions, the Inspectorate and the Regulator.

2. **Emulator and CPS test kit refinement:** Refinement of the emulators and CPS test kit is necessary. The refinements are mainly aimed at expediting the test process.

3. **Test facility:** The need for a CPS test facility still exists. This project highlighted the key aspects such a facility should address:
    - TRL4 Surface CxD interaction scenarios
    - TRL4 UG robustness testing
    - EMC testing of CPS products

4. **Operating environment:** Quantifying the influence of factors affecting CPS performance in the operational environment is necessary. Factors such as EMI/EMC, friction coefficients, road widths, ramp gradients, turn radii, etc. all influence the performance of CPS products. Ideally, the CPS FTPR and CPS Test Specification should test CPS products in such a way that CPS products will function correctly in the operational environment. Understanding the operational environment and quantifying its effect on CPS products will further improve CPS product verification, leading to more mature CPS products.

5. **ISO/TS 21815-2:2021 review:** A review of the ISO/TS 21815-2:2021 standard is needed.

Document revision history

Table 14: Document revision history

Date	Revision	Author	Amendment
2023-09-26	0	HA Hamersma	First draft, sent to W Penny & G Guthrie for updates and additions
2023-09-27	0.1	WC Penny	Updates and corrections made, sent to H Hamersma for final revision
2023-09-28	1	HA Hamersma	Release version, sent to Minerals Council
2023-11-29	2	HA Hamersma	**Final release**. Feedback from Minerals Council incorporated.