COLLISION PREVENTION SYSTEMS

TESTING FACILITY NEEDS REPORT

(I.E., WORK PACKAGE 10)

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

REV 3

CPS Testing Facility Needs Report Acceptance			
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1 Purpose of this document

The purpose of this document is to define the test facilities, the equipment required and testing scope at each test facility, to enable the integrated CPS Testing Regime for Trackless Mobile Machines (TMM) in the SA Mining Industry (SAMI). It provides cost estimates as well as potential future opportunities for investments in test facilities.

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.)

Accelerated Development	Developing CPS products in a coordinated and integrated way, that will require less time (for the entire SAMI need), than the previous individual mine and supplier / OEM driven CPS product development approach.
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 includes the functionality and characteristics that comply with the RSA TMM collision prevention regulations. (TMM Regulations 8.10.1 and 8.10.2 and the 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 a warning or collision avoidance functionality.
Controlled area	Area that is dedicated to testing with no interference from vehicular or pedestrian traffic. Example: Gerotek Test Facilities, section on mine isolated from any mining activity, demarcated area at TMM OEM assembly plant.
CxD	Collision warning/detection/management Device
CxDC	CxD Controller, a subsystem of the CxD, that is typically the computer that contains the decision-making logic.
DAQ	Real time computer with data acquisition and control capabilities. Has ISO21815 interface. Example: DSpace MABX II.
Data scientist	Experienced person in the field of data processing and statistics. This person will analyse data collected during TRL9 pilot site roll-out testing.

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 something s/he hears, sees, or feels, the total reaction time can be broken down 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 and/or position of perceived danger.
DMRE	Department of Mineral Resources and Energy.
Effective Warning (Surface)	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.
Effective Warning (Underground)	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.
EM engineer	Qualified person (BEng, BTech) in the EMC environment with experience in EMI/EMC testing.
EMC	Electromagnetic Compatibility.
EMI	Electromagnetic Interference.
EMESRT	Earth Moving Equipment Safety Round Table.
Employee	Any person who is employed or working at a mine.
Functional Specification	A specification that define the function, duty, or role of the product/system. Functional specifications define the tasks or desired results by focusing on what is to be achieved rather than how it need to be done.
F&TPR	Functional and Technical Performance Requirements
HP GNSS	High Precision Global Navigation Satellite System, capable of measuring position with an absolute accuracy of 0.1m and velocity to within 0.2km/h with an update rate of 100Hz. Example Racelogic VBOX 3i.
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.
ICMM	International Council on Mining and Metals.
Independent	Separate from the CPS product developer. Note: Independent does not imply accredited 3rd party, although, where required by local or international standards, it includes accredited 3rd parties.
Independent person	A person, typically a test-, software- or EM engineer, who is not affiliated with the CPS provider or TMM OEM, that can provide an unbiased assessment.
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/DTS21815-2, 2. The user interface – Also sometimes referred to as the Graphic User Interface (GUI) when 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, and/or a fatigue management system. Note: An interface implies that two separate parties (independent systems), are interacting with each other, which might present interoperability and/or EMI and EMC challenges.
Integrated Testing Regime	A holistic method of testing, optimising existing testing facilities that are currently available irrespective of who owns them. This method ensures specific CPS tests are only done once (CxD and TMM CPS Product combinations) and verification is done as early as possible in the development process.
Loss of control	The uncontrolled movement of a TMM due to operator, machine, or environmental reasons. Note: Section 8.10.3 pf MHS Act. Loss of control may result in 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.)
MC	Machine Controller.
Minerals Council	Minerals Council South Africa.
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.
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 an experienced person in the specific field.
Reasonably practicable measure	Reasonably practicable means practicable with regards 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 any means of removing or mitigating that hazard or risk, (c) 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.
SP GNSS with self-recorder	Standard Precision Global Navigation Satellite System capable of measuring position with an accuracy of 1.5m with an update rate of 10Hz. Can also store its own data. Example: UBlox C102-F9R.
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.
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: 2021 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."
Software engineer	Qualified person in the communications/computer environment with extensive experience in ISO21815 programming and testing.
Stop	ISO/TS 21815-2: 2021 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 the 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 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.
Stage gate	A step in the testing regime / process where the CPS product system is tested against acceptance criteria, the failure of which would limit the CPS product system from moving to the next step in the regime / process.
This document	Testing Facility Needs Report. A document that defines the test facility, the equipment required and testing scope at each test facility, to enable the integrated CPS Testing Regime for Trackless Mobile Machines (TMM) in the SA Mining Industry (SAMI).
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.
TMLP	Traffic Management Leading Practice: The MOSH Traffic Management Leading Practice for Open Cast/Cut mines in South Africa.
TRL	Technology Readiness Level: A technology maturity framework for measuring and monitoring technology maturity in 9 increasing levels from TRL 1 to TRL 9.
Test engineer	Experienced person in the engineering/mining environment with extensive experience in CPS testing.

Technician	Competent person with testing experience in the mining / vehicle environment, e.g. testing technician, TMM OEM technician, CxD technician or auto electrician, etc.
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, 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.
Vicinity (Underground TMM and pedestrians)	The distance/time 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, 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.
V-V	Vehicle to Vehicle.
V-P	Vehicle to pedestrian.
Walking speed	In the absence of significant external factors, the average human's walking speed is 1.4meters per second. This is included to help define the crawl speed of vehicles.
WP 9	Work Package 9: Testing protocols (including legacy equipment.) One of the work packages of the Industry Alignment on TMM Collision Management Systems Project: CAS READINESS PHASE.
3rd Party	An entity appointed to execute work, (testing, witnessing of testing and verifying portfolios of evidence), on behalf of SAMI. Note: The purpose of 3rd party execution is to establish independence and to eliminate duplication.

3 Executive Summary

Testing and verification of conformance to the Functional and Technical Performance requirements of CPS products are major elements of the accelerated CPS development process. Being a safety system, the consequence of a non-functioning CPS can be very significant. Many lessons have been learned from the CMS tests done, and tests not done, since 2018. Testing is costly, time consuming and with potential safety risks during testing. The Integrated CPS Test Regime has been specifically designed to address these three challenges. It is based on the following principles:

- Testing as much as possible at the lowest level of component, module, or element. This will shorten the periods associated with redesign, rework and other design corrections.
- Test as early in the development process as possible (lowest possible Technology Readiness Level). In particular, on-mine testing, (TRL 7 and up), must be minimized to limit production losses, increase test repeatability and keep the safety risk as low as possible. Several CPS functionalities can be tested off-site at suitable testing facilities. On-mine testing is done within a mining regulated lease area and therefore the testing must comply with special health and safety requirements and standards. On-mine testing requires the use of mining TMMs and authorized TMM operators, both of which must be removed from operation. The cost of on-mine testing is therefore not only a direct cost, but also an opportunity cost of lost production. These costs are very significant and dwarfs any facility and testing setup cost that would be required to do any off-site testing.
- The integrated CPS Test Regime includes Stage Gate testing at specific Technology Readiness Levels in the accelerated CPS development process. To ensure that all Stage Gate testing outcomes are acceptable to all mines (and therefore do not need to be redone by every/many mines) Stage Gate testing is done by an independent 3rd party testing entity, except for TRL 6, where only a portion of the testing is done by a 3rd party. This provides for an objective evaluation at each Stage Gate.
- The total number of tests to be done on mines are minimized by using pilot mines to facilitate specific CPS configurations (CxD/TMM combinations/mining methods) for testing on behalf of all mines using such configurations. This naturally requires some mines to be willing to act as Pilot CPS Testing mines. TRL 7 tests must be done in an environment that closely resembles the operating environment, thus testing on mines. Collaboration and cost sharing are the obvious incentive for all mines to support the approach of pilot testing mines. A condition for this approach to be successful is visibility of the population of TMMs (Types and Models) for which CPS products must be developed. It can be realistically assumed that not all TMM types and models that are currently used on mines will require CPS products. This is part of the reason why the completion of the Traffic Flow and Risk analysis, that forms part of the low hanging fruit initiative is so important. The availability of the actual TMM population (Type and model) of TMM's for

which CPS products must be developed is therefore a critical enabler for the successful execution of the development and testing approach.

- The integrated CPS Test Regime is set up to do as much as possible testing at the TRL 4 Stage Gate at a 3rd Party facility or TMM OEM facility overseen by a 3rd party, thus limiting the impact on production, ensuring repeatable testing, and providing a sufficient margin of safety during testing.
- Sharing of test facilities and capabilities between TMM OEMs and CxD providers to minimize the cost of testing facilities, testing infrastructure and TMMs to perform tests.
- Sharing of the cost to establish testing capability by all parties (mines, CxD providers and TMM OEMs), as well as executing the 3rd party testing. Since all parties will benefit significantly from shared testing and testing facilities, a suitable mechanism must be agreed for the funding of the shared facilities and testing.

The report addresses:

- the test facility and test equipment requirements,
- available testing facilities,
- alternative approaches,
- time and cost estimates,
- potential funders, and
- future opportunities for developed test facilities.

The testing approach followed to date tested very simplified interaction scenarios and assumed that if these tests were successful, the CPS will be fully functional in an operational environment. This approach, while very attractive, is also very risky. Being a legislated system, the approach leaves a mine with no option other than to fix the system by trial and error, whilst shortcomings are discovered during operation. Such an approach may be affordable for tier 1 or 2 mines, however smaller mines, quarries and small-scale miners are not able to afford, or execute such a process. At the heart of the accelerated CPS development initiative is unambiguous requirements, a formal development approach and a strong testing focus.

The additional testing required for verifying CPS solutions are significant and are well defined and documented in this report.

From the report, the CxD testing to be done at TRL 4 is the key to cost and time optimization of the initiative at large. When considering a reduction of the CxD tests to be done at TRL 4, the potential cost and time consequence to do it at a later TRL, does not warrant it.

The duration of facility development/enhancement required for CxD testing of surface CPS products at TRL 4 is significant given the overall project completion expectations, however, the basis of the accelerated CPS development initiative is extensive collaboration. Although the report does not venture into exploring outside of the scope of work, it is however very likely that amongst the CPS collaboration partners and government institutions, alternative test facility options may exist that are feasible to be used as-is, or that can be enhanced quicker.

Availability of test facilities and testing setups cannot be viewed in isolation, as it is only one element of the overall development initiative. A formal constraints analysis of all elements will provide decision makers with the necessary information to make informed decisions. Elements to be included in such an analysis are:

- How long will CxD developers take to have their existing products aligned with the Functional and Technical Requirements Specification?
- How long will it take for mines to agree an approach/framework for frequency spectrum management?
- How long will it take partners to agree on a standardized V2X approach for CPS products, to ensure interoperability?
- How long will it take for CxD providers, TMM OEMs and 3rd Party integrators to establish formal commercial agreements?
- What types of TMMs and how many of each need to be provided for by CPS developers?

The report highlights the fact that CxD testing for underground TMMs does not require facility development/enhancement and can start as soon as CxD providers have demonstrated readiness at TRL 3 and TRL 4. This provides an opportunity to focus on a segment of the TMM regulations that, based on lagging indicators, have the potential to save TMM related serious injuries and fatalities. Agreeing an accelerated focus on that segment with the DMRE will go a long way in establishing trust and demonstrating commitment.

The report discusses alternative testing facility options, some with better future prospects for South Africa than others. Potential funding options are also discussed.

It is important that senior leaders consider these with a view of saving livelihoods and improving South Africa's economic growth.

4 Conclusions

- The tests required for validating CPS systems for surface TMMs are more (in number) and more challenging than perceived before.
- Testing as much as possible of the CxD functionality at TRL 4 is imperative.
- While the Integrated CPS Test Regime will significantly advance the maturity of existing CPS products, the timelines associated with CxD testing for surface TMMs at TRL 4 are challenging.
- The current scope for considering potential testing facilities are bound by the scope of formal, existing and planned testing facilities.
- Opportunities that might exist with TMM OEMs, mines, government and other partners might provide feasible opportunities for a CxD testing facility for surface TMMs.
- Testing cost, while not insignificant, is relatively small in comparison with the potential investment in CPS products that the mining industry will make in the next few years.
- The expected timelines for the availability of new/upgraded testing facilities, necessitate collaboration of the highest order between all partners and government.

5 Recommendations

It is recommended that:

- The Minerals Council South Africa, as the accelerated CPS development facilitator, initiates and concludes a series of bilateral and collaborative engagements with mining, supplier and government partners, to identify potential testing facilities that can be used as-is or can be enhanced in time to meet the TMM regulatory requirements.
- Mining houses consider donating low kilometre LDVs or funds, whilst SANRAL and other agencies of government are approached for participation and co-funding.
- The CPS User Requirements and Functional Specifications are made available to CPS developers and TMM OEMs as soon as possible so that a formally agreed set of requirements can be available soonest.
- That CPS development agreements between CxD, 3rd Party providers and TMM OEMs be finalised, such that as soon as an agreed set of requirements are available, CPS developers can do a gap assessment and gap closure planning (schedule), based on the CPS development readiness criteria and the functional and technical performance requirements. This schedule will inform the date that the CxD testing facility for TRL 4 testing must be available.
- The funding needed to procure test equipment is made available urgently so that equipment can be procured and commissioned soonest (3-6 months).
- The funding needed to develop a suitable CxD test facility for surface mining equipment is prioritised and obtained through collaboration with a variety of stakeholders and partners, including government agencies.
- Construction of a suitable test facility commences as soon as alternatives with partners have been concluded, and the best viable option has been chosen.
- A more accurate estimate of the types of TMMs, brands and models for which CPS products need to be developed are done.
- Based on the fleet needs, development of TMM CPS products (i.e. upgrading the TMMs to be intelligent, equipped with ISO/TS 21815-2:2021 interface, machine controller and brake by wire capability) is prioritised. This will allow for additional time to establish a CxD testing facility for surface TMMs without unduly delaying the overall initiative.
- A formal constraints-based schedule be developed for the entire accelerated CPS development, to determine the optimum timing that different elements of the initiative need to be available. This will also greatly assist with other ecosystem element development.
- A TMM regulatory focus on underground TMMs be agreed with unions and the DMRE, with a view of accelerated upliftment of the suspended regulations for underground TMMs.
- CxD testing for underground TMMs be expedited and start as soon as new test equipment is commissioned (3-6 months).
- That the resolution of technical uncertainties with regards the functional and technical performance requirements for underground TMMs be prioritised. (Frequency spectrum management, V2X standards, and others as identified).

This will enable CPS developers to do the gap assessment against the full set of functional and technical requirements.

- TRL7 pilot test mines be confirmed by Q2 2022 for underground TMMs and Q4 for surface TMMs, in order to identify suitable space and infrastructure for TRL 7 testing.

6 Context of this document

This document is one of the deliverables of Work Package 10: Testing Facilities Needs Report of the CAS Readiness Phase work of the INDUSTRY ALIGNMENT ON TMM REGULATIONS; SPECIAL PROJECT OF THE MINERALS COUNCIL SOUTH AFRICA.

7 Background

Regulations: 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.

Product System Complexity: A CPS is a Product System that is complex, comprising multiple elements (sub systems) with some sub systems comprising components that are still in technology development.

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

Collaborative approach: SECDI proposed a collaborative approach for the accelerated CPS product development and testing as documented in REVIEW REPORT: Collision Management Systems Technical Specification Guideline: SME and UME REV 2.

Considering the number of potential tests that will have to be performed, given the reality of over 200 open cast/pit mines, 25 CxD providers, 5 interface providers and numerous TMM models on surface operations only, the most viable approach is:

- An integrated, collaborative testing regime, that will enable every test conducted on a specific CPS combination, to be used by all mines, having such a CPS combination on their mine, as proof of conformance.
- That mines introduce as many as possible Level 1 to 6 collision controls (as defined by EMESRT), for TMM related processes and ensure physical separation of TMMs, if reasonably practicable. The MOSH Traffic Management Leading Practice for Surface Operations and the MOSH Traffic Management Technical Guide for Underground Operations was specifically developed to assist mines with Traffic Management. Traffic Management controls covers the major portion of EMESRT Level 1-6 controls.
- Advocating for a high-level risk informed approach to the introduction of CPS regulations into the SAMI.

8 Principles of the Integrated CPS Testing Regime

The principles of the Integrated CPS Testing Regime were first defined in the CPS Integrated Testing Regime document. It is repeated here to provide context to the content of this document.

The following principles are the basis of the integrated CPS Test Regime:

- A single set of User Requirements, Functional and Technical performance requirements, and testing criteria for CPS products.
- Testing as much as possible at the lowest level of component, module or element.
- All Stage Gate testing to be done by an independent 3rd party testing entity, except for TRL 6 where only a portion of the testing is done by a 3rd party.
- A single set of test protocols for 3rd party testing, with clear acceptance criteria.
- Minimizing of the total number of tests to be done on mines. This will be achieved by using off-site testing (TRL 4 and 6) before proceeding to pilot mines (TRL 7).
- Sharing of private test facilities and capabilities between TMM OEMs and CxD providers, to minimize the cost of testing facilities, testing infrastructure and TMMs to perform tests.
- Sharing of the cost to establish testing capability by all parties (mines, CxD providers and TMM OEMs), as well as executing the 3rd party testing.
- Rigorous CPS development criteria that CPS providers, (CxD and TMM CPS Product providers), must demonstrate, in a structured ecosystem readiness framework.
- Proof of conformance verification tests, to confirm conformance to all CxD and TMM CPS Product test criteria must be performed by the CPS produc providers themselves. The 3rd Party Stage Gate testing is independent verification tests and not development tests.
- 3rd party witnessing of testing and portfolios of evidence of conformance to development and testing requirements and criteria.

To minimise the use of resources required from the SAMI to facilitate the TRL testing, the following methodology has been followed;

- Test what can be tested as early as possible, at the lowest TRL possible.
- Test only what has changed between TRLs.
- Leverage production environment, while minimizing the impact on production, to perform higher TRL testing.

This methodology implies that more testing will be done in earlier TRLs and will place most of the test facility requirement on the TRL4 stage gate.

9 Stage Gate Testing – High Level

The Integrated CPS Testing regime includes four stage gates. The goal of each stage gate is briefly summarized here for the sake of continuity.

9.1 Technology Readiness Level 4 (TRL4): Prototype Testing

The TRL4 stage gate is the first independent 3rd party testing that the CxD and TMM CPS PRODUCTS will be subjected to. At this point, the CxD and TMM CPS Products are tested independent of each other, and the stage gate testing is different for each:

- The CxD tests are performed with light vehicles using representative technologies in a controlled environment, to ensure that the CxD complies with all TRL4 functional performance requirements, as set out in the CPS Functional and Technical Performance Specification.
- The stage gate testing comprises of seven distinct tests:
    - ICASA Type Approval (for surface mining equipment),
    - ISO/TS 21815-2:2021 bench test,
    - Fail-to-safe test (including self-diagnostics),
    - Interaction scenario detection and tracking test,
    - CxD controller test. This is the most important test, verifying that all the scenarios in the URS can be executed, as well as the EMESRT scenarios. Including LO status, LO type, RO status and RO type.
    - Log Keeping functionality.
    - Effective Warning Test,
        - Operator,
        - Pedestrian.

TRL 4 CxD Stage Gate testing must be done on a 3rd party testing site that is specifically set up and equipped to:

- Ensure a controlled environment,
- Ensure a repeatable test setup for all CxD products,
- Ensure data logging integrity,
- Ensure that TMM CPS Product tests are done in a controlled environment, to verify intelligence and brake performance and consist of five tests;
    - ISO/TS 21815-2:2021 bench test,
    - SANS 1589 / ISO 3450 brake performance,
    - Machine response to Machine Controller commands,
    - TMM Sensing and log module and data sharing test,
    - Machine response to CxD commands.

TRL 4 TMM CPS Product Stage Gate testing should be done at the TMM OEM factory or assembly site, or at an acceptable TMM rebuilding/assembly contractor's site. These tests can also be done on Pilot test mine (or even any mine) sites if there is not a specific TMM type or model available at a more suitable location.

9.2 Technology Readiness Level 6 (TRL6): Integration Stage Gate

The TRL6 stage gate verifies the CxD and TMM CPS Products' integration. It considers both physical and functional integration, verifies and tests that the process of integration has not deteriorated the performance that each system had in isolation. The TRL6 test will consist of the following;

- Physical integration verification will be done to verify completeness, accuracy and quality of installation and commissioning procedures.

- CxD and TMM CPS product element failures will be simulated to verify fail-to-safe behaviour and to verify the removal and installation sequences and the durations of all the different elements.
- CPS tests will be done in a controlled environment on one machine to ensure successful integration. It is divided into 4 separate tests:
    - Simplified detection test.
    - TMM response to CxD interventions (machine delays, deceleration rates).
    - EMC testing to SANS 13766:2013.
    - Fail to safe testing of the integrated CPS.

The EMC testing as well as a part of the TMM response tests can/will be done with a stationary machine, while the other tests will require dynamic manoeuvres. Since tests will be done with a maximum of two machines in a controlled environment, it will not require significant space on the test facility for this TRL stage gate. It will be ideal to do all the prospective CxD products in close succession so that the specific TMM (Type, Brand and Model), can be out of production for the shortest possible time. The two TMMs used for testing should not be the same, in this way two machines are tested simultaneously. These tests will ideally be done at the same site where the TMM CPS TRL 4 tests are done.

9.3 Technology Readiness Level 7 (TRL7): Pilot site interaction stage gate

The CPS (CxD-TMM system) will be evaluated at the TRL7 stage gate in a representative, operational environment for the first time. The TRL7 stage gate consists of the following test;

- CxD-TMM system tests are done in a representative environment to determine whether the CxD can take environmental effects into account. Three tests are to be done in the following way;
    - Reduced interaction scenario detection and tracking test.
    - CxD controller (This is a repeat of some of the tests done with test vehicles, but this time when fitted to the actual TMM.
    - Effective warning with real operators.

This stage gate will make use of dynamic manoeuvres with multiple TMMs, to test that the performance of the CPS system is acceptable in a representative environment. The facility requirements will be significant in terms of space and number of machines that will have to be taken out of production. A big enough area of the mine will have to be demarcated for testing. If such does not exist outside the production area, it might further impact on production during testing. Adequate operators and support staff to maintain the CPS products in working order, will also need to be readily available during installation and testing. Facilities such as a test office (porta cabin with electricity), enough ablution facilities, safety and risk officers, road signs to demarcate test area, risk assessments, change management for staff awareness, dust suppression, etc. need to be made available.

9.4 Technology Readiness Level 9 (TRL9): Pilot site roll out

This is the final stage gate where the CPS (CxD-TMM system) will be evaluated and will take the form of an extensive data collection and analysis exercise, while machines are in production, with the aim to validate the mine's traffic management plan and identify and rectify interaction hot spots (if any exist). This stage gate test will require the installation and commissioning of all the required TMMs that work within the pilot operational area. For this stage gate testing, the required site infrastructure: beacons, GPS coverage, communication infrastructure to download logs from machines and analysis capability to process and interpret the data, will be required. A dedicated team (preferably from the mine) will be required to analyse every intervention event, to determine the source, nature and action to be taken. Ideally it will be a data analyst, (someone that can do heatmaps etc.), someone from safety to ensure process governance and someone responsible for traffic management.

10 Test facilities need

This section describes the test facility needs at each stage gate in detail.

10.1 TRL4 CxD stage gate

The TRL4 stage gate is the first interaction that a CxD provider or TMM manufacturer will have with a 3rd party testing body and should be considered as an important test to validate the CxD functionality. Consequently, the outcome of this stage gate is not only to allow or disallow progression to a higher TRL, but rather to identify what mistakes the developer has made and how they can be resolved/rectified.

As mentioned in Section 9.1, seven tests exist for this stage gate, and can be done at three separate facilities. Sections 9.1 to 9.4 explain the different needs and are summarised in Appendix A.

10.1.1 ICASA type approval (surface only)

The ICASA type approval process requires the CxD developer to perform the necessary EM tests in accordance with the applicable standards at an accredited test laboratory and submit the reports along with supporting documentation to ICASA.

The ICASA type approval process is fortunately something that is in place in South Africa and does not require any additional facilities to provide a service for the SAMI. Table 1 provides a short summary of the test facility needs.

Table 1: ICASA type approval facility needs summary

Test: ICASA type approval
Site: Facility type 1, i.e., EM test laboratory and ICASA offices.
Equipment: Accredited test laboratory.
Machines: None.
Time: 6 weeks.
Human resources: 1 EM test engineer.

EM testing can be done within a few days and type approval usually takes 30 days [1]. ICASA type approval is only required of a system intended for surface operations (including underground mines with significant risk of collision when a TMM is brought to surface).

10.1.2 ISO/TS 21815-2:2021 bench and Fail-to-safe test

The ISO/TS 21815-2:2021 bench test and the fail-to-safe test (including self-diagnostics), can be done with capability that has been developed previously and will not require additional facilities. See Table 2 for a summary.

Table 2: ISO/TS 21815-2:2021 bench and Fail-to-safe test facility needs summary

Test: CxD ISO/TS 21815-2:2021 bench and Fail-to-safe test
Site: Facility type 2, i.e. indoor lab or office space. **Equipment:** 1 DAQ. **Machines:** None. **Time:** 3 days. **Human resources:** 1 Software engineer.

In this test, a DAQ emulates a TMM and is used to confirm that the CxD can communicate in accordance to ISO/TS 21815-2:2021 and CxD fail-to-safe testing is done by inducing failure modes to the CxD, such as interruption to communication and power, while noting the response.

10.1.3 Interaction scenario test for surface TMMs

The detection and tracking, CxD controller, and log keeping tests will be done and the functional requirements will be evaluated against the interaction scenarios that have been identified in the User Requirement Specifications and the F&TPR specification. Ultimately, it is these interaction scenarios that drive the requirements of the test facility at this TRL. Log keeping functionality, as well as the effective warning requirements, will be tested simultaneously with the detection and tracking tests.

Table 3 lists 16 scenarios in the first row and 16 test configurations in the first column for surface mining operations. As expected, every scenario will have at least one test configuration, in which the functionality of the CPS system will be tested. However, as can be seen in Table 3, some scenarios can infer multiple test configurations – these are denoted by more than one "X" in the scenario column. The opposite can also happen, where a specific test configuration can do multiple scenarios and is denoted by more than one "X" in the test configuration row.

Table 3: Interaction scenarios for surface TRL4 stage gate

Scenarios / Test configuration	S1 restricted area (no-go based on TMM type)	S2 speed limited zone	S3 dove-tail	S4 curving dove-tail	S5 T-junction	S6 Intersection	S7 Priority road with multiple T junctions	S8 Passing slow moving TMM (multi?)	S9 Passing brokendown TMM (multi?)	S10 Head-on & passing (straight & curved)	S11 LDV approaching HME (safe park vs. not)	S12 Dump	S13 Pit	S14 hard-park	S15 brake ramp	S16 Congested areas*
restricted area (no-go based on TMM type)	X					X						X	X			
escorted vehicle	X															
speed limited zone		X										X	X		X	
dove-tail & overtaking			X					X	X			X	X	X	X	
curving dove-tail				X												
T-junction					X	X	X									
Priority road multiple interactor							X									
head-on & passing								X	X	X		X	X			
Multi object overtake								X	X							
curved head-on & passing										X						
MI-type test											X					
dump												X				
inverted restricted area												X	X			
pit													X			
parking area														X		X
90deg ramp access															X	
Vechicles needed																
HME	1	1	2	2	2	2	3	3	2	2	1	2	2	3	2	2
LDVs	3	0	1	0	0	1	0	0	0	0	1	1	1	0	0	1
FEL/graders	0	0	0	0	0	0	0	1	0	0	1	1	1	0	0	1
Other (water tanker etc)	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0
total	4	1	3	2	2	3	3	4	2	2	3	5	5	3	2	4

Since the scenarios identified in the User Requirement Specification document are more comprehensive than the previous MOSH CMS Test Evaluation Guideline, the space and equipment requirement is more. The multiple interactor scenarios at this TRL are an addition to the previous guideline and requires additional vehicles for the different scenarios. The addition of these multiple interactor scenarios require expansion of existing test facilities. The multiple interactor scenarios will require seven light vehicles representing:

- Three HMEs.
- Two LDVs.
- One FEL/grader.
- One water bowser.

Each vehicle must be equipped with a suite of measurement and control instrumentation. Choreographing multiple interactor scenarios will be a technically challenging task, that will require careful planning and execution.

Table 4: Scenario interaction for surface facility need summary

Test: Vicinity detection, CxDC, log keeping tests
Site: Facility type 3, i.e., Controlled area with good surface (high friction) for light vehicles. **Equipment:** 3 DAQs, 3 HP GNSS, 5 SP GNSS with self-recorders. **Machines**: 8 light vehicles total with CxD (with ability to drive at 5km/h or slower) installed, of which are 5 moving and 3 have brake robots (can auto slow and stop). **Time:** 5 days testing, 5 days analysis. **Human resources**: 1 test engineer, 5 test drivers, 1 technician, support facilities (ablution, control office, parking, risk officer, safety officer, etc.)

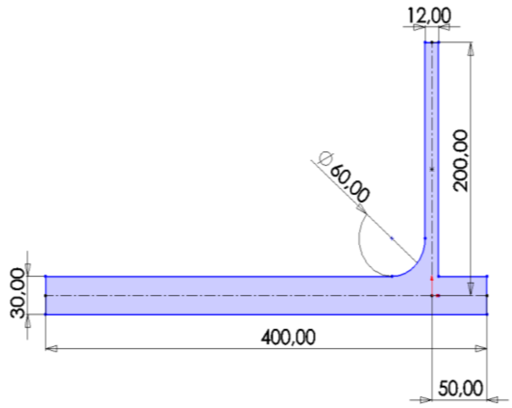


Figure 1: Spatial requirements in meters for surface TRL4 stage gate

10.1.4 Interaction scenarios test for underground TMMs

As for the surface interaction scenarios, Table 5 lists eleven scenarios with eleven test configurations for underground mining operations, based on the User Requirement Specifications and the F&TPR specification. Again, each scenario has at least one test configuration in which the CxD functionality will be tested.

Table 5: Interaction scenarios for underground TRL4 stage gate

Scenarios	S1 Passengers	S2 Exiting	S3 Boarding	S4 Motion inhibit	S5 Workshop	S6 Breakdown	Pedestrian triggered emergency stop	S7 Pedestrian approach	S8 Obscured pedestrian approach (turn)	S9 Loading	S10 Reversing TMM	S11 Obscured pedestrian approach (blind rise)
Passengers	X	X	X									
MI				X								
TMM + pedestrian with TMM approaching					X	X						
Pedestrian stop							X					
Pedestrian approach & passing								X			X	
Multi pedestrian approach & passing								X				
TMM turning to obscured pedestrian & passing									X			
Multiple TMMs with pedestrian approaching										X		
Blind approach (rise)												X
TMM	1	1	1	1	2	2	2	1	1	2	1	1
Pedestrian	4	4	4	1	1	1	1	10	1	1	1	1

The total number of pedestrians and vehicles needed per scenario is listed at the bottom of the table. Since scenarios for underground are limited to pedestrian interactions only, the test facility requirement is less onerous than for surface operations. Table 6 summarizes the facility needs for underground TRL4 CxD tests.

Table 6: Scenario interaction for underground facility need summary

Test: Vicinity detection, CxD, log keeping tests
Site: Facility with controlled area with good surface (high friction), (tar or cement, not gravel) for light vehicles. **Equipment:** 2 DAQs, 2 HP GNSS, 1 SP GNSS with self-recorders, 10 pedestrian tags. **Machines:** 2 light vehicles with CxD installed, both moving and fitted with brake robots. **Time:** 5 days testing, 5 days analysis. **Human resources**: 1 test engineer, 1 test driver, 1 technician.

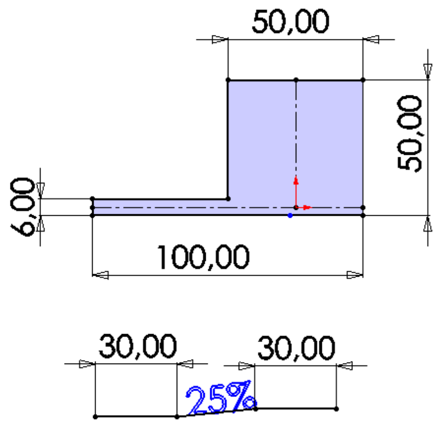


Figure 2: Spatial requirement in meters for underground TRL4 stage gate

10.2 TRL4 TMM CPS Products Stage Gate

The TMM CPS Products have two functional tests at this stage gate, namely an ISO/TS 21815-2:2021 communication bench test and a brake performance test. Fortunately, the facilities to conduct these tests already exist, as the brake performance requirement has long been enforced, and the ISO/TS 21815-2:2021 bench test has been developed previously. No additional facility needs are required for this stage gate. A detailed summary of test needs is provided in Appendix B.

10.2.1 ISO/TS 21815-2:2021 bench test

This bench test is similar to the one done with the CxD developer, except here the DAQ simulates a CxD controller to check for ISO/TS 21815-2:2021 compliance on the side of the OEM TMM. Table 7 provides a short summary of the facility needs.

Table 7: Summary of ISO21815 bench test facility need

Test: TMM OEM ISO/TS 21815-2 bench and Fail-to-safe test
Site: Facility type 2, i.e. indoor lab or office space. **Equipment:** 1 DAQ. **Machines:** 1 TMM. **Time**: 3 days. **Human resources:** 1 Software engineer.

10.2.2 Brake performance test

Brake performance of all underground TMMs needs to comply to SANS 1589:1994 and surface TMMs to ISO 3450:2011. All TMMs shall be tested after the TMM has been fitted with a machine controller. The accuracy of the machine state is to be confirmed as well and includes all information that is sent by the machine controller (for example ground speed measurement, movement direction, gear selection).

Table 8 lists some of the facility requirements for this test. It must be noted that legacy equipment will in all likelihood only be found on a mine, not at an OEM factory/assembly plant. In such instances, the brake tests will have to be performed on the mine site.

Table 8: Summary of brake performance test facility need

Test: TMM OEM brake performance test for machines < 50t	**Test: TMM OEM brake performance test for machines > 50t**
Site: Facility type 3, i.e. controlled area with high friction coefficient surface Equipment: 1 DAQ, 1 SP GNSS Machines: 1 TMM Time: 3 days Human resources: 1 Test engineer	Site: Facility type 4, i.e. typically controlled area at mine with good surface Equipment: 1 DAQ, 1 SP GNSS Machines: 1 TMM Time: 7 days Human resources: 1 Test engineer

10.2.3 Machine response to Machine controller commands

At this point, a Machine controller will have been fitted and a DAQ used to emulate a CxD to trigger commands and note the TMM's response. These tests can be performed at any safe area where the machine can drive in a straight line. Table 9 provides a summary.

Table 9: Summary of TMM response to machine controller commands

Test: Fail-to-safe and TMM response test
Site: Facility type 3, i.e., controlled area with high friction coefficient, or facility type 4, i.e., controlled area at mine with good surface. **Equipment:** 1 DAQ. **Machines:** 1 TMMs with MC fitted. **Time:** 3 days at OEM, 7 days at mine. **Human resources:** 1 Test engineer.

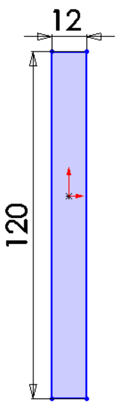


Figure 3: Space requirement for machine response testing at TRL6

This response test is done to determine if the machine braking system functions as expected with commands sent to the Machine Controller. For example, the way the machine controller responds to a slowdown command, by utilising the retarder or brakes.

10.3 TRL6 CPS (CxD-TMM CPS Products) stage gate

Once the CPS developer has integrated with the TMM, the test facility requirement is largely dictated by the TMM's access to test areas and its availability when not in use for production. It can be expected that the TMM will most likely be at the OEM assembly plant, or at a mine where it is to be used in production or is already being used in production (the case for legacy equipment). See Appendix C for more detail.

10.3.1 Fail-to-safe & TMM response

The fail-to-safe and TMM response tests require little space along with only one data acquisition computer. These tests can be performed at any safe area where the machine can drive in a straight line and interact with a pedestrian tag, geo-fence, beacon, or another TMM.

Table 10: Summary of TMM response and fail-to-safe testing

Test: Fail-to-safe and TMM response test
Site: Facility type 3, i.e., controlled area with high friction coefficient, or facility type 4, i.e., controlled area at mine with good surface. **Equipment:** 1 DAQ, 1 SP GNSS. **Machines:** 1 (underground) or 2 (surface) TMMs with full CPS system. **Time:** 3 days at OEM, 7 days at mine. **Human resources:** 1 Test engineer.

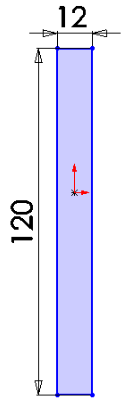


Figure 4: Space requirement for machine response testing at TRL6

The TMM response test is used to determine the delay between the CxD command signal and machine action, as well as the deceleration rates that the TMM can achieve.

10.3.2 SANS 13766:2013 EMC

To test the electromagnetic compatibility of the integrated CxD-TMM system, the test method described in the SANS 13766:2013 standard is recommended. This standard recognises that the size and operating parameters of earth moving machines are unique and can be challenging to traditional methods of EM-testing. SANS 13766:2013 describes a comprehensive "open-air" test method that requires a flat open area of 30m radius, that has an ambient EM noise level 10 dB below the specified levels, listed in the standard.

Table 11: Summary of EMC testing facility requirement

Test: SANS 13766:2013 EMC test
Site: Facility type 5, i.e. flat open space with no EM reflecting surfaces. **Equipment:** SANS 216-1-1 (CISPR16-1-1) compliant. **Machines:** 1 TMM with full CPS system. **Time:** 3 days. **Human resources:** 1 EM engineer.

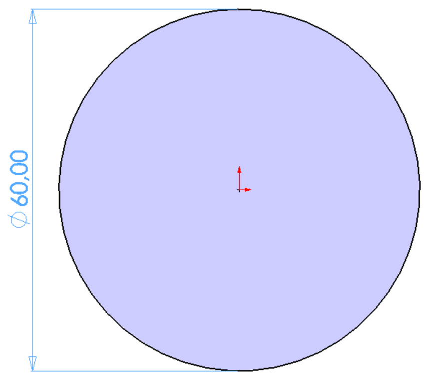


Figure 5: Space requirement for EMC testing at TRL6

10.4 TRL7 PILOT SITE INTERACTION

The pilot site interaction stage gate is the first test to be done in a representative environment. Thus, it is also the first test that will have a direct impact on pilot mine resources and production. To minimise the impact of this, a "test only what has changed" approach is followed to reduce the number of scenarios that need to be tested. See Appendix D for a detailed summary.

10.4.1 Reduced surface interaction scenarios

To test the CxD-TMM system in a representative environment, significant resources will be required at a pilot site to test all the scenarios that has been done in TRL4. However, if one considers that (1) the added complexity of the environment and, (2) the larger TMM vicinity, are the only two significant changes from the lower TRLs, then one may argue that the functionality of the detection and tracking is the only consideration necessary in this TRL. As such, only some of the scenarios listed in the TRL4 stage gate have to be tested to prove detection and tracking functionality and is listed in Table 12.

Table 12: Reduced interaction scenarios for surface TRL7 stage gate

Scenarios / Test configuration	S1 restricted area (no-go based on TMM type)	S2 speed limited zone	S3 dove-tail	S4 curving dove-tail	S5 T-junction	S6 Intersection	~~S7 Priority road with multiple T-junctions~~	~~S8 Passing slow moving TMM (multi?)~~	~~S9 Passing brokendown TMM (multi?)~~	S10 Head-on & passing (straight & curved)	~~S11 LDV approaching HME (safe park vs. not)~~	~~S12 Dump~~	~~S13 Pit~~	~~S14 hard-park~~	~~S15 brake ramp~~	~~S16 Congested areas*~~
restricted area (no-go based on TMM type)	X					X						X	X			
escorted vehicle	X															
speed limited zone		X										X	X		X	
dove-tail & overtaking			X					X	X			X	X	X	X	
curving dove-tail				X												
T-junction					X	X	X									
~~**Priority road multiple interactor**~~							X									
head-on & passing								X	X	X		X	X			
~~**Multi object overtake**~~								X	X							
~~**curved head-on & passing**~~										X						
~~**MI-type test**~~											X					
~~**dump**~~												X				
~~**inverted restricted area**~~												X	X			
~~**pit**~~													X			
~~**parking area**~~														X		X
~~**90deg ramp access**~~															X	
Vechicles needed																
HME	1	1	2	2	2	2	~~3~~	~~3~~	~~2~~	2	~~1~~	~~2~~	~~2~~	~~3~~	~~2~~	~~2~~
LDVs	2	0	1	0	0	1	~~0~~	~~0~~	~~0~~	0	~~1~~	~~1~~	~~1~~	~~0~~	~~0~~	~~1~~
FEL/graders	0	0	0	0	0	0	~~0~~	~~1~~	~~0~~	0	~~1~~	~~1~~	~~1~~	~~0~~	~~0~~	~~1~~
Other	0	0	0	0	0	0	~~0~~	~~0~~	~~0~~	0	~~0~~	~~1~~	~~1~~	~~0~~	~~0~~	~~0~~
total	3	1	3	2	2	3	~~3~~	~~4~~	~~2~~	2	~~3~~	~~5~~	~~5~~	~~3~~	~~2~~	~~4~~

As can be seen in Table 12, the 16 scenarios listed previously have been reduced to seven. The total number of TMMs required is also considerably less (total of four) than with the TRL4 stage gate (total of seven). Of the total four required, two machines should be HMEs and two should be LDVs.

Table 13: Summary of surface TRL7 testing facility requirement

Test: Pilot site surface
Site: Facility type 6, i.e. controlled and representative area at surface pilot mine.
Equipment: 3 DAQs, 3 HP GNSS.
Machines: 2 HMEs and 2 LDVs with full CPS systems.
Time: 2 Days testing, 5 days analysis.
Human resources: 1 Test engineer, 2 TMM operators, 2 test drivers, 1 technician.

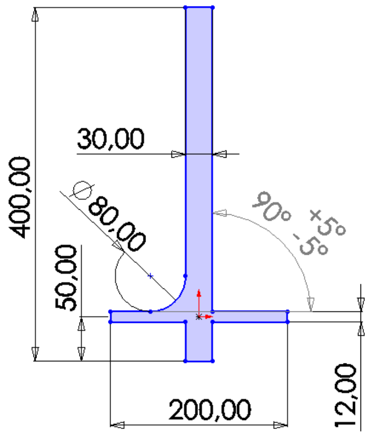


Figure 6: Space requirement for surface TRL7 stage gate

10.4.2 Reduced underground interaction scenarios

The same arguments that were used to reduce the surface interaction scenarios cannot be applied for underground operations. Since the environment is drastically different from any testing that has been done at the lower TRLs, all interaction scenarios must be considered at this stage gate. Table 14 lists the same scenarios that need to be tested at TRL7 for underground operations, but with reduced space requirements in the last column.

Table 14: Reduced interaction scenarios for underground TRL7 stage gate

Test configuration \ Scenarios	S1 Passengers	S2 Exiting	S3 Boarding	S4 Motion inhibit	S5 Workshop	S6 Breakdown	Pedestrian triggered emergency stop	S7 Pedestrian approach	S8 Obscured pedestrian approach (turn)	S9 Loading	S10 Reversing TMM	S11 Obscured pedestrian approach (blind rise
Passengers	X	X	X									
MI				X								
TMM + pedestrian with TMM approaching					X	X						
Pedestrian stop							X					
Pedestrian approach & passing								X			X	
Multi pedestrian approach & passing								X				
TMM turning to obscured pedestrian & passing									X			
Multiple TMMs with pedestrian approaching										X		
Blind approach (rise)												X
TMM	1	1	1	1	2	2	2	1	1	2	1	1
Pedestrian	4	4	4	1	1	1	1	10	1	1	1	1

The space requirements in Table 14 have all been limited at 50x6m. The most significant changes are on the "MI" and "Pedestrian stop" test configurations but should remain representative. Figure 7 and Table 15 highlights some of the test facility needs.

Table 15: Summary of pilot site interaction test for underground

Test: Pilot site underground test
Site: Facility type 7, i.e., controlled and representative area at underground pilot mine. **Equipment:** 2 DAQs, 2 Lidars, mannequin, 10 pedestrian tags **Machines:** 2 TMMs with full CPS systems. **Time:** 2 Days testing, 5 days analysis. **Human resources:** 1 Test engineer, 2 TMM operators, 1 technician.

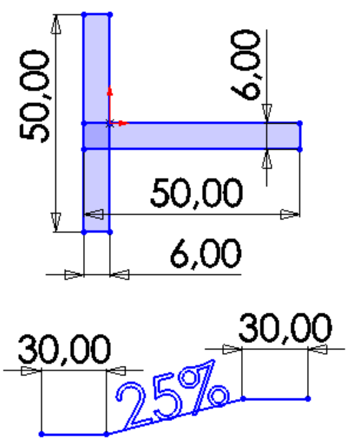


Figure 7: Space requirement for underground TRL7 stage gate

10.5 TRL9 Pilot site roll-out

For the final test, a section of the mine is used as a testing area while the mine is in full operation. By rolling out the full CPS system, areas can be identified where there are interactions between machines (for surface mines), or between machines and pedestrians (for underground mines). This will give the mine an opportunity to re-evaluate its traffic management plan (where there are many interactions at specific locations) or update its operator training (where there are many interactions for a specific operator). Appendix E lists the detail around the test facility needs for this stage gate.

10.5.1 Log keeping and traffic management plan validation

Data logging and analysis forms the basis of this TRL stage gate. For the first 3 months of the test, partial functionality of the CPS system will be switched on and only detect and log interactions. Thereafter, the CPS system will detect, warn and intervene for 3 months. Thus, the test facility needs will be;

- Full CPS system on all machines within the chosen section in the mine.
- Download or streaming of data at regular intervals to a central hub.
- Analysing the data to identify interaction areas.
- Address the hot spot interaction areas.
- Compare data to traffic flow risk assessment and traffic management plan and revise / implement if necessary.

Table 16: Summary for Pilot site roll-out test

Test: Pilot site surface test	Test: Pilot site underground test
Site: Facility type 8, i.e. section of regular mining operation Equipment: CPS system on all machines, log downloading infrastructure, data analysis capabilities Machines: 100% of fleet equipped with full CPS system within section Time: 6 months (3 months detection only, 3 months detection and intervention) Human resources: 2 Data scientists	Site: Facility type 9, i.e. section of regular mining operation Equipment: CPS system on all machines, log downloading infrastructure, data analysis capabilities Machines: 100% of fleet equipped with full CPS system within section Time: 6 months (3 months detection only, 3 months detection and intervention) Human resources: 2 Data scientists

Data will have to be downloaded at least once per shift and processed to identify high risk areas and validate the traffic management plan. It is envisaged that there will be significant data processing involved with this TRL and two dedicated data scientists will be required. Appendix E details the facility requirements.

11 Test facility needs

To date, the testing according to the MOSH CMS Test Evaluation Guideline was conducted with two stage gates, namely the 'lab-scale' test and the 'single-machine' test. These two stage gates are similar to the TRL4 CxD and TRL7 Pilot Site stage gates of the Integrated CPS test regime, respectively.

As already mentioned, the Integrated CPS test regime differs from the MOSH CMS Test Evaluation Guideline, specifically with the introduction of clearly defined multiple interactor scenarios. The surface mining multiple interactor scenarios require significant space, as indicated by Figure 1.

This Section discusses whether existing test facilities can be used to conduct the TRL4 CxD tests, as well as alternate approaches that should be considered.

11.1 Existing test facilities

Gerotek Test Facilities have been used extensively by the University of Pretoria to conduct 'lab-scale' tests. The Gerotek Test Facilities is a vehicle proving ground to the west of Pretoria and is owned by Armscor SOC Ltd. Gerotek Test Facilities are an ISO 17025 international accredited test facility that provides repeatable, scientific vehicle and product testing services to the industry.

11.1.1 Testing to date

All 'lab-scale' tests conducted to date have been done on the following test tracks (see Figure 8):

- The Straight Track for all straight-line interactions, such as head-on, dovetailing, etc.
- A section of the Dynamic Circle for intersections and curves.

Figure 8: Gerotek Test Facilities tracks used for lab-scale testing

The Straight Track is a 1km long concrete test track, that is 12m wide for the first 700m and then widens to 30m from 800 to 900m, after which it narrows again to 12m.

The Dynamic Circle (radius 100m) has a section on its north-western edge where a small intersection or curved scenario can be set up. With limited run-up area, intersection interaction and curve speeds are typically limited to 10km/h (see Figure 9). The curved section of the circle cannot be used as a run-up for the intersection test, because it may negatively affect the CxD's path prediction and limit repeatability of the test. It is unrepresentative to use the 100m radius circle for the curved interactions, because it approaches a straight-line interaction. Intersections and curves were demarcated with traffic cones.

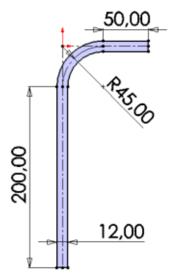
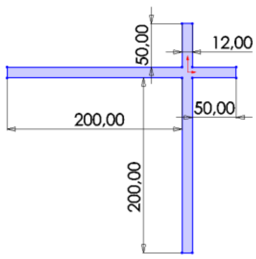
All surface and underground 'lab-scale' tests have been conducted on these tracks at Gerotek Test Facilities. The existing test facilities are sufficient to conduct all TRL4 underground interaction scenario testing.

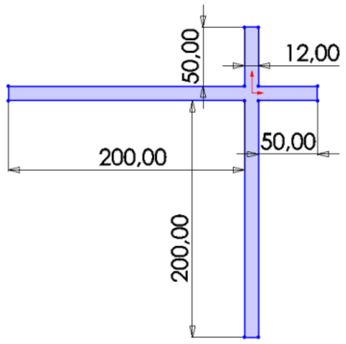
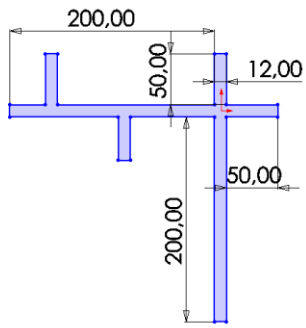
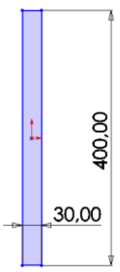
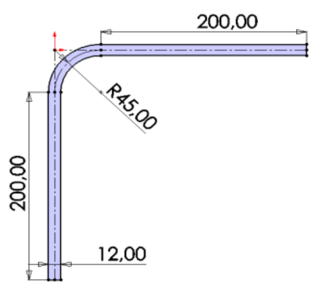
Figure 9: Intersection test on the Dynamic Circle, approximately 100m run-up from the east (yellow line) and 50m run-up from the south (green line), 35m radius curve test in orange

11.1.2 New test requirements

The new TRL4 surface CxD interactor scenarios (discussed in Section 10.1.3) that cannot be tested at Gerotek Test Facilities, due to space limitations are presented in Table 16.

Table 17: Surface interaction scenarios that cannot be tested at Gerotek Test Facilities

Scenario	Reason	Requirement
S4 – Curving dovetail 	Insufficient space to accelerate test vehicle to 40km/h before entering curve	200x12m run-up before 90deg curve of 45m radius, 50m run-off area after curve
S5 – T-junction 	Insufficient run-up area to accelerate test vehicle to 40km/h before intersection	Two tracks forming 200x12m run-ups before crossing at 90deg

S6 – Intersection 	Insufficient run-up area to accelerate test vehicle to 40km/h before intersection	Two tracks forming 200x12m run-ups before crossing at 90deg
S7 – Priority road with multiple junctions 	No suitable test facility with multiple access roads	Two tracks forming 200x12m run-ups before crossing at 90deg, multiple 50m access roads joining one of the run-ups
S8 – Passing slow moving TMM 	Straight track too narrow	400mx30m straight track
S10 – Head-on & passing 	Insufficient space to accelerate test vehicle to 40km/h before entering curve	200x12m run-up before 90deg curve of 45m radius, 200m run-off area after curve

11.1.3 The case for intensive TRL4 testing

Theoretically the testing that must be done at TRL4, and that cannot be done at the current facilities can be moved to TRL6 (the six scenarios listed in Table 17. This however will have the effect that:

- Production TMMs must be used as opposed to test LDVs. The opportunity cost is that up to 10 TMMs (limited congestion scenarios) must be removed from production, with their operators.
- The machines will then have to be fitted with complete CPS's.
- Operators will have to be trained to deal with emergencies that can cause real TMM accidents with HMEs.
- Repeatability of tests will not be possible unless the same size of good surface (tar or cement) areas as per the TRL4 needs are available.
- If it rains the tests will have to be postponed until the surface is dry again (can be days)
- For every on mine test (pilot mines) significant logistic requirements will have to be available.

A simplified opportunity cost model is discussed below.

Table 18 – Technical pros and cons of limited TRL4 and increased TRL7 pilot site testing

Pros	Cons
• Can start (limited) TRL4 testing sooner • Test facility upgrade cost saved	• Will have to increase testing at pilot sites (TRL7) • Increased opportunity cost with pilot site testing (loss of production) • Increased safety risk at pilot site (difficult scenarios untested) • CxD developers only realise mistakes later – added time for redesign, further development, re-testing, etc. • CxD shortcomings are difficult to pinpoint, because of increased number of variables (environmental & TMM) • Loss of test repeatability

Limiting the testing at TRL4 and increasing the testing at TRL7 pilot sites will have significant opportunity cost implications (loss of production). The following example illustrates the opportunity cost:

Assuming the following:

- Three haul trucks must be taken out of production for four days (two days for installation of CxD, two days for testing), thus 96 hours of production time lost.
- Each haul truck has 200t capacity.
- A haul cycle (from dump to pit and back) takes one hour for each haul truck.
- Thermal coal export price of US$130/ton[1].

[1] Approximate commodity price on 28 Sept 2021

- Exchange rate of ZAR15/USD[2].
- Value of ore in haul truck tray is 50% of export price (further value added at processing plant.

The opportunity cost of conducting one TRL7 test will then be:

$$OppCost = NumTrucks \times Capacity \times Hours \times HaulTime \times Price \times ExchangeRate \times Value$$

$$OppCost = 3 \times 200 \times 96 \times 1 \times USD130 \times \frac{ZAR15}{USD} \times 50\%$$

$$OppCost = ZAR56.2\ million$$

This opportunity cost only considers the cost of using three haul trucks. Additional TMMs will also be needed, specifically LDVs, FELs, graders and water tankers.

A large section of the mine will also have to be demarcated for testing, further disrupting mining operations.

In contrast, if an intense testing effort is invested in TRL4, the opportunity cost for TRL7 will be significantly reduced. If the entire complement of scenarios are tested at TRL4, the testing at TRL7 is limited to verifying TRL4 results. There will be an opportunity cost associated with TRL7 testing for this case too, but considerably less. Consider the following example:

Assuming the following:

- Two haul trucks must be taken out of production for three days (two days for installation of CxD, one day for testing), thus 72 hours of production time lost.
- Each haul truck has 200t capacity.
- A haul cycle (from dump to pit and back) takes one hour for each haul truck.
- Export coal price of US$130/ton[3].
- Exchange rate of ZAR15/US$[4].
- Value of ore in haul truck tray is 50% of export price (further value added at processing plant).

The opportunity cost of conducting one TRL7 test will then be:

$$OppCost = NumTrucks \times Capacity \times Hours \times HaulTime \times Price \times ExchangeRate \times Value$$

$$OppCost = 2 \times 200 \times 72 \times 1 \times USD130 \times \frac{ZAR15}{USD} \times 50\%$$

$$OppCost = ZAR28.1\ million$$

The opportunity cost is thus halved when considering only the haul trucks. The test area needed will also be smaller, no other earth moving TMMs will be needed (only two LDVs). All of these factors thus further motivating extensive testing at TRL4 rather than TRL7.

[2] Approximate exchange rate on 28 Sept 2021
[3] Approximate commodity price on 28 Sept 2021
[4] Approximate exchange rate on 28 Sept 2021

It is anticipated that up to 20 CxD products will have to be tested and thus a saving of up to R561 million can be achieved by extensive testing at TRL4 rather than at pilot mines.

11.2 Alternative approaches

Since the full complement of surface interaction scenarios cannot be tested at existing test facilities, and the opportunity cost of limited TRL 4 surface testing is prohibitive, alternative approaches must be considered.

11.2.1 Simulation

The use of a simulation model is a very attractive alternative to physical testing. Simulation-based testing:

- expedites the development process,
- is 100% repeatable.

Simulation software packages that can simulate automotive sensors and vehicle and pedestrian interactions are readily available, but these software packages are unproven for mining applications – they are almost exclusively intended for urban and highway driving environments. Another limitation of the software packages is that the sensors typically included do not include the most prevalent mining CPS sensor technologies. The software packages can model camera sensors, lidar sensors and GPS, but radar modelling, EM field sensors (as used in UG Coal) and RF time-of-flight (ToF) sensors (used extensively for both surface and underground mining) are not included at all. This will require extensive simulation validation testing for the mining applications.

Another concern with simulation-based testing is the interface with the existing CxD developers. In-the-loop testing will be needed, meaning that the CxD software or hardware (or both,) will have to interface with the simulation model. This means the interface between the CxD sub-systems and the simulation model will have to be standardised. While this is entirely possible, it does require a level of expertise and experience that has not been demonstrated to date.

A further aspect that must be considered is simulation model validation. It is of utmost importance that any simulation model is validated against experimental tests. This implies that some testing will still be necessary, i.e. TRL4 interaction scenario testing cannot simply be replaced with a simulation model.

Commercial software packages that can simulate sensors and vehicle interactions retail for approximately R1 million per annum per licence seat. The time to develop a simulation model with the required capabilities is unknown, but an optimistic estimate is 12-18 months. If simulation models were initiated in 2016/7 it would have been the cheapest and fastest overall cost testing option. Although not a feasible option for the accelerated CPS development initiative a simulation model for future use should be a serious consideration for the SAMI.

11.2.2 Test facility development

Another option is the upgrade of existing test facilities or the development of a new test facility.

Option 1 – Upgrading Gerotek Test Facilities

There are plans to upgrade Gerotek Test Facilities to include a large dynamic test area. These plans are in their early stages and no clear indication of timelines is available. SANRAL has indicated that they are willing to fund the developments, but no agreement has been signed to date. The proposed plans are indicated in Figure 10. These upgrades of the High-Speed Track at Gerotek Test Facilities will be sufficient to test the entire complement of TRL4 surface interaction scenarios.

Figure 10: Potential Gerotek Test Facility upgrades

Option 2 – Upgrading University of Pretoria Eng 4.0 laboratories

The University of Pretoria recently embarked on a partnership with SANRAL and the CSIR to establish an integrated education, certification, reference, and research facility, known as Engineering 4.0. This is not only because it is the fourth Engineering building of the University of Pretoria, but it also refers to engineering of the future, with engagement of emerging technologies of Industry 4.0. The first phase of the project was completed in February 2020.

Engineering 4.0 is a research hub that aligns with the United Nations' 17 Sustainable Development Goals (SDGs), specifically innovation, infrastructure, sustainable cities, and communities. Some of the facilities already completed include the National Roads Reference Laboratory and an Active Traffic Lane that joins the N4 highway heading into Pretoria.

Engineering 4.0 is situated on the University of Pretoria's Hillcrest campus and is in close proximity to the CSIR, Future Africa, the Innovation Hub, the SEZ Mamelodi and the N1/N4 interchange (Proefplaas interchange). It is incorporated into the Hatfield Precinct Plan. Figure 11 shows the location of Engineering 4.0.

Figure 11: Location of Engineering 4.0

Included in the future development phases is a test track that is suitable for the TRL4 surface interaction scenarios. Architectural drawings for the test track and support buildings (such as stores, offices, parking, ablution, etc.) are already available with quantity surveyor costing estimates and clear construction timelines. The proposed test track is shown in Figure 12.

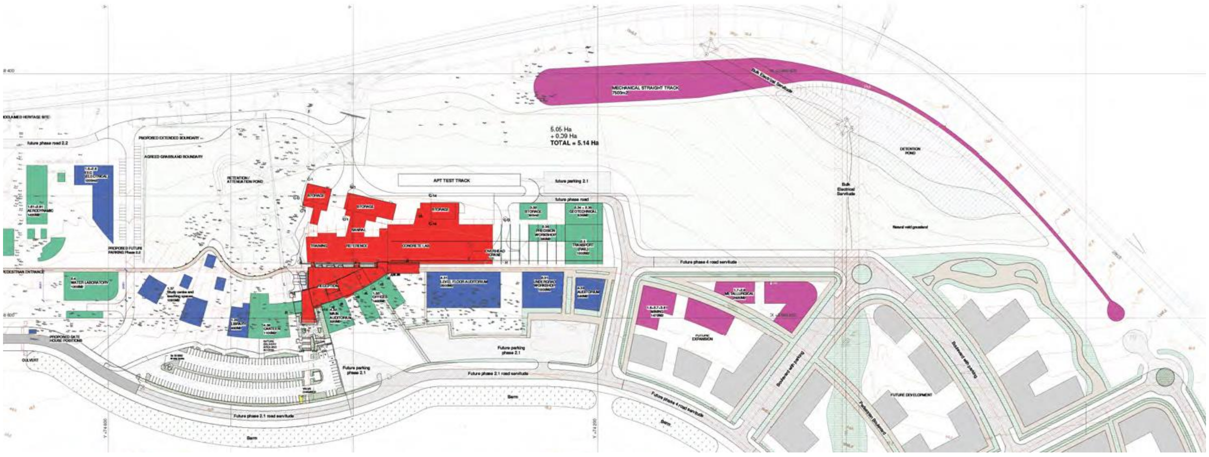


Figure 12: Architectural drawing showing proposed test track (magenta, top right). Red buildings have been completed

Construction of the test track and buildings will take approximately 25 months and will cost approximately R200 million.

11.3 Time and cost summary

11.3.1 Test equipment and instrumentation (Test Setups)

Appendices A to E contain detail of the equipment needed for each stage gate. Some of the equipment is already available (e.g. funded through previous CPS projects, such as MHSC CoE project), but the equipment is insufficient for the needs of the Integrated CPS test regime. Table 19 summarizes the additional equipment that is needed.

Table 19: List of equipment needed for testing

Item	Quantity		Cost/unit	Lead time	Commisioning
	UG	SME			
Test vehicles with low-speed capability (e.g. low mileage LDVs with low range gearbox)	2	8	R250 to 300k	2 weeks	3 months
High precision GNSS	0	1	R500k	3 months	1 month
Standard precision GNSS	0	4	R10k	3 months	1 month
Lidar	2	0	R150k	3 months	1 month
Data acquisition system with control capability	1	2	R250k	3 months	2 months
Brake robot	2	3	R80k	3 months	2 months

The total equipment and instrumentation cost estimate is thus approximately R2.5 million for surface mining equipment and R1 million for underground. Instrumentation needs to be imported, often with a lead time of 3 months. Commissioning of new instrumentation should take approximately 2-3 months.

11.3.2 Test facility development

The test facilities needed and several alternative approaches were discussed in detail in Sections 11.1 and 11.1.3. Table 20 summarizes the four options.

Table 20: Facility development time and cost summary

No.	Option	Time	Cost	Risk
1	Use existing facilities (intense TRL7 testing)	3-6 months	Development: R0 Opportunity: R500 million (additional)	• Increased safety risk on pilot sites • Loss of repeatability • CPS products redesign delays
2	Simulation model	18 months plus validation	R5-10 million	• Unproven • Existing CxD technologies cannot be tested/simulated • Most prevalent sensor technologies cannot be simulated
3	Upgrade Gerotek Test Facilities	Unknown	Development: R50 million	• Unknown timelines • Government bureaucracy “red tape”

No.	Option	Time	Cost	Risk
4	Engineering 4.0 test track	24 months	Development: R200 million	• Construction delays • Sustainable business model

12 Potential funders and future opportunities

The biggest portion of the capital expenditure to implement the Integrated CPS Test Regime will be spent on developing/upgrading the test facility. Equipment costs and test costs pale by comparison.

One possible method of funding the development/upgrade of a test facility is through collaboration, not only within the SAMI, but within South Africa.

The local transport industry is acutely aware of the need to develop a test facility where modern, intelligent transportation systems can be tested. International research indicates that Autonomous Vehicles (AVs) and especially Connected Autonomous Vehicles (CAVs) offer new possibilities for significantly improving safety and efficiency by reducing or eliminating driver error and producing data that can be used intelligently and in real-time to optimise the whole transport system, including road infrastructure and maintenance.

Road safety is a global concern. The World Health Organisation (WHO) has stated the following [2]:

1. "**Over 3 700 people die** on the world's roads **every day** and tens of millions of people are injured or disabled every year. Children, pedestrians, cyclists and older people are among the most vulnerable of road users. WHO works with partners - governmental and non-governmental - around the world to raise the profile of the preventability of road traffic injuries and promote good practice related to addressing key behaviour risk factors – speed, drink and driving, the use of motorcycle helmets, seat-belts and child restraints."
2. "Road traffic injuries are the eighth leading cause of death for all age groups. More people now die as a result of road traffic injuries than from HIV/AIDS, tuberculosis or diarrhoeal diseases. Road traffic injuries are currently the leading cause of death for children and young adults aged 5–29 years, signalling a need for a shift in the current child and adolescent health agenda which, to date, has largely neglected road safety."
3. "With an average rate of 27.5 deaths per 100,000 population, the **risk of a road traffic death is more than three times higher in low-income countries than in high-income countries** where the average rate is 8.3 deaths per 100,000 population. Furthermore, the burden of road traffic deaths is proportionately high among low- and middle-income countries in relation to the size of their populations and the number of motor vehicles in circulation."
4. "There has been **no reduction in the number of road traffic deaths in any low-income country** since 2013. Regional rates of road traffic deaths in Africa and South-East Asia are highest at 26.6 and 20.7 deaths per 100,000 population respectively. This is followed by the Eastern Mediterranean and Western

Pacific regions, which have rates comparable to the global rate with 18 and 16.9 deaths per 100,000 population respectively. The Americas and Europe have the lowest regional rates of 15.6 and 9.3 deaths per 100,000 population respectively."

5. "**More than half of all road traffic deaths are among vulnerable road users: pedestrians, cyclists and motorcyclists**. Africa has the highest proportion of pedestrian and cyclist mortalities with 44% of deaths. Car occupants make up 29% of all deaths."

6. "Road infrastructure is strongly linked to fatal and serious injury causation in road traffic collisions, and research has shown that **improvements to road infrastructure**, particularly design standards that take into account the safety of all road users, **are critical to making roads safe**.

7. "Vehicle safety is increasingly critical to the prevention of crashes and has been shown to contribute to substantial reductions in the number of deaths and serious injuries resulting from road traffic crashes. Features such as electronic stability control and advance braking are examples of vehicle safety standards that can prevent a crash from occurring or reduce the severity of injuries. Despite these potential benefits, not all new and used vehicles are required to implement internationally recognized safety standards. Progress with uptake of the eight priority standards has been very limited since the last review. To-date, 40 mainly high-income countries have implemented 7–8 of these standards. Eleven countries apply two to six of the eight priority standards and 124 apply one or none of the priority standards. Since the last review, one additional country, India, is applying the front and side impact protection standard."

8. "The **number of road traffic deaths continues to climb**, reaching 1.35 million in 2016, while the rates of death relative to the size of the world population has stabilised in recent years. The progress that has been achieved in a number of countries to stabilise the global risk of dying from a road traffic crash **has not occurred at a pace fast enough to compensate for the rising population and rapid motorization of transport** taking place in many parts of the world. At this rate, **the SDG target to halve road traffic deaths by 2020 will not be met**. This review of key risk factors does show, however, that **progress is being made in improving key road safety laws, making infrastructure safer, adopting vehicle standards and improving access to post-crash care**. Further progress will depend upon future success in addressing the range of significant challenges which remain."

South African Statistics show that 13591 people died on SA roads in 2015 costing the economy around R3.9 million per death [3].

The development of AVs has gained extensive momentum and some commercial applications will arrive on roads in the near future. Current AV technology has, however, been developed for first-world conditions with excellent transport infrastructure and road maintenance.

The impact of AV technologies on the South African transport system is unknown. This includes aspects such as the use of AVs in non-highway conditions, impact on pedestrians, the readiness of transport infrastructure, as well as the impact on policy, regulation, and legislation. Furthermore, the sensing and data capturing capabilities of AVs can be used to monitor the condition of the road infrastructure with rapid feedback on potential problems.

AV technology has the potential to change transportation patterns dramatically. Equipping passenger, freight, and public transport vehicles with this technology could have far-reaching consequences for safety, congestion, travel times, equity, energy consumption, air quality and accessibility, depending on when and how the technology is adopted. Transportation Agencies will need to rethink the tools and assumptions to conduct transportation planning considering this developing technology.

It is well recognised that the widespread adoption of fully autonomous vehicles may not be realised in developed countries for decades, and it is even less likely in the developing country environment; however, it is imperative that agencies must develop a better understanding of the transportation planning consequences of these technologies. It is of particular importance as investment decisions are being made on infrastructure projects that will be implemented in the short and medium to long term. It is furthermore important that implementing agencies, such as SANRAL, are proactive in preparing for the potential implementation of these new technologies. Even small numbers of AVs may have a significant positive impact on the availability of data as these vehicles are fitted with many sensors of which the data can be used for e.g. road maintenance prediction purposes. SANRAL is aware of the need for such a facility and has set the wheels in motion to establish such.

AVs present uncharted waters for South Africa, with hardly any researchers working in the field. The development of local capacity and capability that can be deployed timeously in our transport system so that we can reap maximum benefits from the technology is paramount.

It is recommended that the SAMI and the SA transportation industry collaborate at the highest level to establish an AV test facility that caters to both of their needs. Stakeholders in the two industries include:

- SAMI
  - The Mine Health and Safety Council
  - The Minerals Council South Africa and its members
  - The Mining Equipment Manufacturers of South Africa
  - CONMESA
  - CPS product developers
- Transport industry
  - SANRAL
  - The Automotive Business Council (NAAMSA)
  - The Automotive Industry Development Centre (AIDC)
- Government departments

- Department of Mineral Resources and Energy
- Department of Transportation
- Department of Trade and Industry
- Department of Science and Innovation
- Department of Higher Education and Training

It should also be noted that many funding schemes promoting industry-academia partnerships are available. Investment by industry partners often unlocks equivalent amounts of funding (i.e. if the industry gives R100, the university will match it).

A collaborative effort from the wider South African industry to develop a suitable AV test facility will improve local transportation safety, both on public roads and on mining roads. Such a test facility will serve an expanding need for testing modern AV technology in representative environments. Establishing a world-class AV test facility will confirm South Africa as the gateway for modern transportation technology to sub-Saharan Africa.

13 References

[1] ICASA, n.d., *Type Approval,* accessed 27 August 2021, https://www.icasa.org.za/pages/type-approval

[2] WHO.2021. *Road traffic injuries,* accessed 30 September 2021, https://www.who.int/health-topics/road-safety#tab=tab_1

[3] RTMC. *Cost of crashes,* accessed 30 September 2021, https://www.rtmc.co.za/index.php/publications/reports/cost-of-crashes

Appendix A: TRL4 stage gate test facility requirements

Test	Site requirements	Space	Equipment	Machines	Time	Human resources	3rd party test cost
ICASA type approval	Type 1 facility: EM test laboratory and ICASA approval offices	Small	Approved Test Laboratory	None	6 weeks	1 EM engineer	±R15k per test
ISO 21815 bench test **Fail-to-safe**	Type 2 facility: Indoor laboratory or office	Small	DAQ with ISO21815 interface	None	3 days	1 Software engineer	±R15k per test
Surface Vicinity detection **Surface CxD controller**	Type 3 facility: Controlled area with good surface for light vehicles, high friction coefficient.	Figure 1	3 DAQs with ISO21815 interfaces 3 HP GNSS 4 SP GNSS with self-recorders	8 light vehicles with CxD installed 5 moving 2 with brake robots	5 days setup and test 10 days analyse and report	1 Test engineer 5 Test drivers 1 Technician	±R250k per test
Underground Vicinity detection **Underground CxD controller**	Type 3 facility: Controlled area with good surface for light vehicles, high friction coefficient.	Figure 2	2 DAQs with ISO21815 interfaces 2 HP GPS 10 pedestrian tags	2 light vehicles CxDCs installed 2 driving 2 with brake robots	3 days setup and test 5 days analyse and report	1 Test engineer 1 Test driver 1 Technician	±R100k per test

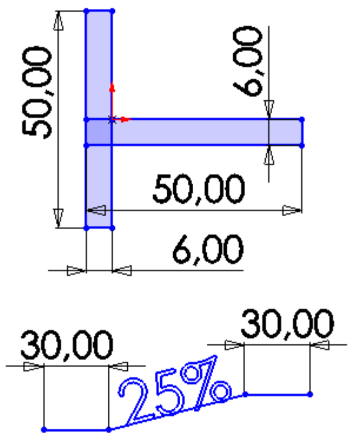
Appendix B: TRL4 TMM OEM stage gate test facility requirements

	Site requirements	Space	Equipment	Machines	Time	Human resources	3rd party test cost
ISO/TS 21815-2:2021 bench test	Type 2 facility: Indoor laboratory or office	Small	DAQ with ISO21815 interface	1 TMM	3 days	1 Software engineer	±R15k per test
SANS1569:1994 / ISO 3450:2011	Type 3 facility: Controlled area, high friction coefficient OR Type 4 facility: Controlled area at mine with good surface	UG: 100 x 6m SME: 1km x 12m	DAQ with ISO21815 interface	1 TMM	3 days	1 Test engineer	±R25k per test
Machine response to machine controller commands	Type 3 facility: Controlled area, high friction coefficient OR Type 4 facility: Controlled area at mine with good surface	100 x 12 m straight	DAQ with ISO21815 interface	1 TMM	3 days	1 Test engineer	±R15k per test

Appendix C: TRL6 stage gate test facility requirements

	Site requirements	Space	Equipment	Machines	Time	Human resources	3rd party test cost
Basic vicinity detection test **Machine response to CxD commands**	Type 3 facility: Controlled area, high friction coefficient OR Type 4 facility: Controlled area at mine with good surface	100 x 12 m straight	1 DAQ 1 HP GNSS	1 TMM with CPS system	1 day	1 test engineer	±R25k per test
EMC testing to SANS13766	Type 5 facility: EM test site, low EM noise	30 m radius flat area	CISPR 16-1-1	1 TMM with CPS system	3 days	1 EM engineer	±R25k per test

Appendix D: TRL7 stage gate test facility requirements

	Site requirements	Space	Equipment	Machines	Time	Human resources	3rd party test cost
Surface reduced interaction scenarios	Type 6 facility: Controlled area on pilot mine site	Figure 6	3 DAQs 3 HP GNSS	2 TMMs and 2 LDV with CPS system	2 days testing 5 days analysis and reporting	1 test engineer 2 TMM operators 1 test driver 1 technician	±R150k per test
Underground reduced interaction scenarios	Type 7 facility: Controlled area on pilot mine site		2 DAQs 2 Lidars	2 TMMs 10 cap lamps	2 days testing 5 days analysis and reporting	1 test engineer 2 TMM operators 1 technician	±R150k per test

Appendix E: TRL9 stage gate test facility needs

	Site requirements	Space	Equipment	Machines	Time	Human resources	3rd party test cost
Surface Log keeping and TMP validation	Type 8 facility: Surface mine pilot site	Section of mine operation	CPS system on all TMMs: detection only	TMM with CPS system	3 months detect, 3 months detect and intervene	2 Data scientists	±R150k per test
Underground Log keeping and TMP validation	Type 9 facility: Underground mine pilot site	Section of mine operation	CPS system on all TMMs: detection and intervention	TMM with CPS system	3 months detect, 3 months detect and intervene	2 Data scientists	±R150k per test

Appendix F: Testing responsibilities

Test number	Test to be done	Applicable at which stage gate	At which test facility	Applicable to who	Who will do the test
1	ICASA Type approval	TRL4	Type 1	CxD developer	3rd party (Accredited Test Laboratory)
2	CxD>>Machine ISO/TS 21815-2:2021bench test	TRL4	Type 2	CxD developer	3rd party
3	Fail-to-safe test	TRL4	Type 2	CxD developer	3rd party
4	Vicinity detection	TRL4	Type 3	CxD developer	3rd party
5	CxD controller	TRL4	Type 3	CxD developer	3rd party
6	Machine>>CxD ISO/TS 21815-2:2021bench test	TRL4	Type 2	TMM OEM	3rd party
7	SANS1589 / ISO3450 brake performance	TRL4	Type 3 or Type 4	TMM OEM	Self-regulation
8	Machine response to Machine controller commands	TRL4	Type 3 or Type 4	TMM OEM	Self-regulation
9	Basic vicinity detection test	TRL6	Type 3 or Type 4	CxD developer & TMM OEM	3rd party
10	Machine response to CxD commands	TRL6	Type 3 or Type 4	CxD developer & TMM OEM	3rd party
11	EMC testing to SANS13766	TRL6	Type 5	CxD developer & TMM OEM	3rd party
12	Pilot site interaction tests	TRL7	Surface: Type 6 Underground: Type 7	CxD developer	3rd party
13	Pilot site roll-out	TRL9	Surface: Type 8 Underground: Type 9	CxD developer	3rd party