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PDS VALIDATION FRAMEWORK: PHASE 3

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MINING3

ACARP

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Final Report

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Abstract

Due to the harsh environments that may be present at a mine site, vehicle collisions and interactions can be commonplace. Of more concern are 1) the dynamic nature and complexity of these interactions – especially when considering the catastrophic nature of an interaction that involves high-risk mining vehicles; and 2) the difficulty that both end-users and suppliers have in understanding the capability of the systems in varied conditions and sites.

With this in mind, there are two key objectives of the ACARP C26028 PDS Validation Framework Phase 3 project. The first is to develop a scientific and feasible baseline PDS industry testing framework, and the second is to validate the testing methodology in a meaningful and measurable way. The intent behind these objectives is to provide end users and suppliers with baseline test data that indicates whether or not a PDS satisfies fundamental capability needs before full-scale piloting of a PDS occurs on a mine site. If a system cannot pass these fundamental baseline tests, there is no point to a site implementation involving even more complex and dynamic vehicle interactions and the need for more rigorous testing that integrates multi-variate complex dynamic scenarios, specific operational control level assessment, environment, and other integration requirements.

Mining3 also provided for Phase 3 of this project, an updated to a Phase 2 deliverable, the PDS Sensor Toolkit as technology has advanced to some extent since Phases 1 and 2 were completed. The Sensor Toolkit and the newly developed website serving as a PDS project knowledge repository available to the industry, also supplement the Phase 3 testing framework developed for this study. Mining3 will update the repository from time-to-time.

The Phase 3 baseline series of tests developed are stand-alone and do not need to be conducted in an active production environment (hence the term baseline). If followed as prescribed, the baseline testing framework can be successfully used as a screening strategy in system selection. It is important to note that the baseline testing framework does not take into consideration any pre-existing site controls (up to level 6) that can be found within the end-user operations. Nor does the baseline testing framework take into consideration complex, multi-variate dynamic vehicle interactions that may be found within end-user operations. The baseline testing regime is solely meant to de-risk decision making and provide meaningful information to end-users and suppliers alike, as to whether or not the system can demonstrate basic functional capability and whether or not the system should progress to a site pilot or case study for broader implementation, and to some extend it may provide insight about system development modifications that may be necessary for successful site implementation.

The successful documentation of these concepts (see Appendix B and supplementary documentation) and the launch of an online PDS toolkit (see Section 5), assists in bridging knowledge across all stakeholders in the industry towards improved systems, and, ultimately, the implementation of said systems. Furthermore, the development, execution and successful validation of a testing framework for PDS is demonstrated in this report, representing key advantages in four specific areas:

- **Realistic:** the ability for the methodology to involve representative vehicles (i.e., a Haul Truck (HT)) within representative scenarios as identified through: (a) an independent review; and (b) existing documentation such as EMESRT Performance Requirement 5A (PR-5A);
- **Technically/Physically Achievable:** the ability for a test methodology to be adopted at different sites, utilising different PDS from different suppliers, with capability reporting possible to understand key (baseline) factors;
- **Efficiency:** the ability for the methodology to, under the use of large, high-risk vehicles (i.e., a HT), be performed in a relatively short time period for practicality (approx. 9h for all tests, with a proposed test period of approx. 2 days – taking into account repeat tests and breaks); and
- **Scientifically Rigorous**: the ability for the methodology to involve a suite of tests that include repeatability and randomization towards determining statistically significant findings.

In addition, project results include providing valuable insight towards the development of PDS, through recommendations and guidelines that include:

1. User Interface (UI) development recommendations to enable practical and safe implementation of PDS – see Appendix A for further information.
2. A review of key sensor technologies prevalent towards PDS development; and
3. The development, validation and discussion of practical tests towards PDS capability documentation that is safe, repeatable, and scientifically rigorous.

Understanding key sensor technologies prevalent towards PDS allows end-users, and to an extent the developers themselves the following:

- A high-level understanding of what each sensing technology is capable of
- What each sensing technology attempts to accomplish
- The specific sensing technology details and high-level working principles,
- The advantages and limitations of emerging state-of-the-art technology ; and
- The state of play regarding considerations pertaining to the sensing technology, possible evaluation techniques to verify the sensing accuracy and robustness of each technology, as well as conclusions and recommendations.

More information regarding the test plan and outcomes, and final recommendations are provided in Section 7 and Section 8, respectively.

Acknowledgements

We wish to thank and acknowledge the many contributions and support provided over the years for the Project (Phases 1, 2 and 3). Mining3 is most grateful for each and every effort made by all the many people who helped deliver the project in one way or another.

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Contents

1 INTRODUCTION

Harsh and complex environments can present unwanted interactions between vehicles, vehicles and structures/obstacles and vehicles with people on foot. Given that these types of environments are prevalent at most mine sites across the world, there is a high demand for Proximity Detection Systems (PDS) to be integrated into normal mine operations. This demand stems from the dynamic nature and complexity of commonplace interactions involving vehicles – especially when considering the high consequence nature of an unwanted interaction that involves large mining vehicles. Although this demand is valid, PDS require testing and verification before site implementation – a crucial step that involves fundamental understanding of a system's capability.

This report aims to develop and validate a testing framework to improve and introduce PDS to the industry by demonstrating baseline capability. Following this initial step will allow PDS suppliers and end-users to collaborate and assist vehicle operators in mitigating, or ultimately, eliminating, the risk of unwanted vehicle interactions in the mining industry. At a basic level, the function of a PDS involves:

1. Constantly monitoring for Remote Objects (RO) of interest (such as other vehicles, site personnel, nearby structures, etc.,) around a host (Local Object (LO)) vehicle through the use of sensing technologies (such as Light Detection and Ranging (LIDAR), Stereo Cameras, Radar, or Global Positioning System(s) (GPS)).
2. Using an intelligence layer to determine if, or when, the host vehicle is at risk of an unwanted interaction, and aptly provide additional information to the operator (such as the position of threat, present speed information of surrounding objects, recommended actions to take, etc.).

The current challenge with such systems, notwithstanding the complex development cycle of said systems, are:

1. Limited scientific methods or pathways to provide accuracy reporting or reliability information of PDS in the context of complex production environments
2. Limited guidelines for developers, Original Equipment Manufacturers (OEM) and mine operators (end-users) to understand the implemented technology against the, at times, complex and harsh environments present at production sites

Given these reasons, it is important that high-level, scientifically rigorous, guidelines are developed towards: (a) bridging the knowledge and communication gaps present between industry members; and (b) to aid in the PDS development process to provide safe, well tested systems toward collision avoidance in the coal mining industry.

2 PROJECT OBJECTIVES

The overall aim of this project is to provide guidelines toward the functionally capable development of PDS, as well as address the challenge of how to verify and validate PDS in a rigorous yet practical manner. The following specific objectives will be addressed:

1. Develop an open, standardized, peer-reviewed validation framework for Proximity Detection System (PDS) developers and end-users toward PDS development and performance verification for Surface Mining. The final outcome will provide:
   (a) Guidance towards User Interface (UI) design, functionality, and testing recommendations and considerations
   (b) Guidance towards PDS sensor considerations, covering common sensor technologies used; sensor fusion towards PDS development; and testing recommendations
   (c) Prevalent scenario(s) and key factor identification toward test plan development using a scientifically rigorous Design of Experiments (DOE) and other vital tests. Note, this phase aims to consider only Control Level 7 (L7) capability reporting, with Control Level 8 (L8) where possible. Control Level 9 (L9) will not be covered and may require additional research towards its validation in the field.
   (d) Pathways to validation with end-user engagement, including performance against prevalent scenarios, assessment of testing outcomes and change management recommendations.
2. In line with Objective 1, we propose a scientifically rigorous testing procedure to:
   (a) Describe a series of tests that demonstrate the generic underlying capabilities of a PDS
   (b) Demonstrate the outcomes from the recommendations provided in Objective 1
   (c) Identify what sort of testing PDS suppliers/Original Equipment Manufacturers (OEMs) should (to our ability) to demonstrate their system's capability, range, accuracy and reliability
   (d) Identify further recommendations that may arise/were missed in the development of the guideline
3. Compile together a reference document (this Final Report) containing all the learnings from Objectives 1 and 2 above.

3 BACKGROUND

The Phase 1 aim was to align and build upon the proximity detection requirements identified in PR5A. Phase 1 included identifying the important components of a *DRAFT* testing methodology that can accurately and consistently assess the performance of Proximity Detection Systems (PDS) in open-cut mining.

The Phase 2 aim was to conduct a series of industry workshops with PDS Suppliers, Original Equipment Manufacturers (OEMs), EMESRT, CSIRO, and industry members, to finalize Phase 1 outputs (functional testing requirements) and to develop the project execution plan for Phase 3 field testing. It is envisioned that the additional industry engagement workshops will also focus on gaining commitment of test participant volunteers (OEMs, PDS Suppliers, and site) for the field validation of the open specification testing methodology.

The Phase 3 aim was to identify and bridge existing gaps with the current methodology, and put the updated plan to the test in a simulated surface operation. In this stage we will conduct a comprehensive field validation process, and also deliver a proposed implementation strategy that contains a change management plan and training strategy. The field validation will involve testing Potentially Unwanted Events (PUE) scenarios as defined in the EMESRT PR5A performance requirement. The methods for testing each configuration will be defined and then tested in a repeatable way, so that consistent and reliable results can be achieved by PDS users and suppliers that apply the framework. Many manufacturers and mines are already doing these tests without a common methodology; therefore the development of a testing framework that would provide mining users with a higher level of confidence in their investment's capability, as well as to reduce exposure to vehicle interaction incidents, is of high value.

3.1 The (Project) Concept

The aim of the project is to align and build upon the EMESRT PR5A body of work to develop a set of common functional tests that are *baseline* for validating a given PDS' capability relative to control levels 7 and 8 in open-cut mining. This will involve conducting comprehensive field testing of the methodology by using actual PDS units in a realistic environment – a proving ground at the Mining3 Test Facility.

3.2 Advantages Over Prior Research

As there is no current rigorous method of verifying that the statement of intent of a proximity detection device reflects the actuality of the system performance once implemented, this framework will provide a path for the evaluation of technologies in a structured, industry-applicable methodology. Furthermore, the key advantages presented in this phase include: (a) instrumentation development in an open-source context to gather crucial data towards evaluation (i.e. the design of a Data Acquisition System (DAQ) – see Section 7); and (b) the execution and discussion of a field test plan, which includes methodology validation.

3.3 Report Outline

The outline of the report is as follows: (a) important considerations regarding the User Interface (UI) will be discussed – detailed more in Appendix A; (b) followed by discussions around the developed, currently online, PDS toolkit – detailed more in Appendix B; (c) the report will then discuss the development of a test plan through the identification of prevalent scenarios applicable to PDS, including discussions regarding its development, execution and findings; and finally (d) this report will present recommendations regarding key findings and test outcomes.

4 USER INTERFACE DESIGN CONSIDERATIONS

This section is summarized in Appendix A and is a collation of findings from previous work carried out by Professor Robin Burgess-Limerick from The University of Queensland. Appendix A includes major findings of User Interface (UI) design and the process of obtaining these findings. It includes a list of Do's and Don'ts of UI design and recommendations for improving a UI and what will be detrimental from a human-factors perspective.

The necessity for continuous monitoring of the UI system is described and what the monitoring should produce; for example:

- how the operators are adapting, suggested changes from operators, reports about effectiveness, etc.;
- how to make changes to the system;
- guidelines for change management; and
- how to show confidence in updates prior to roll out.

Prof. Burgess-Limerick also emphasizes what is yet to be explored scientifically to ensure that the designers take time to consider these aspects.

5 PDS SENSOR TOOLKIT

For the sake of brevity, this section is summarised in Appendix B and highlights underlying fundamentals of different Proximity Detection System (PDS) sensing technologies as documented by Dr. Herman Hamersma from The University of Pretoria (UP). Appendix B includes a brief description of each sensor's working principle, as well as its advantages, limitations and considerations relevant to each technology when implemented towards proximity detection. The full review, as documented by Dr. Herman Hamersma, is available as supplementary documentation[1]. This includes additional information, such as: (i) potential evaluation procedures for both the individual sensor; as well as (ii) special considerations when using a multi-sensor suite. The work expressed in Appendix B and the full supplementary document, was crucial towards the successful launch of an online PDS Toolkit developed by Mining3 [13].

6 INCIDENT REPORTING AND PREVALENT SCENARIO IDENTIFICATION

6.1 Incident Reporting

Evaluation of incident data enabled the understanding of prevalent scenarios that are high-risk at mine-sites. This exercise aided in refining and, ultimately, defining the test scenarios utilised in the development of a test plan. This exercise also reflects leading industry work to provide functional/performance requirements/ scenarios, which will have influence on Proximity Detection System (PDS) development. For the purposes of prevalent scenario identification, this report focuses mainly on Powered Haulage (as classified in[2]) – specifically under the code: 153.210.300.400.500, where:

- The origin or cause of the accident is –- Powered Haulage (153)
- The type of accident is –- unspecified contact with objects and equipment (210)
- The consequences by degree of disability are –- unspecified (300)

[1] ACARP PDS Validation Framework: PDS Sensing Capability Assessment
[2] ISO 19434:2017+A1:2019, Mining — Classification of mining accidents

- The consequences by nature of injury are –- unspecified (400)
- The consequences by part of the body injured are –- unspecified (500)

The following minimal information from each incident was gathered to understand the incident at a high-level:

- An incident summary
- Illumination/environmental conditions (includes weather; time of day; and road conditions)
- Mobile plant information

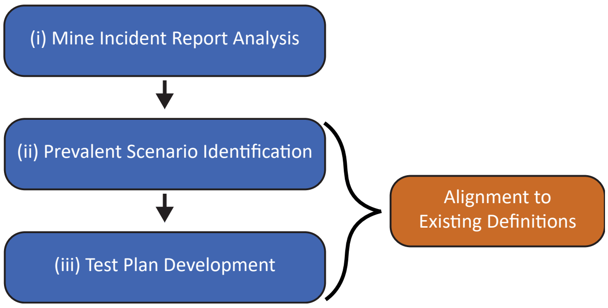


Figure. 1: Illustrates a process that was followed through independent analysis towards the identification of the Prevalent Scenarios for test plan development.

6.2 Prevalent Scenario Identification

This section identifies recommended Prevalent Scenarios through a prescribed process for independent testing/evaluation utilising the proposed test methodology in Section 7. The Prevalent Scenario identification process is outlined in Figure 1, where: (i) a comprehensive analysis of mine incidents involving Powered Haulage was conducted to identify common situations that can be tested by the PDS; (ii) consultation and refinement of the identified scenarios to known interactions, such as those identified in EMERST PR-5A [23]; and (iii) the identification of possible test metrics, based on each Prevalent Scenario, to develop successful test plans for reporting the PDS capability.

Through this process, an investigation into Australia (specifically a collation of information from Queensland, New South Wales, and Western Australian mine accident databases) and the United States of America (US) (reported by the US Department of Labour, Mine Safety and Health Administration (MSHA)) was conducted, which reviewed fatalities, as well as serious accidents and near-miss cases where possible. While additional databases can be analysed, this sub-set of data provides an initial view of the process and its outcome.

From this investigation, the following recommended Prevalent Scenarios were identified as scenarios that may be mitigated with PDS implementation. Furthermore, these scenarios demonstrate alignment with interactions detailed in EMESRT Performance Requirement (PR-5A) [23], and the Queensland Government, Department of Natural Resources, Mines and Energy Guidance Note QGN 27 Collision Prevention [24]:

- **Scenario 1: Intersection Conflict:** Vehicles involved in incidents that were the result of entering/interacting at an intersection.
- **Scenario 2: Work Area Conflict:** Vehicles or persons within a defined work area of heavy machinery/vehicles while the later was in operation.
- **Scenario 3: Tailgating/Direct Conflict:** Vehicles involved in rear-ended or front-on collision incidents between each other while in motion.
- **Scenario 4: Static Road Hazard Conflict:** Vehicles involved in collision incidents with static road hazards (e.g., parked vehicles, road works, etc.) while in motion.
- **Scenario 5: Void Conflict [Loss of Control]:** A void was present, causing the primary vehicle to fall/lose control.
- **Scenario 6: Incline/Decline Conflict [Loss of Control]:** The primary vehicle was on an incline/decline where invalid speed control caused the vehicle to lose control.

Please refer to Appendix C for a summary of the collected incident data, including conclusions and alignment to other scenario classifications. It must be made clear that, while only six (6) Prevalent Scenarios have been identified, the number of interactions may be larger given: (a) the type/number of vehicles tested; and (b) the number of speed combinations tested. This being said, with the summarised scenarios defined, a clear test plan/methodology can be defined, as will be discussed in Section 7.

7 THE BASELINE PDS CAPABILITY METHODOLOGY

The following section details the fundamental development and evaluation process of a Proximity Detection System (PDS) test methodology to demonstrate baseline capability, which includes: (a) the application of the prevalent scenarios (identified in Section 6) towards a scientifically rigorous and adaptable test plan; (b) the design of a Data Acquisition System (DAQ) to capture required data; and (c) a recommended evaluation process towards characterising PDS capability for end-user selection.

7.1 The Test Plan and the Prevalent Scenarios

As detailed in Section 6, this phase of work has identified the need to test six (6) scenarios that are prevalent in mining environments involving vehicle-to-vehicle and vehicle-to-person scenarios. Note that, while this work has identified and summarized these cases to just 6, it is paramount that end-users evaluate and identify specific cases that are more representative of their own site, with the overall objective of the current test plan being:

1. The identification of key factors for base-line testing
2. The design of test(s) to be reproducible and representative (i.e., with representative vehicles, such as a Haul Truck (HT) under a stringent, risk-averse choreographed methodology)
3. The design of test(s) to be conducted in a time efficient manner, while maintaining statistically significant quantities of data for analysis

The validation of this plan is undertaken using three (3) in-kind contributions from PDS suppliers. For the purposes of anonymity, the names of each supplier is omitted from this report; however basic information regarding the main sensors used is highlighted to allow commentary towards guideline recommendations and test methodology outcomes – note that, the purpose of this testing phase is not on providing evaluation of each PDS performance, but rather to demonstrate the capabilities the method is able to show through its scientifically rigorous process. Each supplier reference is noted below in Table 1, with a description of the primary sensor technology used.

Supplier Designation	Primary Sensor
1	Vision-Based
2	Global Navigation Satellite System (GNSS)
3	GNSS

Table 1: The PDS supplier designations used in validating the test methodology detailed in this report.

7.1.1 The Base-Line Factors for Testing

It is important that a test methodology identifies and, at least in terms of a baseline, evaluate key factors that may contribute to a PDS' capability to perform. EMESRT PR5A [23] provides clear expectations of what a Level 7 (L7) system needs to "perceive or comprehend":

- **L7 Awareness:**
    - An ability to provide enhanced situational awareness
    - Alerts the operator to a potential abnormal situation
    - Provides context of the situation to the operator
        - *Where is it?*
        - *What is it?*
        - *How far away is it?*
        - *What is its heading?*
        - *How fast is it going?*
    - Supports visual confirmation for the operator
- **Level 8 (L8) Advisory:**
    - Determines an imminent thread of collision
    - Provides a specific instruction to the **Operator** to intervene (Act)
    - Operator assesses the instruction in relation to other contributing factors, then intervenes (Acts)

A primary aim of this test methodology is to be as agnostic as possible towards a variety of different PDS that are designed with different philosophies in mind. Using the defined expectations above, four (4) key factors – that also relate to the identified main suite of sensors (Section 5) – were used in the test plan development as they will remain constant across most major systems. These are:

- **Distance:** the relative position between two vehicles
- **Speed:** the speed of each vehicle
- **Object Size:** the size, or type, of vehicle being used: e.g., a HT versus a LV
- **Trajectory:** the type of trajectory followed when each object is dynamic, categorized as straight-line or arc trajectories

Distance and speed are self-explanatory, given that most, if not all solutions to PDS require this level of design inherently. Size is an interesting case, which may seem like a factor that does not contribute significantly to the overall functionality, but has been identified as key for some sensors, namely camera-based and Light Detection and Ranging (LIDAR) sensing technologies. Inherently, while other technologies may not be directly affected by the object size, for example, GNSS sensors, proper installation and external noise may prove troublesome when implemented on increasingly larger equipment. Finally, trajectory is deemed a key factor due to the dynamic nature of the implementations of PDS. In fact, one may postulate that, while the other factors are important, this factor will truly demonstrate the capability of the system due to the overtly complex nature of how a vehicle may move in the environment. This being said, the main levels to this factor are either straight-line or arc manoeuvres, which constitutes to a majority of vehicle interactions; however, it is recommended that specific cases be tested if there are any variants that are not strictly covered by this test plan as mentioned previously, this methodology is a foundational stepping-stone for common areas.

7.1.2 The Mining3 Test Pad/Facility

In order to verify the reproducibility and repeatability of this methodology, a suitable test site is a necessity. All the tests were conducted on-site at the Mining3, Pinjarra Hills CAT 777B testing area, pictured in Figure 2. A temporary control station (pictured in Figure 2) was commissioned to manage the tests in a defined exclusion zone such that vehicle activity was carried out in a safe, controlled manner.

Figure. 2: Test pad at Mining3 used to validate and improve the test methodology.

7.1.3 Test 1: Detection Shape/Zone Classification

The purpose of this first test is to quantify the detection shape/zone around the Local Object (LO) –- in this case, the HT –- when the Remote Object(s) (RO) are either static or dynamic. Conceptually, these tests were originally designed to be in a static-static configuration –- meaning that both the LO and RO were to be stationary (static) during a record of data. This was initially tested using Supplier 1's PDS, which demonstrated a minor inconvenience in capturing data within a reasonable timeframe (the time taken to position; record, reposition only to capture small amounts of positional data); however, the need to improve this test to be static-dynamic –- meaning the LO is to be static while the RO is dynamic –- was required due to the potential for dynamic detection zones being prevalent in certain systems. This means that these systems may vary their region of detection/interest with respect to speed – a reasonable characteristic. Therefore, in order to accommodate as many PDS as possible, Test 1 was altered to a static- dynamic case and was validated using Supplier 2 and 3 PDS units. The methodology of this test is as follows:

- the LO (CAT 777B HT) is to be static at the centre of the testing area (Figure 3).
- the RO (a Light Vehicle (LV) or person) is to be dynamic (from the outer circle) towards the LO at various orientations in an anti-clockwise fashion, as depicted in Figure 3.
- Each orientation will involve three (3) different speeds (only applicable to the LV). These speeds are designated as *Low*, *Mid* and *High*, representing approximately 5 km, 10 km, and 20 km, respectively.
- When in motion, the LV is to stop when alerted to do so. If no alert is provided before the designated stopping zone, the LV must decrease speed to a safe stop.

As observed in Figure 3, there are two representative *Work Area* regions designated as the *Inner* and *Outer* regions, with radii of approximately 12.5 m and 25 m, respectively. These areas represent the **minimum** and **maximum** controlled testing area(s) possible at the Mining3 site due to: (a) vehicle turning radius limitations (specifically in the case of the HT); and (b) physical site limitations (i.e. bund limitations). The rationale for designating these areas simply as *Inner* and *Outer*, was to allow for potential system generalization, as well as customization depending on the situation.

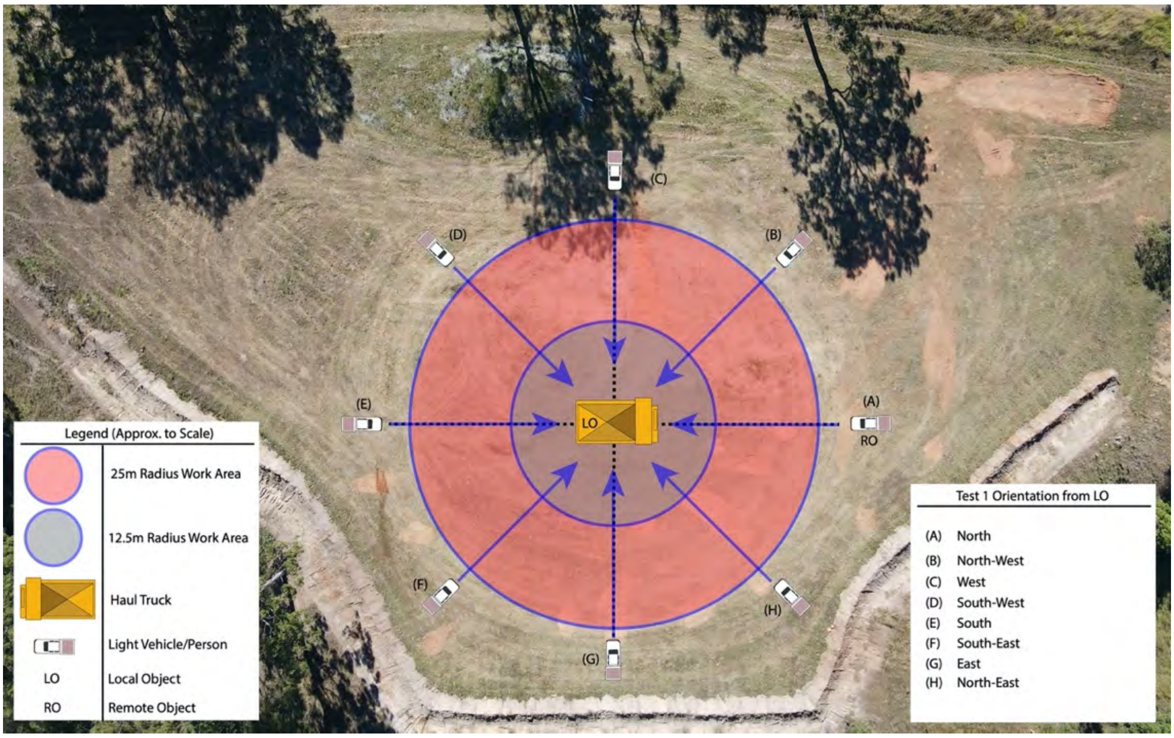


Figure. 3: An overhead representation of Test 1, represented at the Mining3 Test Facility. Please note that all object and work areas are done approximately to scale to provide an indication of size.

Furthermore, note that the orientation about the LO is represented as a compass rose (e.g., *North*, etc.). It is important to clarify that this does not represent a *geographical* orientation, but once again, a simple designation of the orientation about the LO for the purposes of reporting and analysis.

The test structure/order is illustrated in Table 2, below. Note that the main factors being evaluated are: (a) the **Object Size**; (b) the **Distance**; and (c) the **Speed** – for further information on these key factors, please refer to Section 7.1.1. **Object Size**, in this instance, refers to evaluating the performance of a PDS with respect to detecting an approaching vehicle against an approaching person from all major angles of approach. In addition, the **Speed** of approach is also a key factor to be evaluated with respect to each object type – this is incredibly important when characterizing the expected outcomes from a selected PDS; for example, the alert type may be different depending on the interacting 'object'. While **Distance** is not explicitly tested in Table 2, the position of each object is captured with respect to time (synchronized between all acquisition computers comprising the DAQ – see Section 7.2) in order to characterize how alert types *may* differ between tested systems.

Following the test methodology, post analysis of the data is conducted whereby: (a) the positional information, captured using the DAQ, of both the LO and RO is mapped to the captured (time synchronized) visual image of each PDS infrastructure available to each vehicle (i.e. a User Interface (UI)); and (b) subsequently categorized based on the alert type recorded at that time – for more information regarding the post analysis procedure conducted, please refer to Section 8.

Run Order	Object Size (RO)	Orientation	Speed (*Designation*)
1	LV	North	Low
2	LV	North	Mid
3	LV	North	High
4	LV	North-West	Low
5	LV	North-West	Mid
6	LV	North-West	High
7	LV	West	Low
8	LV	West	Mid
9	LV	West	High
10	LV	South-West	Low
11	LV	South-West	Mid
12	LV	South-West	High
13	LV	South	Low
14	LV	South	Mid
15	LV	South	High
16	LV	South-East	Low
17	LV	South-East	Mid
18	LV	South-East	High
19	LV	East	Low
20	LV	East	Mid
21	LV	East	High
22	LV	North-East	Low
23	LV	North-East	Mid
24	LV	North-East	High
25	Person	North	Low*
26	Person	North-West	Low*
27	Person	West	Low*
28	Person	South-West	Low*
29	Person	South	Low*
30	Person	South-East	Low*
31	Person	East	Low*
32	Person	North-East	Low*

Table 2: The defined run order for Test 1. Note that vehicle-vehicle interactions aim to evaluate three speed designations, while the person category is expected to be dynamic only at walking pace – assumed to be approximately* $5\,\mathrm{km\,h^{-1}}$.

7.1.4 Test 2: Design of Experiments Evaluation

While the test discussed in Section 7.1.3 allows us to define/understand the PDS shape of detection, this second test (pictured in Figure 4) serves the ultimate purpose of categorizing the PDS performance and capability to the End-user regarding more complex, dynamic motion of each of the key objects. Note that, while Test 1 was defined with repetition for analysis, this test includes randomization and repetition in a Design of Experiments (DOE) methodology; conducted to evaluate PDS performance in a stringent and rigorous manner.

To highlight a specific purpose of this overall test procedure, it is paramount that each test be conducted in a safe and repeatable manner. Repeatable, in this context, does not refer to scientific analysis, but rather the ability for the aforementioned tests to be easily reproducible and repeated at various sites – be they mine sites, or third-party test environments. Therefore, it is important that each of these tests be defined in such a way as to ensure the safety of those performing the test, as well as defining a procedure that allows for time efficient data capture – more so an important point considering both objects (ideally large mining vehicles, such as the HT tested in this study) will be alternatively dynamic in specific cases. Note that, while a dynamic-dynamic style test would be the ultimate, and desired, test configuration, due to safety concerns this Test will also be a static-dynamic configuration similar to Test 1. In addition, due to safety, only two (2) vehicles will be tested at one time, where no pedestrian tests are required for Test 2 (i.e., only vehicles).

The methodology of this test is as follows:

- The RO – in this case, the LV – will be either **static** or **dynamic** depending on the run conducted (a row from the text matrix defined in Table 3). For example, when the RO is **static**, the LO – in this case the HT – will be **dynamic**, and vice versa.
- The dynamic vehicle will start at a pre-determined position (either an **inner** or **outer** starting position – see Section 7.1.3 for more information regarding these definitions, and Figure 4 for their visual position on the test pad) and proceed at the designated speed, entering either an 'arc' or 'straight' path (Figure 4).
- The static vehicle remains stationary at the centre of the test pad at the same orientation (example pictured in Figure 4) to maintain consistency.
- In the case of an 'arc' trajectory, the dynamic vehicle will continue around the perimeter of a circle (**inner** or **outer**) until a full revolution is performed.
- In the case of a 'straight' trajectory, the dynamic vehicle will continue along the designated straight trajectory (**outer** or **inner**) until the vehicle has reached the end point (designated as (E) and (F) on Figure 4, respectively).
- Once a test has been completed, specific choreography is defined to ensure safe and practical re-positioning of each test vehicle. This is illustrated in Figure 5, which represents an example changeover between the HT and LV along 'black' trajectories. The position of the starting and end points for this test allow each vehicle to safely re-position without high-risk interaction. Note that, while this describes a safe procedure, it is recommended that additional controls (i.e., radio contact, etc.) be put in place to ensure the safe implementation of the test and it's reposition at all times.

The test structure/order is detailed in Table 3, below. Note that, unlike Test 1, all four (4) factors are being evaluated – for further information regarding each factor, please refer to Section 7.1.1. Note that each run (a row on Table 3) is grouped within a *block*; each block consists of sixteen (16) runs (a combination of each of the 4 factors) that are repeated three (3) times, hence, 3 main blocks of tests were required. Furthermore, each block represents randomization to evaluate the PDS unit's performance – this can be seen through the comparison between the standard and run order in Table 3. Three (3) of the 4 main factors are defined by designations, similar to that of Test 1, where: (a) **Speed** has either a low or high designation. For the tests conducted on-site, these values were roughly 5 km h^{-1} and 10 km h^{-1}, respectively; (b) **Distance** has either an inner or outer designation. For the tests conducted on-site, these values were approximately 12.5 m and 25 m, respectively, from the centre point of the test pad (pictured in Figure 4); and (c) **Trajectory**, which has a designation of either 'arc' or 'straight'. Note that **Object Size** is being tested through the use of two vehicles of different shape and size (HT vs. LV), where the designation of *static* vs. *dynamic* is used to describe the motion of each vehicle with respect to the RO, where: (a) when the RO is static, the LO is dynamic; and (b) when the RO is dynamic, the LO is static.

Figure. 4: An overhead representation of Test 2, represented at the Mining3 Test Facility. Please note that all object and work areas are done approximately to scale to provide an indication of size.

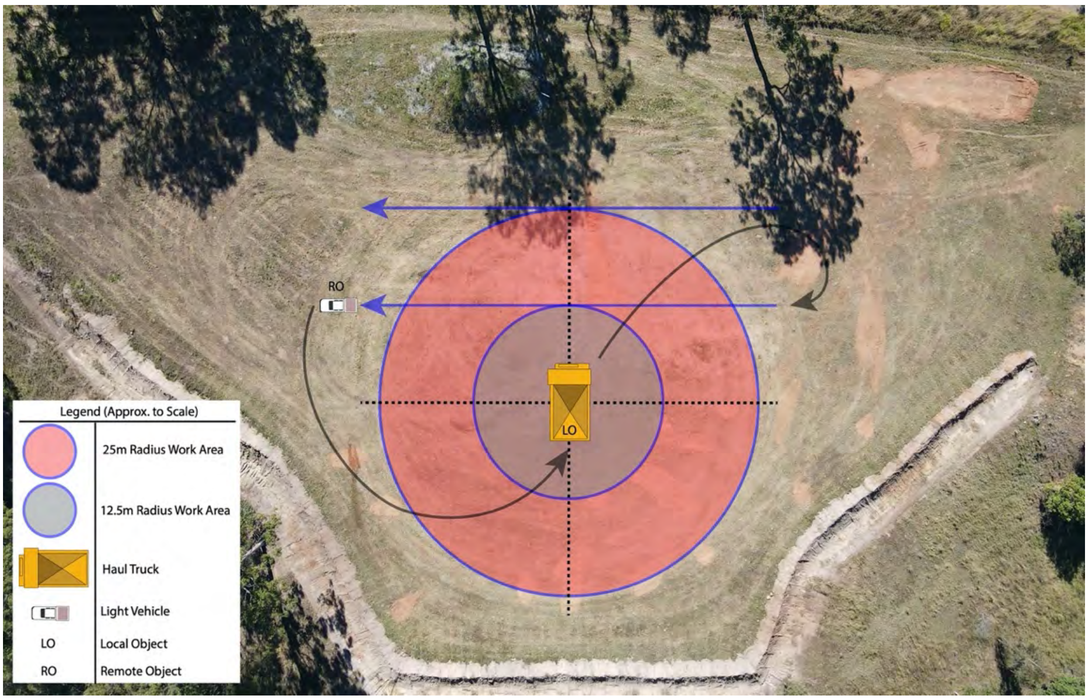


Figure. 5: An overhead example of the choreography used for Test 2, represented at the Mining3 Test Facility. Please note that all object and work areas are done approximately to scale to provide an indication of size. Furthermore, note that the choreographed movements to setup to a new test are represented by the 'black' arrows.

Standard Order	Run Order	Centre Point	Blocks	Object Motion (RO)	Speed (*Designation*)	Distance (*Designation*)	Trajectory (*Designation*)
45	1	1	3	Static	Low	Outer	Arc
47	2	1	3	Static	High	Outer	Arc
34	3	1	3	Dynamic	Low	Inner	Straight
48	4	1	3	Dynamic	High	Outer	Arc
36	5	1	3	Dynamic	High	Inner	Straight
37	6	1	3	Static	Low	Outer	Straight
43	7	1	3	Static	High	Inner	Arc
40	8	1	3	Dynamic	High	Outer	Straight
33	9	1	3	Static	Low	Inner	Straight
41	10	1	3	Static	Low	Inner	Arc
35	11	1	3	Static	High	Inner	Straight
44	12	1	3	Dynamic	High	Inner	Arc
38	13	1	3	Dynamic	Low	Outer	Straight
42	14	1	3	Dynamic	Low	Inner	Arc
39	15	1	3	Static	High	Outer	Straight
46	16	1	3	Dynamic	Low	Outer	Arc
18	17	1	2	Dynamic	Low	Inner	Straight
17	18	1	2	Static	Low	Inner	Straight
27	19	1	2	Static	High	Inner	Arc
26	20	1	2	Dynamic	Low	Inner	Arc
31	21	1	2	Static	High	Outer	Arc
22	22	1	2	Dynamic	Low	Outer	Straight
24	23	1	2	Dynamic	High	Outer	Straight
23	24	1	2	Static	High	Outer	Straight
19	25	1	2	Static	High	Inner	Straight
20	26	1	2	Dynamic	High	Inner	Straight
25	27	1	2	Static	Low	Inner	Arc
30	28	1	2	Dynamic	Low	Outer	Arc
21	29	1	2	Static	Low	Outer	Straight
32	30	1	2	Dynamic	High	Outer	Arc
29	31	1	2	Static	Low	Outer	Arc
28	32	1	2	Dynamic	High	Inner	Arc
1	33	1	1	Static	Low	Inner	Straight
3	34	1	1	Static	High	Inner	Straight
16	35	1	1	Dynamic	High	Outer	Arc
8	36	1	1	Dynamic	High	Outer	Straight
9	37	1	1	Static	Low	Inner	Arc
15	38	1	1	Static	High	Outer	Arc
6	39	1	1	Dynamic	Low	Outer	Straight
5	40	1	1	Static	Low	Outer	Straight
10	41	1	1	Dynamic	Low	Inner	Arc
12	42	1	1	Dynamic	High	Inner	Arc
4	43	1	1	Dynamic	High	Inner	Straight
13	44	1	1	Static	Low	Outer	Arc
2	45	1	1	Dynamic	Low	Inner	Straight
11	46	1	1	Static	High	Inner	Arc
7	47	1	1	Static	High	Outer	Straight
14	48	1	1	Dynamic	Low	Outer	Arc

Table 3: The defined run order for Test 2. Note that these tests only consider vehicle-to-vehicle interaction in a static-dynamic configuration.

7.1.5 Test 3: Straight Line Choreographed Scenarios

Test 1 and 2, as previously mentioned in Section 7.1.3 and Section 7.1.4, respectively, represent scientifically rigorous testing that can present performance characteristics of a PDS unit. While these tests are fundamentally important in order to visualize, or characterize, the capability of a PDS, it is not complete without one final round of tests. The purpose of Test 3 is to choreograph specific prevalent scenarios that may be pertinent to the viability of using a particular PDS at a particular mine-site; these tests, in a way, allow customization towards specific areas of important application that were not otherwise covered in Test 1 and Test2.

As detailed in Section 6, this study has identified, at a very high-level, six (6) prevalent scenarios that are common across most mine-sites and interactions involving mining vehicles. It is recommended that, at least at a base-level, all 6 be tested in these rounds of tests; however, through application and validation on-site at the Mining3 Test Facility, there are considerations that may be required if this were to be done safely. On the point of safety, it was important that only those tests that were able to be performed safely, be implemented and discussed; therefore, the following main scenarios were developed and tested (including their representative 'prevalent scenario' in **bold**):

1. **Test 3.1 Work Area Conflict [1]:** A static-static configuration focusing primarily on the alert type and timing when cold-started; i.e. when the PDS unit is turned on for the first time, simulating the start-up of a vehicle and detecting surrounding static objects (person or LV) at three (3) points of interest: (a) the front of the vehicle; (b) on the side(s) of the vehicle; and (c) behind the vehicle. Note that, for the purposes of validating this test, the LO was considered as the HT, being a higher risk vehicle in this particular encounter – see Figure 6 for an illustration of this test.
2. **Test 3.2 Work Area Conflict [2]:** A static-dynamic configuration test whereby the LO (i.e. the HT) is static, while the RO (i.e. the LV) is dynamic on straight-line trajectories around the LO. Given that this test is similar in concept to Test 2, only the side of the LO and behind the LO was considered. This allows identification of any issues when changing the orientation of the static, high-risk vehicle. Note that each test comprised of altering the RO speed between a designated *low* and *high* speed of choice (approximately 5 km h^{-1} and 20 km h^{-1}, respectively) at two distances from the LO – this being the designations of *inner* and *outer* – see Figure 7 for an illustration of this test.
3. **Test 3.3 Road Hazard Conflict [1]:** A static-dynamic configuration test whereby the LO (i.e., the HT) is dynamic, while the RO (i.e., the LV) is static. Once again, this may be similar to the previous test, or even Test 2; however, this is an important check that also includes the use of a pedestrian (i.e. a mannequin) to categorize functionality when simulating a simple passing case that will always occur. Note that each test comprised altering the LO speed between a designated *low* and *high* speed of choice (approximately 5 km h^{-1} and 10 km h^{-1}, respectively) along the *inner* trajectory designation (closer distances may also be tested if safe to do so; ideally this should be the separation between a standard passing distance, which may depend on site constraints). Furthermore, a reverse variant of the same test should be performed if possible – see Figure 8 for an illustration of thistest.
4. **Test 3.4 Road Hazard Conflict [2]:** A dynamic-dynamic configuration test whereby the LO and RO are both dynamic, simulating a passing encounter between each other. This is an important test to characterize any unexpected behaviour in a very common encounter; specifically false positive behaviour. Note that each test comprised of altering the LO and RO speed between a designated *low* and *high* speed of choice (approximately 5 km h^{-1} and 10 km h^{-1}, respectively). Furthermore, tests that include both vehicles at the same speed (e.g. both at low speeds), as well as tests where each vehicle is dynamic at alternative speeds (e.g. the LO at low speed, and the RO at high speed, and vice versa) are recommended. As per Test 3.3 above, the parallel gap between the two vehicles should be to the standard passing distance (which may vary ac- cording to each site), set to be approximately 12.5 m for on-site validation – see Figure 9 for an illustration of this test.
5. **Test 3.5 Tailgating/Direct Conflict [1]:** A static-dynamic configuration test whereby the LO (i.e. the HT) is dynamic on a direct trajectory with the RO (in this instance, either the LV or a pedestrian object, such as a mannequin). Note that, while this is a very important test to be performed, it is also one of most high-risk tests that was conducted and validated. Please refer below regarding actions performed in terms of risk management controls to ensure the safe implementation of this test case. In addition, three (3) speed designations (*low*, *mid*, and *high*) were tested using the HT, set to be approximately 5 km h^{-1}, 10 km h^{-1}, and 20 km h^{-1} for on-site validation – see Figure 10 for an illustration of this test.

As can be seen from the above list, three (3) of the main six (6) prevalent scenarios were choreographed and able to be tested. The remaining three (i.e. **Intersection**, **Void**, and **Incline/Decline**) were unable to be tested due to site limitations and, most importantly, safety (particularly in the case of the **Intersection Conflict**, which requires both vehicles to be dynamic at each other in potential collision encounters). It is highly recommended that these conflicts be performed in simulation towards capability identification to ensure the safety of all participants. Of the remaining three, two conflicts (**Work Area** and **Road Hazard**) presented two variants that are recommended to be performed as a baseline, with the final conflict (**Tailgating/Direct Conflict**) prioritized to be evaluated with the higher risk vehicle (in this case, the HT) being dynamic. As identified above, this particular conflict scenario is of high risk, and requires additional controls: (a) the LV **must** be unmanned and placed on a muck-pile (as pictured in Figure 10) in order to allow a more risk managed execution of a direct drive at the LV; (b) preferably the HT should be automated (unmanned) to execute a start and stop. However, if unable to do so, the driver must begin stopping at a pre-defined safe distance to ensure no collision occurs between the muck-pile and LV; and (c) the same controls should also be maintained with the use of a mannequin – although the requirement to be on the muck-pile may not be required.

Figure. 6: An overhead representation of Test 3.1, represented at the Mining3 Test Facility. Please note that all object and work areas are done approximately to scale to provide an indication of size.

Figure. 7: An overhead representation of Test 3.2, represented at the Mining3 Test Facility. Please note that all object and work areas are done approximately to scale to provide an indication ofsize.

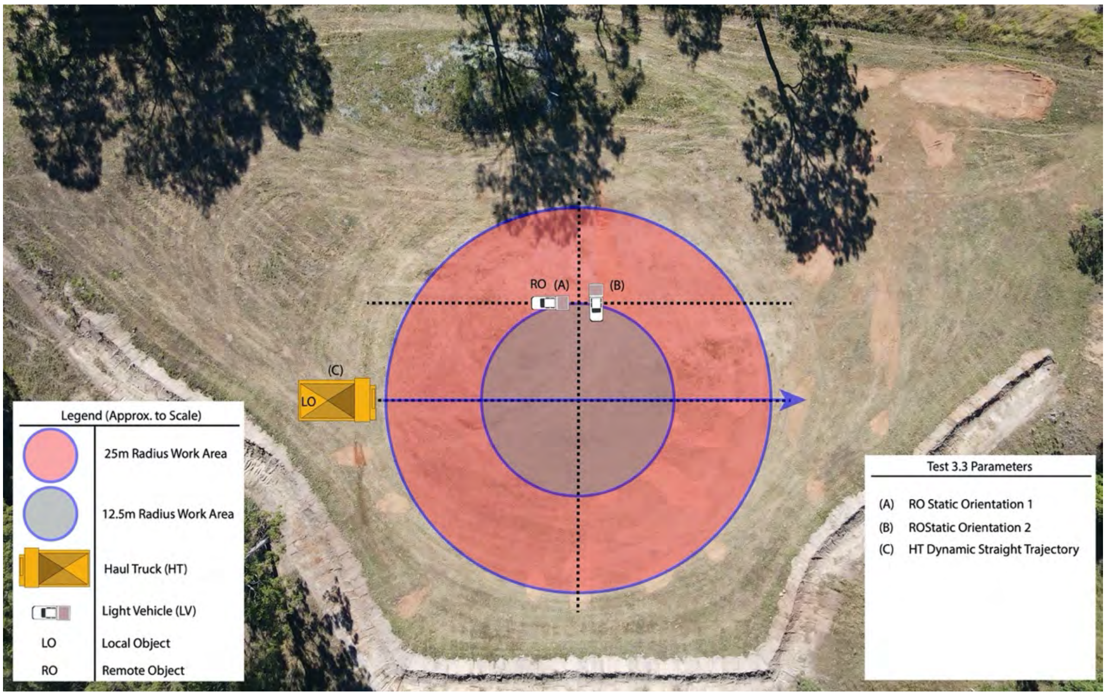


Figure. 8: An overhead representation of Test 3.3, represented at the Mining3 Test Facility. Please note that all object and work areas are done approximately to scale to provide an indication ofsize.

Figure. 9: An overhead representation of Test 3.4, represented at the Mining3 Test Facility. Please note that all object and work areas are done approximately to scale to provide an indication ofsize.

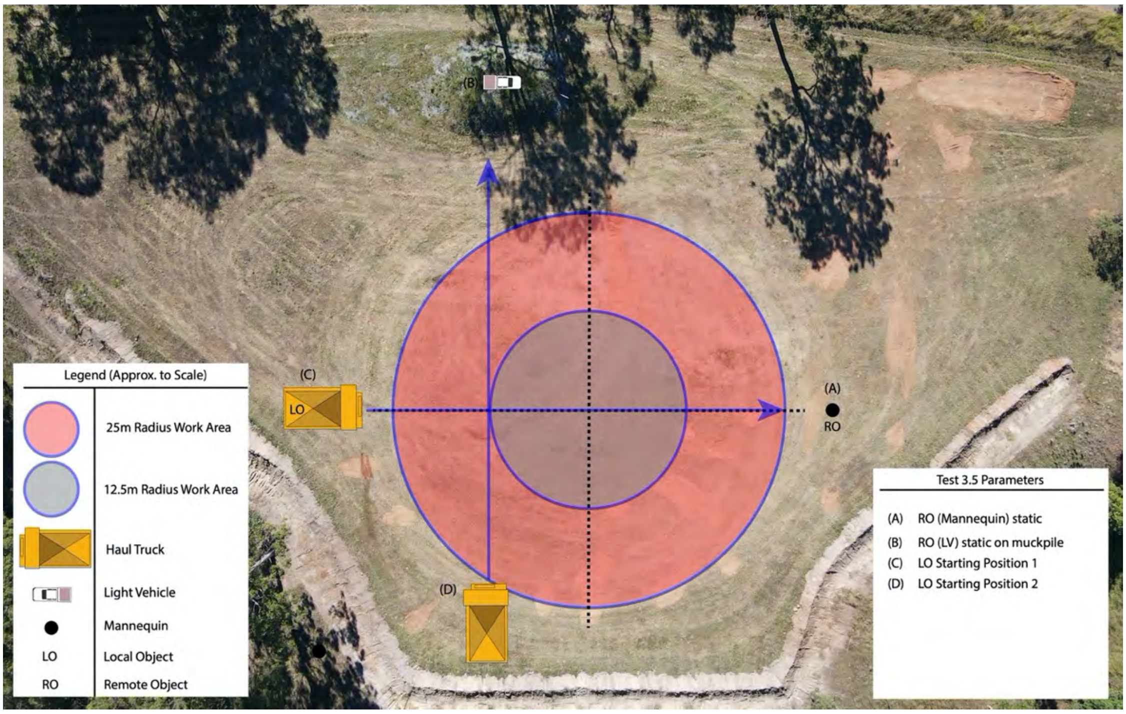


Figure. 10: An overhead representation of Test 3.5, represented at the Mining3 Test Facility. Please note that all object and work areas are done approximately to scale to provide an indication ofsize.

7.2 The Data Acquisition System

A Data Acquisition System (DAQ) consisting of various sensors, computers and storage devices was purposely designed to acquire the test data at Mining3's Pinjarra Hills Test Site. In addition to acquiring data, the design of the DAQ allowed Mining3 to explore various DAQ technologies, methodologies and strategies to share key findings and recommendations with industry. A summary of the key functional requirements relating to the design of the DAQ is included in Table4.

The Mining3 DAQ consisted of four (4) individual sub-systems, each consisting of different sensors, computers and recording devices. Each of the sub-systems were connected, synchronised, and controlled over a local network. The four main sub-systems of the DAQ are the control centre, the Local Object (LO) system, the Remote Object (RO) system, and a fixed system directly located in the test area (referred to as *Bystander*). Other components of the DAQ included an aerial drone and various other cameras. Further detail relating to each of the four main components of the DAQ is provided below and a summary of the DAQ components is shown in Figure 11.

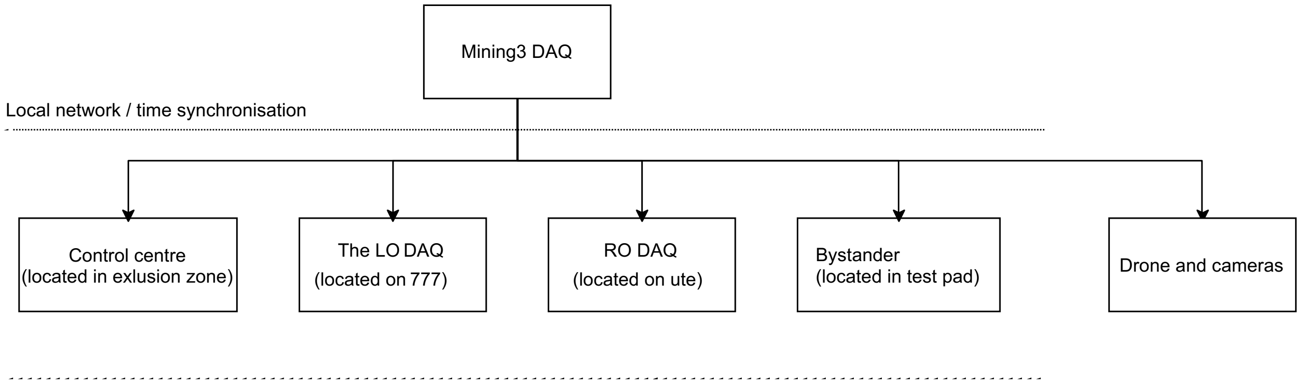


Figure. 11: High-level summary of the Mining3 Proximity Detection System (PDS) DAQ components.

7.2.1 The Control Centre

The control centre (Figure 12) was located in the test pad exclusion zone and included the main control laptop as well as other fixed-location sensors. The main tasks of the control centre were to:

- monitor and synchronise the time between all of the DAQ sub-systems;
- monitor the status of all the sensors, computers and recording devices;
- check the integrity of the data throughout the test process; and
- acquire, convert, and record Light Detection and Ranging (LIDAR) data from a fixed location in the environment.

7.2.2 The Local Object/Haul Truck System

The LO/Haul Truck (HT) DAQ system (Figure 13) was installed on the HT and included various sensors (positioned at different locations), a computer, storage devices, and the main network equipment for the DAQ. The LO/HT DAQ system was used in both a static and dynamic configuration (depending on the test) and was located in the actual test area. The main tasks of the LO/HT DAQ system were to:

- provide the wireless network coverage for the test pad;
- acquire, convert and record sensor data from the perspective of the HT (including the alarm states of the HT PDS units); and
- to host the time server used to synchronise all the sub-systems.

Type	Requirement	Notes/Additional Information
Data	• Acquired data to allow for the evaluation of the relative and absolute position, orientation, and velocity of both the LO and RO while in a stationary and dynamic state • Acquired data to allow for the detection and logging of various static and dynamic alarm states towards correlation of the alarm states to the states of the test vehicles	• The relative position, orientation, velocity and alarm states of each unit allows for the evaluation of the performance of different alarm states • Velocity is required to evaluate the performance of dynamic alarm zones
Redundancy	• Acquisition: (a) from different viewpoints; (b) from static and dynamic platforms; (c) using different sensing configurations; and (d) using different sensing technologies (modalities)	• Data redundancy minimises the risk of corrupt or incomplete data caused by sensor failure or drop-outs • Acquiring data using different sensing modalities, viewpoints, and different sensor configurations provides opportunities to gain valuable insight into: (a) the effectiveness of different sensing technologies and configurations; and (b) required levels of redundancy
Integrity	• DAQ to allow for data integrity checks before, during, and after test activities	• Data acquisition can be an expensive process • Checking the integrity reduces the risk of collecting incomplete or incorrect data
Technology	• The DAQ technology to avoid/minimise interference with other Supplier technologies • The DAQ technology to be independent from the Supplier technologies • If possible, DAQ technology to contain technology that is of a different modality to the technologies used in Supplier unit(s)	• Interference needs to be considered to reduce the risk of corrupting the data (e.g. infrared LIDAR may interfere with an infrared camera • Independent technology is recommended to avoid the potential of experimental bias during the testing and evaluation processes • Independent technology also allows for the acquisition of the raw sensor data, which is typically more complete and useful during evaluation processes • Acquiring data using different sensing modalities reduces the potential for bias during the evaluation process (e.g. two GNSS units using similar satellite constellations
Robustness	• Selection of DAQ technology to consider the following environmental/test conditions: (a) shock and vibration; (b) dust; (c) direct sunlight; (d) rain; and (e) communication (network) dropouts	• Environmental and test conditions may affect the data integrity
Flexibility	• DAQ to allow for *in-situ* debugging and modification	• The ability to modify the hardware or software of the DAQ allows for adaptability to changes in the experimental setup/plan

Table 4: Summary of the key functional requirements relating to the design of the Mining3 PDS DAQ.

Figure. 12: Management of the data recording and data integrity checking process using the control centre laptop.

(a) (b)

Figure. 13: HT DAQ system including the: (a) data logging box; and (b) haul truck equipped with the dual antenna Global Navigation Satellite System (GNSS) unit.

7.2.3 The Remote Object/Light Vehicle System

The RO/Light Vehicle (LV) DAQ (Figure 14) system was installed on the LV and included various sensors (positioned at different locations), a computer and storage devices. The RO/LV DAQ system was used in both a static and dynamic configuration (depending on the test) and was located in the actual test area. The main tasks of the RO/LV DAQ system was to acquire, convert, and record sensor data from the perspective of the LV (including the alarm states of the LV PDS unit).

Figure. 14: LV instrumented with the sensor bracket containing the dual antenna GNSS system, stereo camera and LIDAR.

7.2.4 The External System within the Test Area

This system (referred to as *Bystander* – Figure 15) is a self-contained DAQ that was installed at a fixed location within the test area. The main task of the Bystander DAQ system was to acquire, convert, and record sensor data from perspectives that were not safe for humans to accomplish (e.g., close to the HT during motion).

Figure. 15: Bystander DAQ system including the battery, mini-computer and stereo camera located within the test pad

7.2.5 Hardware

This section provides further details relating to the hardware that was used in the Mining3 PDS DAQ. The DAQ included a variety of different sensors and sensor configurations including:

- Different types (modalities) of sensor technologies:
  - 2 × dual antenna and inertially-aided GNSS units
  - 2 × LIDAR
  - 2 × Cameras
  - 3 × Stereo Cameras
- Different sensor configurations:
  - Static sensor configurations
  - Dynamic sensor configurations
  - LO/RO mounted configurations
  - Monochrome and colour cameras
  - 360° and conical LIDAR
  - High-grade and research-grade LIDAR
  - Industrial-grade and research-grade stereo cameras

A high degree of data redundancy was considered to minimise the risk of loss of data, and to better understand the benefits of the use of redundant data sources. Details relating to the DAQ hardware is summarised in Table 5 to Table 8.

Component	Hardware	Notes/Additional Information
Recording Device	• Dell XPS Laptop	• A laptop allowed the control centre operator to manage the test process, perform data integrity checks, and debug any issues that may have occurred during the data acquisition process • The laptop was used to record the control centre LIDAR data
Sensor 1	• Neptec Technologies Opal-PS00 LIDAR	• The Neptec Opal is a high-grade LIDAR with obscurant penetration (e.g., dust-penetration) capabilities and a 120° conical Field of View (FOV)

Table 5: Summary of equipment used in the control centre DAQ.

Component	Hardware	Notes/Additional Information
Recording Device	• Nexcom 2623 Modular Vehicle Computer System (MVS)	• An industrial-grade computer (MVS) was used to record HT sensor data, including hosting the time synchronisation server. • A 30 Ah LiFePO4 enclosed battery allowed the MVS to operate while the HT was in a stationary configuration
Network	• Ubiquiti Unifi UAP-AC-M access point	• A Wi-Fi access point was configured with a high-gain omni-directional antenna to provide high-speed communication to components • High-speed and reliable network connectivity was essential for checking the integrity of high-throughput data streams (e.g., image streams and point clouds, etc.)
Sensor 1	• Advanced Navigation Spatial Dual GNSS unit	• An inertially-aided and dual antenna GNSS unit was used to record the position, orientation, and velocity of the HT. • An inertially-aided GNSS unit allowed for more accurate and reliable state estimation and the dual antenna configuration allowed for more accurate orientation estimation (particularly at low speeds) • The GNSS antennas were installed on each side of the HT with as much antenna separation as possible (approx. 5 m) • The GNSS receiver (including the Inertial Measurement Unit (IMU), magnetometers, etc.) was installed on the operator cabin
Sensor 2	• Logitech C170 USB camera	• USB cameras were used to record the alarm state of each of the PDS units for the following key reasons: (a) simple integration (not requiring CAN-bus integration); (b) allowed for detailed evaluation of PDS interface (relevant for level 7 detections); and (c) allowed for the logging of more detailed data (e.g., level 8 detections, relative LO/RO states, etc.)
Sensor 3	• Carnegie Robotics Multisense S21 stereo camera	• The Multisense S21 (MS21) is an industrial-grade stereo-camera which is able to process depth information (in the form of intensity encoded point clouds) using the on-board processing capabilities of the camera • The MS21 was configured with a monochrome sensor and wide 115° FOV • The MS21 was located on the front of the HT and was used to record visual and geometric information of the test pad from the perspective of the HT • The visual and geometric information recorded by the MS21 allowed for the measurement of the relative position of the RO with respect to the LO

Table 6: Summary of equipment used in the LO/HT DAQ.

Component	Hardware	Notes/Additional Information
Recording Device	• Dell XPS Laptop	• A laptop was used to: (a) record the LV sensor data; (b) provide accurate estimation of the speed of the LV (the vehicle odometer was found to be inaccurate at low speeds); (c) position and orient the LV in the test pad; and (d) check the integrity of the LV data (in combination with the control centre integrity checks)
Sensor 1	• Advanced Navigation Spatial Dual GNSS	• Similar GNSS to the HT GNSS unit • The GNSS antennas were installed onto a custom-designed sensor bracket that was mounted onto the LV • The antennas were configured in a Fore-Aft configuration with as much antenna separation as possible (approximately 3 m) • The GNSS receiver (including the IMU, magnetometers, etc.) was installed in the centre of the LV and in line with the GNSS antenna
Sensor 2	• Logitech C170 USB camera	• See Table 6
Sensor 3	• FLIR Bumblebee XB3 colour stereo camera	• The Bumblebee XB3 (XB3) is a research-grade stereo camera that records raw image data - depth information needs to be post-processed on an external computer • The XB3 was configured with a colour sensor and 66° FOV • The XB3 was installed on the front of the LV sensor bracket and was used to record visual and geometric information of the test pad from the perspective of the LV
Sensor 4	• Beijing Surestar Technology R-Fans-32	• The R-Fans-32 is a 32-plan 3D LIDAR with a horizontal FOV of 360° and a vertical FOV of 24° • The R-Fans was positioned directly above the GNSS receiver (simplifying the alignment process) and located on the LV sensor bracket • The R-Fans was elevated approximately 300 mm above the sensor bracket to minimise interference with the GNSS antenna • The R-Fans provided a 360° geometric measurement of the test pad from the perspective of the LV • The point cloud data produced by the R-Fans allowed for the measurement of the relative position of the LO with respect to the RO

Table 7: Summary of equipment used in the RO/LV DAQ.

Component	Hardware	Notes/Additional Information
Recording Device	• Intel NUC (small form factor) computer	• A low-powered and small form factor computer was mounted to a tripod with a dedicated power station to convert and record stereo camera data from within the test pad
Power	• Hyundai LiFeP04 Power Station	
Sensor 1	• FLIR Bumblebee XB3 monochrome stereo camera	• The XB3 used on Bystander was a monochrome variant of the unit used on the LV (see Table 7)

Table 8: Summary of equipment used in the Bystander DAQ.

7.2.6 Software

The software component of the DAQ consisted of three key components:

- **Sensor drivers:** The DAQ system included two LIDAR scanners, three (3) stereo cameras, two (2) USB cameras, and two (2) GNSS systems. Various sensor drivers were required to convert the raw sensor data into useable evaluation data (e.g., converting LIDAR network packets into 3D point clouds). Robot Operating System (ROS) – an open-source software – provided drivers that were used in the PDS project for streamlined data recording, visualisation, and evaluation processes.
- **Time Synchronisation Software:** Time synchronisation was performed using an internet connection and a local network. The Chrony time synchronisation software was used to host a time-server on the HT DAQ allowing for synchronisation to reference time servers (via the internet connection) and synchronisation be- tween all the DAQ sub-components (via the local network).
- **Recording and Data Integrity Checking Tools:** Various recording and data integrity checking tools were written to manage the data recording and integrity checking processes. The DAQ data sources were recorded using ROS allowing for effective data compilation, visualisation and evaluation.

7.2.7 Implementation and Compilation

Approximately 10TB of evaluation data from the three (3) different DAQ sub-systems was acquired during the testing process. The test data consisted of:

- 2 sets of 3D point clouds collected from the different LIDAR;
- 3 sets of raw stereo camera images and point clouds from the stereo cameras;
- 2 sets of USB image and audio streams of the PDS interfaces;
- 2 sets of high-frequency GNSS data from both the LV and HT; and
- photos and videos obtained from various cameras and an aerial drone.

The test data was combined onto one desktop computer for integrity checking, visualisation and evaluation purposes. As the data was recorded using the ROS framework with time-synchronised computers, data preparation and compilation was relatively nontrivial. The point clouds for the two (2) XB3 stereo cameras were generated during the visualisation / evaluation process using ROS and the processing power of the desktop computer.

The sensor data was compiled into a ROS-based visualization tool (RVIZ) to allow for better insight, debugging and evaluation of the test data. The visualization tool (illustrated in Figure 16) included:

- a 3D model of the test pad, HT and LV;
- an overlay of the point clouds generated by the LIDAR and stereo cameras; and
- a set of synchronised image streams from each of the stereo and USB cameras.

7.2.8 3D Models

3D models of the test pad, HT and LV (illustrated in Figure 17) were created for visualisation and evaluation of the test data. The position and orientation (for both dynamic and static cases) of the virtual test pad, HT and LV was determined by the GNSS data. 3D models (consisting of a relatively accurate representation of the geometric and visual characteristics of the test environment) allowed for the creation of a digital representation of the test activities. This allowed for:

- effective, intuitive and detailed data evaluation;
- better understanding of the test conditions (the ability to perceive the sensor data in an intuitive way);
- more detailed data integrity checks; and
- an intuitive method to understand the benefits of different types of sensor modalities and levels of data redundancies.

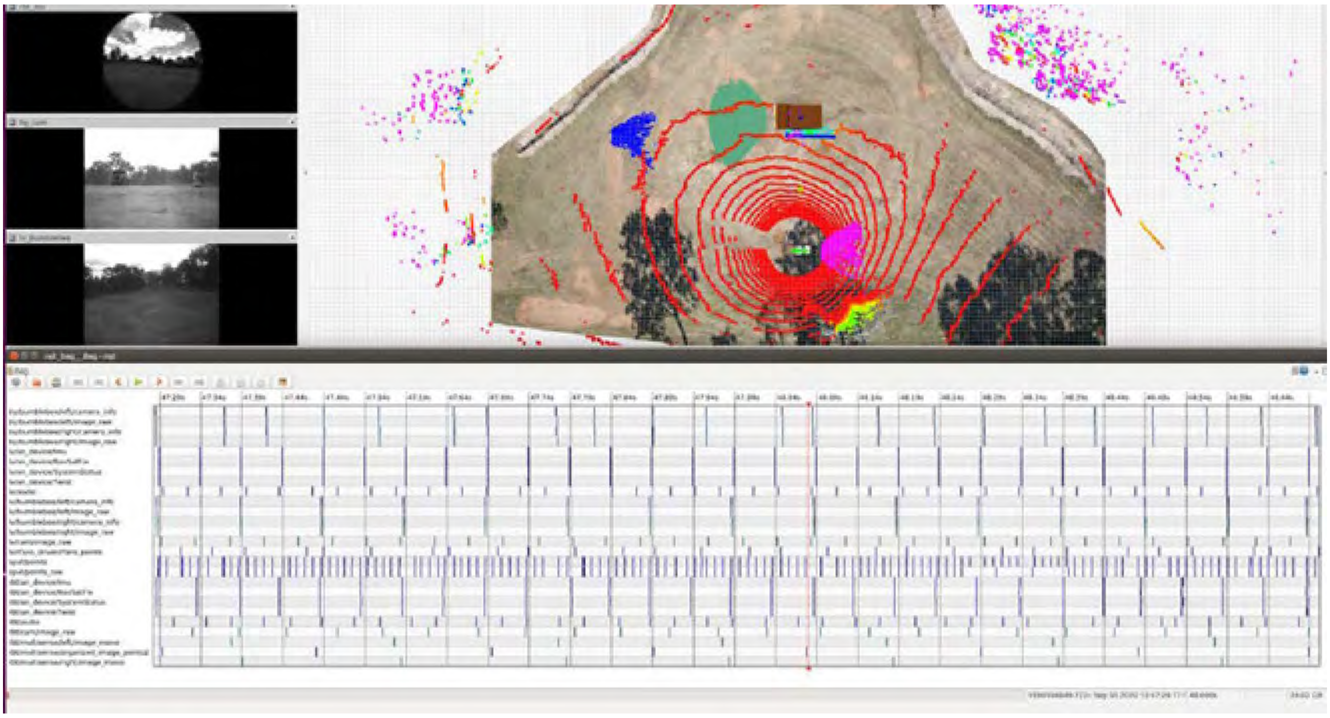


Figure. 16: Illustration of the visualisation and evaluation tool consisting of (top left) image streams; (top right) the visualisation environment; and (bottom) synchronised data messages for each of the DAQ sensors. The visualisation environment consists of 3D models of the map, LV and HT. Point clouds from: (blue) the Bystander stereo camera; (Green) the HT stereo camera; (Magenta) the LV stereo camera; and (Multi-coloured) the LV LIDAR are overlaid in the visual environment.

(a) (b) (c)

Figure. 17: Illustration of: (a) the LV; (b) the map; and (c) HT 3D models.

7.2.9 Point Cloud Data

Point clouds are sets of 3D points in space that consist of the X, Y and Z coordinates, and, in some cases, the intensity information of each point. The point clouds generated by the LIDAR and stereo cameras were included in the visualisation tool as '3D objects' similar to the 3D models. The position and orientation of each of the point clouds were measured and then verified and refined using the 3D visualisation tool. The point cloud overlay provided an additional source of information (using different sensing modalities) to the GNSS data. An example of the point cloud overlay is shown in Figure 18.

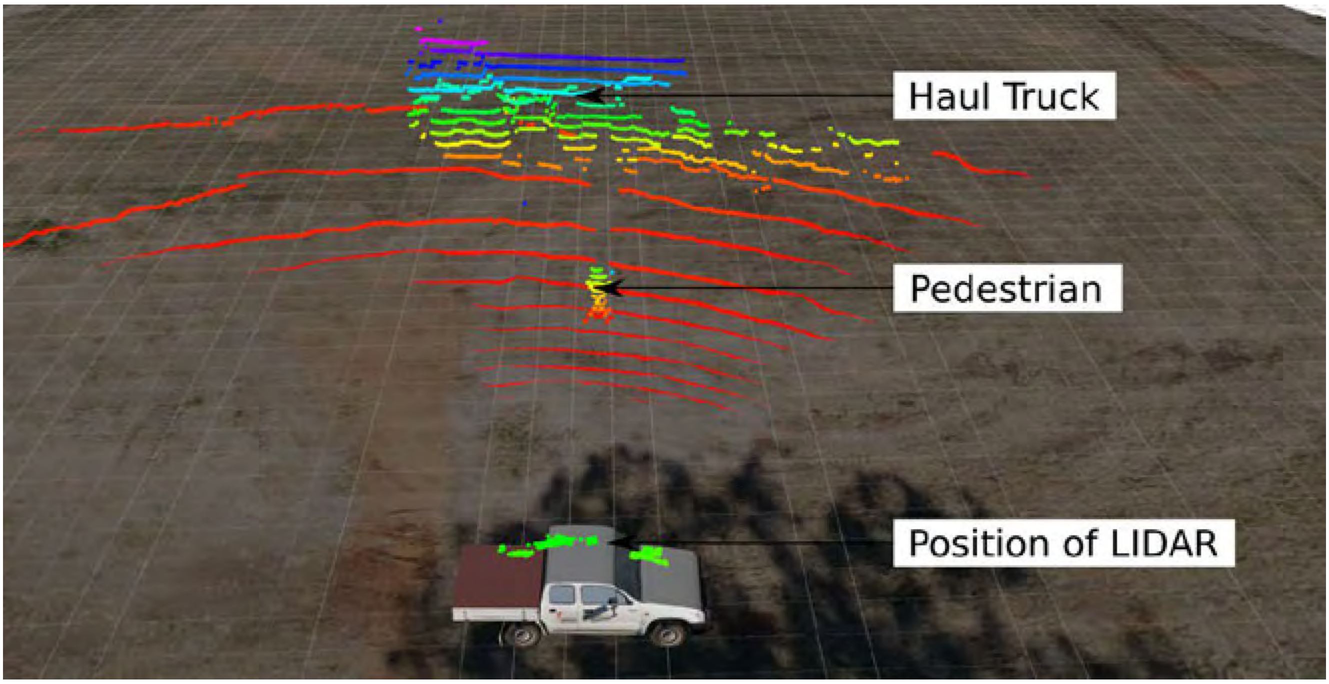


Figure. 18: Illustration of the virtual environment including a point cloud generated from the LV LIDAR

7.2.10 Image Data

Time-synchronised image streams (examples illustrated in Figure 19) from the stereo and USB cameras were included alongside the 3D models and point cloud data. This allowed for the correlation of PDS alarm events to relevant vehicles positions (and associated velocities) and orientations determined the different data sources.

Figure. 19: Example images captured from various cameras during test activities

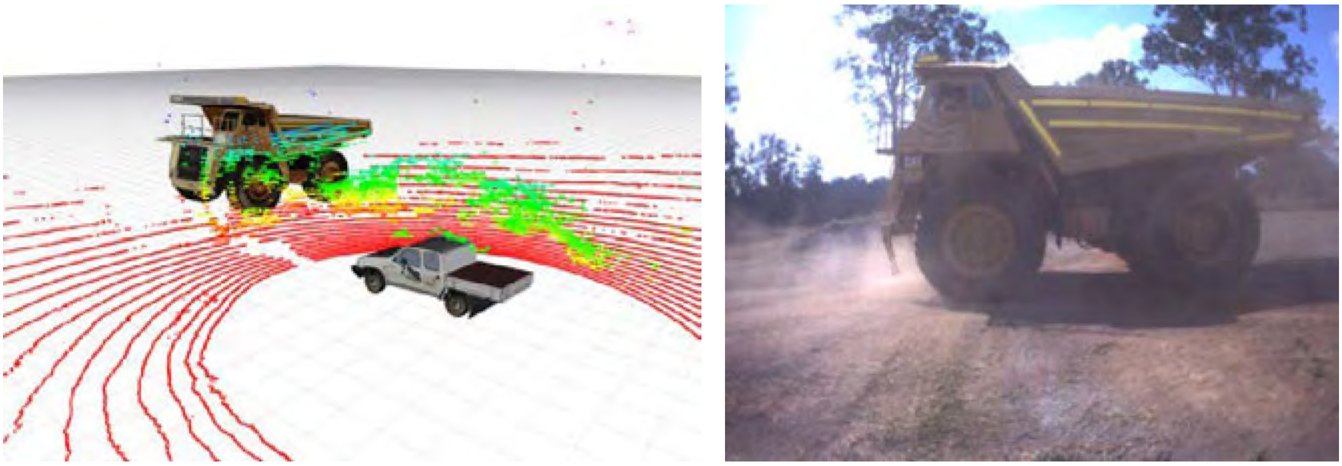
7.3 Data Acquisition System (DAQ) Performance and Recommendations

This section provides general recommendations regarding the design and implementation of a DAQ for the testing and evaluation of Proximity Detection System (PDS) units based on observations made during the project.

7.3.1 Sensor Performance

Various environmental conditions were observed to impact the performance of the DAQ sensors and (in some cases) the performance of the PDS units. For example:

- Dust was observed to affect the data of both vision and Light Detection and Ranging (LIDAR) systems, and was observed to alter both the geometric and textural nature of the data (See Figure 20):
  - Other methods, such as parameter tuning and software-based filtering, were not considered
- Direct exposure to sunlight and shadows were observed to affect the data of vision-based technologies in the form of textural changes, poorly exposed images and lens flare (See Figure 21):
  - It is expected that this affect can be addressed with parameter tuning and image processing; however, this was not considered in this project (out of scope)
- In some cases, a noticeable disparity was observed between the LIDAR and Global Navigation Satellite System (GNSS) data (See Figure 22):
  - The reason for the disparity may have been caused by changes in satellite constellations or occlusion of the GNSS satellite data by surrounding trees



(a) (b)

Figure. 20: Illustration of the effect of dust in: (a) the point cloud; and (b) image data. The green points located above the Light Vehicle (LV) in (a) are LIDAR returns produced by dust

Figure. 21: Illustration of an over-exposed image caused by exposure of the camera to direct sunlight (no changes to the auto-exposure algorithms were considered in this project).

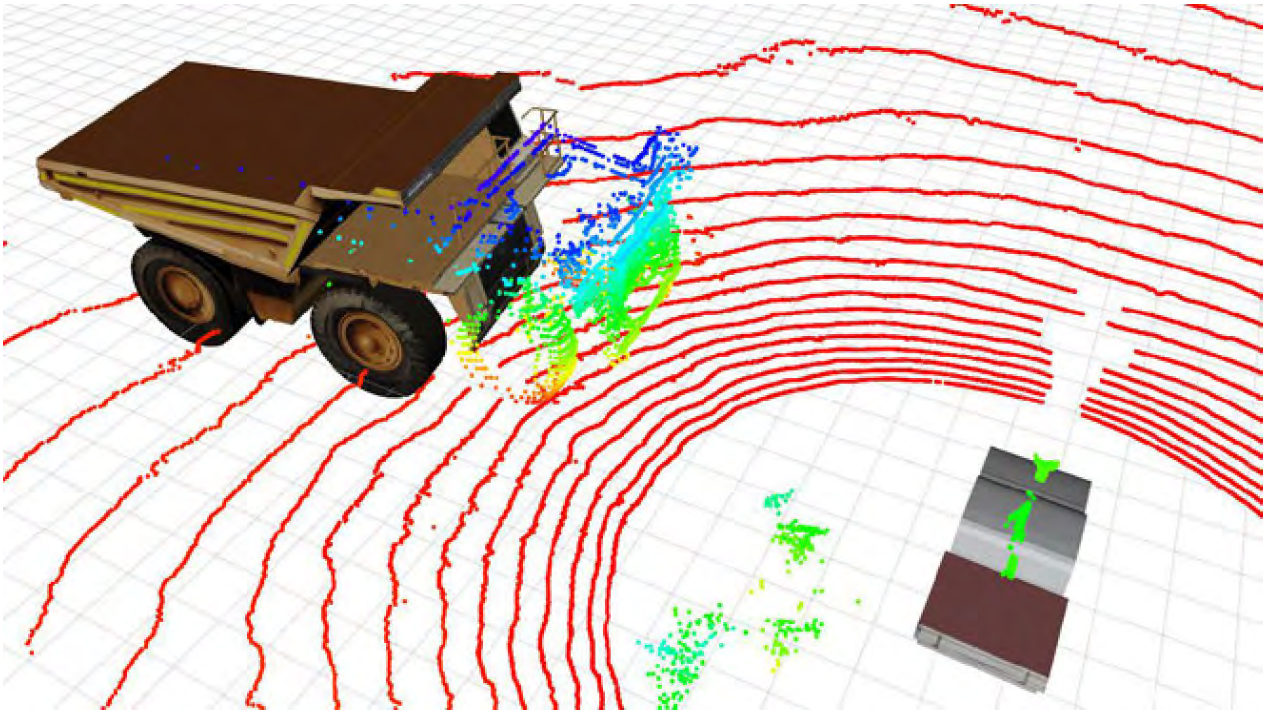


Figure. 22: Disparity (of more than 1 m*) observed between the Haul Truck (HT) GNSS and LV LIDAR data.*

7.3.2 Data Visualisation

A high-quality 3D visualisation framework (see Section 7.2.8 was shown to be a valuable tool that increased the effectiveness of the data acquisition, data integrity checking, and data evaluation processes. Examples are discussed below.

During the data acquisition process, the visualisation tool (in additional to analysis) was used to position and align the LV into the required test location by aligning the virtual Local Object (LO) model to the required test location (marked on the virtual test pad map). This resulted in faster, more accurate and consistent, set up procedures. This process is illustrated in Figure 23.

Figure. 23: Illustration of the use of the visualisation tool to position the LV between test activities. The green target represents the position and orientation of the LV and the red target represents the position and orientation of the required test location.

The visualisation tool was used to check the time synchronisation between the test data, the quality of the sensor data, as well as the relative transformations between the GNSS antenna, GNSS Inertial Measurement Unit (IMU), LIDAR, and stereo cameras. During the data integrity checking process, a scaling error in one of the stereo point clouds was observed and was rectified prior to further testing. The use of a visualisation tool allowed for a more detailed, intuitive and overall, more effective investigation into the state of the evaluation data.

In general, the visualisation tool was found to be an effective and intuitive method for evaluating the test data by allowing for the detection of different alarm states and the correlation to test factors such as:

- the relative position and orientation between the LO and Remote Object (RO);
- the relative speeds between the LO and RO; and
- the environmental conditions during the test activities.

Furthermore, the tool was also used to verify that the correct experimental configuration was used in each test (by verifying the relative position, orientation and speed of the different objects) and for detecting disparities between the LIDAR and GNSS data (further integrity checks). It is recommended to use, where possible, visualisation tools to assist with the data acquisitions, integrity checking and evaluation processes – examples of which are provided later in Section 7.4.

7.3.3 Data Redundancy

Sensing redundancy (the use of multiple sensors to measure the same test parameter) reduced the risk of loss of data. Although many data integrity checks were performed, it was found that in some cases one of the sensor data streams was either corrupt, incomplete, or lost. Redundant sensor data allowed for data evaluation during these situations. Redundant sensor information is particularly important when acquiring site data which can be costly to obtain.

The use of different sensing technologies (modalities) allowed for the identification of the sensitivities of different technologies to various environmental conditions, allowed for the use of complementarities between technology types, and allowed for more effective data integrity checking. Examples include:

- The use of GNSS data during periods with relatively high levels of dust;
- The use of the global consistency of GNSS data to determine the relative position of the test objects at large distances, and the use of the relative accuracy of the LIDAR data to verify the GNSS data at close distances;
- The use of LIDAR data to obtain a relatively accurate estimation of the geometric state of the test objects and the use of the camera data to obtain a high-resolution estimate of the visual state of the test objects; and
- The comparison of LIDAR and GNSS data to estimate the accuracy of the GNSS data

Furthermore, the use of audible sensing, through the on-board mounted USB cameras, presented opportunities to verify and effectively determine PDS alerts compared to their visual representation on their respective interfaces. This was highly important when: (a) the PDS screen becomes occluded due to sunlight; or (b) the interface is out of frame from the camera's view (movement over time due to undulations on the road). Numerous instances of this occurred, and easily rectified through evaluating the audible response. Overall, it is recommended to consider using redundant sensor data that considers different sensor technologies when designing a DAQ.

7.3.4 Equipment and Configuration

During the data acquisition process, different sensor types and configurations were used to acquire the evaluation data. Some general observations are discussed below:

1. The use of two dual-antenna GNSS units was found to be the most effective method for measuring the relative position and speed between the two different test objects. The use of GNSS systems solved for the object detection and identification (data association) steps, therefore simplifying the data evaluation process.
2. The use of a 360° LIDAR located at the central point of the LV was shown to be a valuable and complementary source of evaluation data. The LIDAR was found to provide an alternative source of geometric information that could be used to determine the relative distance between the two test objects. The LIDAR data provided an effective means for determining the relative position between the two test objects as the LIDAR was not as dependent on transformation information relating to the position of the equipment on the vehicles. Furthermore, the LIDAR data was not dependent on the position of satellites or occlusions of satellite data from surrounding trees.
3. The use of multiple cameras in the test pad was found to provide valuable evaluation data. The vast amount of visual information was particularly useful in investigating outlier data.

4. The use of in-vehicle odometers was found to cause variability in the vehicle speed and a GNSS speed module was used as a more accurate replacement.
5. The use of an aerial drone was found to provide a valuable source of evaluation data from a different perspective; however, the battery life (approximately 20 min), including the need for frequent battery swap-outs, was found to slow the data acquisition process.
6. The use of cameras to record the alarm states of the PDS units was relatively easy to implement (no need to interface into different PDS interfaces) and was shown to provide a vast amount of useful information (including both visual and auditory alarm states). Data evaluation using visual data of the PDS User Interface (UI) was, however, found to be time consuming and challenging to automate. It is recommended to, if possible, record the alarm states from the actual PDS unit using a communication interface such as Controller Area Network (CAN) BUS for automation as well as the visual information form the PDS UI for additional information.

7.4 The Data Evaluation Process

As detailed in Section 7.2, the custom Data Acquisition System (DAQ) used for validation purposes served as an important baseline to: (a) capture redundancies (additional sensors, such as stereo-vision cameras, etc.) in the event additional information is required towards determining a Proximity Detection System's (PDS) capability;
(b) use these redundancies (sensors) to capture and provide additional learnings about the sensors themselves (see Section 7.2 for more information); and (c) capture important information in a passive way, without direct access to the PDS unit – accomplished through the use of mounted on-board cameras and audio equipment, time-synchronized with Global Navigation Satellite System (GNSS) and attitude data for state-space information.

In summary (see Section 7.2), the DAQ enabled the capture of the following, key points of data:

- The relative position and orientation between the Local Object (LO) (i.e. the Haul Truck (HT) in our validation procedure) and the Remote Object (RO) (i.e. the Light Vehicle (LV), or pedestrian object – mannequin – in our validation procedure).
- The relative speeds between the LO and RO (notably, between the HT and LV).
- Visual and audio capture of each installed PDS interface (on both the HT and LV) – providing information regarding the output from the PDS' decision process and alert type.

Using the above information, and the visualization tool detailed in Section 7.2, the subsequent methodology was followed to evaluate the data:

1. Each run (detailed in Section 7.1) for a specific test is used as a template for adding observations and other parameters (see Table 9 below for an example run (run 1), illustrating the capture of observations and data integrity checks for Test 1 using Supplier 2) during the evaluation process.
2. Using the recorded data, each run is played back using the Robot Operating System (ROS) framework (see Section 7.2 for more information), with positional, speed and time data captured using custom Mining3 software written in the Python language (saved separately for post analysis). Note, this capture includes a correlation *ID* that is used in post analysis graphing (see below for more information). In addition, this process is for GNSS data captured for the HT or LV; for a pedestrian object the Light Detection and Ranging (LIDAR) data is used, in tandem with the ROS framework (which provides the ability to measure within the simulated environment), to document relative positions when an alert is noted – this is largely a manual process. The implementation can differ based on the user's discretion; however it is recommended that this be written in Python if possible, for ease of use with ROS.
3. As each run is played back, the PDS interface(s) available on each vehicle (if applicable) is viewed through recorded footage (time-synchronized) from on-board mounted cameras. The PDS interface output/behaviour (i.e., a visual alert, or detection) is correlated to an *Alert Type* designation (see below, for more information) and any observations are noted (see template structure in Table 9) – once again, this process is manual.
4. Once each run has been analysed using the steps detailed above, the saved positional and speed information, correlated to an *ID* for each *Alert Type* is then used in post analysis graphing to illustrate the effect of key factors (see Section 7.1.1 for more information). We recommend the use of MATLAB (if available) or Python for post analysis.

Run Order	RO & LO check	Date	Weather	Observations
1	*pass*	2020-08-18	Cloudy	• HT PDS detection (Control Level 7 (L7)) noted for all runs • LV PDS detection (L7) noted for all runs • Noted LV orientation switching on PDS interface • LV audio noted before HT PDS alert (all runs) • LV speed ramp up noted before each run

Table 9: An example evaluation table for Test 1 using Supplier 2. Note the observations added for each run during the evaluation process, including integrity checks and weather information.

7.4.1 The Alert Type Designation

Initially, it was proposed to evaluate a system based on its expected performance and its actual performance using *true positive*, *false positive*, *true negative*, and *false negative* analysis. With the information captured from the DAQ, this is very possible under the current test plan; however, this is very dependent on the available test area and its ability to adapt to a PDS' parameters – meaning that, for example, the *inner* and *outer* radii can be designed to be within and outside a PDS' zone of influence, respectively. Doing this would allow easy identification of whether the actual performance (i.e., a detection in the *inner* zone is a *true positive*; or no detection in the *inner* zone is a *false negative*, etc.). Unfortunately, as was discussed in Section 7.1, there may exist constraints on these radii simply from: (a) the minimum turning radius of the vehicles being tested; and (b) the potential for certain systems to have *dynamic* detection zones that make this task particularly difficult. Instead, the evaluation of capability can be done through characterizing what alerts occur, when they occur, and if this alert was considered as *unexpected* under the context of a specific test (e.g. say one alert tended to always trigger when the LO and RO are within a certain distance to each other, yet, on certain runs, there were cases where this did not occur). This can allow an end-user to easily identify the potential variation evident in one system versus another.

To do this, a generic term (the *Alert Type*) was coined to designate each PDS against specific alarm outcomes (i.e., L7 or Control Level 8 (L8), etc.), an *Alarm Type* is defined from a characterization of 1 and onwards; this allows:
(a) generalization of the alarm amongst different PDS; and (b) easy demonstration of the available intelligence layer(s), and its subsequent performance, by the hierarchy of alarm types without specifically addressing what that may be (a challenging task when direct access to the PDS unit may not be available). For example, say a PDS unit (called A) has: (i) a visual alert at L7 when an object is detected; (ii) an audible alert when L8 is triggered; and (iii) a *different* audible alert when another level of intelligence (be it L8 or Control Level 9 (L9)) is triggered. Say another system (unit B) has: (i) an audible alert at L7 when an object is detected; and (ii) only one other alert (visual/audible) that is triggered for an intelligence response. Both these systems, irrespective of their sensor suite or overall intelligence, only conveys, in the case of A and B, three (3) and two (2) alert types to their driver's, respectively. Categorizing them as such (i.e., A has three alert types (type 1, 2 and 3), and B has two alert types (type 1 and 2)), immediately conveys that one unit has additional intelligence to its counterpart, irrespective of what that intelligence is. Note that, while it may seem like more intelligence is better, it may not always be the case, so discretion is advised. Ultimately, this provides a more high-level, simplified, designation of the PDS' alert type.

Under this designation it becomes almost trivial to identify how specific factors may affect a PDS when each of these alert types are triggered. For example, using unit A, we may find that *Alert Type 1*, triggered more often under slower speed, than higher speeds on the LV; or that *Alert Type 2* and *Alert Type 3* intermittently triggered when the LV was at high speed, and more consistently at low speeds, etc. In more cases than not, L7 is always designated as *Alert Type 1*, so this can provide a direct comparison of this type of alarming. It is, of course, important to report what each *Alert Type* corresponds to in a capability report; however, for a quick review of a PDS' performance, especially between two or more PDS, this provides a more efficient and simpler outcome. A real example of this reporting method is presented in Section 7.4.2, using Test 1, 2 and 3, with Supplier 2 and 3 provided PDS – two units that use the same primary sensor (GNSS).

7.4.2 Test 1 Outcomes and Learnings

Illustrated below in Figure 24 and Figure 25 are the evaluation outcomes for Supplier 2 and 3, respectively, under Test 1 (includes all runs conducted). Please note that it is not the objective of this report to compare each supplier's PDS outcome, but rather to demonstrate how the capability of each system can be evaluated under the proposed test methodology, including insight extracted from the analysis regarding the key factors (see Section 7.1.1). Each *Alert Type* is designated by a colour for visual representation, this being *green*, *yellow*, *orange*, and *red* for *Alert Type 1*, *Alert Type 2*, *Alert Type 3*, and *Alert Type 4*, respectively. Note that these colours are not required, and any designation is acceptable. Furthermore, it is certainly possible to have more that 4 *Alert Types*; however, using the Supplier provided units for validation of the methodology in this phase, only 4 were identified at a maximum. In both Figures (Figure 24 and Figure 25), (a), (b) and (c) represent the tested speed designations of *low*, *mid*, and *high*, respectively. Furthermore, the top and bottom rows in each figure represent the *Alert Type* designations captured from the perspective of the LV and HT PDS units, respectively. Note that the *North* and *West* orientations are provided to visually indicate the orientations tested, including an image of the HT to indicate its approximate position – this is not to scale, just as a visual indicator – and the direction of travel undertaken by the LV (arrow).

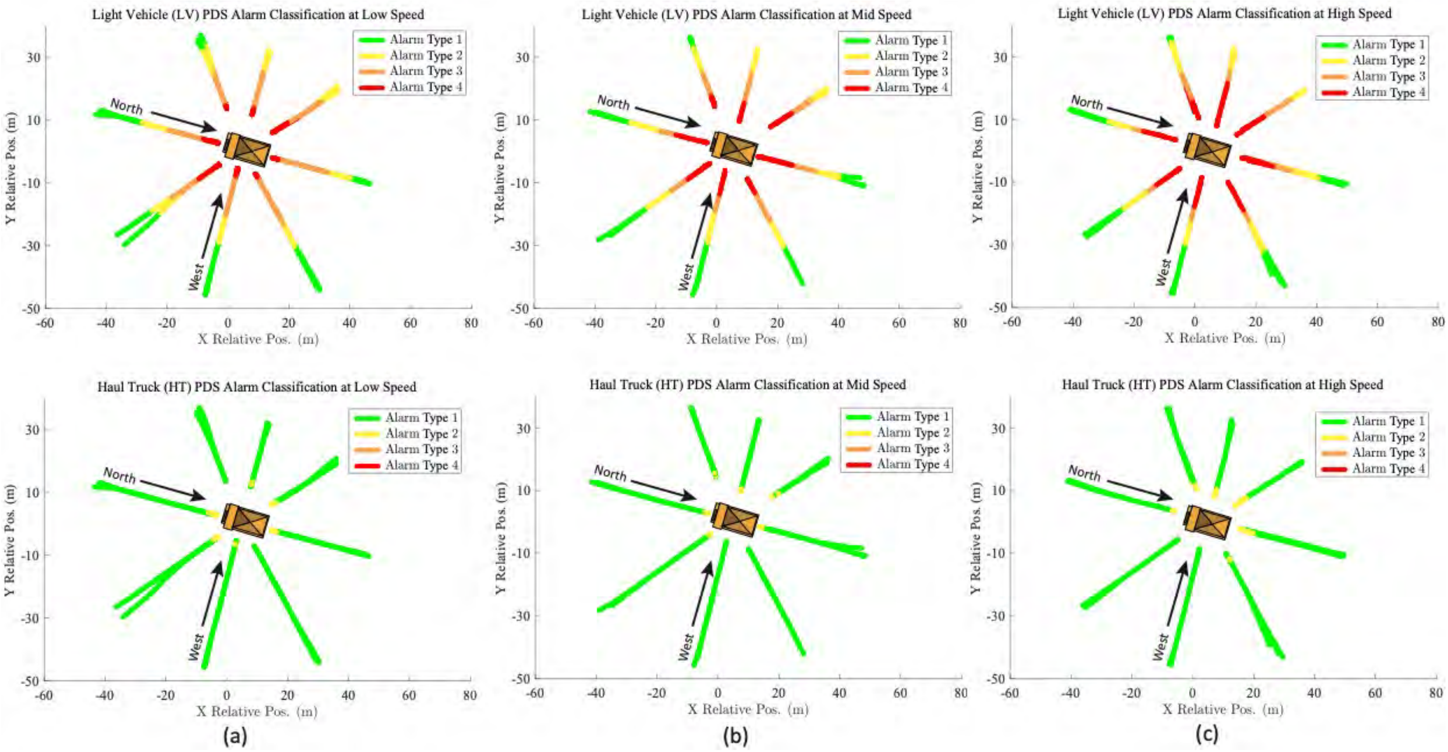


Figure. 24: Visualization of the Test 1 evaluation for Supplier 2, where (a), (b) and (c) represent the results from low, mid, and high-speed designations, respectively. The top and bottom row of plots represent the Alert Type response from the perspective of the LV and HT, respectively. Note that North and West are indicated in each plot (including the direction of travel of the LV), where an image of the HT is placed approximately at its static position – this is not to scale, only a visual representation.

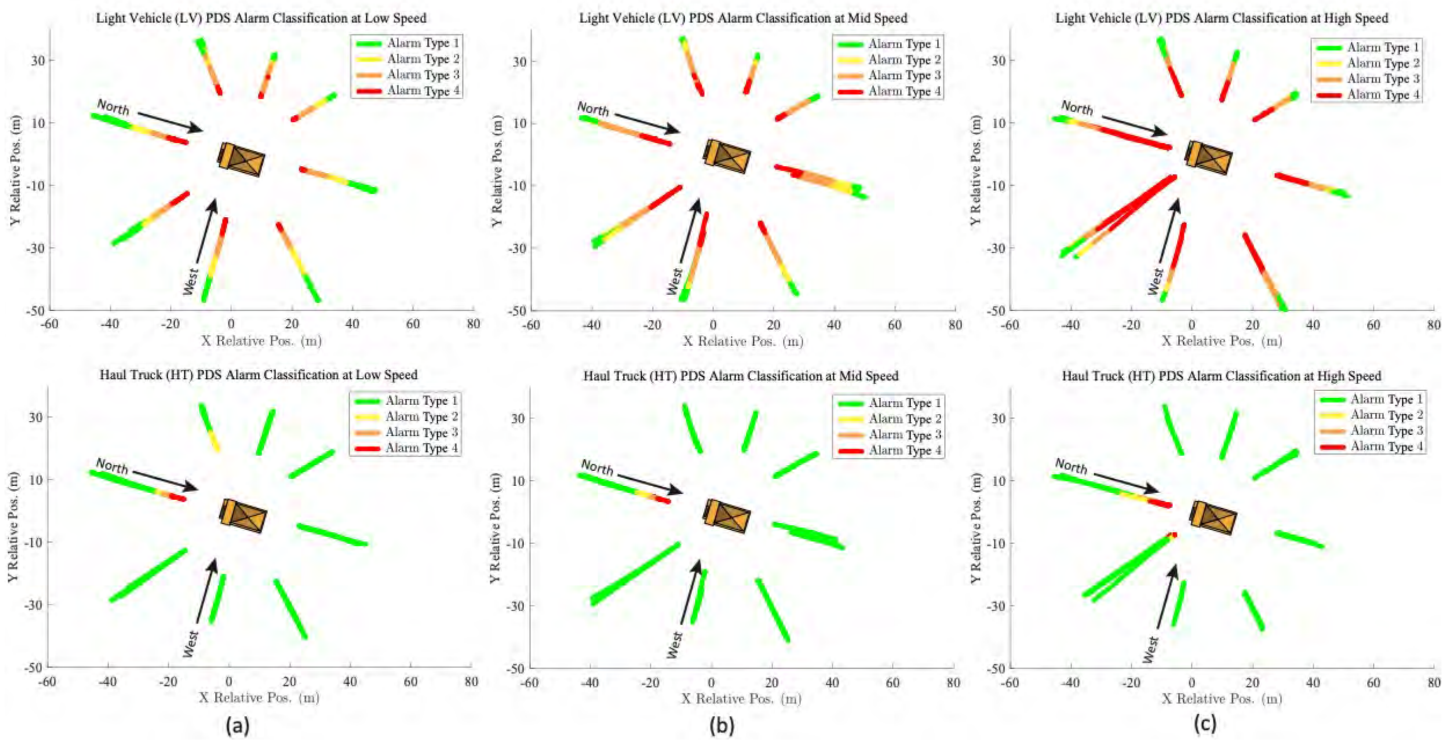


Figure. 25: Visualization of the Test 1 evaluation for Supplier 3, where (a), (b) and (c) represent the results from low, mid, and high-speed designations, respectively. The top and bottom row of plots represent the Alert Type response from the perspective of the LV and HT, respectively. Note that North and West are indicated in each plot (including the direction of travel of the LV), where an image of the HT is placed approximately at its static position – this is not to scale, only a visual representation.

Immediately, it is clear that **Speed** is a factor in both PDS units from each of the suppliers. This is shown by the increase in the number of higher *Alert Types* recorded at higher speeds (i.e., more occurrences of *Alert Type 2* and upwards as the speed of the dynamic vehicle – the LV – increases). This was an expected result, given that both PDS units were known to have dynamic detection zones; therefore, Test 1 successfully fulfills its purpose by demonstrating the expected shape with the increase in speed. Furthermore, there are additional interesting outcomes that can be learned from this visualization of information:

- Supplier 2's units have different behaviour between vehicles, where the LV has a higher number of *Alert Types* being conveyed to the driver, while the HT only had two (2) *Alert Types*. While this is not a negative finding, it is certainly interesting to note, as the expectation was that both PDS units, on each vehicle, alert the driver in similar means – which is certainly not the case here. This contributes to **Object Size** being a potential factor with this system, where not necessarily the physical size of the object impacts the sensor's behaviour, but its size and type may imply different intelligence behaviour in the User Interface(UI).
- To the above point, this behaviour may be similar with Supplier 3's outcomes; however, as can be seen in Figure 25, the HT's response, at least in its forward direction, demonstrates the same number of *Alert Types* as the LV, being conveyed to its driver. Note that, this unit had higher functionality with forward and reverse gear implementation; for consistency, only the forward gear tests were conducted; therefore, if a reverse test were to have been conducted, the same behaviour may be evident in the *South* orientation. In addition, it is recommended that both vehicles be tested in Test 1; however, due to time limitations, only the high-risk vehicle was tested (i.e., the HT). This may allow further characterization of *Alert Type* behaviour (and their potential differences) between vehicles, as well as between units from different suppliers.
- **Speed** was clearly evident from this analysis as a factor for both systems. In addition, one can note that Supplier 2's **Speed** factor seems to largely impact the higher *Alert Types* (i.e., 3 and 4) more than the lower *Alert Types* (i.e., 1 and 2) – where *Alert Type* 1 and 2, amongst each run and each speed test, seemed to occur similarly, with no noticeable reduction (Figure 24). In contrast, Figure 25 implies that Supplier 3's PDS prioritizes a reduction in the lower *Alert Types* (i.e., 1 and 2) to ensure the higher *Alert Types* (i.e., 3 and 4) are conveyed faster to the driver, potentially allowing stopping at an earlier point in time (somewhat evident in the results captured).
- In both cases (Supplier 2 and 3), the dynamic vehicle (i.e., the LV) seems to be the dominating system in alerting the driver – a design choice that may be different in other systems. Interestingly, this behaviour is unexpectedly different (i.e., less alerting) for Supplier 3's PDS when tested under non-direct encounters (i.e., in Test 2 – see Section 7.4.3 for more information) – implying a system that prioritizes direct encounters, over basic proximity; a demonstration of capability through this methodology.
- In both cases (Supplier 2 and 3), there are some notable areas of variances in the system's behaviour. While it is difficult to statistically represent this variance, it can be visually identified where: (a) some *Alert Types* triggered out of expected order (i.e. *Alert Type 3* triggered before *Alert Type 2*) – evident in Figure 25; and (b) where some expected *Alert Types* did not trigger at certain orientations to the LO – evident in both Figure 24 and Figure 25. In such cases, it is recommended that variant cases be additionally tested to fully understand if these occurrences were outliers or system issues; due to time considerations, this was not a priority, but nevertheless, a key recommendation in the future implementation of this test methodology.

Overall, from the execution of Test 1, it is clear that the shape/zone of a PDS can be certainly inferred and, in most cases, quantified with respect to the recommended, baseline factors. Of note are the following additional findings from executing Test 1 at the Mining3 test site:

1. Test 1, which involves dynamic vehicles, can be implemented in a safe and practical manner, with the developed DAQ presenting valuable data towards understanding the effect of key factors on the PDS detection zone/shape.
2. Overall, the Test 1 process took an average of approximately 2.5 h to complete, with an approximate average time of 4.6 min per run – captured with the updated Test 1 plan (Section 7.1.3) using Supplier 2 and 3 units. This includes: (a) time taken with both types of RO (i.e., the LV and the pedestrian object); and (b) in-between setup timing for the re-positioning of the RO.
3. Demonstrate a potential reporting process that captures interesting findings with respect to the effect of the PDS zone to identified, baseline factors.

7.4.3 Test 2 Outcomes and Learnings

This section aims to provide outcomes and potential learnings from the execution of Test 2 at the Mining3 test site. As per Section 7.4.2 above, the same *Alert Types* and colours are utilized for consistency. Test 2, given that it has the Design of Experiments (DOE) test structure, presents a challenge towards analysis; however, one can regard analysis by grouping each run according to each main **factor**. Given that there are four (4) baseline factors, this presents sixteen (16) variants (i.e., a combination of each type of factor). Each of the 16 can then be grouped according to a specific factor for analysis. As an example, Figure 26 and Figure 27 (for Supplier 2 and 3, respectively) below aims to present findings with a focus on the **Speed** factor, analysing the following additional factors: *Static LV*; the *Inner* designated radial distance (approximately 12.5 m); and the *Arc* trajectory. Please note the following, with respect to Figure 26 and Figure 27:

- (a-b), (c-d) and (e-f) each represent a test block (1, 2 and 3) under the DOE methodology, respectively; where each block is, in essence, a repeat of the same run to understand potential variability.
- (a, c, and e) and (b, d and f) represent the HT and LV PDS perspective of the same test case(s), where each column designates the results between the *low* and *high* vehicle speed (aimed to be approximately 5 km h^{-1} and 10 km h^{-1}, respectively).
- The top row(s): (a-b), (c-d) and (e-f) presents the relative position analysis between each vehicle.
- The bottom row(s): (a-b), (c-d) and (e-f) presents the relationship between the relative position, and the speed of the dynamic vehicle, which, in this case, is the HT.
- An image of the LV is illustrated to convey its position and orientation with respect to the conducted test case – note that this is not to scale. In addition, the direction of travel of the dynamic vehicle (i.e., the HT) is also illustrated for convenience.

The following findings can be found for Supplier 2:

- As highlighted in Section 7.4.2, Supplier 2's PDS only has two (2) *Alert Types* on the unit installed on-board the HT – this explains the main difference between each perspective (Figure 26(a, c, and e)) and Figure 26(b, d and f)), where the LV installed PDS from the same supplier provides two (2) extra types of alarming to the driver.
- **Speed** may be a factor for the *dynamic* object, but not necessarily the *static* object using the Supplier 2 system. As evident in Figure 26 (a and b), the HT PDS only alerted higher than *Alert Type 1* when under the *high-speed* designation. In contrast, the change in speed (of the dynamic vehicle) seems to have had no influence on the *Alert Type* occurrence when viewed from the LVs perspective (the static vehicle in Figure 26(b, d and f)), where there is a consistent occurrence of each *Alert Type* at a specific distance to the other object regardless of the dynamic object's speed.
- Interestingly, the alert distances between the LV and HT are also not the same. While this is not a negative finding, it is certainly interesting to note that, in this particular test case, the HT only tended to alert (higher than *Alert Type 1*) when in very close proximity (approximately within a relative distance of 10 m), compared to the system on-board the LV (started alerting higher than *Alert Type 1* when within an approximate relative distance of 35 m). Note that this is significant, given that *Alert Type 1*, at least with the systems used for validation, defined a *L7*.
- The difference between the LV and HT units is also evident with regards to timing. Some may expect these units to typically trigger at similar times (if they are truly proximity based). When we compare the performance between *block 1* and *block 2* (i.e. Figure 26 (a-b) and (c-d)), we note that the higher alert on the HT in *block 1* did not translate to a similar higher alert (irrespective of its type) being triggered by the LV around the same time and position. This may be due to a number of reasons, such as different zone configurations between vehicles; however, the results from *block 2* indicate that these two alert types can occur at the same time (the *Alert Type 2* vs. *Alert Type 4* on the HT vs. LV, respectively during the curved portion of the run).
- Overall, minor variances are noted for each block, with consistent performance. These minor variances may be attributed to positional error (using GNSS), where this system, in particular, emphasizes alerting based on proximity (which may be changing due to speed).

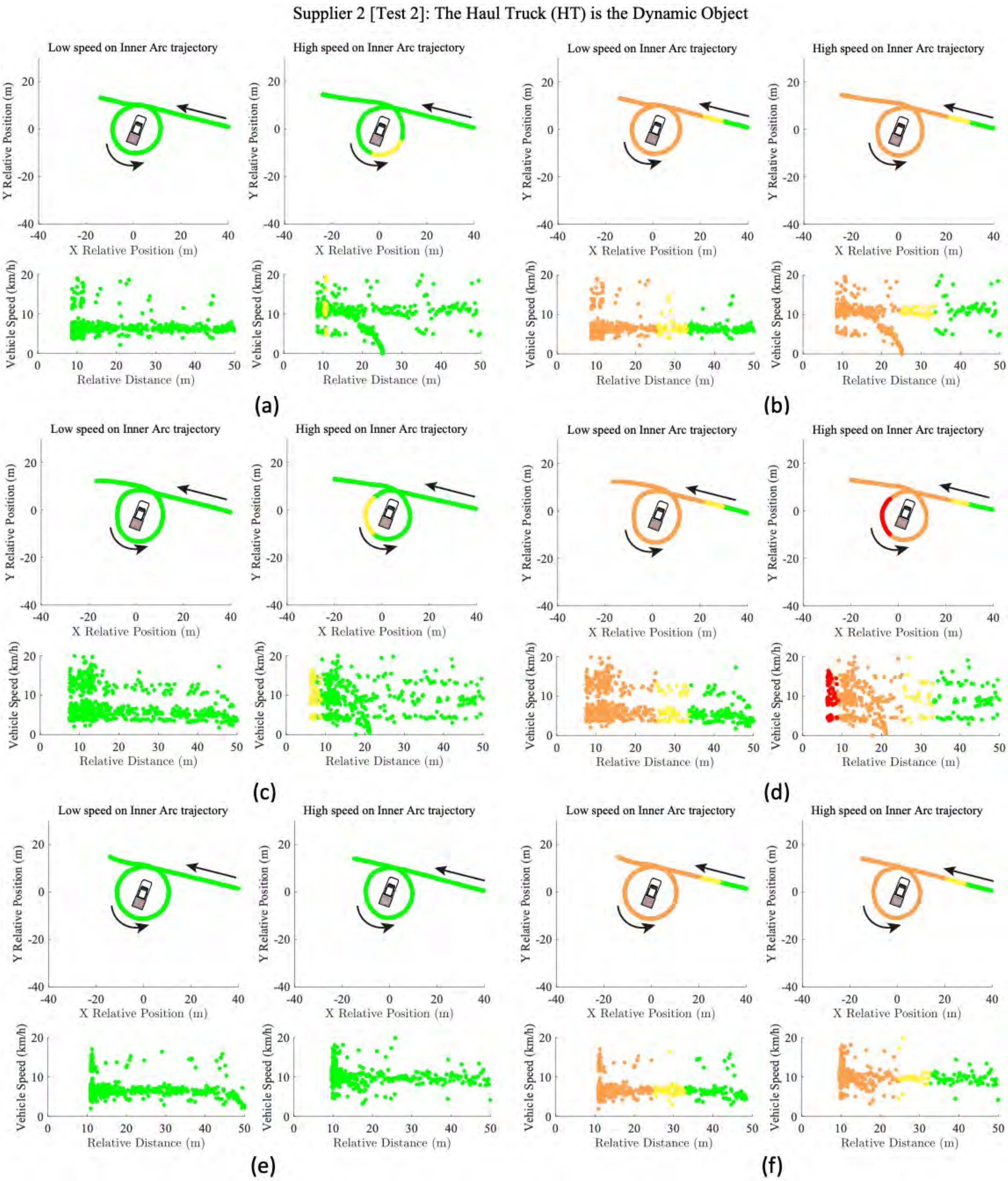


Figure. 26: Visualization of an example Test 2 evaluation for Supplier 2, where (a, c, and e) and (b, d, and f) rep- resent the results from the perspective of the HT and LV PDS units. (a-b), (c-d) and (e-f) represent three repeated blocks for variance analysis. Note that the top and bottom rows (for each block) represent the relative position analysis and relationship between the relative distance and the dynamic vehicle's speed designation, respectively. Furthermore, each column (1/3 and 2/4) represents a speed designation (i.e., low or high, respectively) to compare between each PDS perspective. In addition, the LV position and orientation (not to scale), as well as the dynamic vehicle's (HT) direction of travel, is illustrated for convenience.

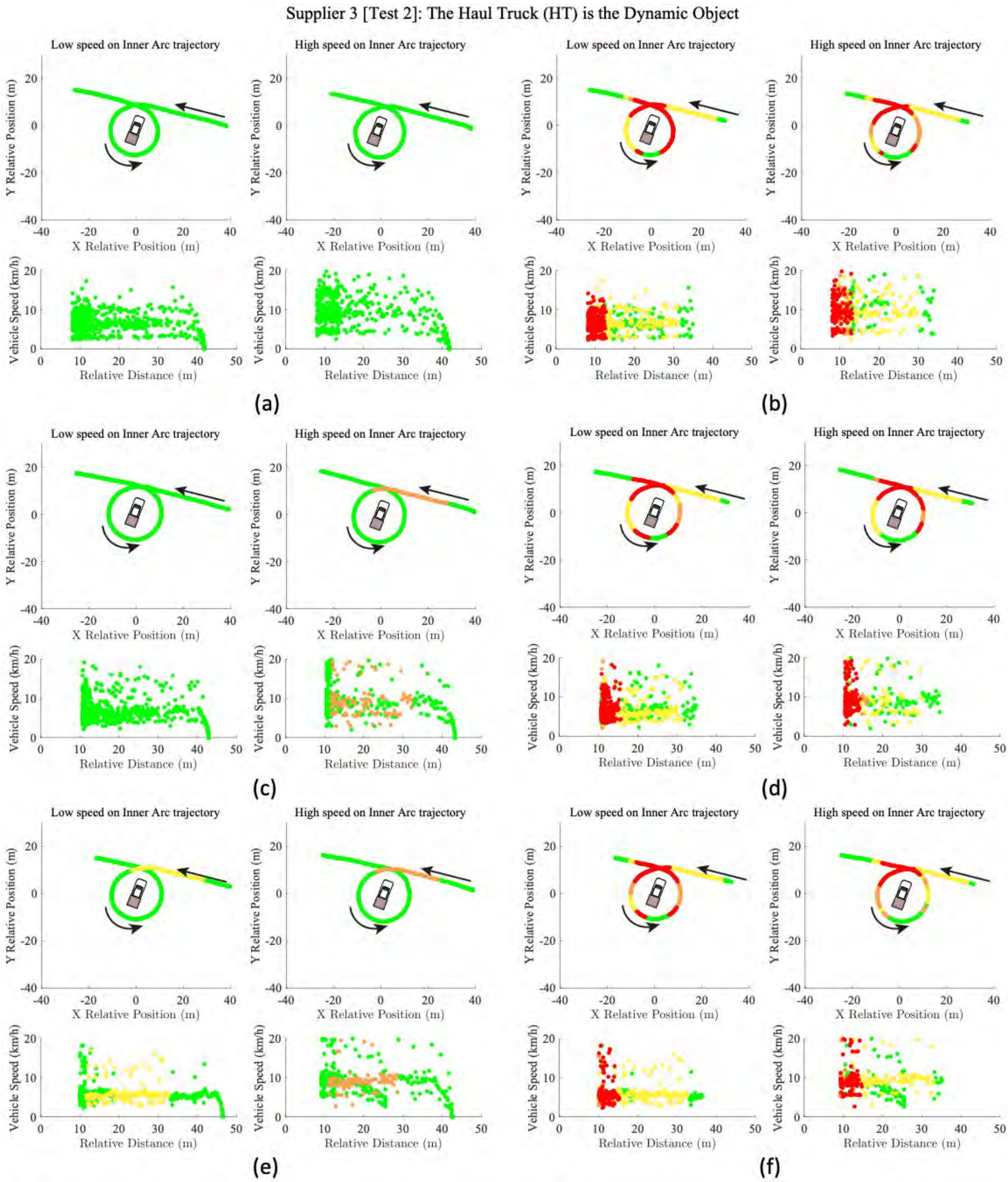


Figure. 27: Visualization of an example Test 2 evaluation for Supplier 3, where (a, c, and e) and (b, d, and f) rep- resent the results from the perspective of the HT and LV PDS units. (a-b), (c-d) and (e-f) represent three repeated blocks for variance analysis. Note that the top and bottom rows (for each block) represent the relative position analysis and relationship between the relative distance and the dynamic vehicle's speed designation, respectively. Furthermore, each column (1/3 and 2/4) represents a speed designation (i.e., low or high, respectively) to compare between each PDS perspective. In addition, the LV position and orientation (not to scale), as well as the dynamic vehicle's (HT) direction of travel, is illustrated for convenience.

The following findings were noted for Supplier 3, including examples differences with respect to Supplier 2:

- Similar to Supplier 2, there is evidence that this PDS is also significantly impacted by the **Speed** of the dynamic vehicle – as seen by the higher *Alert Types* being triggered by the HT PDS when dynamic about the static LV.
- An interesting difference between the two systems is that Supplier 2's PDS, in most recorded cases, has a sequential change in *Alert Types* with respect to distance; meaning that *Alert Type 1* will occur first, followed by *Alert Type 2*, etc, until the dynamic vehicle leaves the zone of influence in the reverse alert order. In contrast, it is evident that Supplier 3's PDS triggers its *higher alerts* (i.e. *Alert Type 2* and onwards) dependent on additional/different intelligence; where the relative distance between vehicles has no sequential behaviour (noted by the overlap between *Alert Types 1 and 2* in Figure 27). This indicates that this system considers *when* an encounter occurs and is over based on additional intelligence, rather than on set proximity zones (i.e. the frontal crossing point of the static vehicle as the dynamic vehicle enters/exits the arc).
- Reviewing the performance of Supplier 3's PDS with respect to each block (i.e. each repeated case), reveals that the system generally performs consistently (evident from the repeated, and consistent, trigger of *Alert Type 2, 3 and 4* from the LVs PDS when the dynamic HT begins entering/exiting the arc for its test case). However, between entering and exiting the arc, there are notable cases of variance in the LV PDS alert triggering which may correspond to tuning issues while completing a *complex curving* trajectory. This is a significant find, and a notable advantage of the test plan to be able to report this type of capability to the end-user.
- Interestingly, the dynamic object tends to alert less than the static object. While this is, once again, not a critique of the system, it is an interesting finding to convey that PDS design is a difficult component to truly evaluate, and a demonstration of its performance in this manner may be more advantageous to understand how this system is expected to perform on-site in order to tailor it towards site specific controls.

While this report only discusses one (1) variant (of sixteen (16)), this section demonstrates that:

1. Test 2, a rigorous DOE, is able to be executed successfully in a safe manner, using heavy mine vehicles (such as a HT).
2. Overall, the Test 2 process took an average of approximately 3 h to execute (approximately 1 h per block), with an approximate average time of 4 min per run – captured with the updated Test 2 plan (Section 7.1.4) using Supplier 2 and 3 units. This includes: (a) time taken with respect to each block, as there could not be significant breaks within a block; and (b) in-between setup timing for the re-positioning of vehicles.
3. Take advantage of the DAQ designed to capture timely information in order to successfully report on the capability of two Supplier donated PDS.
4. Demonstrate a reporting process that captures interesting results and performance towards PDS selection – especially considering the results above when using two separate systems using the same primary sensor.

While this test presents significant advantages in terms of execution and repeatability, there are some noteworthy limitations:

- The factors (discussed in Section 7.1.1) used for this validation study are *baseline*, and it is recommended that more factors (if identified) be tested. An outcome of this test validation process is the justification for each of the four (4) baseline factors proposed; evident in tests using the Supplier donated PDS; however, as detailed in Section 7.2, additional factors (specific to each sensor) may also be prevalent, and the current plan does not, by default include these factors.
- Execution of the Test 2 plan (see Section 7.1.4), while successful and feasible in a safety and data collection perspective, has the potential to be onerous, provided *additional* factors also be explored. This being said, safety was a key component of this test, which included safety management and choreography for larger, more risky vehicles. It is the position of this report that, while additional factors may extend the time taken, the overall time taken is within acceptable margins in order to effectively and efficiently quantify PDS capability.

7.4.4 Test 3 Outcomes and Learnings

This section aims to provide outcomes and potential learnings from the execution of Test 3 at the Mining3 test facility. Once again, for consistency, the same *Alert Types* and colours are used. In addition, a new *Alert Type*: *Alert Type 5*, was designated for detection outcomes from a pedestrian – this was kept consistent for convenience, and labelled separately as, in most cases, a system may have a different alert outcome between a pedestrian and a vehicle interaction (as was the case with the two supplier donated systems) due to multiple factors; one of which being the use of a different sensor method.

As detailed in Section 7.1.3 and Section 7.1.4, Test 1 and 2 are largely more analytical based tests designed to capture general PDS performance to the four (4) baseline factors. Test 3 (described in more detail under Section 7.1.5) presents choreographed scenarios that, while it is recommended to have repeated tests, does not absolutely require it. Rather, it is a snap-shot of prevalent scenario(s) (identified in Section 6) to quantify performance when under specific cases. Ultimately, the goal of this section is to: (a) demonstrate that key scenarios can be practically implemented on-site with respective machinery; and (b) use the reporting methodology from previous sections (Section 7.4.2 and Section 7.4.3) to quantify capability and identify areas that may present potential issues.

<u>**Test 3.1: The Start-Up Evaluation**: An</u> important outcome from the incident analysis (Section 6) was the evidence of a high number of incidents involving work areas; particularly when both vehicle types are static and close to each other during routine maintenance. In these cases, the PDS, depending on their design, may be switched off when the vehicle itself has its ignition off. Because of this, the knowledge of where an obstacle exists when the driver of a larger, more potentially dangerous, vehicle re-starts for movement is paramount to say the least. Therefore, this test serves the purpose of understanding the timing capability of a PDS when turned on from an off position. In most PDS, there are inherent start up procedures that must be completed to boot up required sensors, or connect to a network; understanding what this timing is can be crucial to planning operations guidelines onsite. For example, using the supplier donated units (Supplier 2 and 3), Figure 28 and Figure 29 illustrate the outcome from a *Start-Up* test from the LOs point of view (i.e. HT). Please note the following additional information regarding this test:

1. Figure 28 (a) and (b) represent the outcomes when the RO is the LV and a pedestrian object, respectively. Note that the LO is the HT for all tests conducted.
2. A test was conducted on three (3) positions about the LO, this being the *Front*, *Side* and *Rear* of the LO. Note that each position required the RO to be as close as possible to the LO.
3. The timeframe was designated as when a respective PDS screen switched on for the first time, until a visual or audible alert was issued regarding the RO being tested. This was done in an effort to maintain consistency between different PDS.
4. Supplier 2's system (between the LV and HT) has different modes of operations (and *Alert Types*) compared to Supplier 3's system. Therefore, both the LV and HT alert outcomes were noted for Supplier 2, whereas for Supplier 3 (Figure 29), only the HT PDS was examined, given that the system on-board the LV has similar functionality.

It is immediately evident that both systems present significant delays upon start-up, thus demonstrating the efficacy of this test method, and its subsequent importance for understanding PDS capability. Please note the following key findings:

- Both systems performed at similar start-up times around the LO consistently, with the exception of Supplier 2's PDS, which showed a faster detection when placed in *Front* of the LO – Figure 28 (a).
- With regard to Supplier 2's unit; the performance between the HT and the LV units were similar, which is a good outcome. Notably, the detection of the pedestrian object is much faster than the detection of a vehicle, most likely due to the use of different sensing mechanisms for this purpose.
- With regard to Supplier 3's unit; the performance between the detection of a vehicle and pedestrian offers no difference in implementation. Furthermore, the long bar is due to an audible alert being issued first, prior to visual detection on the interface – there is also a manual input stage that added additional time until visual detection was evident; hence the long period between an audible alert and visual detection.

- When comparing Supplier 3 to Supplier 2, there are notable differences to discuss: (a) the overall difference in detection time (comparing HT performance) between the two units ranges between approx. 30 sec to 45 sec in the case of detecting a LV; even more so when detecting a pedestrian object (an approximate difference of 1 min). Given that both systems utilize the same primary sensor, with the exception of additional sensors, it is entirely possible to improve this start-up time for safety considerations.

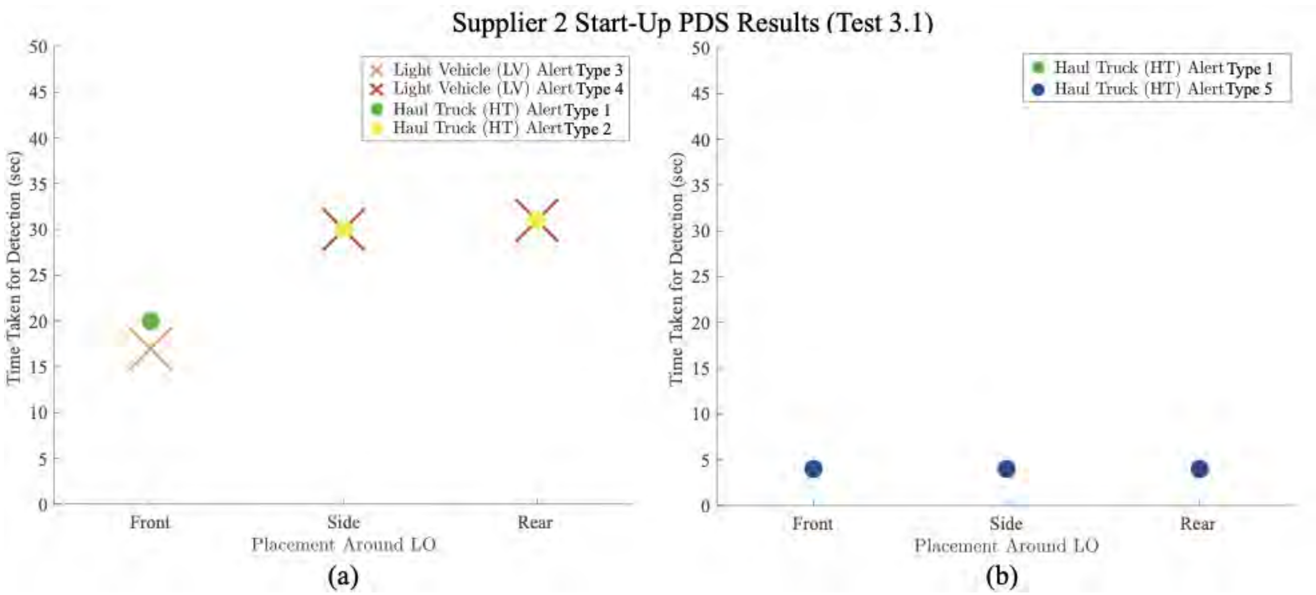


Figure. 28: The timing outcome from a Start-Up test using Supplier 2's PDS. Note that the starting point was when the respective PDS screen first turned on, until either: (i) visual detection of the other object was noted; or (ii) an audible alert was issued when detected. (a) represents the test between the LO (i.e., the HT) and the RO (i.e., the LV). (b) involves the pedestrian object as the RO.

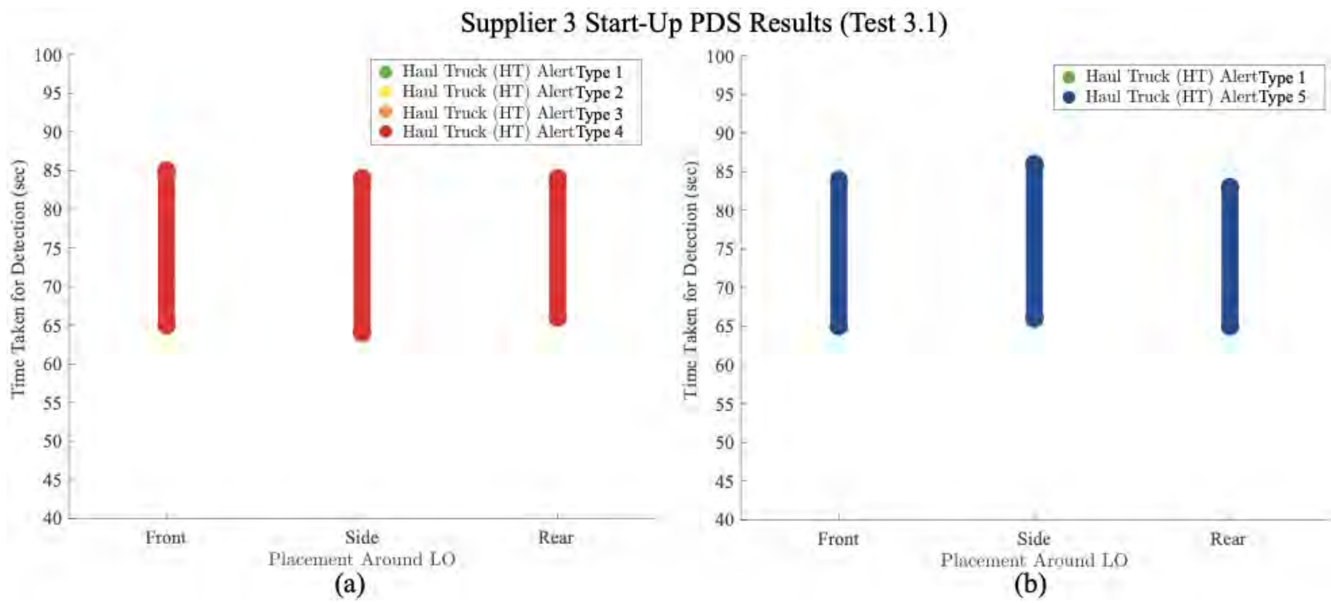


Figure. 29: The timing outcome from a Start-Up test using Supplier 3's PDS. Note that the starting point was when the respective PDS screen first turned on, until either: (i) visual detection of the other object was noted; or (ii) an audible alert was issued when detected. (a) represents the test between the LO (i.e., the HT and the RO (i.e., the LV). (b) involves the pedestrian object as the RO.

Test 3.2 and Test 3.3: Variant Cases for Test 2: As discussed briefly in Section 7.1.5, the orientation of the static object was not directly considered within Test 2. Ultimately, considering a work area conflict, it is important to quantify direct pass trajectories around a vehicle, specifically around its rear and sides. Figure 30 and Figure 31 represent the outcomes from tests involving Supplier 2 and 3, respectively, for Test 3.2. Test 3.3 is also evaluated simultaneously, as it is a similar test with the two vehicles switched; therefore, Figure 32 and Figure 33 represent the outcomes from tests involving Supplier 2 and 3, respectively for Test 3.3. Please note that:

1. (a), (b) and (c), (d) in each figure, represent tests conducted along the side and rear of the HT, respectively. In the case of Test 3.3, the side and front of the LV was considered, given that it is more representative of a possible *Intersection* scenario.
2. (a) and (c) represent the outcome from the perspective of the HT, while (b) and (d) are from the LVs perspective in all four (4) figures.
3. The left and right columns of each sub-figure (i.e. (a), (b), (c) and (d)) designate the speed of the dynamic object to be either *low* or *high*, respectively. This was maintained at approximately 5 km h^{-1} and 20 km h^{-1}, for *low* and *high*, respectively under Test 3.2. Note that for Test 3.3, the *high* value was set lower at 10 km h^{-1} to ensure safety from movement of the HT.
4. Illustrations of the HT and LV are provided for presenting their respective orientations for the test; however, these are not to scale.

Overall, for both Test 3.2 and 3.3, the following important findings were noted:

- It is clear, from Supplier 2's perspective, that the alert performance is consistent with findings from Test 1 and 2; notably that the proximity is based on **Distance** between the two objects in question. Although previous findings suggest **Speed** is another factor, it may be evident that this only applies to direct encounters, and not passing encounters, as demonstrated here. Interestingly, higher *Alert Types* were noted when passing behind the HT, as opposed to its side; suggesting that the shape of detection may extend further in the frontal and rear sections of each vehicle – although this does not align with findings from Test 1 (once again, perhaps altered performance based on direct or passing encounters).
- Similarly, the findings from Supplier 3's tests also present alignment to previous conducted tests; namely highlighting that the PDS prefers alerting more on a *static* object, rather than a *dynamic* one in most encounters. In comparison to Supplier 2, it is important to note that the orientation plays a significant role in alert rates, where rear encounters produced higher *Alert Types* in comparison to side pass cases. This is consistent with the expected shape of detection prioritizing the front and rear portions of the vehicle over the sides. **Speed**, on the other hand, may present some issues when passing on the rear (or front), considering that a lower speed produced *higher Alert Types* – this could be a tuning issue, given that the performance when passing along the side of the HT did not present a similar outcome.
- Evaluation of Test 3.3 outcomes alongside Test 3.2 presents interesting outlier conditions: (a) for Supplier 2, even though the same **Distance**-based outcomes are present when the HT is dynamic, there is clearly different performance outcomes between the system on-board the LV and the HT. For one, the dynamic nature has no effect on the alert outcomes; rather the LV, under both Test 3.2 and 3.3, alerts more than the system on-board the HT. This is quite consistent with previous tests (Test 1 and 2), where the LV tends to have higher alerts by design; (b) for Supplier 3, the LV, now the *static* object, alerts more as expected, with the same frontal preference noted in Test 3.2. Although, there were considerably more alerts, and variability, noted on the dynamic vehicle in this test, as indicated by Figure 33 – potentially due to **Speed** being a factor as, once again, the slower speed had *higher* alerts triggered.

An additional test was conducted using Supplier 3 to determine the effect of a pedestrian object when the HT is dynamic. Figure 34 illustrates the outcome of this test, and presents an issue with regard to detecting pedestrian objects relative to motion: the priority, in the case of Supplier 3's system, is not to detect pedestrian objects in a dynamic fashion; rather, it is designed for detection when static. This is shown by Figure 34, where, regardless of the speed, an alert is issued when the dynamic HT is about to encounter the object (albeit, successful detection and visual indication is provided much earlier, as evident by *Alert Type 1* – a good outcome).

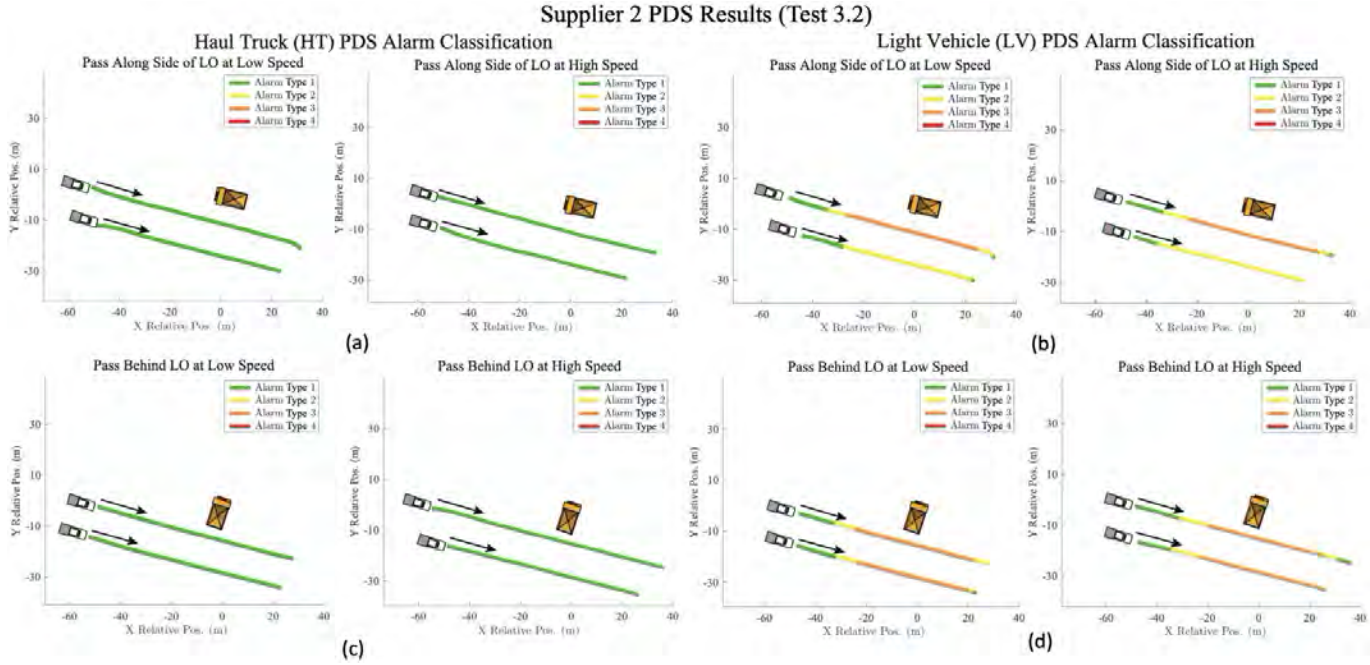


Figure. 30: The alert outcome using Supplier 2's PDS for a dynamic pass by the LV. Note the direction of travel indicated by the arrow in each figure.

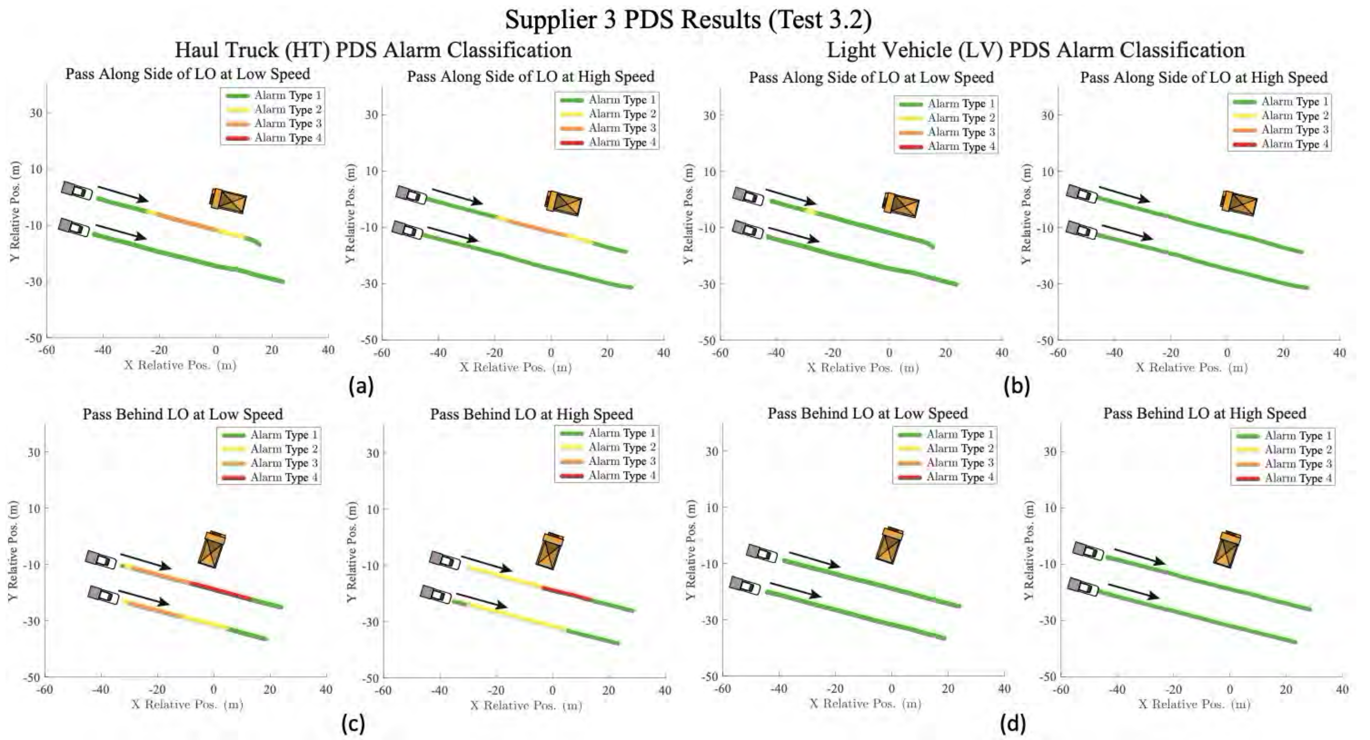


Figure. 31: The alert outcome using Supplier 3's PDS for a dynamic pass by the LV. Note the direction of travel indicated by the arrow in each figure.

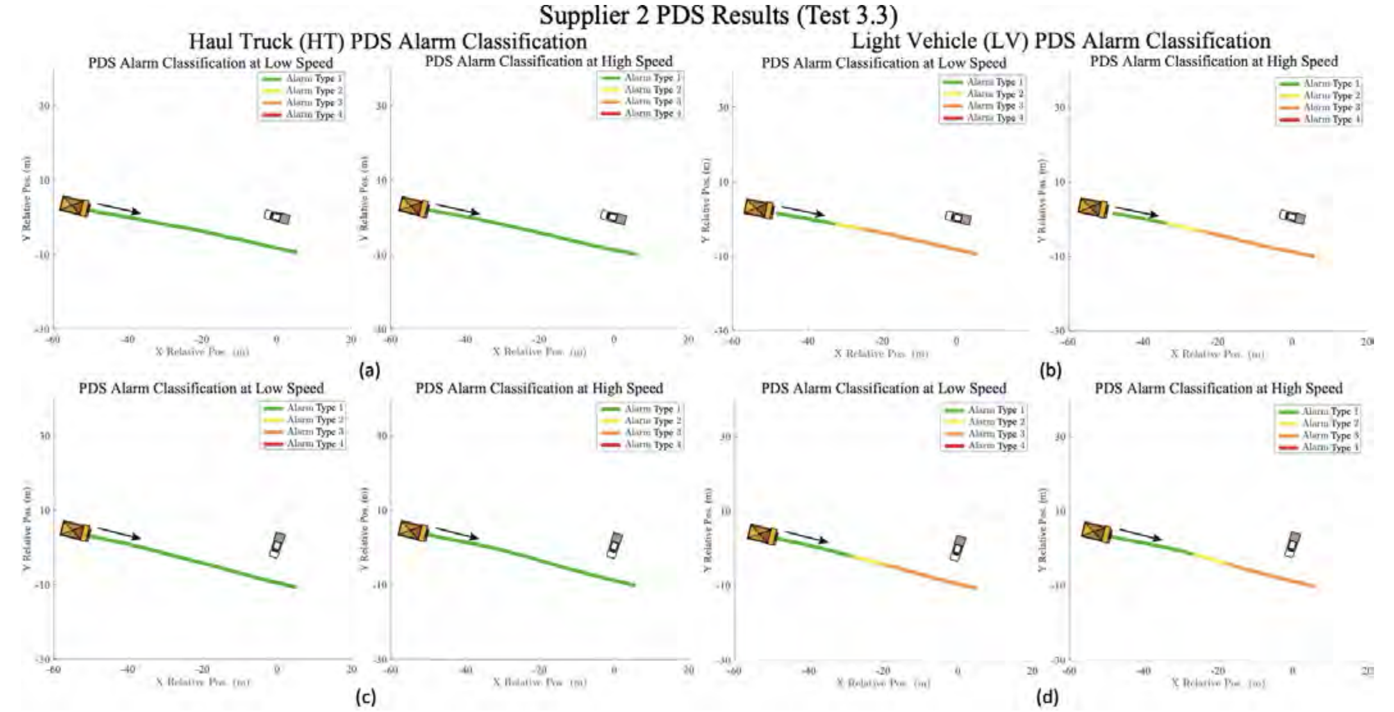


Figure. 32: The alert outcome using Supplier 2's PDS for a dynamic pass by the HT. Note the direction of travel indicated by the arrow in each figure.

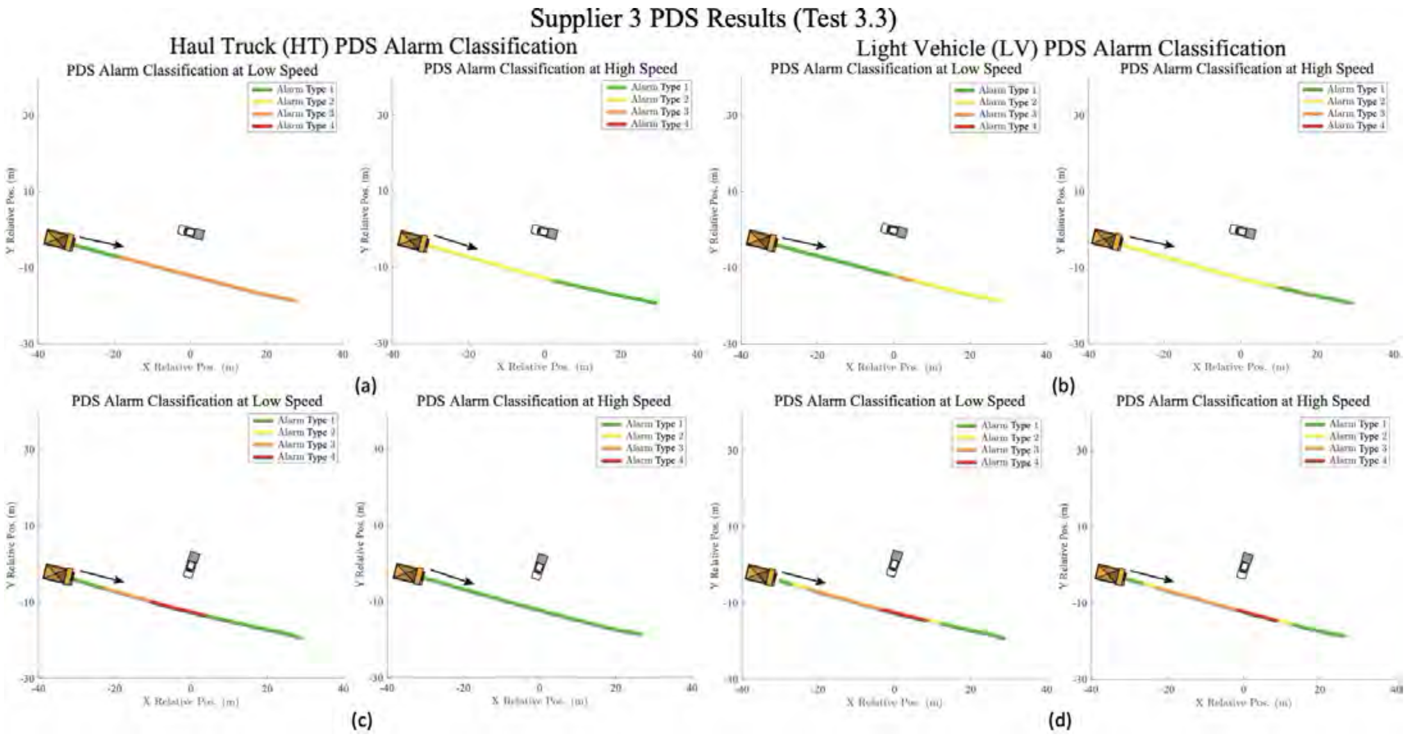


Figure. 33: The alert outcome using Supplier 3's PDS for a dynamic pass by the HT. Note the direction of travel indicated by the arrow in each figure.

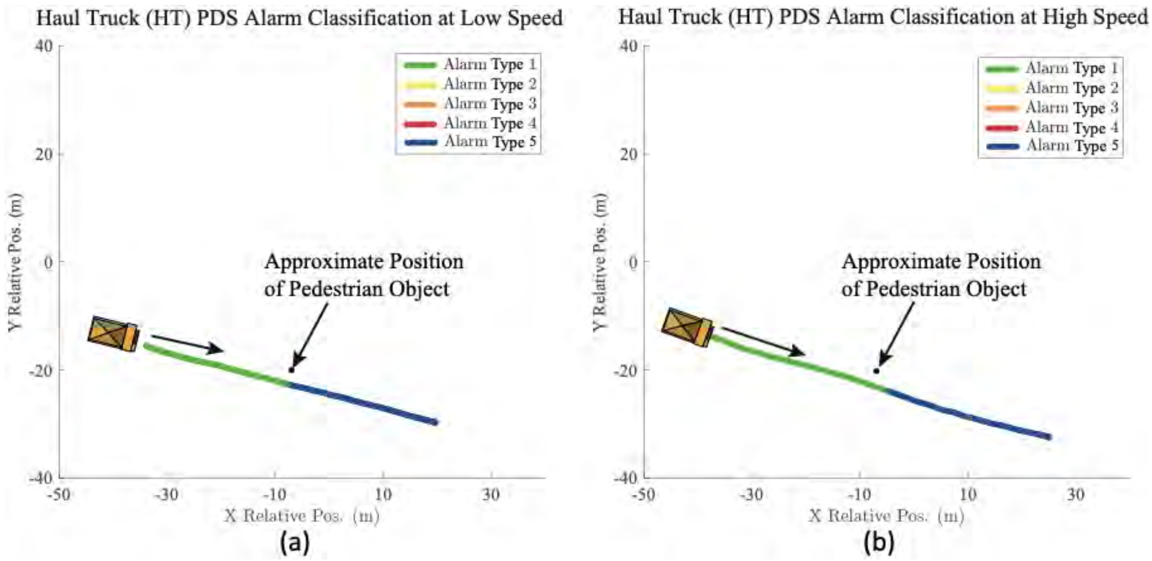


Figure. 34: The alert outcome using Supplier 3's PDS for a dynamic pass by the HT with the presence of a pedestrian object. Note the direction of travel indicated by the arrow in each figure, including the pedestrian object's approximate position.

While static cases are an important design consideration, specifically in maintenance cases, it is also paramount to consider earlier alerting on top of visual detection to the driver, who may be distracted during the action. Sub- sequent tests, particularly direct encounters, also re-affirm this finding.

<u>**Test 3.4: Dynamic-Dynamic Pass**: Of all</u> the proposed tests, including Test 1 and Test 2, this may be one of the most important for the following reason: a passing, dynamic-dynamic case is the most prevalent scenario under nor- mal operating conditions. Understanding PDS capability under these cases is equally as important to characterize any unforeseen behaviour. Figure 35 and Figure 36 illustrate the performance outcome under this test for Supplier 2 and 3, respectively. Please note the following regarding each of the figures below:

1. In Figure 35: (a) and (b) represent *low* and *high-speed* designations, respectively. Similarly, in Figure 36: (a-c) and (b-d) represent *low* and *high-speed* designations, respectively.
2. For added analysis, the approximate passing point was noted in Supplier 3 test runs. This was done to demonstrate how the Supplier 3 PDS stops alerting almost immediately once a pass has occurred. Further- more, two new cases were considered where each dynamic object has an alternative *low* and *high-speed* designation.
3. Illustrations of the LV and HT are provided to demonstrate their respective orientations, including their directions of travel – note, these are not to scale.

From this analysis, the same performance outcomes were found as expected – i.e., **Speed** and **Distance** being clear factors, with higher *Alert Types* triggering in *high-speed* designated tests. Note that in both systems, an alert is provided prior to a passing encounter. While this indicates successful performance from both supplier units, the methodology presented demonstrates that, while alert performance is occurring as expected, each of these *Alert Types* may provide audible alerts in unnecessary cases, which may lead to operator tampering of PDS units on-board. The ability to identify this early on allows both users and developers to efficiently see to changes if necessary – especially if, in the case of Supplier 2, the alert continues for some time post encounter, as opposed to Supplier 3's system, which stops an alert as soon as the encounter has passed.

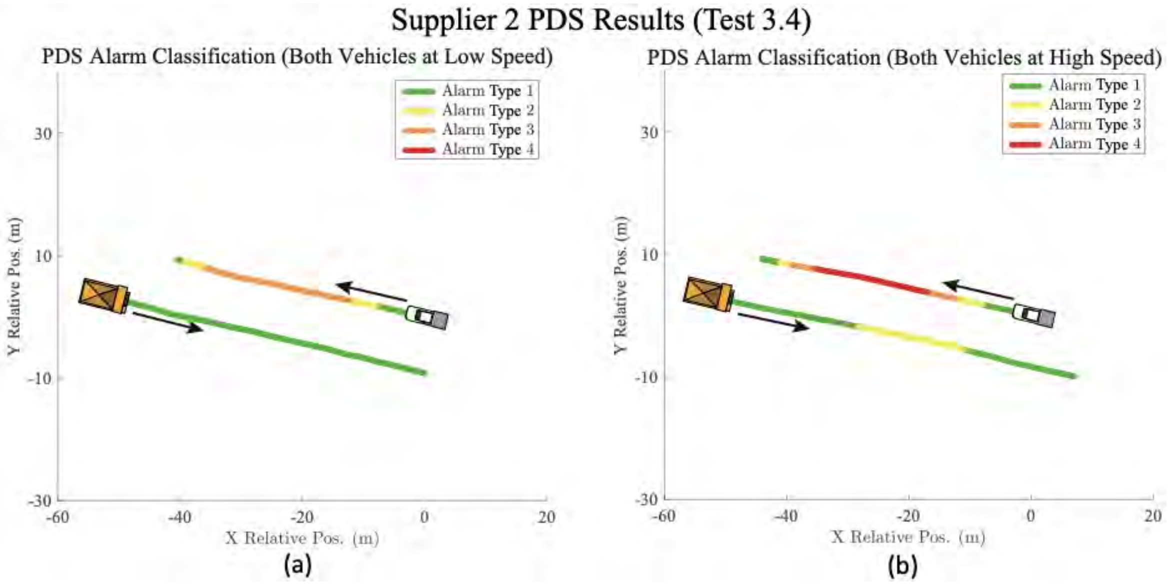


Figure. 35: The alert outcome using Supplier 2's PDS for a dynamic-dynamic pass by the HT and the LV. Note the direction(s) of travel indicated by the arrow in each figure.

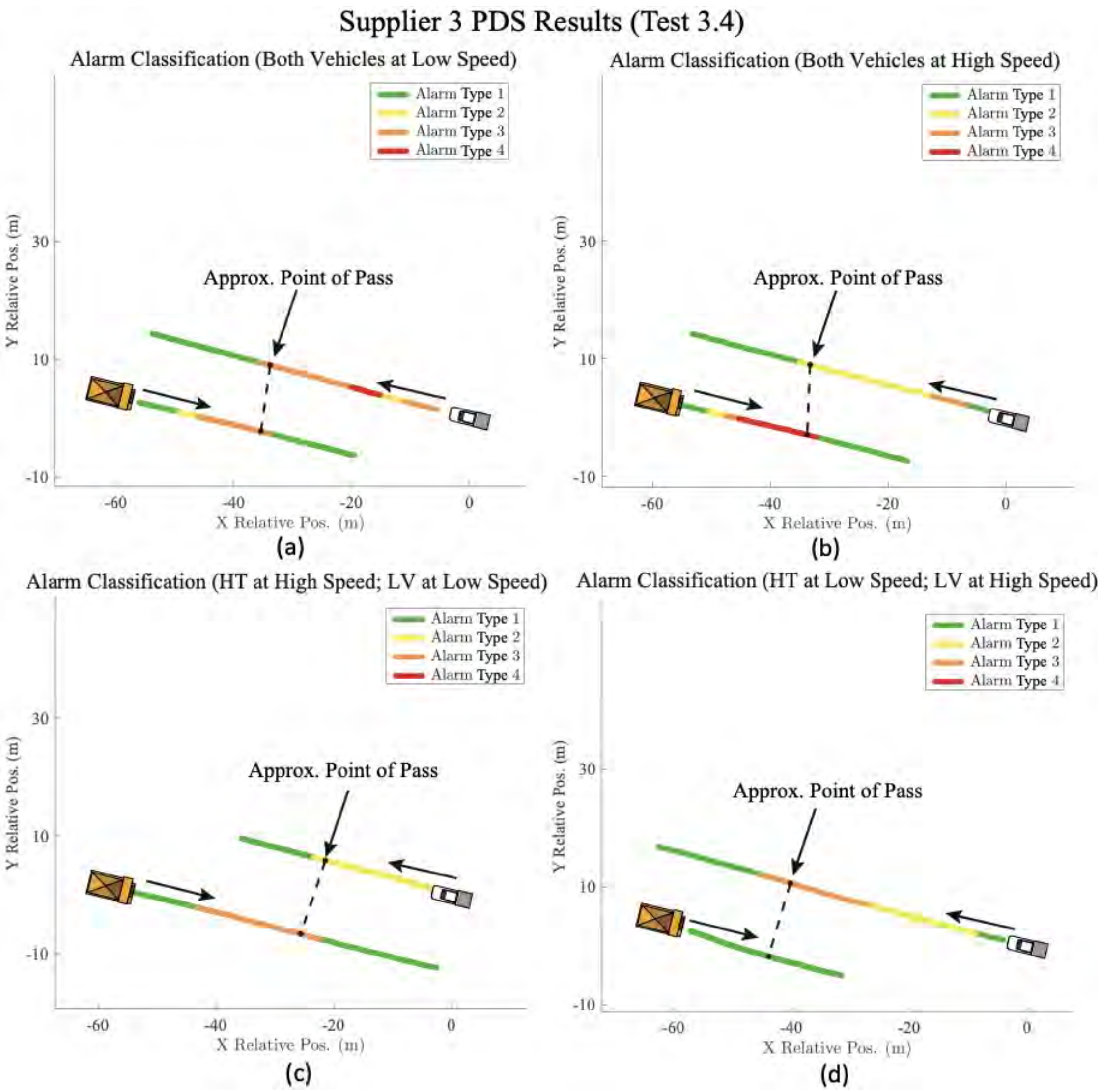


Figure. 36: The alert outcome using Supplier 3's PDS for a dynamic-dynamic pass by the HT and the LV. Note the direction(s) of travel indicated by the arrow in each figure

Test 3.5: The Direct Encounter: Test 3.5 presents one of the most difficult tests to conduct, primarily due to safety concerns. One of the successful outcomes of this phase, is the championing of safety when conducting all the proposed testing – this is important to the reproducibility of the methodology. Under this method, direct encounters between a LO (i.e., the HT) and a RO (i.e., a LV and a pedestrian object – mannequin) were successfully implemented. Figure 37 and Figure 38, illustrate the performance outcome against the LV using Supplier 2 and 3, respectively; while Figure 39 and Figure 40 demonstrate capability against a pedestrian object using Supplier 2 and 3, respectively. Please note the following regarding each image below:

1. In Figure 37: (a) and (b) represent the perspectives of the HT and LV, respectively; where only a single speed (the *mid* speed designation of approximately 10 km h^{-1}) was used – this was in an effort to keep safety parameters in check during the first execution of this test case. As can be seen with Figure 38, all three (3) speed designations were used later under Supplier 3 testing in a safe manner.
2. Supplier 2's system, as detailed in earlier sections, presents a system that has mildly different functionality between the LV and HT units. Because of this, priority was given to review the perspective of both systems in this case.
3. In Figure 38, only the HT perspective was evaluated, as this was the primary system on-board the dynamic object.
4. In Figure 39 and Figure 40: (a), (b) and (c) represent three (3) speed designations of *low*, *mid*, and *high*, at approximately 5 km h^{-1}, 10 km h^{-1}, and 20 km h^{-1}, respectively. Furthermore, note the approximate position of the pedestrian object (mannequin) in each of the test cases.

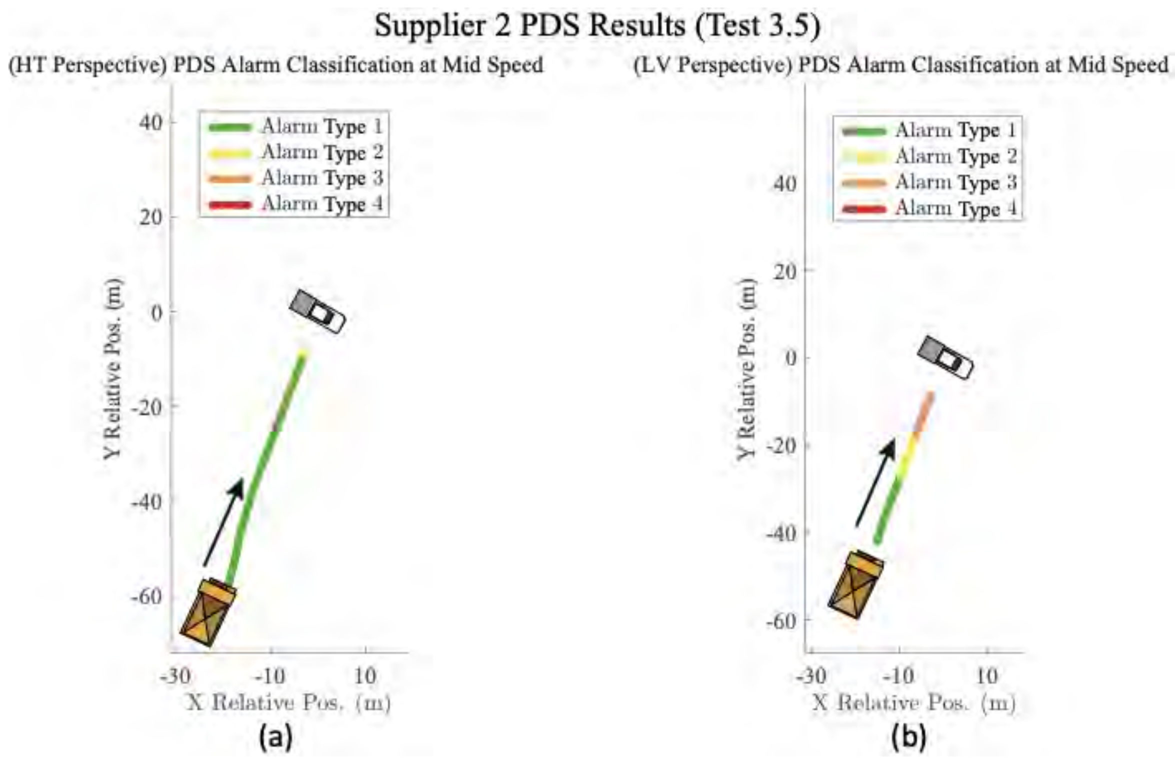


Figure. 37: The alert outcome using Supplier 2's PDS for a direct encounter by the HT and the LV. Note the direction of travel indicated by the arrow in each figure.

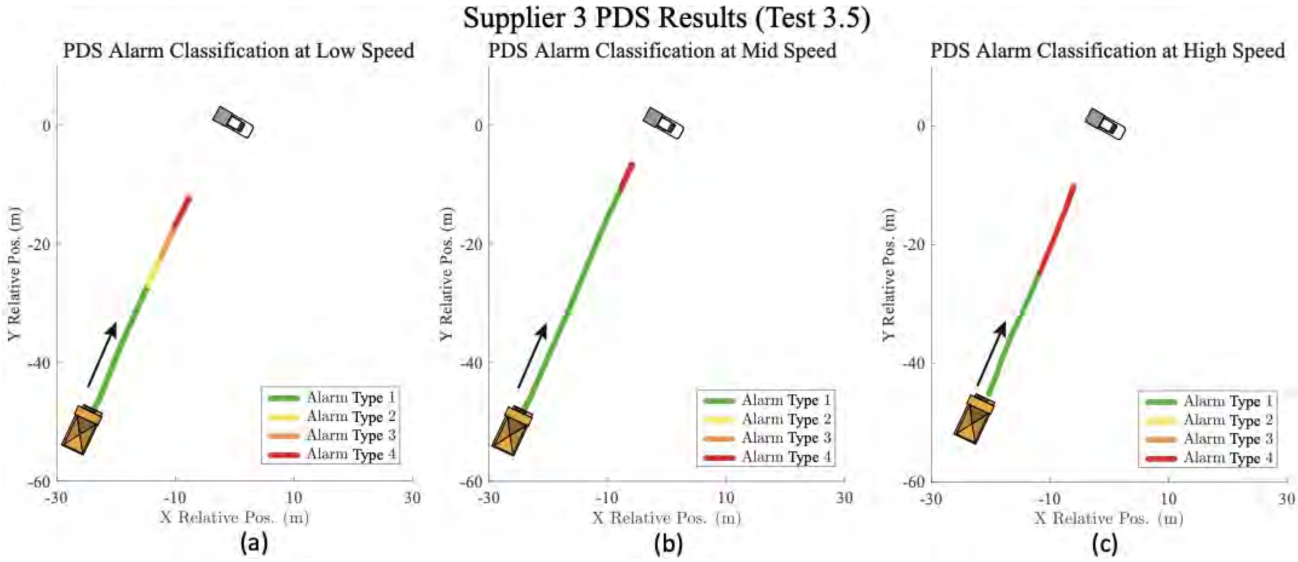


Figure. 38: The alert outcome using Supplier 3's PDS for a direct encounter by the HT and the LV. Note the direction of travel indicated by the arrow in each figure.

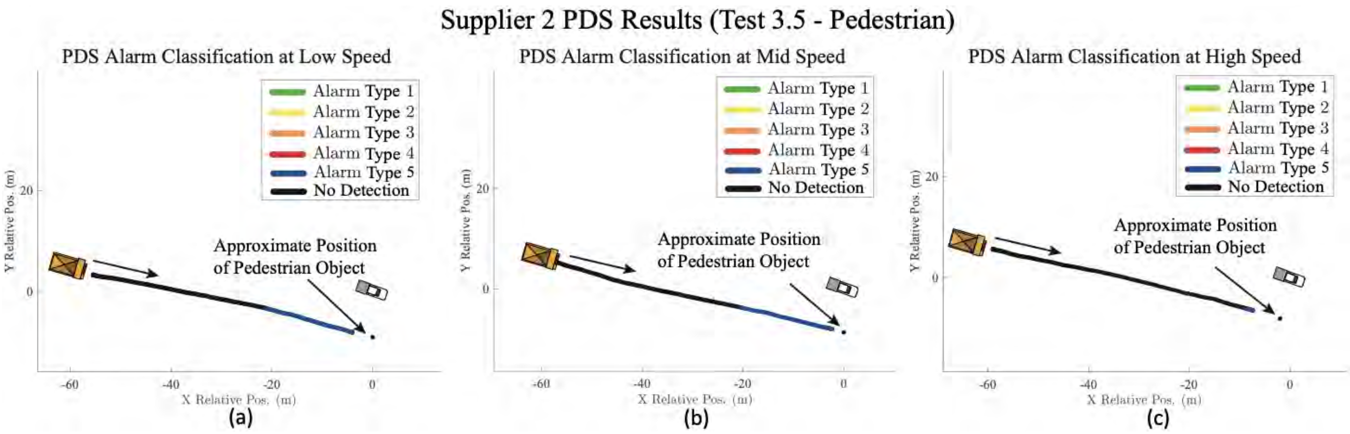


Figure. 39: The alert outcome using Supplier 2's PDS for a direct encounter by the HT and the Pedestrian object. Note the direction of travel indicated by the arrow in each figure.

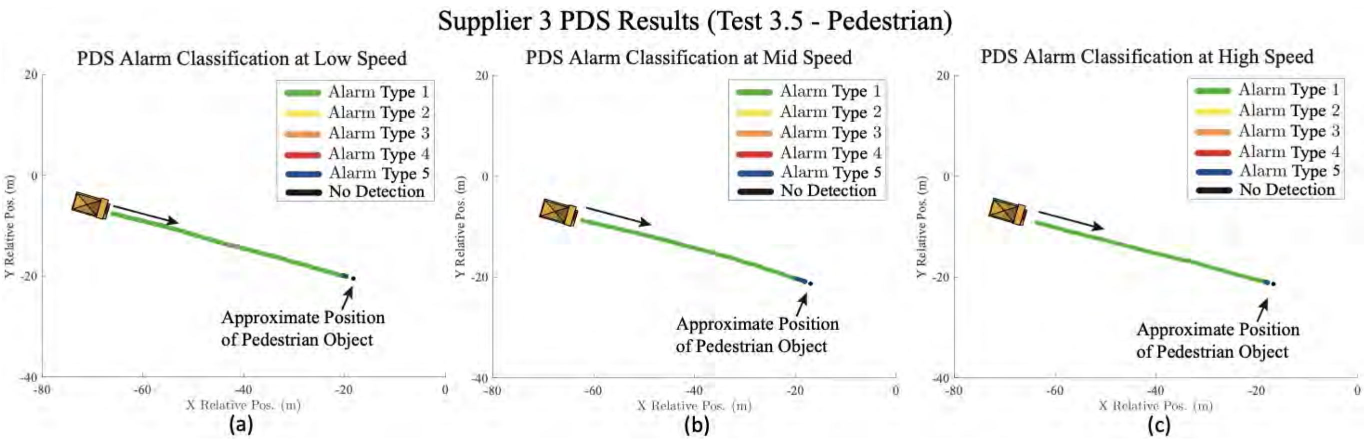


Figure. 40: The alert outcome using Supplier 3's PDS for a direct encounter by the HT and the Pedestrian object. Note the direction of travel indicated by the arrow in each figure.

Provided the earlier analysis of each system, the expected outcomes are once again evident in these results. The following additional performance outcomes were observed:

- Although **Speed** is a known factor for Supplier 2, a direct encounter with the LV (Figure 37) illustrates that this may not be the case for the HT system, which alerted almost too late prior to a safe stop. In contrast, the LV PDS system demonstrated effective alerting as the HT steadily approached. This disconnect may prove to be an issue given these kinds of scenarios; however it is successful to note that detection of each vehicle is evident at all times on both systems.
- With regard to Supplier 3's system; the alert triggering with respect to **Speed** is once again evident in the results captured (Figure 38) – the increased alert time is very important considering higher speed direct encounters.
- Both supplier's PDS demonstrate an inability to dynamically alert to a pedestrian object. While this is a design decision made for other scenarios, typically static-static configurations in a work area, a direct conflict with a pedestrian is still a potential action to avoid. Demonstrated in Figure 39 is the ability of Supplier 2's system to alert early in certain cases (*low* and *mid* speed considerations) to the possibility of contact with a pedestrian – noted is the late alert triggered under a *high-speed* encounter. In addition to this, it is clear that this alert is the *only* form of indication to the driver of a pedestrian encounter, as earlier detections are not evident using this system (illustrated by the region of no detection leading up to contact).
- Supplier 3, on the other hand, allows for early detection (noted that the pedestrian object is detected by *Alert Type 1* for the entire duration of each run) albeit with a very late alert region. Given the larger detection region, it is certainly more plausible to avoid a direct encounter with Supplier 3's system.

In summary, the implementation of Test 3 proved successful; not only with safety in mind, but also towards extracting knowledge regarding specific, prevalent scenarios. In addition, the proposed testing was executed in a timely fashion (taking approximately 1.7 h and 3 h to complete considering both Supplier 2 and 3 on-site testing, respectively), leading to an efficient set of tests that have been feasibly proven to implement with representative machinery – note the larger testing time for Supplier 3, given added testing between implementation. Given these advantages, there are some limitations to consider for future improvement:

- While safety was of paramount concern, it unfortunately restricted conducting all of the six (6) prevalent scenarios on-site. This being said, evidence has been gathered to demonstrate the efficacy of implementing some high-risk cases; such as dynamic-dynamic passing encounters (i.e., Test 3.4) and direct encounters (i.e., Test 3.5). Intersection cases involving more direct encounters with each vehicle was strictly avoided due to their high-risk status. These cases may be more feasibly tested in simulation environments.
- In addition to safety, there were prevalent scenarios that could not be explored simply because the test environment could not realistically accommodate them (i.e., *void* and *incline/decline* cases). This may be potentially avoided given a proving ground exist with these requirements available. In the absence of such facilities, simulation, once again, is a viable option to explore under these circumstances.

8 OVERALL OUTCOMES AND RECOMMENDATIONS

8.1 Advantages of the Methodology

Section 7 provides details regarding a test methodology that allows end-users to quantify the performance of a Proximity Detection System (PDS) through the use of: (a) a shape/detection test to provide insight into the behaviour of the detection range of a PDS; (b) a rigorous and scientific Design of Experiments (DOE) that integrates four (4) baseline factors determined to affect PDS performance; and (c) choreographed prevalent scenarios that may be pertinent to most mine sites. Overall, the purpose is to provide a high-level, generalized test plan to capture the performance towards PDS selection and final implementation. Given that this is a monumental task, this report and project provides these fundamental steps to ensure the industry can adapt more of these systems into full operation in the near future. Ultimately, this methodology provides the following summarized advantages (detailed more in subsequent sections):

1. **Realistic Representation:** the ability for the methodology to involve representative vehicles (i.e. a Haul Truck (HT)) within representative scenarios as identified through: (a) an independent review; and (b) existing documentation such as EMESRT PR5A.
2. **Technically/Physically Achievable:** the ability for a test methodology to be adopted at different sites, utilising different PDS from different suppliers, with capability reporting possible to understand key (baseline) factors
3. **Efficiency:** the ability for the test plan to, under the use of high-risk vehicles such as a HT, be performed in a relatively short time period to allow efficient testing and capability reporting.
4. **Scientifically Rigorous:** the ability for the methodology to involve a suite of tests that include repeatability and randomisation towards determining statistically significant findings.

8.1.1 Realistic Representation

It is important to understand the representation of the test plan under different PDS units, specifically regarding *realistic* representation. Section 5 describes the main types of sensors being used in the industry to date, and covers solutions that may use combinations of each of these sensors towards a final PDS solution. With this in mind, it is paramount that a generalizable test methodology be developed that utilises representative vehicles (i.e., a HT) as well an understanding of prevalent scenarios (see Section 6) that apply to many different sites. It may seem impossible, given the variability that can potentially exist amongst systems and sites; however, if we were to evaluate these systems at a high-level, then, at least towards getting a preliminary understanding of the system's capability, it is possible to evaluate different PDS using the same, baseline, test plan from Section 7 – providing a representative test methodology.

8.1.2 Technically/Physically Achievable

For the test plan to be a viable tool for the industry, it is important that the achievability of the methodology be evaluated. One method to accomplish this task is to implement the test plan at a different site, with its own constraints, and understand any gaps that required immediate action. A separate team from The University of Pretoria (UP) implemented the first version of the test plan (version 1) at their vehicle testing facility in South Africa. An important point to note regarding the subsequent discussion:

- *Version 1, as described above, is a very early iteration of the test plan, and has been subsequently updated from this point in time through the feedback acquired from this study, as well as through testing with supplier donated PDS (the final plan is detailed in Section 7). While the feedback in this section is based on this first iteration, it ultimately provided commentary on the main tests (i.e., Test 1, 2 and 3 from Section 7), which have remained largely the same throughout this project phase.*
- *Only Light Vehicles (LVs) were considered at the UP site. This provides an interesting commentary not only on the achievability of the test plan, but also the representation of the plan when different vehicle sizes were considered on a different site.*

Including the implementation of the test plan onsite, as well as offsite, the following key points of feedback were noted for all tests (Tests 1, 2 and 3):

1. The first iteration of Test 1, as discussed in Section 7, involved purely static-static configuration testing. Through testing onsite and offsite, it was paramount that changes be made to include dynamic cases to characterize dynamic zones on specific PDS.

2. Work area radii were given specific metrics (e.g., 12.5 m), which may lead to confusion and issues on implementation at different sites. A key outcome was the recommendation to include general designations (e.g., *inner* and *outer*) to describe radii or trajectories to ensure easy implementation (noted in Section 7 are the actual metrics used onsite purely for validation purposes). Furthermore, if possible, the designations should coincide with a PDS' detection zone(s) (e.g., the *inner* may be set within the zone where Control Level 7 (L7) is expected to alert). While this is important, and will provide additional insight when testing, it may not be crucial as the reporting method (detailed in Section 7.4) attempts to provide a more high-level, generalized indicator of a system's behaviour. Of more importance is the definition of each radii with respect to the minimum turning radius possible from key test vehicles (e.g., the HT used onsite limited the *inner* radius to be 12.5 m).

3. The DOE (Test 2) test process is a key capability assessment section of this test plan; however, as noted from onsite and offsite implementations, this test can be significantly onerous, especially when involving larger, more risky mining vehicles such as a HT. Ultimately, however, as will be detailed in Section 8.1.3, the measures taken to improve efficiency through a safe implementation has demonstrated its viability/feasibility for testing – an important point to make when considering more realistic vehicles, such as a HT.

4. While all of the tests (Test 1, 2 and 3) are recommended to be performed by both PDS developers and end-users, Test 2, specifically may not be required during the development stage, but rather more towards an end-user's capability assessment of the system once it has reached maturity.

5. Important to testing is the concept of redundancy in order to ensure all data is captured to ultimately inform the capability assessment. The Data Acquisition System (DAQ), described in Section 7, allowed the onsite team to complete all tests with additional redundancies in place. It is also worth mentioning, and is a recommendation within this report, that additional redundancies, such as the inclusion of instructions on test run repetition if a capture was not completed, be put in place.

6. The detection of the environment (i.e., trees, berms, undulations, traffic cones, observers, etc.) should be considered, including how to handle these factors during the test(s). The exclusion of non-environmental objects (i.e., traffic cones) should be done where the test(s) are conducted – unless they require testing (user's discretion). Any factors/objects that are part of the environment (such as undulations), may be an important aspect to consider in evaluating the capability of the system. Overall, it is recommended that the test be conducted onsite at a representative environment to its final implementation site. This being said, control should be exerted on external factors to quantify the PDS performance overall.

In summary, the execution of the test plan (even in its first iteration) demonstrated a key outcome of the test methodology: its practical setup at another site under different constraints. In addition, the learnings detailed above served to improve the test plan to its final version detailed in Section 7. Not only does this exercise demonstrate the efficacy of the test plan's achievability, but also of its realistic representation using different test vehicles; although more types of vehicles may be tested to understand any further underlying gaps. Ultimately, this shows that key vehicle types (e.g., HT and LV) can be successfully tested at different sites. The DAQ also presents an advantage towards achievability, given that its design promoted:

- an open-source platform (the Robot Operating System (ROS) environment) that can be developed and used my most parties; and
- an acquisition method that does not require direct access to a PDS – captured, alternatively, through the use of on-board mounted cameras, time synchronized with positional data.

8.1.3 Efficiency

Efficiency is a key metric when considering a validation methodology. The time taken could become lengthy when multiple users require testing, say, at a particular site; or testing on-site at a representative mine site may also prove difficult if time is a factor, which could halt or cause delay to production cycles. Therefore, it was a key goal of the test development process to design a set of tests to be conducted as fast as reasonably possible, even when considering safety. This is a great outcome from the validation testing conducted on-site, as the total time taken to do all three (3) tests are limited to approximately 9 h to complete; realistically, taking into account other factors, such as break-time, and unforeseen repetition of tests, these tests could be completed within the span of two (2) days. In addition, it is worth mentioning that the personnel required for this task was also between three (3) to four (4); enabling swift completion of the tests – note that more would, of course, be better; however, added personnel comes with additional risks onsite, and should be managed accordingly.

8.1.4 Scientific Rigor

Finally, this study is not complete without discussing arguably one of the main objectives: the scientific rigor of the test methodology. While multiple testing methods can be defined, primarily with a focus on the prevalent scenarios, without having a detailed DOE, this can remove the methodology's statistical assessment capability. Doing a DOE style test enables repeatability and randomisation to understand how key factors interact under a complex test protocol, providing insight such as the variability of the alert responses. It is, therefore, a key advantage of this methodology to include this aspect (with other standardised scenario testing) to get an overall picture of the PDS' capability.

8.2 Notable Limitations and Gaps

While the advantages are significant, as captured in Section 8.1, there are notable limitations that should be addressed, particularly towards future improvements and potential changes to technology:

1. Each test highlighted its own limitation, such as the inability to capture all prevalent scenarios under Test 3 (Section 7.4.4); or that additional factor inclusion within Test 2, may present longer, potentially more onerous, testing (Section 7.4.3). In all these cases, most, if not all, of these limitations may not be present at other sites, and can be adapted towards. Nevertheless, it is crucial that they be identified at this stage, and understand the *baseline* nature of the test methodology.
2. While the test plan itself presents itself as efficient (Section 8.1.2), the analysis of data could be staggeringly onerous, particularly with the acquisition of additional data at the user's discretion. This is largely due to the manual nature of capturing *Alert Types* by visually inspecting the on-board camera outcome and correlating this to the positions of test objects within the scene. Ultimately, additional autonomy could be developed to significantly speed this process up. Alternatively, while this report champions the idea of non-direct access to a PDS device; if available, this would allow easier processing of *Alert Types*, assuming this data can be time synchronized to externally captured, ground-truth information.
3. The objective of these baseline tests is to categorize L7 capability, and represent higher intelligence where possible (i.e. documentation of higher *Alert Types*, which, at a very high-level, provides an understanding of, at least, Level 8 (L8)). Level 9 (L9) was not part of the scope of this work; however this is an area that requires its own type of validation given that it involves specific instruction to the **machine** to intervene (Act).

8.2.1 Gap Analysis

Prior to the beginning of Phase 3, a preliminary gap analysis was performed towards methodology unification. This early iteration is summarized below in Figure 41, which specifically discusses areas such as: (a) in-line/parallel conflict cases; (b) complex trajectories, such as curves and intersections; (c) the level of practical implementation (i.e., field trial readiness through a plan and developed instrumentation – DAQ); and (d) the validation of the test plan itself. Alternatively, Figure 42 highlights the completed areas of interest with respect to the aforementioned criteria, with additional information pertaining to remaining gaps (discussed above).

	Experimental Design/Theory	Field Test Executable Plan	Field Test Instrumentation and Hardware	Methodology Validation
Object Detection Validation (Inline/Parallel)	Developed	Developed	Not Completed	Severely Limited
Detection Validation (Inline/Parallel)	Developed	Developed	Not Completed	Severely Limited
Object Detection Validation (Intersections/Curves)	Severely Limited	Severely Limited	Not Completed	Severely Limited
Detection Validation (Intersections/Curves)	Severely Limited	Severely Limited	Not Completed	Severely Limited

Figure. 41: A summary of the gaps highlighted towards the end of Phase 2 and beginning of Phase 3.

	Experimental Design/Theory	Field Test Executable Plan	Field Test Instrumentation and Hardware	Methodology Validation
Object Detection Validation (Inline/Parallel)	Developed	Developed	Developed	Developed
L8-L9 Detection Validation (Inline/Parallel)	Developed (Limited)	Developed (Limited)	Developed	Developed
Object Detection Validation (Intersections/Curves)	Developed (Limited)	Developed (Limited)	Developed	Developed
L8-L9 Detection Validation (Intersections/Curves)	Developed (Limited)	Developed (Limited)	Developed	Developed

Figure. 42: A summary of the gaps highlighted at the end of this phase, providing a direct comparison to gaps detailed prior to Phase 3.

As can be seen from Figure 42, significant improvements have been made and performed in this phase, particularly towards field testing and validation. Note that sections of *Developed (Limited)* were categorized to capture: (a) specific L8 and L9 testing, which was not the objective of this methodology (highlighted above); and (b) specific scenarios that, while have been developed and are recommended (i.e. the six (6) prevalent scenarios from Section 6), could not be safely executed: dynamic-dynamic intersections being the key scenario unable to be tested onsite for safety concerns. Overall, these gaps can be remedied by involving high-fidelity simulation to remove any form of risk, and ultimately, run numerous iterations to quantify performance.

8.3 PDS Technology Maintenance and Performance Considerations

Maintenance requirements associated with the introduction of new technology to a mining operation is critical to its ongoing success, and should be considered in the decision making and change management process. The additional maintenance requirements will likely depend on the equipment manufacturer, sensing technology, and site conditions. PDS units are relatively complex systems and are likely to consist of multiple different sensing, processing and operator, and machine interface components. A large component of PDS technology exists in the form of software and electrical components. This allows PDS units to perform most of the required checks automatically and remotely. Examples include automatic sensor checks, automatic recalibration, and general system diagnostics. Additional maintenance requirements are likely to include:

- inspection of mounting brackets for damage or misalignment;
- checking of fasteners to ensure that they have not become loose and are not damaged;
- general inspection and cleaning of hardware components; and
- inspection of cables and connectors to ensure that they are securely connected and not damaged.

Although PDS sensing technologies typically do not use serviceable components, there are some additional technology-specific maintenance requirements that should be considered in the decision-making process. These additional requirements are listed below:

- **Cameras:**
  - Cameras located at the extremity of mining vehicles would require more regular inspections and maintenance.
  - Camera image sensors are typically protected by some form of protective lens. The camera lens will require regular inspection for damage or build-up of contaminants such as dust, mud and insects. The camera lens will require removal and cleaning of contaminants or replacement of lens.
  - If the vision system includes a processing unit, this will need to be inspected for build-up of debris to ensure effective cooling.
- **Electromagnetics (EMs):**
  - Battery-powered EM tags will require regular charging and additional inspections.
- **Light Detection and Ranging (LIDAR):**
  - LIDAR sensors located at the extremity of mining vehicles would require more regular inspections and maintenance.
  - LIDAR emitters and detectors are generally protected by some form of optical window. The optical window will require regular inspection for damage or build-up of contaminants such as dust, mud and insects. The window lens will require removal and cleaning of contaminants or replacement of window.
- **Radio Detection and Ranging (RADAR):**

– RADAR located at the extremity of mining vehicles would require more regular inspections and maintenance

– RADAR transceivers are generally protected by some form of protective case. The transceiver will require regular inspection for damage or the build-up of contaminants (particularly mud).

- **Radio Frequency (RF) Time-of-Flight (ToF):**

  – Battery-powered RF tags will require regular charging and additional inspections.

- **Global Navigation Satellite System (GNSS):**

  – Battery-powered GNSS tags will require regular charging and additional inspections.

  – GNSS antenna will require additional inspections to ensure that the antenna surface is free of damage and contamination.

  – Antenna brackets need to be inspected to ensure that they are correctly aligned and are secured to the host vehicle.

In addition to the information provided in the PDS Toolkit (see Section 5 for more information), this section provides some additional information and considerations relating to the performance (accuracy and repeatability) of different PDS technologies against relevant factors. The performance of each of the different PDS technologies is likely to be affected by many factors. Some potential examples include:

- the type of the sensing technology;
- the site conditions;
- the grade of the sensor;
- the quality of the sensor calibration (typically performed at the manufacturing facility);
- the quality of the commissioning process of the proximity detection system; and
- the quality and frequency of maintenance practices.

Furthermore, to the factors listed above, Figure 43 provides a summary of key technology-specific factors that are likely to affect the performance of each of the different PDS sensing technologies. Note that the information provided is a high-level summary and does not apply to all possible technologies on the market. The information is therefore, meant to be used as a guideline or general indication.

	Factors	Camera	EM	LIDAR	RADAR	RF	GNSS
Extrinsic	Dust	✕		✕	!		
	Low-light Conditions	✕					
	Direct Sunlight	✕		!			
	Shadows	✕					
	Severe Weather Conditions (e.g. rain, snow, etc.)	✕		✕	!		!
	Contamination (e.g. lens, optical window, etc.)	✕		✕	✕	✕	!
	Status of Satellite Constellations						✕
	Occulsion of Satellite Radio Signals (e.g. trees, etc.)						✕
Intrinsic	Calibration of Sensor (lens distortion, point cloud, etc.)	✕		✕	✕		✕
	Calibration of Sensor Position (w.r.t. Host Vehicle)	✕	✕	✕	✕	✕	✕
	Blind Spots (Field of View)	✕		✕	✕	✕	
	Quality of Object-to-Object Communication		✕			✕	✕
	Requires Line-of-Sight	✕		✕	✕	✕	

Legend

! Factor may affect performance of sensing technology

✕ Factor likely to affect performance of sensing technology

Figure. 43: Summary of factors that are likely to affect the performance of key PDS sensing technologies in a mining configuration.

9 CONCLUSIONS

In conclusion, the development of a validation framework towards Proximity Detection System (PDS) presents a significant challenge considering: (a) the large areas of guidance required for all industry stakeholders in the PDS development space (i.e., developers, Original Equipment Manufacturers (OEMs) and end-users); and (b) detail field executable testing that is, not only representative to most mine sites, but also enables practical, safe testing and capability reporting. This report successfully demonstrates these key objectives through a validated methodology presenting:

- **Realistic Representation:** the ability for the methodology to involve representative vehicles (i.e., a Haul Truck (HT)) within representative scenarios as identified through: (a) an independent review; and (b) existing documentation such as EMESRT PR5A;
- **Technically/Physically Achievable:** the ability for a test methodology to be adopted at different sites, utilising different PDS from different suppliers, with capability reporting possible to understand key (baseline) factors: (i) *Speed*; (ii) *Distance*; (iii) *Object Size/Type*; and (iv) *Trajectory* – i.e. curving or straight);
- **Efficiency:** the ability for the methodology to, under the use of large, high-risk vehicles (i.e., a HT) be performed in a relatively short time period (approx. 9 h for all tests, with a proposed test period of approx. 2 days, given unforeseen repeated testing, or breaks.); and
- **Scientifically Rigorous:** the ability for the methodology to involve a suite of tests that include repeatability and randomisation towards determining statistically significant findings.

Overall, the findings and learnings throughout this process hope to enable PDS implementation to be as effective as possible in the future, with areas of future research being:

- Simulation-based implementation of prevalent scenarios that are unsafe, and time onerous, to accomplish – such as Control Level 8 (L8) and Control Level 9 (L9) testing, including *Intersection* scenarios involving more dynamic-dynamic encounters between vehicles.
- Repetition of the test plan at other proving grounds, or representative mine sites to determine further gaps that may require attention; possibly through the involvement of other vehicle types (i.e. a Dozer).

A User Interface (UI) Design Considerations

The following section comprises work completed by Professor Robin Burgess-Limerick, toward findings from previous extensive work carried out on User Interface (UI) design. It contains a list of Do's and Don'ts of UI design and highlights continual monitoring of the UI system.

A.1 Human-Systems Integration for New Technology in Mining

Human-Systems Integration (HSI) refers to a set of systems engineering processes originally developed by the US Defence industry [1] to ensure that human-related issues are adequately considered during system planning, design, development, and evaluation [7]. In fact, the US Defence acquisition program managers are required to:

Have a plan for HSI in place early in the acquisition process to optimise total system performance, minimise total ownership costs, and ensure that the system is built to accommodate the characteristics of the user population that will operate, maintain, and support the system[5].

Mines that acquire new technologies, such as Proximity Detection System (PDS), are advised to similarly require vendors to provide a plan for the implementation of human-systems integration processes, in collaboration with the purchaser, to achieve the safety and health objectives of the new technology.

HSI includes six (6) core domains relevant to the introduction of new technology to mining:

- Staffing[6]
- Personnel
- Training
- Human factors engineering
- Safety
- Occupational health

Of these, the Training and Human factors engineering domains are particularly relevant to the implementations of PDS. Systems engineering involves three (3) stages: (i) analysis; (ii) design and development; and (iii) testing and evaluation.

HSI incorporates human-centred analysis, design and evaluation within the broader systems engineering process. That is, HSI is a continuous process that should begin during the definition of requirements for any technology project, continue throughout system design, and throughout commissioning and operation to verify that safety goals have been achieved (as identified in Figure 46). Any introduction of new technology to a mine should include a human-centred design process that, to paraphrase NASA standard 3001 [14], encompasses at a minimum:

- Concepts of operation and scenario development
- Task analyses
- Function and role allocation and definition (between humans and technology, and among humans), including training and competency assessment needs analysis
- Iterative conceptual design and prototyping
- Empirical testing, e.g., human-in-the-loop simulation
- Monitoring of human-system performance during operation

[5] Department of Defence (2008) Instruction 5000.02. – Page 60
[6] Referred to as "Manpower" in previous HSI documents

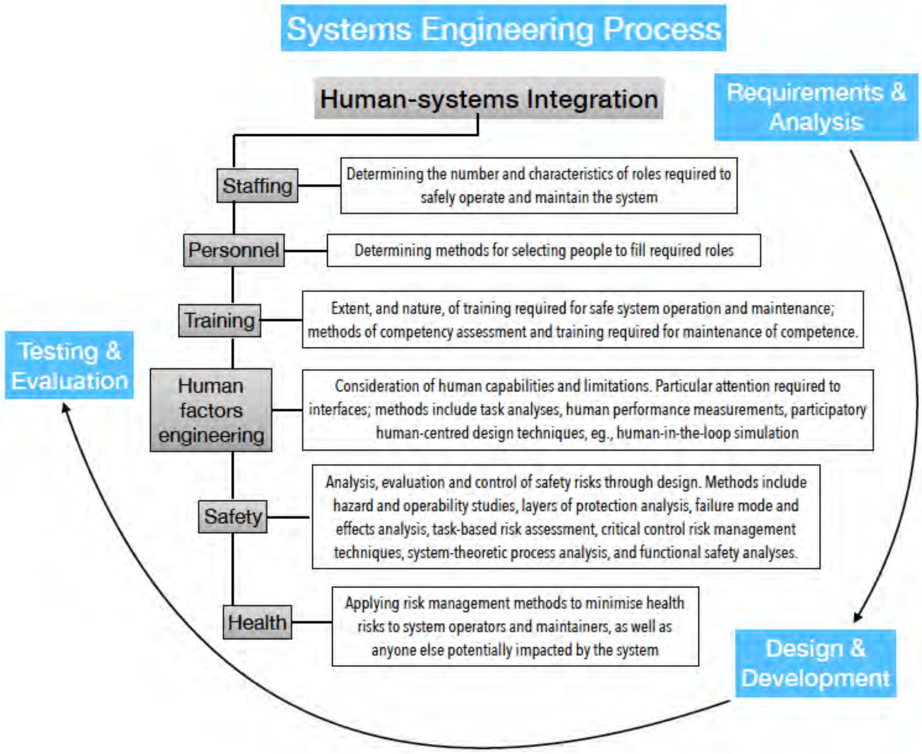


Figure. 46: HSI for the implementation of new technology in mining.

A.2 Human-Systems Integration Program Plan

During the proposal preparation for any new technology, vendors should submit a HSI program plan that details the human-systems integration work that will be performed in collaboration with the purchaser, how it will be done, and by whom. A HSI program plan (adopted from [12] should include:

- **Overview information**
  - An overview of the proposed system.
  - Preliminary concept of operations, associated human roles, and operational environment.
  - Experiences with predecessor systems.
- **Organisational Information**
  - Summary job descriptions and the qualifications of key HSI practitioners within the vendor organisation.
- **Program Risks:**
  - A discussion of how HSI risks will be identified and addressed.
- **HSI Activities:**
  - The specific HSI activities that will be performed by the vendor, in collaboration with the purchaser, to address the relevant core domains of HSI during systems analysis, design, and evaluation.
  - Identification of who will undertake these activities.
- **HSI Schedule:**
  - A milestone chart identifying each HSI activity, including key decision points and their relationship to the program milestones

A.3 Human-Centred Design of Proximity Detection Systems

ISO 9241-210 (2019) *'Ergonomics of human-system interaction, part 210: Human-centred design for interactive systems'* provides principles suitable for guiding the design of PDS. Six (6) principles are outlined:

1. The design is based upon an explicit understanding of users, tasks and environments;
2. Users are involved throughout design and development;
3. The design is driven and refined by user-centred evaluation;
4. The process is iterative;
5. The design addresses the whole user experience; and
6. The design team includes multidisciplinary skills and perspectives

Table 10 below provides more detail of the Human-Centred Design (HCD) activities described by ISO 9241-210 [9]. This toolkit provides much of the information required during activities 1 and 2. The following section provides guidance (now incorporated into the deliverable) to assist in activity 3, and in the design of actions to be undertaken during activity 4. The design of interfaces by which drivers interact with PDS is an area of particular concern, and has therefore, been a primary focus within this report.

Activities	Detail	Outputs
• Understand and specify the context of use	• The characteristics of the users, tasks and organisational, technical and physical environment define the context in which the system is used.	• Context of use description (e.g. user characteristics, tasks and goals, use environment).
• Specify user requirements	• User requirements provide the basis for the design and evaluation of systems to meet user needs. This includes user interface knowledge.	• Context of use specification • User needs description and requirements specification
• Produce design solutions to meet these requirements	• Potential design solutions produced based on the context of use description, the state of the art in the domain, design guidelines, and the knowledge of the design team.	• User interaction specification • User interface specification • Implemented user interface
• Evaluate the designs against requirements	• User-centred evaluation is a required activity at all HCD stages. Two widely used approaches are: (a) Inspection-based evaluation against usability guidelines; and (b) User-based testing	• Evaluation results • Conformance test results • Long-term monitoring

Table 10: Human-centred design activities (adapted from ISO 9241-210) [9]

A.4 Interface Design Guidance

Safe driving requires drivers to maintain situation awareness, that is, to maintain an accurate understanding of the spatial environment and objects within it, the location and relative velocity of other vehicles within the environment, and to predict likely future states. The design and operation of mining equipment poses several threats to situation awareness including restricted visibility and adverse environmental conditions. Distraction by non-driving tasks may also be implicated. Loss of situation awareness is a common causal factor implicated in vehicle collisions on mine sites.

PDS are intended to provide supplementary information to assist drivers maintain accurate situation awareness and avoid collisions. Regardless of the technology by which information regarding the location and velocity of other vehicles is obtained, if the information is to have utility in preventing collisions then it must be communicated to the driver through auditory and/or visual interfaces.

For any proximity awareness technology to be effective in preventing collisions, the following steps must be undertaken accurately, and quickly, by the driver:

- **Detection:** the driver attends to the PDS interface
- **Perception:** the information is interpreted to provide an accurate understanding of the current situation
- **Prediction:** the probability of a future collision is predicted
- **Decision:** a decision is made regarding what action should be taken

Errors, or delays, at any of these stages may lead to failure of the PDS to prevent a collision. The design of the interface by which information about the proximity of other vehicles is provided consequently plays a crucial role in determining the effectiveness of any PDS as a control measure to prevent collisions.

Auditory tones are typically provided to attract attention to the PDS. Variation in timing, pitch or volume of sounds may also be used to convey information about the situation. Auditory information is typically accompanied by a visual display to enhance a driver's ability to maintain situation awareness and make accurate and timely decisions to maintain separation.

The visual interfaces which have been designed for use as part of PDS intended for use on mining vehicles may be broadly divided into:

- Those which provide an alarm accompanied by an indication of the direction of vehicle giving rise to the alarm (examples of such interfaces are provided in Figure 47)
- Those which provide additional information about the identity, location and state of other vehicles with respect to the operator's truck (examples of such interfaces are provided in Figure 48)

Interfaces found in maritime and aviation contexts, such as the Traffic Collision Avoidance System (TCAS), also display predictive information as demonstrated in Figure 49. Particularly, in the case of the TCAS, the situation awareness display is supplemented by visual indication and spoken instructions provided to the pilot which assist to make appropriate decisions by indicating the actions to be taken in order to avoid a collision.

An optimal PDS interface is one which alerts the driver when, and only when, attention to the interface is required. This allows the operator to quickly and accurately understand the current and likely future locations of other vehicles with respect to the driver's own vehicle, and, consequently, allows the driver to make appropriate and timely control adjustments to ensure that adequate separation between vehicles is maintained.

A human-in-the-loop simulation paradigm was utilised in a study conducted by [3] to provide guidance regarding PDS interface design. A 5DT Haul Truck (HT) simulator featuring a six (6) degree-of-freedom (6-DOF) motion platform, realistic HT control layout, and three (3) projector screens was adapted to provide access to the underlying simulation software to allow creation of standardised collision provocative scenarios, and the recording of data describing simulator operator behaviour for subsequent analysis. In this study, the paradigm was initially

Figure. 47: Examples of PDS interfaces providing directional information regarding the proximity of another vehicle.

Figure. 48: PDS interfaces providing additional information about their surroundings.

(a) (b) (c)

Figure. 49: Consumer level marine collision avoidance interface (a) and Aviation TCAS interfaces (b and c).

utilised to compare the driving performance of 36 novice participants randomly allocated to a control condition (no PDS information) and two experimental conditions in which PDS information was provided by two different visual interfaces simulated on a tablet, interfaced with the truck simulator, a "ring" condition, and a "schematic" condition (Figure 50).

Figure. 50: Ring (left) and Schematic (right) interfaces indicating the presence of another truck (unseen) and a stationary light vehicle.

The 'ring' interface condition consisted of a ring of simulated LEDs on the tablet, which became illuminated indicating the direction of approach and the range of other vehicles in proximity to the participant's truck. The simulated LED were illuminated yellow when another vehicle approached within 150 m, red if the vehicle approached within 100 m, and flashing red if within 80 m. The 'schematic' interface provided a continuously updated display of the location of other vehicles. The schematic interface provided additional information over the ring interface in that the relative velocity between the participant's vehicle and surrounding vehicles was available to the operator as the display was continuously updated. The type of approaching vehicle (HT or Light Vehicle (LV)) was also indicated by the schematic interface. Identical auditory information was included in both PDS interface conditions: a low pitch initial tone occurred when another HT or LV first approached within 150 m, followed by two further tones of successively higher pitch as the proximity to another vehicle became less than 100 m and 80 m, respectively.

The data collected provided clear evidence that visual interface design influences the effectiveness of PDS, and that the additional information available in the 'schematic' interface was utilised to reduce collision risk and reduce travel time. When faced with situations with collision potential, novice driver participants assigned to the Schematic interface condition used the additional information available to adjust their speed earlier than participants assigned to either the 'ring' interface, or control conditions, resulting in a higher minimum time to collision, less extreme braking, and a higher minimum cornering speed.

A subsequent study [4] utilised the human-in-the-loop simulation paradigm to examine questions related to the provision of auditory information. This included a comparison of two and three stage alert tones, as well as the utility of speech alerts triggered by predicted collisions. No consistent differences in driver braking behaviour were observed between two and three stage alarm conditions, suggesting that the choice of two or three stage alarms for PDS may be of marginal importance. However, marked differences were observed in the braking behaviour of participants when speech alerts were provided. Provision of speech instruction (e.g. 'brake') rather than tones was effective in increasing the probability that participants would bring the simulated HT to a complete stop when presented with a potential collision situation.

Combining these results, with information available in guidelines provided in other industries[7], yields a set of guidelines for PDS interface design:

- PDS should provide information to drivers via both auditory and visual displays.
- Visual displays should be located within the driver's primary display location, as defined by EN894-4 (that is, between 5° and 40° below horizontal eye height, and less than 35° laterally) and positioned to avoid reducing the driver's external visibility.
- PDS visual displays should provide information regarding the identify, position and relative velocity of other vehicles in proximity to the driver's vehicle.
- Auditory collision warnings should sound when, and only when, the relative velocity of vehicles in proximity to the driver's vehicle indicates an imminent potential collision. (An acceptable false alarm rate of 1 per 200 driving miles have been nominated for light vehicle on-road contexts)
- A speech-based warning should be provided to convey an imminent collision threat. The message should be kept to a single word, such as 'Brake'.
- An auditory warning should not be presented more than three (3) times per potential collision incident. These repetitions should occur in immediate succession.
- The amplitude of auditory signals should be 20 dB-30 dB above ambient noise levels.
- In-vehicle systems which provide concurrent audio should be muted during the presentation of an auditory warning.
- If multiple hazards occur simultaneously, the driver should be provided with auditory warning of the highest priority hazard, while information regarding lower priority hazards is only provided visually.
- It is not known whether low level 'awareness' tones indicating the presence of other vehicles in the vicinity may be beneficial in combination with speech alerts provided in the event of imminent collision. This is likely to be context dependent.

Further generic guidance formulated for driver-vehicle interfaces in on-road vehicles is available [5]; however several open questions remain, and during the design of any specific PDS, there are likely to be context specific interface design decisions that will require further investigation as part of the human-centred design process.

A.5 Interface Design Evaluation

Apart from evaluating an interface design against the guidelines above, and the more generic guidance provided for on-road vehicle interface, a human-centred design process requires user-based testing throughout the iterative design process.

In later design iterations, the use of human-in-the-loop simulation such as described above should be employed, particularly to compare alternative candidate designs where standardisation of the situations examined is required. Simulation also has the advantage of the ability to efficiently, and safely, assess the response of users to collision provocative situations, and unusual combinations of circumstances.

Subsequent acceptance testing of final interface designs requires investigation of real-world user experience. This should be obtained through a combination of: incident analysis, incorporating analysis of in-vehicle monitoring system data; user observation; and user interviews. The human-centred design process also includes long term monitoring of the use of the system.

[7] Young, K., Horberry, T. & Burgess-Limerick, R. (2017) Review of best practice in vehicle interface design. ACARP project C24028 final report. Appendix B.

A.6 Training and Competency Assessment

The implementation of any new technology requires user-training and competency assessment. While simulator training and competency assessment for all drivers would be desirable, the use of online video-based training and competency assessment may offer a more scalable and efficient alternative. Regardless of the medium chosen, the design of training also requires the application of human-centred design principles.

Instructional system design models (such as [8]) apply HCD principles to the design of training, including front- end analysis steps (analysis of the situation, task, equipment interface, trainees, training needs, and resources, leading to the definition of the training functional specifications), followed by design and development steps (training concept generation, training system development and prototyping, and usability testing) and system evaluation steps (determining training evaluation criteria, collection and analysis of this date, and subsequent modification of the training if indicated).

The frond-end analysis (or training needs analysis) step in training design is important. In particular, a comprehensive analysis of the tasks performed by trainees is required before the training needs and associated functional specifications can be determined. The aim of task analysis is to describe the knowledge, skills, and behaviours required for successful task performance, and identify the potential sources and consequences of human error. This task analysis would typically involve interviews with experts, review of procedures, and observations of equipment in use. It should include consideration of the information required by equipment operators and maintainers and how this information is obtained, the decision-making and problem-solving steps involved, the action sequences, and attentional requirements of the task. The task analysis should be conducted systematically, and well documented, to provide a solid foundation for the design of training and to provide a template for future training needs analyses.

An extension of the task analysis to include a ‘cognitive’ task analysis may be justified for more complex tasks – equipment interfaces. Cognitive task analysis seeks to understand the cognitive processing and requirements of task performance, typically through the use of verbal protocols and structured interviews with experts. The outcomes of a cognitive task analysis include identification of the information used during complex decision making, as well as the nature of the decision making. The cognitive task analysis can also reveal information which will underpin the design of training and assessment. Again, the outcome of a cognitive task analysis may include identification of design deficiencies which should be fed back to the larger HSI design process.

The results of the task analysis are also used in the second phase of training design to define the actual contents of the training program, as well as the instructional strategy required. Regardless of the content of the competencies required or the methods employed, most effective instructional strategies embody four (4) basic principles:

1. The presentation of the concepts to be learned
2. Demonstration of the knowledge, skills, and behaviours required
3. Opportunities to practice
4. Feedback during and after practice [16]

Evaluation of the consequences of training is also an essential and non-trivial step, and the task analysis aids in determining the appropriate performance measures to be used in competency assessment. A valid competency assessment requires careful selection of evaluation criteria and measures (closely connected to the task analysis results), and systematic collection and analysis of data. This, in turn, might suggest improvements to the training process for subsequent occasions –- so the whole process often involves a degree of iteration.

B Sensor Technology Capability Assessment

The following section aims to summarise the underlying fundamentals of different Proximity Detection System (PDS) sensing technologies as documented by Dr. Herman Hamersma from The University of Pretoria (UP) – see supplementary documentation more further information[8]. The summary includes a brief description of each sensor's working principle, as well as advantages and limitations relevant to each technology when implemented towards proximity detection. The work expressed in this section is provided from an online PDS Toolkit developed by Mining3 [13].

B.1 Radio Frequency (RF) Time-of-Flight (ToF)

Radio Frequency (RF) Time-of-Flight (ToF) PDS technology utilises RF communications to detect, classify, track and communicate between vehicles, assets and personnel. Radio communication is typically performed with radio transmitters, receivers and transceivers (referred to as radio tags). Radio tags are one of the most prevalent technologies used in PDS solutions.

B.1.1 Working Principle

RF ToF PDS technology requires that single or multiple radio transceivers are mounted onto both the local and remote object. Ranging between multiple radio tags allow a PDS to determine both the distance and position of two objects with respect to each other. The communications between radio tags also allow for the identification of individual objects, simplifying the detection and classification process.

There are many different techniques that are used to estimate the distance and position between radio tags; however, it is believed that most of the PDS solutions use: (a) ToF-based methods for ranging; and (b) multiple transceivers for the position estimation. Ultra-Wideband (UWB) (operating in the range of around 3 GHz to 10 GHz) transceivers are commonly used in PDS due to their relatively high level of accuracy and robustness to multipath effects. RF ToF systems use similar technology to Radio Detection and Ranging (RADAR); however, RADAR- based solutions rely on passive radio reflections and do not require the installation of tags onto remote objects.

B.1.2 Advantages

- Relatively high accuracy
- Suitable for both surface and underground operations
- Suitable for long-range detection
- Relatively robust to terrain and environmental effects

B.1.3 Limitations

- Requires infrastructure to be installed onto remote objects
- Susceptible to Electromagnetic (EM) interference
- Communications require Line-of-Sight (LoS)

[8] ACARP PDS Validation Framework: PDS Sensing Capability Assessment

B.2 Global Navigation Satellite Systems (GNSS)

Global Navigation Satellite System (GNSS)-based technology measures the global position and, in some cases, the orientation of vehicles, assets and personnel that are equipped with GNSS receivers. GNSS-based systems rely on radio signals, which have been broadcast from satellites orbiting the earth. GNSS technology is often referred to as the Global Positioning System (GPS); however, GPS refers to the satellite constellation owned by the United States Government. There are several other satellite constellations in operation, with others scheduled for operation in the near future. Examples include the GLONASS (Russia), BeiDou (China) and Galileo (European Union) GNSS constellations.

B.2.1 Working Principle

GNSS-based technology typically consists of one or more antenna, a receiver and, in some cases, Inertial Measurement Units (IMUs). The various satellites broadcast information relating to their identity, time, status and orbit. Broadcast radio signals are received by the GNSS antenna and processed by the GNSS receiver to determine the global position of the GNSS unit. The information contained in the broadcast radio signals is used to measure the distance between GNSS-unit and the satellites. Line-of-Sight (LoS) from at least four satellites are required to measure the global position of the GNSS-unit. Some GNSS units include IMUs for enhanced localization performance. Other commonly used methods for enhancing the performance of GNSS technology is through the use of differential GNSS (DGPS) corrections and Real-Time Kinematic (RTK) techniques, which require the use of additional GNSS and communication infrastructure [27, 28].

In PDS applications, GNSS units need to be installed on both the local and remote object, and a communication link is required between the two objects. The global position of both objects is then used to calculate the proximity between the objects. To achieve the best outcome through the use of GNSS, high precision (differential) GNSS sensors provide effective performance required to minimise/eliminate nuisance alarms – a key desirable trait within a mature system. Although more precise systems are costly, the benefits are more desirable towards PDS. This improvement is demonstrated in Table 11 below, which illustrates sensor specifications for both standard [25] and high precision (or differential) [26,27,30] GNSS products (currently some of the most used for this purpose). The navigation update rate indicates the number of messages the receiver can handle per second. Horizontal position accuracy is quoted in terms of 95% Circular Error Probability (CEP) – the radius of a circle in which 95% of the values occur. Note the cost difference when considering complete package products [27, 30] against low-level standard modules [25]. Although these cost estimates can change depending on product improvements, additional module integration, etc., the need for more high-precision is demonstrated towards nuisance alarm elimination.

Parameter	Example Product Options		
	uBlox (Standard GNSS) [25]	**Racelogic VBOX 3i Dual Antenna (with DGPS) [27]**	**OXTS RT3000 v3 (with DGPS) [30]**
Max Navigation Update Rate [Hz]	18	100	100-250
Horizontal Position Accuracy	• Using GPS: 2.5m 95% CEP • Using GLONASS: 4m 95% CEP	• SBAS: <1m 95% CEP • RTCM: 80cm 95% CEP • RTK: 2cm 95% CEP	• SBAS: 0.6m 95% CEP • RTK: 1cm 95% CEP
Velocity Accuracy [km/h]	0.2	0.1	0.05-0.1
Heading Accuracy [°]	0.3	0.1	• Single antenna: 0.1 • Dual antenna: 0.05
Cost Estimate (AUD)	$38*	$12,000**	Available on contact

Table 11: Sensor specifications and cost estimates (where available) to demonstrate increased functionality through differential GNSS and other system integration (i.e., IMU and RTK corrections).

* Starting from this approx. price (as retrieved from [29] on the 15/01/2021). Note this is only a module (low level device), and additional functionality can be integrated at the developer's discretion to potentially increase costs substantially. Costs are also subject to change over time.

** Cost assumed to be up to the standard cost (as retrieved from [28] on the 15/01/2021). Additional DGPS functionality (i.e., RTK), will be assumed to cost more than this price point. High cost potentially includes much higher functionality than standard GNSS, such as IMU integration and DGPS, etc., as a complete package for immediate use. Costs are subject to change over time.

B.2.2 Advantages

- GNSS is a mature technology (introduced in the late 1970s) and a vast range of commercial solutions are available
- GNSS allows for Geo-fencing (defining no-go or restricted areas)
- Suitable for long-range applications
- Relatively high accuracy
- Inertial-based solutions can provide high-frequency positioning information as well as attitude (orientation) measurements
- Relatively robust to environmental conditions

B.2.3 Limitations

- Requires infrastructure to be installed onto remote object(s)
- Requires LoS to external infrastructure
- Not suitable for underground applications
- Performance may change depending on the status of the satellite constellations

B.3 RADAR

Radio Detection and Ranging (RADAR) has multiple uses in a variety of fields. The primary objective of RADAR is to detect targets of interest and derive information such as range, angular coordinates, velocity and reflectivity signature [6].

B.3.1 Working Principle

A RADAR transmits Electromagnetic (EM) energy, generated within a transmitter unit, through antenna (serving as a transducer to couple EM energy into the atmosphere) toward a region of interest (through concentration of the propagating EM wave toward a specific direction) at the speed of light [6, 15]. A detection is identified when an object intercepts the propagating energy, causing a scatter, or polarisation, of the energy in various directions. In general, some of this intercepted energy is reflected back towards the original source. Due to the time delay through this process (transmission, reflection and reception of energy), and the speed of energy propagation (speed of light) the range to the reflective surface can be determined [6,15].

There can be potential interference in the form of: (a) internal and external electric noise; (b) reflected EM waves from other irrelevant sources – known as clutter; (c) unintentional EM waves from the environment, referred to as EM Interference (EMI); and (d) intentional jamming from electronic countermeasures [15]. Therefore, the RADAR performance under EM interference needs to be considered. Furthermore, RADAR performance can be influenced by numerous factors, including: propagation frequency, altitude, and humidity (i.e. rain, fog and clouds). Making an informed choice of EM wave frequency lessens this effect resulting in “all weather capable” RADAR [15].

The independent, stand-alone nature of a RADAR sensor is a notable advantage; there is no strict requirement that other objects/vehicles must have a similar system equipped in order for a single system to determine range and velocity information. This being said, further development could be considered when implementing RADAR towards a PDS. This may include sensor fusion techniques for improved performance using other sensor modalities or establishing communication between separate PDS (mounted on the Local Object (LO) and the Remote Object (RO)) to share information towards a better understanding of the environment. Furthermore, multiple RADAR sensors (per PDS unit) may also be required given that RADAR must be mechanically and electrically designed (i.e. designed to rotate) to cover a larger detection region.

B.3.2 Advantages

- No additional infrastructure is required onto remote object(s)
- It is a mature technology in various industries, in particular: the automotive sector

B.3.3 Limitations

- In some cases, additional software may be required for detection, classification and tracking processes
- Potentially subject to blind spots around the equipped machine
- Subject to the Multipath Effect, a phenomenon whereby signals arrive by two or more paths.
- RADAR performance may be affected by harsh weather conditions and may require maintenance to clear dirt and debris from the sensor
- Limited Field-of-View (FOV)
- Difficult to develop a physics-based sensor model for simulation-based testing

B.4 Electromagnetic-Based Sensors

Electromagnetic (EM)-based sensors are often seen in the underground coal mining industry. While other methods may very well be possible, this toolkit discusses two commonly used methods in the PDS area: (a) the detection of objects based on the magnetic flux density; and (b) the use of Near-Field Electromagnetic Ranging (NFER).

B.4.1 Working Principle

There are two main elements that are typically implemented within an EM-based flux density PDS: (a) a set of ferrite-cored generators (placed on the Local Object (LO)) that create a surrounding magnetic field; and (b) a set of magnetic probes or detectors (placed on the Remote Object (RO)) that allow detection of the generated fields [10, 11]. These systems create a safe zone between the LO and RO (in most cases, this is a pedestrian) based on the detected magnetic flux density; therefore, it is important to note that the stability of the magnetic field is essential towards system accuracy [11].

NFER, on the other hand, is a technology that relies on the near-field characteristics of the electric and magnetic components of an electric wave. In far-field EM propagation (such as RADAR), ranging is performed with ToF-based techniques. However, in near-field EM propagation, within approximately one-quarter wavelength of an electrically small transmitter, the electric and magnetic components are 90 degrees out of phase. When further away from the antenna, the electric and magnetic phases converge; therefore, by detecting, measuring and com- paring these phases before they converge, the distance from a transmitter can be determined. It is important to note that the NFER principle requires the antennas (between a transmitter on one object and the receiver on an- other object) to be less than one wavelength from each other; this can potentially limit the detection range [18–20].

In terms of both implementations, EM interference may be possible when considering EM-based sensors for use in PDS; however, due to the low frequency application of NFER, this may not be as prevalent, given that other technologies utilise much higher frequency bands. Another advantage of utilising lower frequencies is that the signal suffers much less signal loss and reflection errors from solid walls.

EM-based flux density technologies are able to propagate through various types of rock mass (including coal), with studies illustrating the induced interfering current of *in situ* coal mass caused insignificant changes in the magnitude of the EM generators: a notable advantage of the technology. However, it must be stated that temperature (both internal and ambient) affecting the generator current can cause location calculation errors; therefore, it is crucial that developers consider this aspect into their development of EM-based flux density PDS [10, 11].

The overall functionality of EM-based technology require infrastructure on both the LO and RO. In terms of NFER, range is determined only by the receiving unit; therefore, additional communication infrastructure is required for range information to be communicated back to the transmitter units. Similarly, it is evident that both a generator (LO) and a detector unit (RO) must be implemented to create a complete magnetic flux based PDS, with additional communication required (i.e. detection alerts given to both the LO and the RO) depending on the system design and implementation.

B.4.2 Advantages

- Both methods do not require Line-of-Sight
- Applicable largely to underground/enclosed applications
- Suitable for both surface and underground operations
- Relatively robust to terrain and environmental effects

B.4.3 Limitations

- Both methods require infrastructure to be installed on both the LO and theRO

- Limited range between objects in comparison to other sensor modalities
- Regarding EM-based flux density PDS, temperature may cause increased location error between LO and RO

B.5 Digital Camera Systems

Digital cameras convert light into electronic signals. The two types of image sensors most often used are: (a) Charged Coupling Devices (CCD); and (b) Complementary Metal Oxide Semiconductors (CMOS). Both of these sensor types are fabricated in silicon and rely on photo diodes that release electrons when light photons collide with the diode [2, 17].

B.5.1 Working Principle

CCD sensors have diodes and storage cells (or buffer bins) for each pixel. Each diode accumulates a charge (proportional to the light intensity) once the shutter opens. The charge is then shifted to neighbouring storage cells and subsequently converted to a digital value through the use of a single Analogue to Digital Converter (ADC). The digital values typically range from zero (no illumination) to 255 (full saturation). CMOS sensors, while similar to CCD in terms of the conversion process of incident photons into electron-hole pairs, convert the charges within the pixel itself, rather than during the readout phase. It is important to note that, while CMOS sensors are known to be: (a) cheaper and simpler in terms of manufacturing; (b) efficient in terms of power consumption; and (c) capable of operation at very high frame rates (at megapixel resolution), they are susceptible to fixed pattern noise due to their many amplifiers at each pixel, with more susceptibility to noise than CCD [2,17].

Regardless of the sensor type (CCD or CMOS), there are additional parameters that contribute to the overall image quality [2]:

- **Sensor sensitivity** (also known as the ISO) is a measure of amplification used prior to the digital conversion. A higher ISO sensitivity requires less light to achieve the same effect as a lower ISO sensitivity.
- **Shutter exposure time** is the time that a photo diode is exposed to light; a higher exposure time gives the photo diode a longer period to build a charge. Low shutter times in dark conditions will lead to under exposure of the camera sensor, compared to high shutter times which lead to overexposure. Furthermore, the type of shutter used (global or rolling) will also affect the ability to capture motion of an object, with rolling shutters prone to image distortion with faster moving objects [17].
- **The lens aperture** is the opening through which light travels to hit the light sensor. A larger opening allows more light photons to enter the camera. The aperture opening is specified by the F-number. The F-number is the ratio of lens focal length to effective aperture opening diameter. A lower F-number denotes a larger aperture opening. Increasing the F-number decreases the image exposure but increases the image field depth.
- **Lens focal length** is the optical distance from the plane at which the light rays converge from the lens. This is related to the magnification of the lens. Focal length thus affects the image region.

Camera sensors, similar to RADAR and LIDAR, can be stand-alone systems, with no strict requirement to communicate on infrastructure between the Local Object (LO) and the Remote Object(s) (RO). However, unlike many of the sensor modalities documented in this report (i.e. near and far field applications using EM RF sensors), camera sensors do not inherently provide object pose or state (position, orientation, velocity and acceleration) estimates. This is a noted limitation of a camera sensor, with additional design requirements (i.e. purpose-built software or algorithms) before a PDS can be fully developed.

This being said, there are numerous methods towards the estimation of object pose and state using cameras, and this can range from: (a) monocular (single camera) implementations to determine range information [21]; to (b) stereography, a technique using multiple cameras with an established baseline, for estimation of range (including direction) to objects [2]. Furthermore, the classification and detection of objects can be performed by a number of different techniques, most notably through the use of feature detections and Deep Learning-based methods [22]. Regardless of the technique(s) used, it is important to design a system that can robustly perceive the environment, with an understanding of any immediate collision threats – whether they be moving or stationary objects of interest – in a timely and efficient manner.

B.5.2 Advantages

- Large Field-of-View (FOV) possible with the use of wide-angle lenses (i.e. Fisheye lens) or multi-camera systems
- No infrastructure is required onto remote object(s) (visually distinct stickers may be used to enhance performance)
- Suitable for both surface and underground applications
- Low power requirements and low-cost relative to other sensors

B.5.3 Limitations

- Camera-based systems are likely to be affected by harsh environmental conditions (e.g. light, dust, rain, fog)
- Camera-based systems require maintenance to clear dirt and other debris from the lens
- Detection, classification and tracking in some cases, can be computationally expensive
- Detection limited to Line-of-Sight
- Stereo-based solutions have either limited range (compared to LIDAR-based solutions) or reduced FOV

B.6 Light Detection and Ranging (LIDAR)

Light Detection and Ranging (LIDAR) is a ranging technique that typically uses the Time-of-Flight (ToF) of emitted, reflected and detected light. LIDAR does not require infrastructure to be installed on the remote object. LIDARs operate by 'scanning' the environment to generate a 2D or 3D geometric and, in some cases, visual representation of the environment.

B.6.1 Working Principle

ToF-based LIDAR emit focused beams of light energy in a specific direction; the light is reflected from surfaces in the environment and detected by detectors within the LIDAR sensor. LIDARs typically operate in the near infrared light spectrum, which is not observable by humans. Scanning is performed by rotating mirrors or by rotating the actual emitter and detector in the LIDAR sensor. 3D scanning is performed by rotating the emitter and detector in different axes or by using multiple emitter and detector pairs. As a LIDAR scans an environment, they create a geometric (range-based) and visual (intensity-based) representation of the environment.

The visual and geometric data produced by LIDARs are known as point clouds. PDS need to process the point cloud data to detect, classify and track remote objects.

B.6.2 Advantages

- No infrastructure is required on remote objects (reflective markers may be used to enhance performance)
- Does not rely on external infrastructure

- Most LIDARs can scan the environment with a large (up to 360°) Field-of-View (FOV)
- Relatively accurate ranging performance
- Suitable for both surface and underground applications

B.6.3 Limitations

- Most LIDARs are likely to be affected by harsh environmental conditions
- The performance of LIDAR depends on the material properties of the surfaces in the scene
- LIDAR sensors may require additional maintenance to clear dirt and other debris from their lenses
- Detection, classification and tracking, in some cases, can be computationally expensive
- Detection of a remote object requires Line-of-Sight

C Incident Data Summary

Figure 51 and Figure 52 below identify incidents with their corresponding association to the recommended Prevalent Scenarios from Australia and the US, respectively.

Type	Intersection	Work Area	Tailgate/-Direct	Static Road Hazard	Loss of Control	Other
Fatalities	2	3	1	0	9a	0
Serious Accidents	5	33	3	1	1	0
Near-Miss	12	0	0	0	1	0
Total	19	36	4	1	11	0

NOTE 1: The incidents in this summary were collated from Queensland, New South Wales and Western Australia.

a 9 fatalities (4 for **Void**; and 5 for **Incline/Decline** cases).

Figure. 51: A summary of incident data from Australia pertaining to Powered Haulage.

Type	Intersection	Work Area	Tailgate/-Direct	Static Road Hazard	Loss of Control	Other
Fatalities	0	4	1	0	12	1
Serious Accidents	0	0	0	0	0	0
Near-Miss	0	0	0	0	0	0
Total	0	4	1	0	12	1

NOTE 1: The incidents in this summary only include fatal cases.
NOTE 2: All incident reports were collected from the US Department of Labour, Mine Safety and Health Administration (MSHA} between 2008 and 2019.

12 fatalities (6 for **Void**; and 2 for **Incline/Decline** cases}. Of the remaining: 3 were due to **Maintenance Issues** with vehicles; and 1 was due to **Overloading** the vehicle.
Represented a combination of **Intersection Conflict** and **Work Area Conflict** cases.

Figure. 52: A summary of incident data from the United States of America (US) pertaining to Powered Haulage.

C.1 Incident Data Conclusions

From a total of 90 incidents reviewed (from both Australia and the US), a breakdown of the collected incident data presents the following conclusions:

- Loss of Control presented the largest percentage of incidents (approx. 23%) that contributed toward a fatality, both in the Australian and US data (a common root cause being the seatbelt, which operators neglected to wear).
- Of the Loss of Control fatalities from both the Australian and US data (21 incidents reviewed), approx. 48% were due to Void cases, while approx. 33% were due to Incline/Decline cases.
- A large percentage of incidents (approx. 44%) were attributed to Work Area Conflict, 10% of which were fatalities (from the US database) –- the remaining 90% were considered as serious accidents.

Additionally, a report published by the Government of Western Australia [3], presented the following key findings relating to a total of 172 vehicle collisions (classified as either driving into a vehicle or being struck by another vehicle) in the Western Australian mining industry:

- Main vehicle types involved in approx. 79% of collisions:
  - Surface Haul Trucks (28%)
  - Light Vehicles (24%)
  - Underground Haul Trucks (7.2%)
  - Loaders (13.3%)
  - Dozers (6.2
- Main repeat incidents between the same type of vehicles in the same area:
  - Waste Dump [Dozer (Local Object (LO)) vs. Surface Haul Truck (HT) (Remote Object (RO))]
  - Ramp [Surface HT (LO) vs. Surface HT (RO)]
- Main LO activity for vehicle collisions:
  - Reversing (24.4%)
  - Traveling on Road (20.3%)
  - Entering or Exiting an Intersection (8.7%)
  - Traveling on Decline (8.7%)
  - Traveling on Ramp (8.7%)
  - Pulling In or Out of a Work Area (7.5%)
- Main repeat incidents between the same type of vehicles, where the LO was conducting the same activity:
  - Reversing [Dozer (LO) vs. Surface HT (RO)]
  - Traveling on Ramp [Surface HT (LO) vs. Surface HT (RO)]

C.2 Scenario Alignment

The following (Figure 53 details an alignment of interaction cases, as defined by EMERST (PR-5A) [4] and QGN 27 [5]; and (b) an alignment of possible test configurations for each scenario, as described by the MINCOSA MOSH Test Evaluation Guideline [8].

Reference Document	Intersection	Work Area	Tailgate/-Direct	Static Road Hazard	Loss of Control	Other
EMESRT PR-5A	[1 - 4]	[5 -10]	[11 - 21]	[22]	[23[d], 24]	N/A
QGN 27	[2, 10]	[1, 6, 8, 9, 11, 13, 14[a]]	[3, 4, 5, 7]	[12[b]]	N/A	N/A
MINCOSA MOSH Tests	[2, 3]	[10, 11, 12[a], 13[a]]	[4 - 6]	[7 , 8]	[1 , 9]	N/A

NOTE 1: The numbers represent a defined interaction, grouped according to the *Critical Scenarios*. A description of each interaction is provided below.
NOTE 2: The numbers for EMESRT PR-SA apply to interactions in an open-cut/surface mine.

a Underground scenario/interaction
b Defined as a *fast* interacting with a *slow-moving* vehicle - categorised as a potentially *Static Hazard* case
Could be aligned with *Work Area* as well as *Static Road Hazard* (passing a static vs. dynamic object)
Identified as a *Void* conflict

Figure. 53: Illustrates the alignment of defined prevalent scenarios to existing scenario classifications.

C.2.1 Interactions as defined by EMERST (PR-5A)

NOTE: Please refer to [4] for more information regarding: (a) the definition of each interaction; and (b) the sub-categorised cases for each interaction.

- T1 – Merge
- T2 – Crossover
- T3 – Junction
- T4 – Intersection
- P1 – Person (direct)
- P3 – Person (indirect)
- P4 – Access and Egress
- V6 – Congested Area
- R1 – Swing
- R2 – Drop
- L1 – Head-on
- L2 – Reverse-on
- L3 – Backup
- L4 – Dovetailing
- L5 – Passing Head-on
- L6 – Passing Reverse-on
- L7 – Overtaking
- L8 – Blind Approach
- C1 – Curving Head-on
- C2 – Curving Dovetail
- C3 – Curving Reverse-on
- O1 – Obstacle
- V1 – Void
- V4 – Loss of Control

C.2.2 Interactions as defined by Guidance Note QGN 27

NOTE: Vehicle to Vehicle (V2V); Vehicle to Personnel (V2P); and Vehicle to Mine Infrastructure (V2I).
For more information, refer to [5].

- (V2V, V2P) – Slow speed (e.g. Park up areas)
- (V2V) – High speed overtaking collision*
- (V2V) – High speed rear end collision (heavy vehicle and heavy vehicle)

- (V2V) – High speed rear end collision (heavy vehicle and light vehicle)
- (V2V) – Slow speed rear end collision (heavy and heavy; heavy and light)
- (V2V) – Collision or reversing over dump
- (V2V) – Head-on collision
- (V2I, V2P) – Forward collision
- (V2V, V2P, V2I) – Reversing collision
- (V2V) – Intersection collision
- (V2V) – Collision mining face
- (V2V) – Collision fast-slow moving vehicles (fast encountering slow)
- (V2P) – Person being entrapped in a workshop scenario
- (V2V) – Underground mining scenario (Loader turning into recess)

C.2.3 Test configurations, as recommended by the MINCOSA MOSH Test Evaluation Guideline

NOTE: see [8] and the references within

- sTCO
- sTC1
- sTC2
- sTC3
- sTC4
- sTC5
- sTC6
- sTC7
- sTC8
- sTC9
- sTC10
- uTC11
- uTC12

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ACARP PROJECT C26028
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PDS VALIDATION FRAMEWORK

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ACARP

ACARP C26028 PDS Validation Framework

Final Report

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1.0 DRAFT	07/09/2018	JK SG MD		
1.3 For Publication	28/12/2018	JK	Tony Egan (ACARP)	Incorporated input and feedback following from EMESRT VI Tripartite Working Group workshop held in Brisbane on 4th – 5th Dec 2018.

Abbreviations, Terms, and Definitions

PDS – Proximity Detection System.

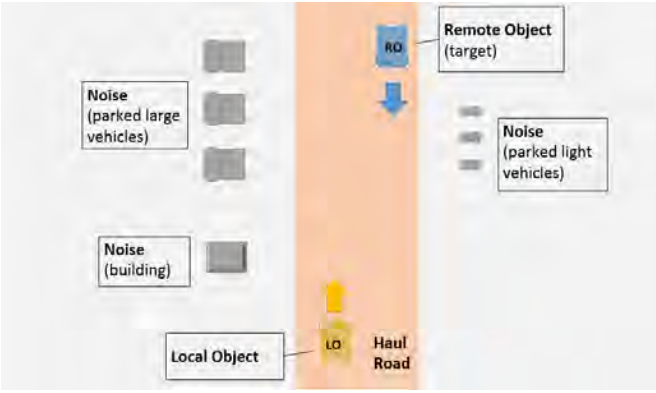
PDS Sensors – Sensors that are a part of the PDS package. These sensors can be in the form of LIDAR, RADAR, Stereo Cameras, etc., are employed by the PDS to sense and detect and track objects of interest around the host vehicle.

PDS Intelligence Layer – This is the module within the PDS package that aggregates and interprets the sensory information from the PDS Sensors, and makes decisions on what actions to take (what signals to generate and the timing of them) based on its pre-programed logic/rules.

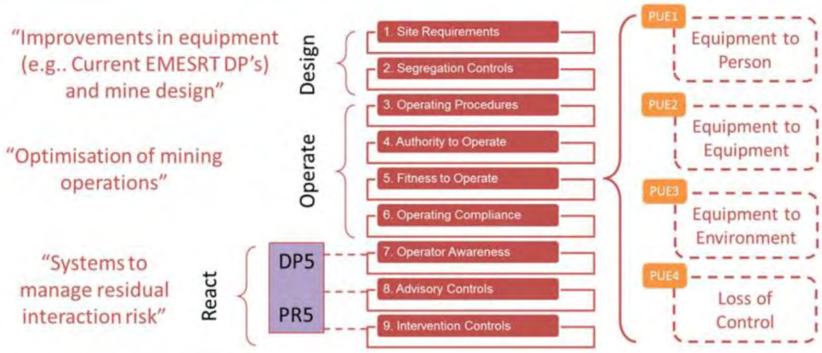
Local Object (LO) – The host vehicle on which the PDS system is installed.

Remote Object (RO) – The object of interest (can be a vehicle, a fixed plant, a human being, or any other physical object) to the LO due to its proximity to the LO or due to it being at risk of getting into a collision / near miss with the LO at the instantaneous state of events.

Noise - Surrounding objects that do not fit the definition of an RO and are hence not of (immediate) concern to the LO .



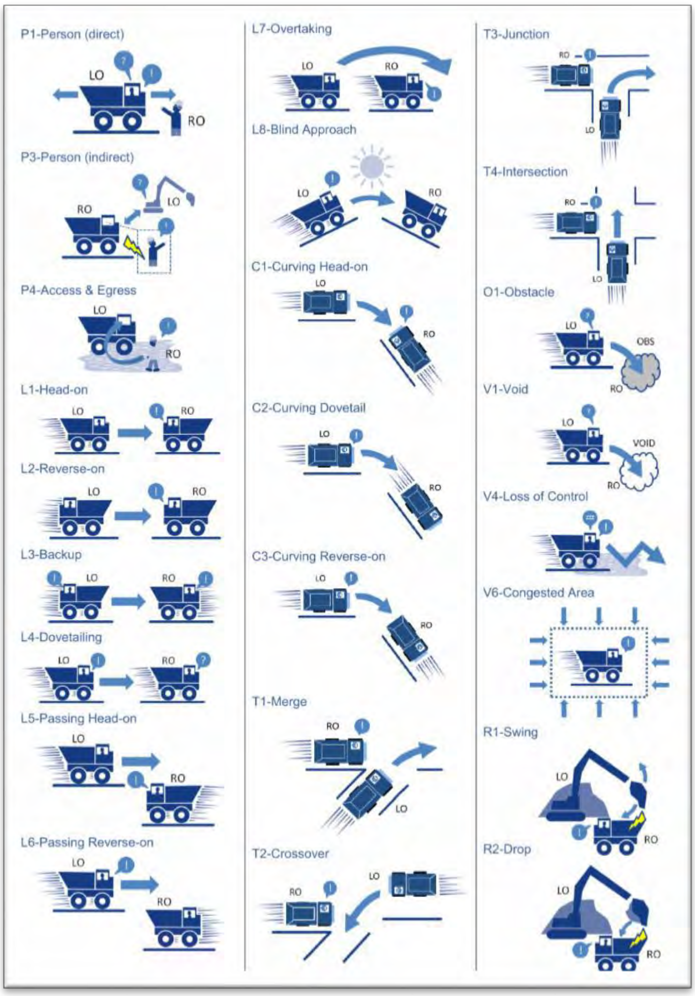
Control Levels 1-9 – First proposed by EMESRT through the PR5A document, this is a hierarchy of nine (9) levels of preventative risk reduction measures arranged by timeframe (long term to immediately prior to a hazardous interaction).



- Level 7: Operator Awareness (cameras, live maps, mirrors, lights, visible delineators).
- Level 8: Advisory Controls (alerts for proximity, fatigue, over-speed, vehicle stability).
- Level 9: Intervention Controls (interlocks that prevent start, slow-stop, rollback, retarder).

PUE – Potential Unwanted Events.

Interaction Scenarios – Scenarios typically associated with potentially hazardous vehicle interactions as defined in EMESRT PR-5A, Section 4.1.1 and illustrated as follows:



PDS Signal – This is the “action” that the PDS system undertakes following a decision made in response to a situation. For the purposes of this project, a distinction is made between the signal and the end effector of the signal, which is illustrated later on in Figure 29.

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Executive Summary

Industry Challenge

At the time of writing, there is currently limited research available to prove the accuracy and reliability of Proximity Detection Systems (PDS) in production environments or to provide operations with a realistic and manageable framework to determine if a particular PDS unit is appropriate for their conditions and needs. Reliability and functionality claims made by suppliers are not easily verifiable by the end user, at least not relative to any known framework, methodology, or standard. Additionally, there are many PDS units and multiple sensing technology categories used such as radio frequency, infrared, radar, ultrasonic, LIDAR, and combinations thereof. Sites can be further confounded when selecting a PDS unit because little is known about the actual strengths and weaknesses of the various sensing technologies or what is effective/ineffective relative to operating conditions.

Summary of outcomes

This body of work has made an attempt at developing a PDS Validation Framework that is scientifically rigorous yet practically achievable for site to implement. The project, which involved an initial investigation into the fundamental problems and challenges of validating such systems, proposes a staged 2-tier approach to PDS validation:

- Tier 1 involves validating the PDS's Object Detection capability against a set of environmental and vehicle speed variables.
- Tier 2 covers the validation of PDS's L8 and L9 capability (see PR5A L1 – L9 hierarchy of controls) in limited choreographed test scenarios.

The basis of the tiered approach is to tackle the challenge in bite-sized chunks. These chunks of tests are highly focussed and should provide clear and conclusive results on which part of the PDS unit's performance may be deficient. It is the intent that any poor performance demonstrated within either Tiers of testing will (depending on final interpretation of the results) invalidate a PDS unit. If a PDS unit is inherently unsuitable due to susceptibility to any of the two suggested Root Causes, by design the tiered approach should require minimal time and resources to quickly but convincingly demonstrate the fact. Additionally, assessing the object detection layer (Tier 1) independent of the intelligence layer (Tier 2) and vice-versa creates less complicated and more manageable tests. The various variables of the operating environment (e.g. High-wall) and operating parameters (e.g. different vehicle speeds, different target sizes) that could affect the PDS unit's operation would not be covered in Tier 2, as these variables (if they are significant factors at all) would have affected the outcome of Tier 2 tests through their effects on the object detection capability, which would already have been discovered in Tier 1 (and hence possibly have invalidated the PDS in question). Thus Tier 2 testing can focus on interaction scenarios and the evaluation of the PDS unit's decision-making instead of being distracted and confounded by the inclusion of operating environment variables.

At the time of writing, only inline vehicle scenarios L1 – L7 (from PR5A) is covered in this body of work, due to time and budgetary constraints on the project, and also due to the fact that inline scenarios typically account for the majority of reported incidents on most common sites. Future scenarios (curving path, intersections, etc.) will be addressed at an appropriate stage in the future.

Limitations

It is important to recognize the limitations of the proposed body of tests in Tier 1 and Tier 2. The scenarios that will eventually be covered (once the test scenarios are expanded beyond the inline L1 – L7 sets) are idealized scenarios, which by design should provide a fairly reliable indication of a PDS unit's robustness and adequacy. However, the reality is that the sheer number of combinations and permutations possible with vehicle arrangements and environmental parameters means that there will always be yet-unknown specific scenarios that could throw "curved balls" at PDS units, which could cause malfunctions, no matter how advanced these products may be engineered. This is a fundamental challenge in attempting to test and commission products whose functionality are contingent on successful operation within, and interaction with, a highly complex environment.

A framework for Learning and Knowledge Capture driven by all stakeholders is extremely important as this will ensure that performance failures in the application environment (if and when they do occur) is converted into critical information that helps drive the development of the next generation of improved and more robust products while simultaneously reducing the set of "unknown unknowns" of the operating environment.

Next steps

As of writing, funding has been approved for the next ACARP phase, which will involve translating and finalizing the proposed test procedures in this body of work into a safely executable field test program that preserves the original rigour of the methodology. Mining3 will seek engagement with expert volunteers from the industry to assist with this process. Importantly, the next phase will also involve field verification of the proposed test program, including logistics of setting up the tests and executing them. Gaps and weaknesses of the current methodology are to be identified, and the methodology is expected to be fine-tuned and improved as a result.

1. BACKGROUND

1.1 Proximity Detection Systems

Vehicle interaction (vehicle-to-vehicle, vehicle-to-person, vehicle-to-structure) and its proper management is an issue for the coal mining industry from safety, cost, and productivity point of views. Proximity Detection Systems (PDS) are designed to assist vehicle operators in reducing or negating risk of vehicle interactions. At the most basic level, a PDS performs this task by

a. constantly monitoring for objects of interest (other vehicles, persons, structures, etc.) around the host-vehicle through the use of sensors (LIDAR, Radar, Stereo Cameras, etc.)
b. using an (artificial) intelligence layer for determining if/when the host-vehicle is at risk of interaction, and if so, determines a set of pre-programmed actions to take (e.g. giving off warning alarms or auditory instructions, performing emergency braking) in order to assist with averting unwanted interaction (collision).

As a useful analogue, Proximity Detection Systems are similar in type to ADAS (advanced driver assist) systems in the automotive industry. They are both distinct to full autonomous controllers in that they only intervene and act when it is determined (by the intelligence layer) that the vehicle operator has departed from a baseline set of actions in a given scenario.

Proximity Detection Systems can be shipped together with OEM equipment as part of an OEM offering, or can be retrofitted onto an existing fleet as a 3rd party device. As of writing, the industry is trending towards implementation of these systems, on a case-by-case basis.

1.2 The Industry Challenge

Currently, there is limited research available to prove the accuracy and reliability of PDS units in production environments or to provide operations with a realistic and manageable framework to determine if a particular PDS unit is appropriate for their conditions and required performance.

There is lack of evidence that sites or PDS suppliers themselves have robust methodologies to scientifically test PDS units in a rigourous, scalable, and achievable manner against user requirements and against realistic operating conditions. Reliability and functionality claims made by suppliers are not easily verifiable by the end user, at least not relative to any known framework, methodology, or standard. Additionally, there are many PDS units and multiple sensing technology categories used such as radio frequency, infrared, radar, ultrasonic, LIDAR, and combinations thereof. Sites can be further confounded when selecting a PDS unit because little is known about the actual strengths and weaknesses of the various sensing technologies or what is effective/ineffective relative to operating conditions.

On a more fundamental level, there is a critical need for the industry to fully comprehend PDS capabilities / limitations, how these relate to (and influence) operator behaviour, and the aggregate implications of these on the bottom-line , i.e. whether overall site safety can be improved after the adoption of PDS, or not (this is further treated in Section 3.10). There is evidence that this awareness may be currently deficient and under-appreciated within the industry. Operating sites will need to reconcile this critical understanding with any strategic decision to adopt PDS units on-site. In parallel, PDS developers will need to utilize this understanding to guide the development of ever more accurate and fit-for-purpose products that are highly-optimized to operational realities and operator behaviour.

1.3 Project Objectives

The aim of this project is to address the challenge of how to verify and validate PDSs in a rigorous yet practical manner. A side (but important) objective is to aggregate critical sensor technology information (strengths and weaknesses of each sensor technology, etc.) into an informative package that is suitable for perusal by the typical end user (sites).

The specific objectives are:

1. Develop an open, standardized, peer-reviewed validation framework for PDS performance verification for Surface Mining, relative to EMESRT PR5A. The final outcome will provide:
    - An explanation of current PDS technology categories, strengths, weaknesses, applications relative to each category, and implementation requirements
    - An open specification testing regime comprised of:
        - Metrics (what to measure)
        - Experimental Design (how to measure)
        - Testing Framework (make the measurements, for each PDS participating)
        - Review (analysis)
2. Conduct a detailed technology review
    - Categorise PDS sensing technologies by type
    - Define the technical and functional capability
    - Define implementation requirements relative to situational, human, environmental, and technical factors relative to the EMESRT developed PR5A VI Scenarios PUE 1 – PUE4
3. Create a reference document (this Final Report) containing all the above.
4. Collaborating on field trials to validate the above framework (*i.e. validate the validation framework*) using actual PDS systems in a production or realistic environment. The intent is to
    a. Assess any issues and operational difficulties associated with implementing the test methods prescribed.
    b. Verify that all proposed procedures are safe to implement.
    c. Make improvements / refinements to the methodology in response to feedback from the above
5. Create a reference document documenting the learnings from #4.

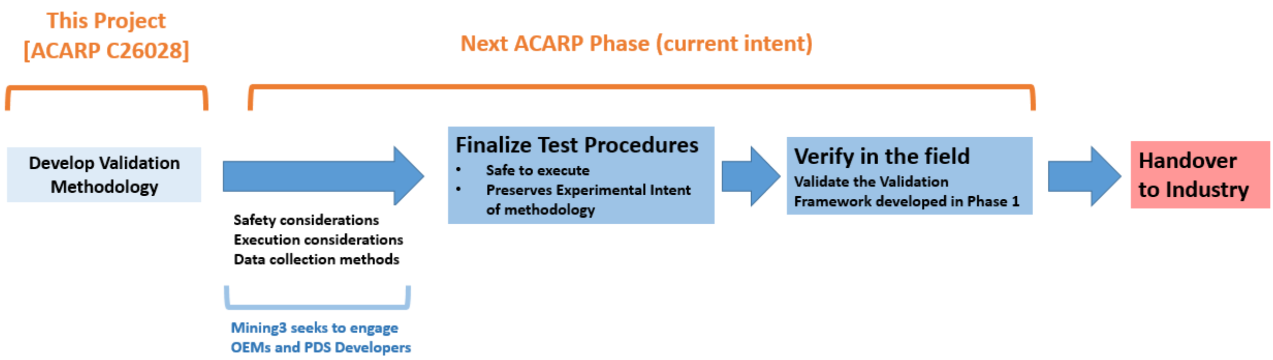


Figure 3 – Roadmap of the current project leading into the next proposed ACARP phase.

1.4 The PDS Model of Operation

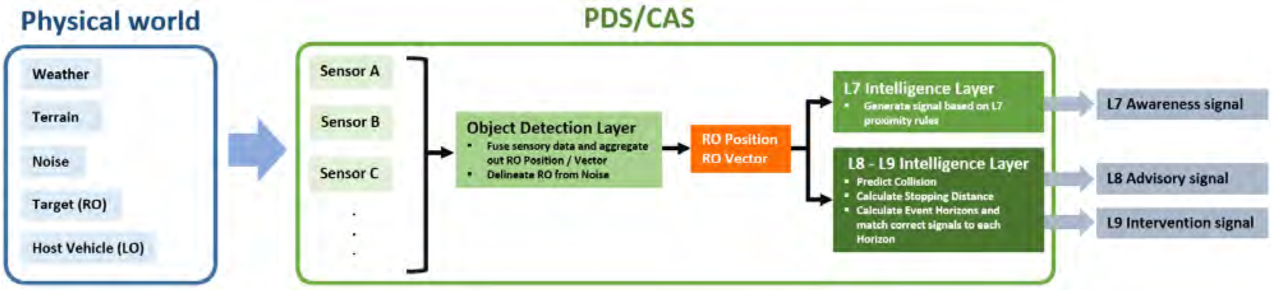


Figure 1 – The PDS Model of Operation

As part of the initial review of the project subject matter, a diagram to represent how PDS units operate (at an abstract level) was developed, This diagram has since undergone a number of revisions (which were previously presented to ACARP through workshops), and is deemed critical in clarifying the underlying motivation behind the methodology proposed in this body of work.

On the left, the blue box represents the Physical World within which the Local Object resides. Components of this set include the Host Vehicle (on which the PDS is installed, henceforth referred to as the Local Object or LO), the Target (or the Remote Object, RO), and elements of the environment e.g. rain, ambient light, terrain, road conditions, etc. The PDS unit (Green Box in the middle) attempts to sense and measure relevant elements of the Physical World in order to execute its L7 – L9 functions. It is useful to make a distinction at this stage with regards to 3 types of (or at least three distinct functionalities of) Intelligence Layers:

1. The **Object Detection Layer** deals with the data input from the various sensor packages, and attempts to aggregate the raw data (data cleaning, data fusion, etc.), delineate the objects/targets of interests (RO) from noise, and generate an accurate awareness of which objects are where in relation to the LO. If the PDS unit's performance is going to be affected by any of the environment variables (e.g. rain, dust, high-wall, different speeds, etc.), it will be manifest and apparent in the output of this layer.

2. The **L7 Intelligence Layer** deals with determining which objects (ROs) satisfy the criteria for the generation of L7 Awareness Signals. These criteria could manifest as fixed proximity-based rules (e.g. a hard proximity of 300m or less triggers the L7 signal), or dynamic rules (e.g. based on closing velocity/time to collision), or a hybrid of both. Key input into this Layer (which will determine the success/failure of the generated signal) is the accurate measurement of the RO's position (the output from the Object Detection Layer).

3. The **L8 & 9 Intelligence Layer** attempts (relatively) more complex processing (collision prediction, stopping distance calculation, event horizon determination). Again the key input into this Layer, which will determine the success/failure of the generated signals, is the RO Position and Vector (heading, velocity). Interestingly enough, if RO Vector is determined at all by a PDS unit (with no vehicle-to-vehicle link), it is most probably derived from some form of backward difference approximation technique based on recorded RO Positions at the most recent time intervals. This makes RO Position accuracy doubly critical.

As can be seen from the model, the accuracy of the RO Position measurement (i.e. the accuracy of the Object Detection Layer output) directly influences the PDSs L7 signal accuracy, while playing a dominant role in the L8- L9 signal accuracies [accurate L8 and L9 functionality is also linked to accurately measuring/estimating Stopping Distance parameters and robust aggregation and processing of all the above information in the intelligence layer].

1.5 A Tiered Methodology

Referring to Figure 2, a natural segregation within the PDS model can be seen, denoted by the dotted red line. The left side of the line encompasses the Object Detection capability of the PDS unit. This area of the system is a common denominator to all PDS units on the market, not in the sense that they all use the same combination of sensors (in most cases they won't), but in terms of its functionality and what metric can be applied to assess the performance in this area. The metric of concern would be the measurement accuracy in locating and detecting the Target (RO). On the right side of the dotted red line, due to the possible variation across different PDS units (in terms of signal configurations, different set of logics and rules programmed into the intelligence layers), prescribing a framework that can adequately deal with said variation does raise the analogy of trying to "compare apples and oranges".

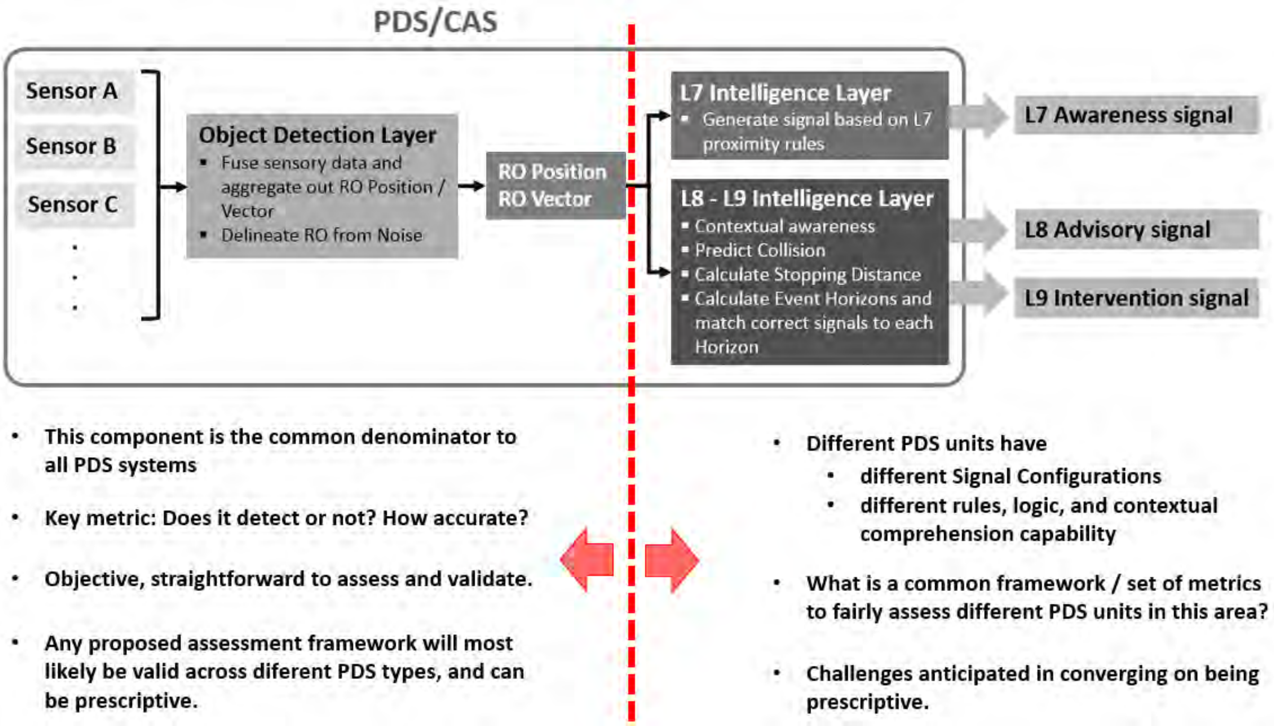


Figure 2 – A natural segregation noted within the PDS Model of Operation

Against the backdrop of the segregation discussed above, a three-tier approach is proposed:

Tier 1 – Object Detection Performance Verification

This phase aims to subject the PDS to the full range of expected operating conditions (speed, gradient, distance, visibility etc.) for a typical surface operation. The key response metric is the PDS unit's accuracy in measuring the RO's true position (relative to the LO) in every situation.

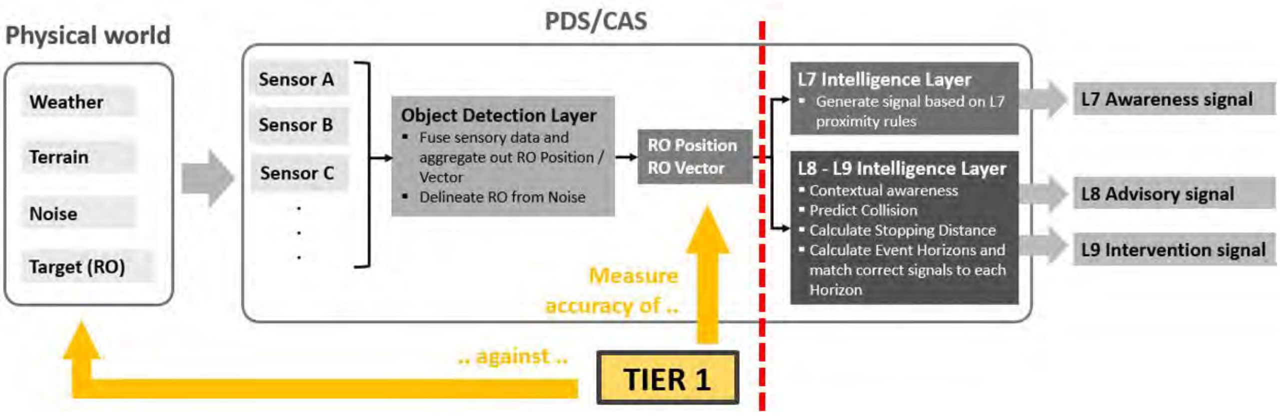


Figure 3 – Tier 1 Testing in the context of the PDS Model of Operation.

Tier 2 – Intelligence Layer Performance Verification
In this phase, the LO and the RO are put through a set of choreographed scenarios that simulate unfolding PUEs (Potentially Unwanted Events, e.g. head-on, rear-end, misjudged clearance during passing head-on, etc.). Both positive cases (where LO and RO are on a path to collision) and negative cases (LO and RO are not on a path to collision) will be tested. The intent is to verify the accuracy of the PDS Intelligence Layer's decision-making in scenarios where the Baseline / Ground Truth Set (what the PDS system is required to do and when it is required to do them) is already known (as the test scenarios and test parameters are well defined).

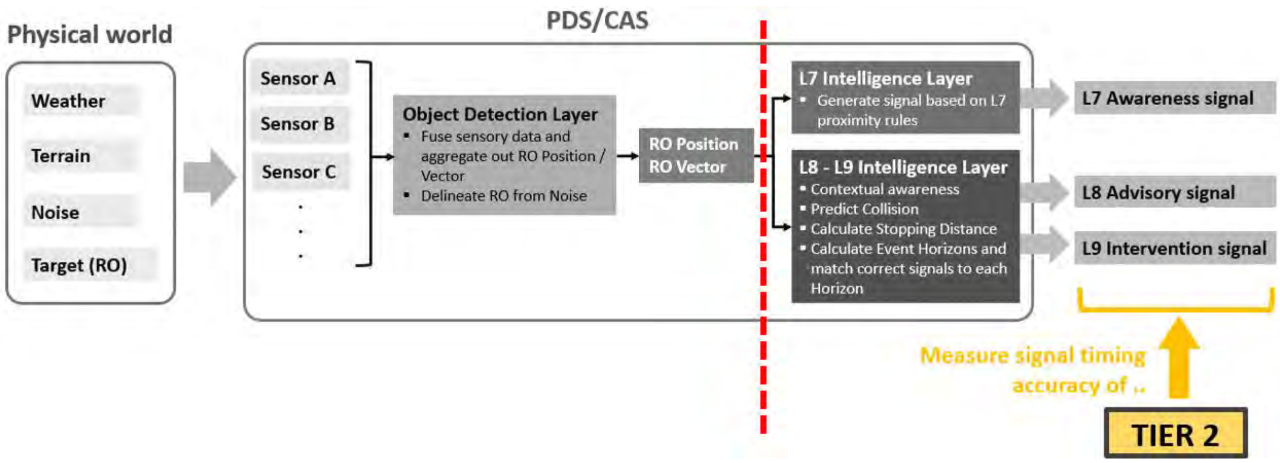


Figure 4 – Tier 2 Testing in the context of the PDS Model of Operation.

Proposed: Tier 3 - Long-term reliability testing (out-of-scope for this project)
This phase is out of scope, but listed nevertheless to highlight its significance. This phase is expected to involve validating the long-term reliability of the PDS units (in terms of uptime and availability) through statistical reliability studies and/or operational monitoring of the products' performance and performance degradation over time. The overarching intent is to ensure the maximum availability (at full functionality) of a critical system through the development of tailored audit, maintenance, calibration, and servicing plans. Tier 3 is out of scope, as this project (ACARP C26028) is ultimately about Product Performance testing, i.e.. does the product work, right here and right now, given a set of test conditions. Verifying the reliability of the PDS over the long run will require a different kind of approach, science, and testing methodology, and should entail a separate project in itself but generally a contractual obligation.

1.6 Methodology rationale

The methodology proposed in this body of work is fundamentally driven by a hierarchy of questions that were developed as part of the early-stage review of the subject matter:

Overarching Project Question: What is a practical (economical) yet rigourous method to test PDS systems?

1. What are the fundamental performance failure modes common to PDS units?
2. What are the root causes to these failure modes?
3. How do we test immunity/survivability of PDS units against these root causes?
4. How do we define what is a suitable/unsuitable PDS to begin with?
5. How do we quickly yet conclusively discount unsuitable PDS units?

The proposed methodology is essentially an attempt to answer these questions methodically and scientifically. The proceeding sections (Sections 1.7 – Sections 1.11) summarize these answers in a Q&A format. Sections 2 and 3 describe the actual body of work for Tiers 1 and 2 respectively.

1.7 What are the fundamental PDS Performance Failure Modes?

The authors would like to make a distinction between Performance Failures and Operational Failures. Performance Failures are the manifest failure of the PDS to function to its stated level of capability or to a specified level of capability due to inherent flaws that can be traced back to the inadequate design of the product. This is distinct from Operational Failures, which are caused by an actual failure (breakdown) of a component or sub-system of the product, or by incorrect installation, setup, and calibration of the PDS unit at the beginning. For example, a PDS System that is designed to rely solely on Stereo Cameras as its sensors will most probably struggle to detect objects in a low-light environment. This is then a Performance Failure (if operating in a low-light environment was a site requirement) as opposed to an Operational Failure as the entire PDS unit could still be operating reliably (in terms of uptime) while failing to detect the object in low-light.

Performance Failure in a PDS unit is manifest in the quality of the generated PDS Signals (L7, L8, L9). Four modes of failure for PDS Signals were identified (see Section 3.8**Error! Reference source not found.** for further treatment of Signal Failures). Upon evaluation, t hese four signal failure modes are attributable to either of two Fundamental Performance Failure Modes of the PDSs, as illustrated in Figure 5 below.

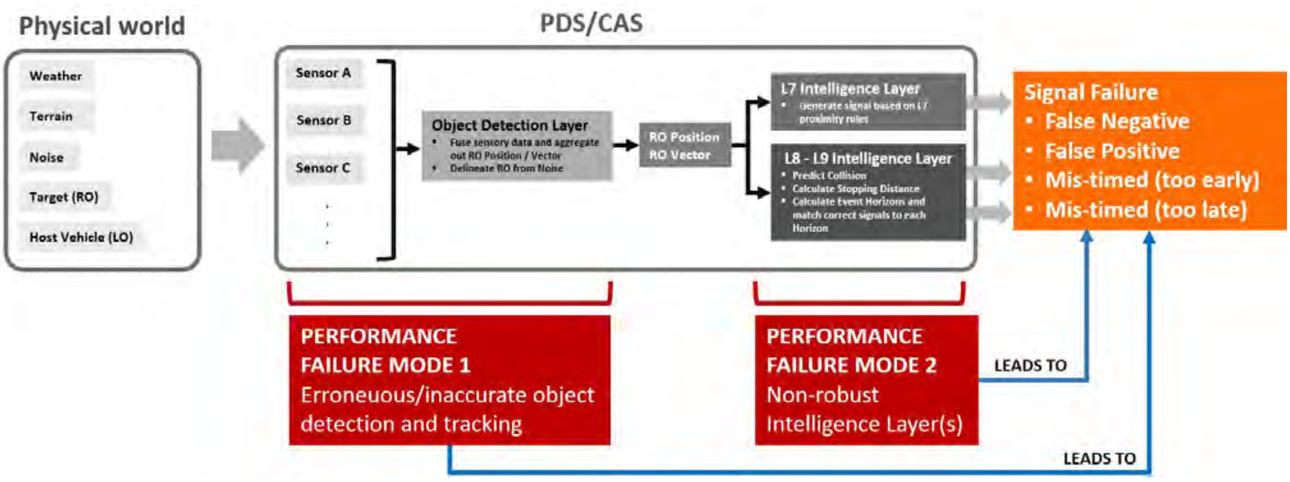


Figure 5 – Performance Failure Modes (Red) and Signal Failure Modes (Orange).

1.8 What are the root causes of these performance failures?

The root causes to these Performance Failure Modes were determined to be:

Fundamental Performance Failure Mode	Root Causes(s)
Erroneous/ inaccurate object detection and tracking. (All systems have a degree of inaccuracy. The error and inaccuracy in this case has exceeded what is determined to be acceptable for the application)	<u>**Root Cause 1**</u> The PDS object detection module (including both sensors and the Object Detection Layer) is incorrectly designed / non-robust, resulting in one of the following (which in turn leads to erroneous/ inaccurate object detection and tracking): ▪ The PDS is not immune to (is affected by) the operating environment (e.g. rain, dust, high-wall). ▪ The PDS is not able to handle the operating conditions (vehicle speeds, vehicle size, etc.). ▪ Fusion of sensory information and filtering of Noise is not handled adequately.
Non-robust intelligence layer	<u>**Root Cause 2**</u> Inadequately designed / programmed intelligence layer.

Table 1 –Root Causes to Fundamental Performance Failure Modes

1.9 How do we test PDS survivability against Fundamental Root Causes?

As a fundamental approach towards validating PDS units, this report proposes the assessing of survivability / immunity of the PDS unit against the Fundamental Root Causes described above. In other words, if the PDS unit can be demonstrated to be immune to the root causes of Performance Failures, the PDS unit is validated. The following methodologies are proposed to assess survivability / immunity against each of the Root Causes.

Performance Failure Root Causes	Proposed assessment methodology
Root Cause 1 The PDS object detection capability (including both sensors and the Object Detection Layer) is inadequately designed / non-robust, resulting in one of the following (which in turn leads to erroneous/ inaccurate object detection and tracking):	A body of tests that subject the PDS system (together with the host vehicle) to typically encountered operational parameters and environmental levels on site, with the intention of assessing the PDS's object detection accuracy under these conditions. These scenarios are to be repeated in order to cover all relevant combinations of variables and their different levels. The performance measure of concern here would be the RO position measurement error made by the PDS throughout the test program.
Root Cause 2 Inadequately designed intelligence layer	A body of tests that subject the PDS system to choreographed scenarios where the PDS Intelligence Layer is required to demonstrate its full advertised capability (e.g. L7, L8 STOP alarm, L9 STOP intervention signal, etc.), and have these capabilities assessed against a known baseline/ground truth (what we know the PDS must do in a given situation).

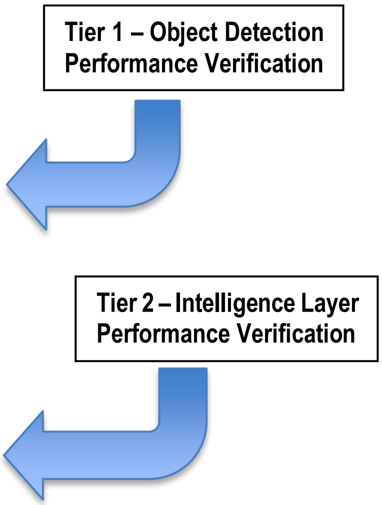


Table 2 – Required assessment methodology to assess a PDS's survivability against Fundamental Root Causes.

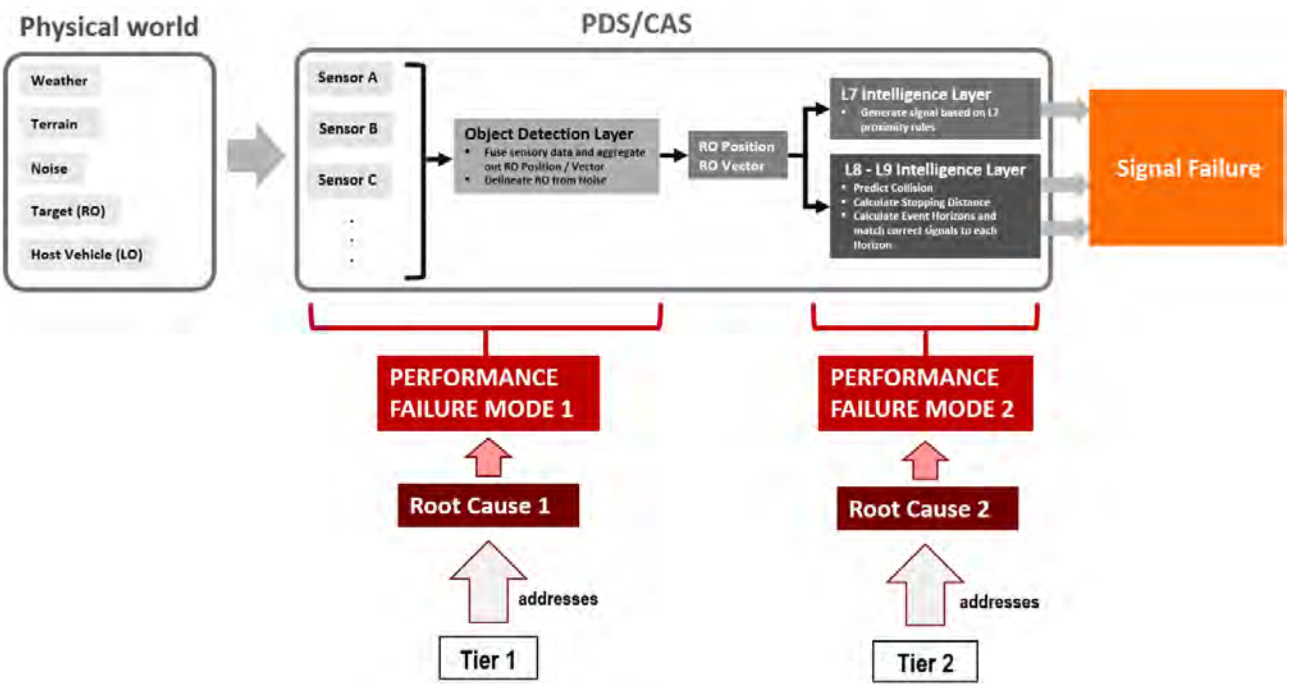


Figure 6 – How Tiers 1 and 2 link back to addressing the Fundamental Performance Failures

1.10 How do we define what is an adequate / inadequate PDS?

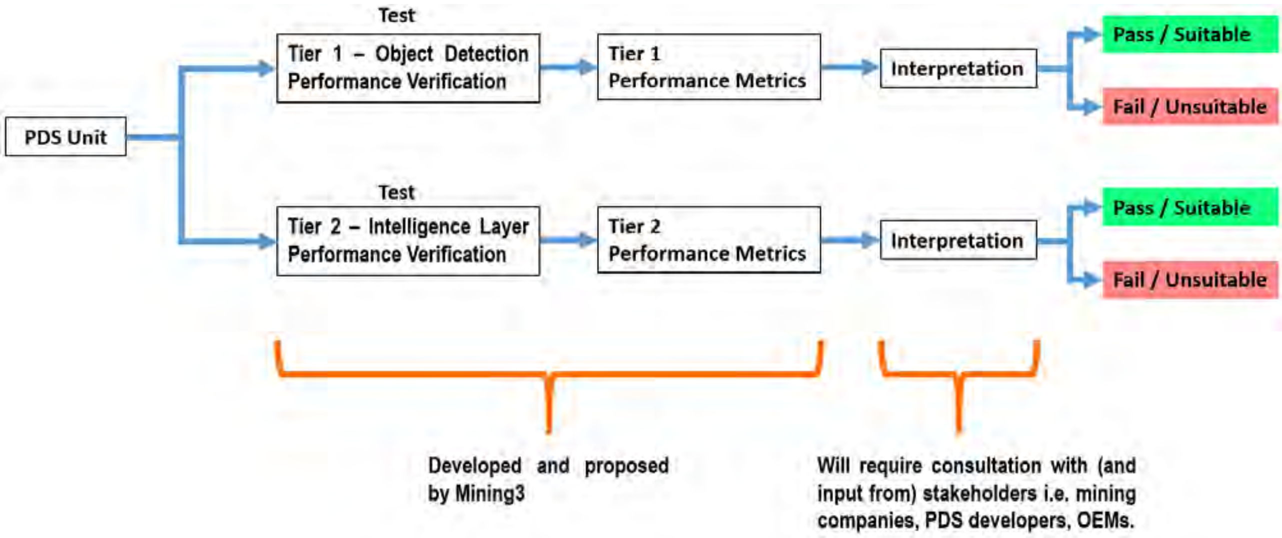


Figure 7 – Summary of how adequacy /validation of a PDS unit is arrived at.

Tier 1 and Tier 2 are designed to measure and provide performance metrics that are deemed relevant to the assessment of a PDS unit's suitability for adoption. Determining the adequacy (pass/fail) of a PDS unit will require interpretation of the recorded performance metrics from each body of tests. Although Mining3 will endeavour to provide recommendations on interpreting the recorded results, final say as to what constitutes pass/fail criteria will require consensus amongst the stakeholders i.e. mining companies, PDS developers, and OEMs.

1.11 How do we quickly yet conclusively discount adequate / inadequate PDSs?

The short answer to this question is the Tiered approach executed in series (Tier 1, then Tier 2). The basis of the tiered approach is to tackle the challenge in bite-sized chunks. These chunks of tests are highly focussed and should provide clear and conclusive results on which part of the PDS unit's performance may be deficient. It is the intent that any poor performance demonstrated within either Tiers of testing will (depending on final interpretation of the results) invalidate a PDS unit. If a PDS unit is inherently inadequate due to susceptibility to any of the two Root Causes, by design the tiered approach should require minimal time and resources to quickly but convincingly demonstrate the fact.

For example, a PDS unit that does not perform object detection reliably at >300m will be found out during Tier 1 Part 1 testing. The client may then not wish to proceed with further tests (Tier 1 Parts 2 – 5 and all of Tier 2) as the Part 1 results may be sufficient in quickly but conclusively invalidating the PDS unit from tender contention if reliably detecting objects at >300m is a critical requirement for the client (due to say higher on-site speed limits). [Conversely, the client may discover that there is a dearth of suitable PDS systems that operate reliably at >300m due to the current state of sensing technologies, and may want to recalibrate its own requirements]

Additionally, assessing the object detection layer (Tier 1) independent of the intelligence layer (Tier 2) and vice-versa creates less complicated and more manageable tests. The various variables of the operating environment (e.g. High-wall) and operating parameters (e.g. different vehicle speeds, different target sizes) that could affect the PDS unit's operation would not be covered in Tier 2, as these variables (if they are significant factors at all) would have affected the outcome of Tier 2 tests through their effects on the object detection capability, which would already have been discovered in Tier 1 (and hence possibly have invalidated the PDS in question).Thus Tier 2 testing can focus on interaction scenarios and the evaluation of the PDS unit's decision-making instead of being distracted and confounded by the inclusion of operating environment variables.

1.12 Which PUE Scenarios are covered in this body of work?

This body of work will assess PDS units against inline and parallel scenarios of PR5A (PUEs L1 – L7) for the time being, due to the following:

- time and resource constraints on this project.
- these scenarios(L1 – L7) are statistically the most significant, with anecdotal evidence that they account for a vast majority of all vehicle interaction incidents.
- the inline and parallel vehicle configurations are much more straight-forward to define and choreograph as compared to the remaining PR5A scenarios that cover Perpendicular / Angled / Curving arrangements. The Ground Truth set (event horizons, signal onset windows, etc.) is additionally less complicated to calculate and define.

This report recommends that further treatment of the other scenarios be undertaken once the test methodology for L1 – L7 has been validated.

Figure 8 – (Left) PUEs L1 to L6 which are addressed in Tier 2 and which account for a majority of all vehicle interactions; (Right) the remaining PUE scenarios.

2. Tier 1 : Object Detection Performance Validation

2.1 Overview

The objective of Tier 1, as covered previously, is to subject the PDS to typically encountered scenarios on-site, with all relevant combinations of the operating environment variables (and their different levels) to be tested. The key performance metric is the PDS unit's accuracy in measuring the target's position throughout this series of tests.

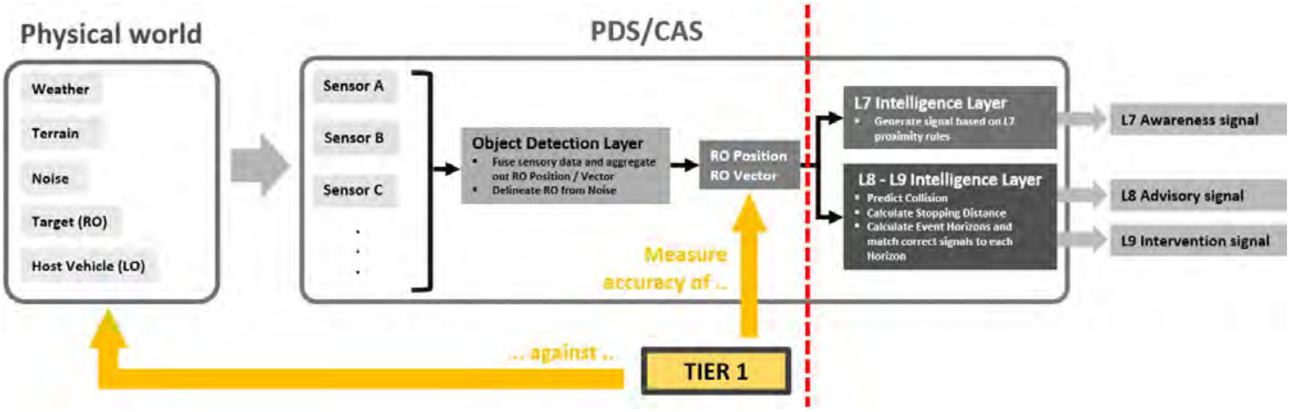


Figure 9 – Tier 1 in context of the PDS Model of Operation.

The Tier 1 test program is to be divided into 4 parts. Part 1 will involve Field of View (FOV) testing, which essentially maps out the zone of detection perimeter of the LO (fitted with the PDS system) under static conditions. Parts 2, 3 and 4 will involve dynamic tests (moving objects, moving LO and moving RO) that attempt to measure the PDS unit's survivability against typical operational parameters (different speeds, terrain, etc.). Parts 2,3, and 4 will be built upon Factorial Design of Experiment (DOE) principles, namely Taguchi Orthogonal Arrays.

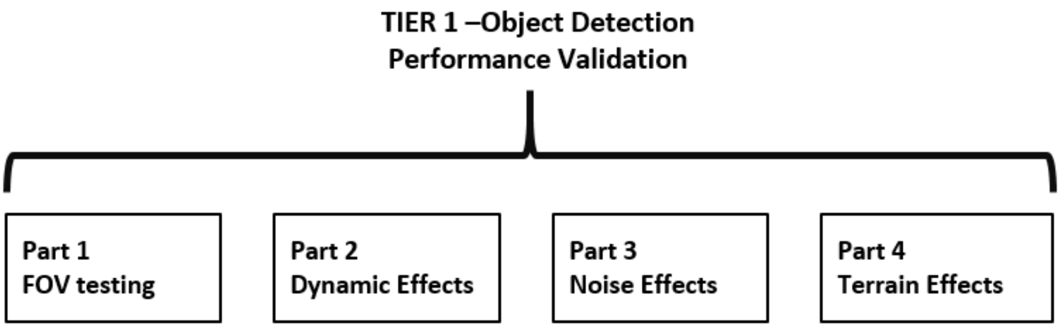


Figure 10 – 4 parts of Tier 1.

Prior to presenting the details of each Part of Tier 1, a treatment of the core concepts and principles behind Tier 1 is provided in Sections 2.1.1 through to 2.1.5.

2.1.1 Factorial Design of Experiments (DOE)

Factorial design of experiments will be the foundation of the Tier 1 test framework. It is useful to provide a brief overview of Factorial Design of Experiments (DOE), as some basic fundamental understanding is required to appreciate and follow the treatment of Parts 2, 3, and 4 later on.

Consider the example (Figure 11) of a potential user of a LIDAR system looking to perform a set of tests to validate the LIDAR's performance against the user requirements. In this case the user has identified 3 main factors to test: (A) Immunity to rain, (B) target distance, and (C) Target size. A table is drawn up (top-right) with the levels for each factor carefully selected based on expected operating conditions. Assume the measured response is a quantitative assessment of whether the target was successfully detected or not.

Factor	Levels		Measured Response
	-1	+1	
A - Rain	None	Present	Does it detect target? (Yes/No)
B - Distance	15m	100m	
C - Target	Tennis ball	Bicycle	

Figure 11 – Example Case: Assessment of a LIDAR system.

A One-Factor-At-a-Time (OFAT) approach would see the user implement a 4-run design, where by each factor is sequentially varied from run to run while the other factors are held at a fixed level (constant variables).

A full Factorial Design would see a 8-run design where each possible combination of levels for each factor is covered.

Full Factorial Design

	Factors		
	Rain	Distance	Target
Run 1	None	15m	Tennis ball
Run 2	Present	15m	Tennis ball
Run 3	None	100m	Tennis ball
Run 4	Present	100m	Tennis ball
Run 5	None	15m	Bicycle
Run 6	Present	15m	Bicycle
Run 7	None	100m	Bicycle
Run 8	Present	100m	Bicycle

2^3 Full factorial (3-factor 2-level)

One-Factor-At-A-Time (OFAT)

	Factors		
	Rain	Distance	Target
Run 1	None	15m	Tennis ball
Run 2	Present	15m	Tennis ball
Run 3	None	100m	Tennis ball
Run 4	None	15m	Bicycle

Figure 12 – Full Factorial Design (left) and an OFAT design (right)

OFAT is one of the uncomplicated experimental/investigation approaches, and is usually one's first exposure to experimenting (as it's the approach taught in high school scientific experiments). It usually requires relatively fewer runs than Factorial approaches.

Full Factorial Design on the other hand, is a more comprehensive approach as each level of each factor is tested against ALL other levels and their possible combinations. This usually results in more runs, but provides a more rigorous ("robust") investigation.

For example, saying that the LIDAR works in rain after an OFAT run of experiment does not carry as much weight (and validity) as making the statement after carrying out a full Factorial investigation. The latter statement is backed by the fact that the rain factor was tested with a tennis ball at 15m, a tennis ball at 100m, a bicycle at 15m, and a bicycle at 100m, whereas the former statement was made on the premise of a single test with the tennis ball at 15m.

Factorial designs also allow the investigation of interactions between factors. i.e. does a factor, at a certain level, cause another factor to affect the response (a.k.a. does one factor "switch on" another factor).

2.1.2 Taguchi Orthogonal Arrays

Full factorial designs, rigorous as they are, quickly become impractical (in terms of number of runs) as the number of factors increase. For n number of factors, a 2-level full factorial design has n^2 number of runs: 5 factors translates to 32 runs, 7 factors 128 runs, and 15 factors 32768.

Factorial Designs that do not include the entire full Factorial set are called Fractional Factorial Designs. A few clever approaches to fractional factorials have been developed, where the main goal is to drastically reduce the number of runs for a given number of factors, while at the same time maintain an appropriate level of robustness (validity) in the design.

One of the more established Fractional designs are Taguchi orthogonal arrays, which has gained acceptance and application across different industries and disciplines. In a Taguchi L8 design (L8 refers to 8 runs), 7 factors are investigated in 8 runs (instead of 128).

Taguchi designs have some remarkable mathematical properties. Notice that in the design table (table of signs) of a Taguchi L8, each column is orthogonal to the other columns, i.e. performing a matrix multiplication of one column against any other column results in 0 (zero). These combinations of signs are fixed and must not be changed. Orthogonality also means balance. Trace vertically through a column, and it will be noticed that +1 and -1 occur the same number of times. Choose any one column and look at the group of plus signs in that column, opposite the four plus signs there are two plus signs and two minus signs in every one of the other six columns (same holds true for the minus signs).

Full factorial design :

- 2^7 = 128 combinations

	Factors						
	A	B	C	D	E	F	G
Run 1	-1	+1	-1	+1	+1	-1	-1
Run 2	+1	-1	+1	+1	-1	+1	-1
Run 3	+1	+1	-1	-1	+1	-1	+1
⋮							
Run 126	-1	+1	+1	-1	+1	-1	-1
Run 127	+1	-1	+1	+1	-1	+1	+1
Run 128	+1	+1	-1	+1	-1	-1	+1

Taguchi L8 Design

- orthogonal arrays (balanced design)
- Robustly assess effects of 7 factors in 8 runs (instead of 128)

	Factors						
	A	B	C	D	E	F	G
Run 1	-1	-1	-1	+1	+1	+1	-1
Run 2	+1	-1	-1	-1	-1	+1	+1
Run 3	-1	+1	-1	-1	+1	-1	+1
Run 4	+1	+1	-1	+1	-1	-1	-1
Run 5	-1	-1	+1	+1	-1	-1	+1
Run 6	+1	-1	+1	-1	+1	-1	-1
Run 7	-1	+1	+1	-1	-1	+1	-1
Run 8	+1	+1	+1	+1	+1	+1	+1

Other Taguchi Designs

- L4 3 Factors, 4 runs instead of 8
- L12 11 Factors, 12 runs instead of 2048
- L16 15 Factors, 16 runs instead of 32,768

Figure 13 – Comparison of a Full Factorial Design (left) and a Taguchi L8 Design, both for 7 factors.

Taguchi designs are one of a few techniques that allow drastic reduction in the number of runs for a given number of factors, while at the same time maintaining an appropriate level of robustness (validity) in the design.

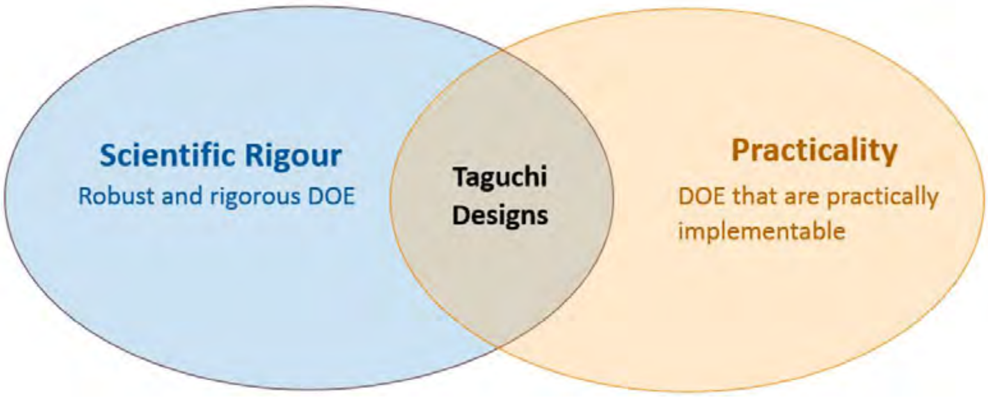


Figure 14 – Taguchi Designs are a compromise between rigour and practicality.

2.1.3 Operating Environment Variables

Prior to the design of experiments, a full treatment of the variables (parameters) of the operating environment that are of concern is required.

A Global Set of 29 variables was developed, with each variable having 2 or more levels. These (variables and levels) were selected based on an objective examination of what open cut mines offer in terms of operating conditions. The intent is to fully capture and represent all possible operating conditions that may affect a PDS unit's Object Detection capabilities in an open-cut mine.

From the Global Set, a funnelling exercise was employed to reduce the number of variables down to a more manageable set of 17, and reduce the number of levels for each remaining variable. This was achieved through a careful evaluation process that involved:

a. prioritising the common denominators across most sites. As an example, within the variable class "Visibility Obscurants", the variable Snow was removed in the funnelling exercise, but Dust was retained, based on empirical experience on the rarity of the former and the prevalence of the latter across most sites. For the example of level removal, the Precipitation (rain) variable has 3 levels in the Global Set ("none", "8mm/hr", and "20mm/hr"), but was reduced to 2 levels in the Standard Set ("none" and "8mm/hr") as 20mm/hr of rain (tropical rain) is deemed not applicable across most sites.

b. reducing apparent replication. For example, within the variable class "Stationary Objects", a parked large vehicle (e.g. haul truck) is deemed an apparent equivalent to a fixed plant (e.g. a demountable structure), so only one (in this case the parked large vehicle variable) and not both are included in the Standard Set.

The essential goal of the Standard Set is to funnel the "trivial many" down to the "significant few" in the interest of practicality. In "outlier" mine sites where some of these removed variables are applicable (e.g. sites in northern latitudes where it snows regularly), it is recommended that a set of specifically designed tests be conducted to supplement the Validation Framework proposed in this report.

Standard Set Variables / Levels

Standard Set Levels

		Variables	Levels				
			L1	L2	L3	L4	L5
Terrain		Highwall	None	Present			
		Open Pit (depth within pit)	None	Present			
		Gradient	-10%	-5%	0% (flat)	5%	10%
Noise (objects not on the direct path of LO)	Stationary object	Signboard	None	Present			
		Building	None	Present			
		Parked large vehicle	None	Present			
		Parked light vehicle	None	Present			
		Gantry	None	Present			
		Roadside Berm		Present			
		Human	None	Present			
	Moving objects	Large vehicle	None	Present			
		Light vehicle	None	Present			
		Human	None	Present			
Weather	Visibility obscurants	Precipitation	None	8mm/hr	20mm/hr		
		Dust (visibility)	None (full vis)	300m	10m		
		Fog (visibility)	None (full vis)	300m	10m		
		Snow	None	Light	Medium	Heavy	
	Lighting	Ambient Light (Lux)	Full day light	Low light (Dusk/dawn)	Night		
		Sun low on the horizon	None	LO's front	LO's rear		
On-road objects		LO Class	Large	Light			
		RO class	Large	Light	Human		
Vehicle Positional and Dynamic Parameters (LO and RO)		$D_{RO-LO-INIT}$	10m	30m	250m	500m	700m
		RO in Front/Rear	Front	Rear			
		$Vect_{LO}$	Forward	Reverse	Turning right	Turning left	
		$Vect_{REL-RO-INIT-SS}$	0	180	90	45	135
		$V_{LO-INIT-SS}$	0	15kmph	30 kmph	50 kmph	
		$V_{RO-INIT-SS}$	0	15kmph	30 kmph	50 kmph	
		D_{OFFSET_LAT}	left 15m	left 7m	0	Right 7m	Right 15m
		Z-offset between LO and RO	0	10m	20m	30m	

Table 3 – The Global Set of variables with the Standard Set variables (and associated levels) highlighted in orange and blue.

2.1.4 Grouping of Variables

It was also noted that there are incentives to carefully segregating variables into logical groups, and then designing test matrices around the smaller groups of variables. Smaller variable groups translate to overall less complicated tests that are easier to control and choreograph. Additionally, if the variables "High-wall" and "Gradient" were separated out, the need to perform the tests on the other 15 variables on an actual mine-site was negated, with it being acceptable that these tests (on the other 15 variables) be done on any large flat surface area.

The four logical variable groups for the Standard Set are

1. **Dynamic Variables**
   These variables cover, where the LO and RO are concerned, the various speeds, lateral off-sets, starting distances apart, heading, etc., which in combination fully define the different vehicle interaction scenarios (head-on, passing head-on, rear-end, etc.)

2. **Terrain Variables**
   These cover 2 variables: the presence of High-walls and Ramps (gradient).

3. **Noise Variables**
   This group specifically refers to the presence of objects (either static or dynamic) that are in the surrounding vicinity of the LO that are not of (immediate) concern/danger to the Local Object, but could still affect and disrupt the measurement of the RO position.

4. **Weather Variable**
   This group deals with the three weather variables addressed in the Standard Set: Precipitation, Dust, and Lighting Conditions.

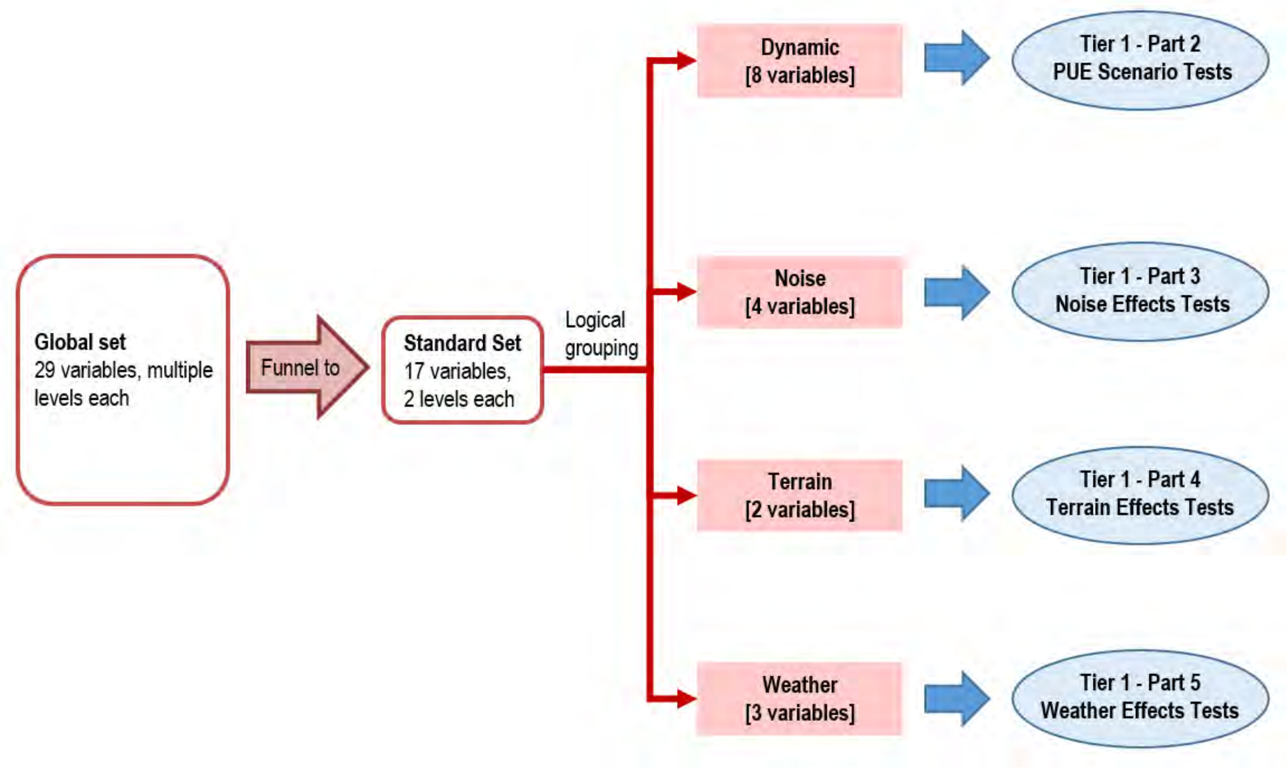


Figure 15 – Grouping of Standard Set variables

The tests for Parts 2, 3, and 4 are directly derived from variable groups DYNAMIC, NOISE, and TERRAIN respectively. Part 5, which will address WEATHER variables (dust, rain, and lighting) is not included in the scope of the current project for now due to the complexities and difficulties in recreating dust and rain conditions in a repeatable and consistent manner for the purposes of testing.

The next step is to apply Taguchi design of experiments to each of Parts 2, 3, and 4.

2.1.5 Tier 1 Measured Response

The measured response in all of Tier 1 tests is the localization error i.e. the difference between the true location of the RO and the PDS's measurement of the RO's location.

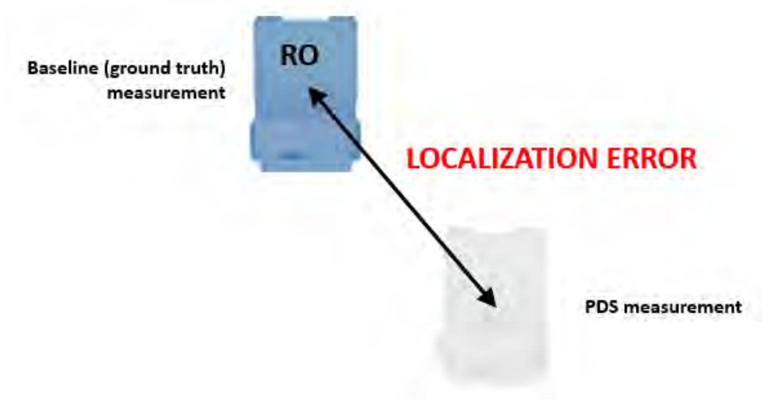


Figure 16 –Tier 1 measured response

2.2 Tier 1 - Part 1 : Field of View Validation

The objective of Part 1 is to fully characterize a PDS unit's Field of View perimeter around the host vehicle (LO) in static conditions, and validate it against user specifications. This user specification covers the desired/required zone of sensing, which in turn is a function of several operational parameters such as on-site speed limits and vehicle-specific blind spots.

The test will involve having the target (RO) located at a series of pre-surveyed / pre-determined points with respect to the LO. An assessment of whether the target is detected by the PDS or not is performed. If detection is successful, the accuracy of the PDS measurement is also then determined. Depending on site requirements, this test will be repeated for different RO (target) classes, which may include: Heavy Vehicles, Light Vehicles, and Humans.

Additionally, Part 1 doubles as a validation test for the PR5A scenario PUE L7 – Pulling Out, which involves static large vehicles being able to detect objects within its blind spots and around its periphery before pulling out and driving off.

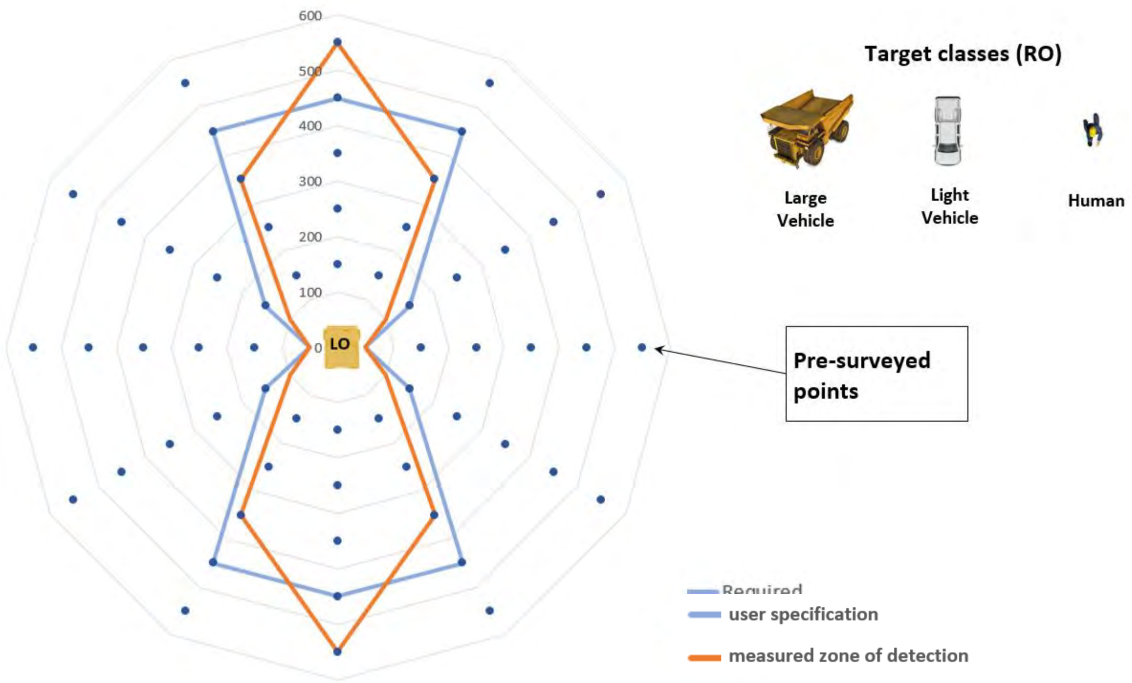


Figure 17 – Basic format of Part 1 testing.

2.3 Tier 1 - Part 2 : Dynamic Variables Testing

Part 2 Dynamic Testing covers the eight LO and RO dynamic variables such as speed, lateral off-sets, starting distances apart, heading, etc. These variables, in appropriate combinations, define the PR5A scenarios L1 – L7. Upon careful evaluation, it was considered that these scenarios (head-on, passing head-on, rear-end, etc.) can be condensed into the following four general classes:

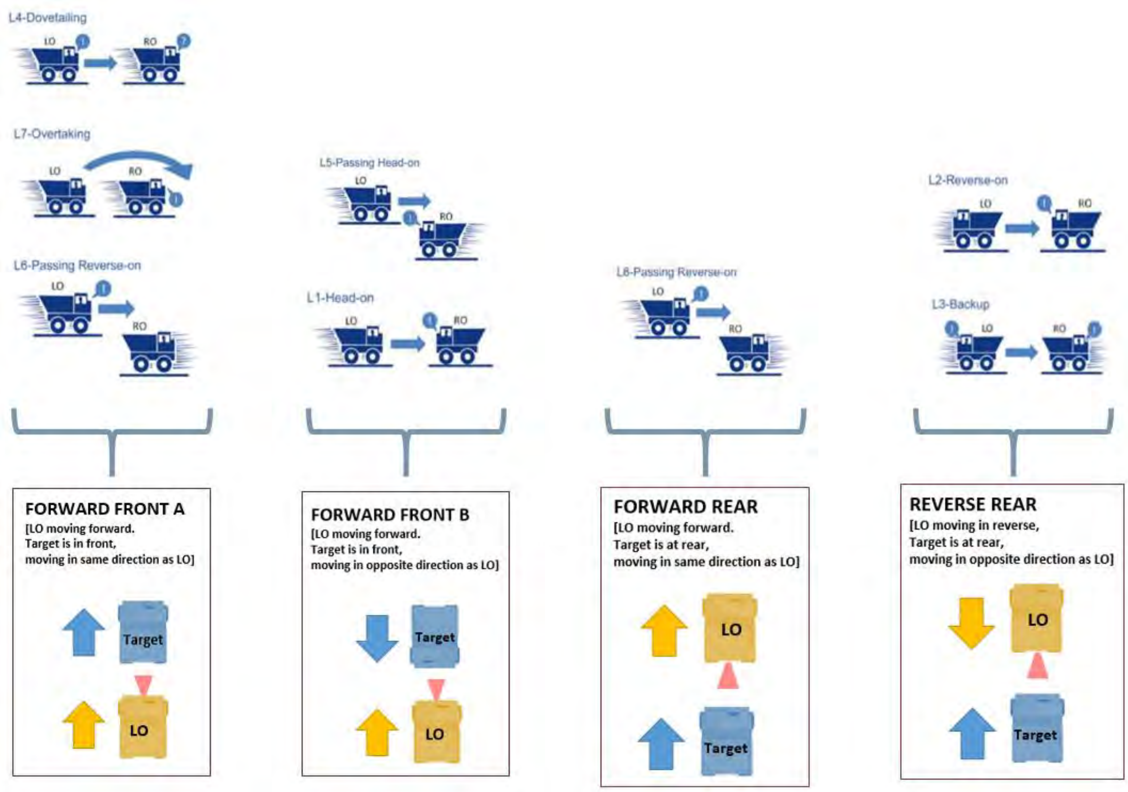


Figure 18

Testing a PDS against the four scenario classes above is deemed a satisfactorily rigorous assessment of the PDS's capability in detecting and tracking dynamic objects in the context of PR5A scenarios L1 – L7. Using the 8 variables of the Dynamics group, a Taguchi L8 (8-run) design and two Taguchi L4 (4-run) designs were developed, which capture all four scenario classes.

Taguchi L8 Design - Forward Front (moving **Forward**, sensing to the **Front**)

Scenario Class A: Runs 1–4; Scenario Class B: Runs 5–8

	Factor Levels					
Runs	RO class	$D_{RO\text{-}LO\text{-}INIT}$	$Vect_{REL\text{-}RO\text{-}INIT\text{-}SS}$	$V_{LO\text{-}INIT\text{-}SS}$	$V_{RO\text{-}INIT\text{-}SS}$	D_{OFFSET_LAT}
Run 1	Large	250m	0	50 kmph	30kmph	Right 15m
Run 2	Light	250m	0	30kmph	15kmph	Right 15m
Run 3	Large	500m	0	30kmph	30kmph	0
Run 4	Light	500m	0	50 kmph	15kmph	0
Run 5	Large	250m	180	50 kmph	15kmph	0
Run 6	Light	250m	180	30kmph	30kmph	0
Run 7	Large	500m	180	30kmph	15kmph	Right 15m
Run 8	Light	500m	180	50 kmph	30kmph	Right 15m

Active Factors and Levels

Active Factors	Selected Levels -	Selected Levels +
RO class	Large	Light
$D_{RO\text{-}LO\text{-}INIT}$	250m	500m
$Vect_{REL\text{-}RO\text{-}INIT\text{-}SS}$	0°	180°
$V_{LO\text{-}INIT\text{-}SS}$	30kmph	50kmph
$V_{RO\text{-}INIT\text{-}SS}$	15kmph	30kmph
D_{OFFSET_LAT}	0m	Right 15m

Taguchi L4 Design - Forward Rear
(moving **Forward**, sensing to the **Rear**)

Scenario Class C

	$D_{RO\text{-}LO\text{-}INIT}$	$V_{RO\text{-}INIT\text{-}SS}$	D_{OFFSET_LAT}
Run 1	250m	30kmph	0
Run 2	250m	50 kmph	Right 15m
Run 3	500m	30kmph	Right 15m
Run 4	500m	50 kmph	0

Active Factors and Levels

Active Factors	Selected Levels -	Selected Levels +
$D_{RO\text{-}LO\text{-}INIT}$	250m	500m
$V_{RO\text{-}INIT\text{-}SS}$	30kmph	50kmph
D_{OFFSET_LAT}	0m	Right 15m

Taguchi L4 Design - Reverse Rear
(moving in **Reverse**, sensing to the **Rear**)

Scenario Class D

	$D_{RO\text{-}LO\text{-}INIT}$	D_{OFFSET_LAT}	RO class
Run 1	250m	0	Light
Run 2	250m	Right 15m	Large
Run 3	500m	0	Large
Run 4	500m	Right 15m	Light

Active Factors and Levels

Active Factors	Selected Levels -	Selected Levels +
$D_{RO\text{-}LO\text{-}INIT}$	250m	500m
D_{OFFSET_LAT}	0	Right 15m
RO class	Light	Large

Figure 19 – Part 2 design of experiments and the scenario classes covered.

Taguchi L8 Design - Forward Front (moving **Forward**, sensing to the **Front**)

	RO class	$D_{RO\text{-}LO\text{-}INIT}$	$Vect_{REL\text{-}RO\text{-}INIT\text{-}SS}$	$V_{LO\text{-}INIT\text{-}SS}$	$V_{RO\text{-}INIT\text{-}SS}$	D_{OFFSET_LAT}
Run 1	Large	250m	0	50 kmph	30kmph	Right 15m
Run 2	Light	250m	0	30kmph	15kmph	Right 15m
Run 3	Large	500m	0	30kmph	30kmph	0
Run 4	Light	500m	0	50 kmph	15kmph	0
Run 5	Large	250m	180	50 kmph	15kmph	0
Run 6	Light	250m	180	30kmph	30kmph	0
Run 7	Large	500m	180	30kmph	15kmph	Right 15m
Run 8	Light	500m	180	50 kmph	30kmph	Right 15m

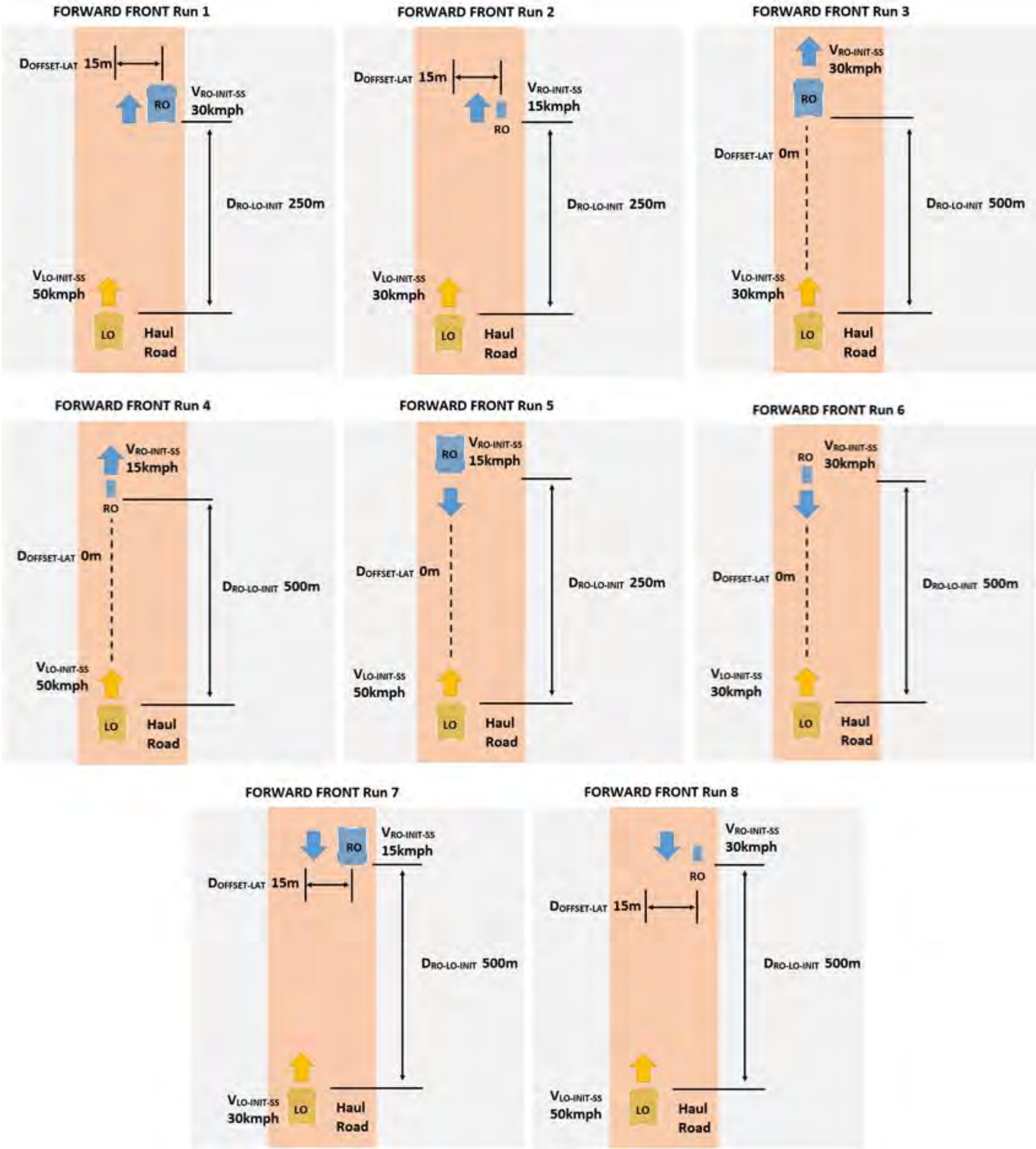


Figure 20 – A visual depection of each run of the Taguchi L8 Forward Front run..

Taguchi L4 Design - Forward Rear

(moving **Forward**, sensing to the **Rear**)

	$D_{RO\text{-}LO\text{-}INIT}$	$V_{RO\text{-}INIT\text{-}SS}$	D_{OFFSET_LAT}
Run 1	250m	30kmph	0
Run 2	250m	50 kmph	Right 15m
Run 3	500m	30kmph	Right 15m
Run 4	500m	50 kmph	0

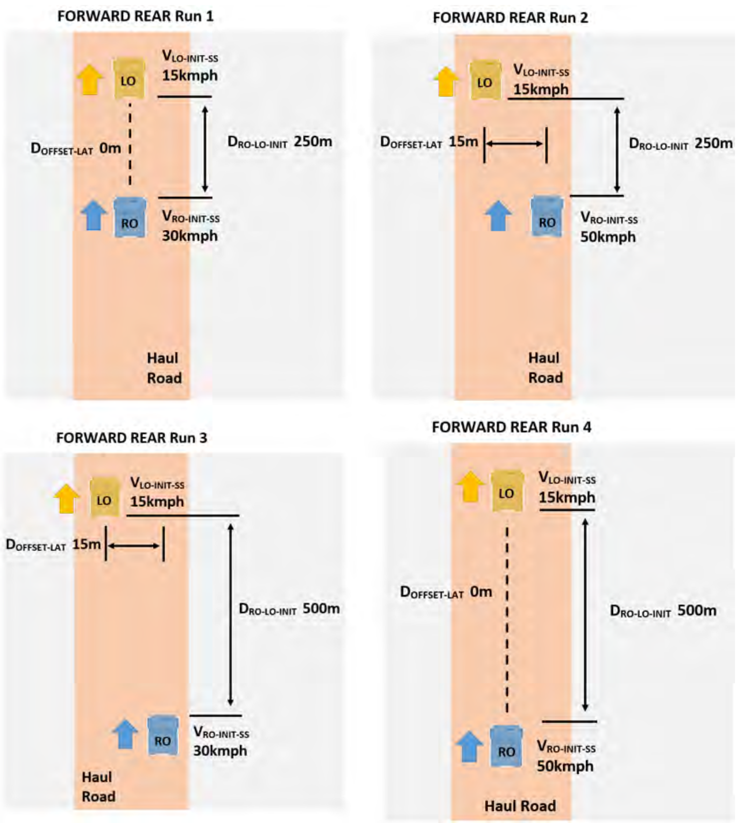


Figure 21 – Visual depiction of each run of the Taguchi L4 Forward Rear design.

Taguchi L4 Design - Reverse Rear

(moving in **Reverse**, sensing to the **Rear**)

	$D_{RO\text{-}LO\text{-}INIT}$	D_{OFFSET_LAT}	RO class
Run 1	250m	0	Light
Run 2	250m	Right 15m	Large
Run 3	500m	0	Large
Run 4	500m	Right 15m	Light

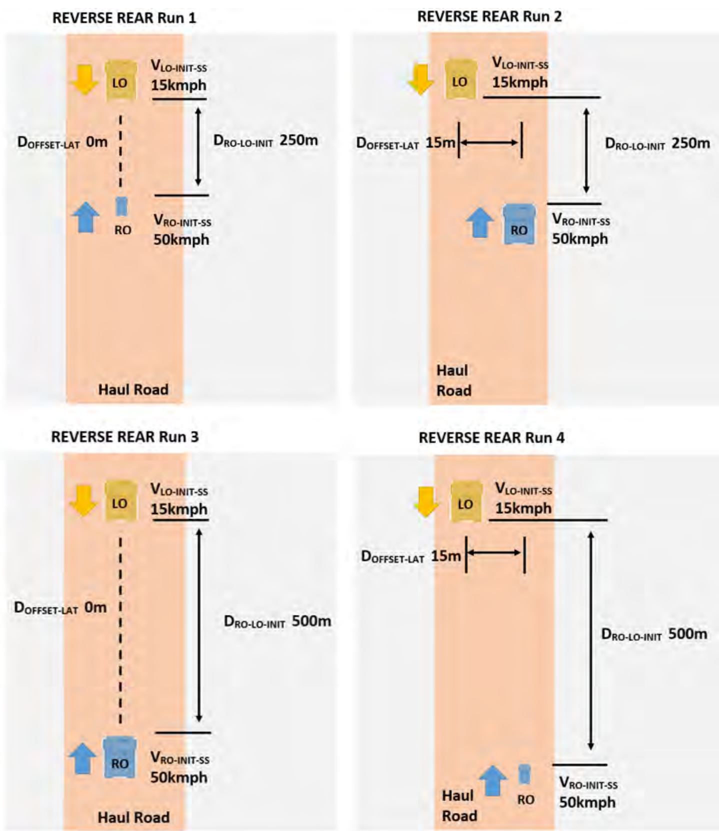


Figure 22 - Visual depiction of each run of the Taguchi L4 Reverse Rear design.

2.4 Tier 1 - Part 3 : Noise Variables Testing

Noise, as defined previously, refers to objects (either static or dynamic) that are in the surrounding vicinity of the LO that are not of (immediate) concern/danger to the Local Object, but could still affect and disrupt the measurement of the RO position. The objective of Part 3 is to validate the PDS's immunity to both static and dynamic Noise (that are typical to operating sites) while performing its function of detecting the RO. A Taguchi L8 design was developed for this purpose. This noise is here defined as either a parked vehicle (of class Heavy Vehicle and Light Vehicle), or a moving vehicle that is on the road with the RO.

Taguchi L8 Design - Noise Effects

	Noise						
	Parked vehicle		Moving Vehicle	RO			
	Starting distance out (m)	Class	Class	Class	$D_{RO\text{-}LO\text{-}INIT}$	$V_{LO\text{-}INIT\text{-}SS}$	Rear (Reverse) / Front (Forward)
Run 1	30m	Light	Light	Large	500m	15kmph	Rear
Run 2	250m	Light	Light	Light	250m	15kmph	Front
Run 3	30m	Large	Light	Light	500m	0	Front
Run 4	250m	Large	Light	Large	250m	0	Rear
Run 5	30m	Light	Large	Large	250m	0	Front
Run 6	250m	Light	Large	Light	500m	0	Rear
Run 7	30m	Large	Large	Light	250m	15kmph	Rear
Run 8	250m	Large	Large	Large	500m	15kmph	Front

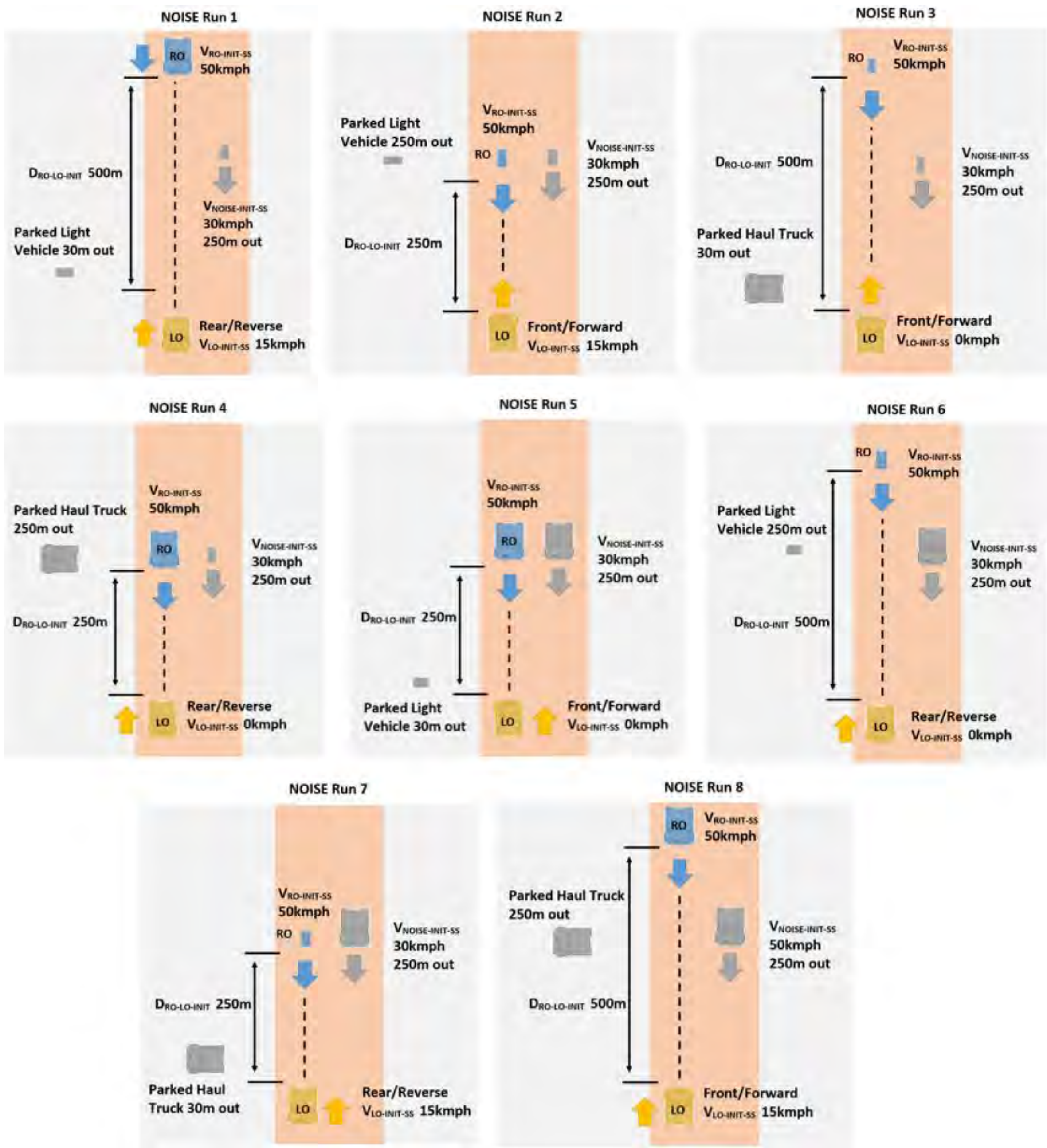


Figure 23- A visual depection of each run of the Taguchi L8 Forward Front design.

2.5 Tier 1 - Part 4 : Site Terrain Variables Testing

Part 4 attempts to assess the PDS system's immunity against two site variables: Gradient (ramp) and High-wall. One Taguchi L4 dynamic design was developed for each of Gradient and High-wall:

Taguchi L4 Desgin - Gradient

	RO Class	$D_{RO-LO-INIT}$	Gradient
Run 1	Large	30m	-10%
Run 2	Large	250m	10%
Run 3	Light	30m	10%
Run 4	Light	250m	-10%

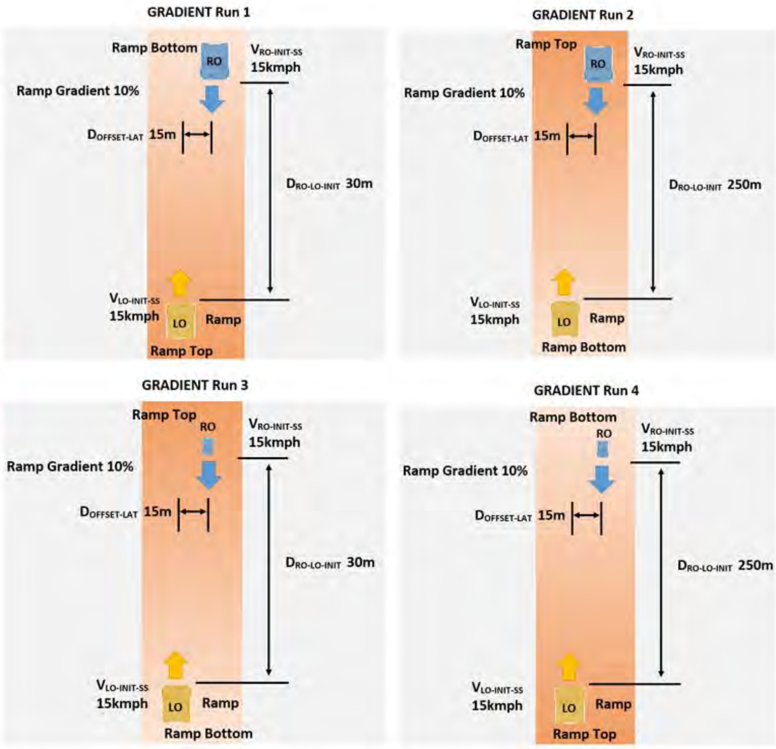


Figure 24 - Visual depiction of each run of the Taguchi L4 Gradient design

Taguchi L4 Design - Highwall

	RO Class	$D_{RO-LO-INIT}$	Highwall Left/Right
Run 1	Large	250m	Left
Run 2	Large	500m	Right
Run 3	Light	250m	Right
Run 4	Light	500m	Left

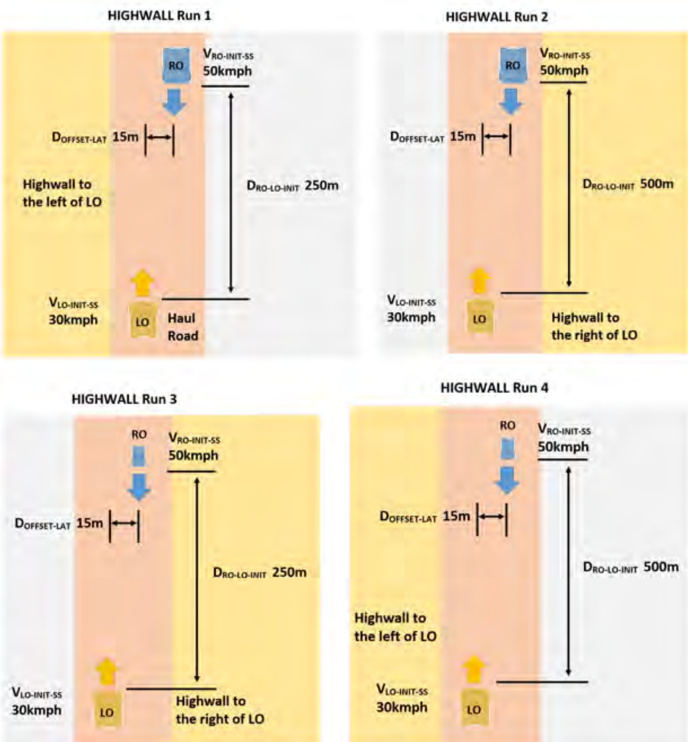


Figure 25- Visual depiction of each run of the Taguchi L4 Highwall design

2.6 Tier 1 Location and Equipment Requirements

Table 4 below summarizes the anticipated physical location requirements and the equipment that would be required to execute Tier 1 as proposed above.

<table>
<tr><th rowspan="2"></th><th rowspan="2">Physical Location Requirements</th><th rowspan="2">Vehicles Required</th><th colspan="2">Data Acquisition Method</th></tr>
<tr><th>Baseline Measurement (Ground Truth)</th><th>PDS Response Measurement</th></tr>
<tr><td>Part 1 - FOV Testing</td><td>Large Flat Area
700m X 100m
minimum</td><td>2 Haul Trucks
▪ Local Object
▪ Remote Object

1 Light vehicle
▪ Remote Object</td><td>Robotic Total Station,
On-ground pre-surveyed demarcation</td><td rowspan="4">Some options:

<u>a) Logging interface to PDS unit:</u>
This can be an RS232 or even a simple UART port on the PDS module, with a serial output for real-time live output (target position). Logging will be done to a laptop via a serial monitor/logger. For dynamic testing (moving vehicles involved), will need to be time-synced with Baseline Logging module (e.g. all synced to International Atomic Clock).

<u>b) Post-test download from PDS module:</u>
Again for dynamic testing, time sync required between PDS module and Baseline Logging module.</td></tr>
<tr><td>Part 2 - Dynamic Variables Testing</td><td>Large Flat Area
1000m X 100m
minimum.</td><td>2 Haul Trucks
▪ Local Object
▪ Remote Object

1 Light vehicle
▪ Remote Object</td><td rowspan="3">For static objects:
Robotic Total Station,
On-ground pre-surveyed demarcation

For dynamic objects:
Visual odometry (pre-surveyed demarcation + drone top-down footage)

RTK GPS installed on all dynamic objects (will require RTK base station or at least a mobile base station)

[RTK GPS can achieve up to centimetre-level accuracy]</td></tr>
<tr><td>Part 3 Noise Variables Testing</td><td>Large Flat Area
1000m X 100m
minimum.</td><td>3 Haul Trucks
▪ Local Object
▪ Remote Object
▪ Noise

2 Light vehicle
▪ Remote Object
▪ Noise</td></tr>
<tr><td>Part 4 Site Terrain Variables Testing</td><td>Mine site/ Quarry with Ramp and High-wall</td><td>2 Haul Trucks
(Local Object, Target)

1 Light vehicle
(Target)</td></tr>
</table>

Table 4 – Proposed location and equipment requirements for Tier 1 body of test.

2.7 A note on ISO 16001

ISO 16001- 2017 specifies general requirements and describes methods for evaluating and testing the performance of object detection systems (ODSs) and Visibility Aids used on earth-moving machines (sic). Where testing Object Detection Systems are concerned, notable areas where the ISO methodology differs from Tier 1 are listed below:

	ISO 16001	ACARP Tier 1
Test variables	Covers a reduced set of variables. Tests are either specified at static conditions or mostly at very low speed settings (4kmph or less).	Includes variables and levels of variables typical of vehicles operating at normal speed limits on at haul roads.
Sensor setup	Sensing modules are placed on specified fixings (in what is essentially a tightly controlled environment), and not on actual vehicles.	Sensors are mounted onto vehicles (LO and/or RO) as per PDS suppliers installation procedures.
Provision for multi-sensor units	Not covered. Each sensor type is to be assessed through tests that are specially designed for the specific technology employed by the sensor.	Assessment focusses on measured Target Location (x-y coordinate of Target's location relative to Local Object), which is expected to be an aggregation and fusion of sensory information coming from (possibly) two or more different sensors. **Assessment is driven by user requirements and not by specific sensor technology (and their weaknesses).**

Table 5 – Notable differences between ISO16001 and ACARP Tier 1.

It is the authors' opinion that both methodologies can be complementary and serve different needs / groups: ISO16001 may be more useful for sensor developers, PDS developers and OEMs during product development, whilst ACARP Tier 1 targets the end-user perspective on testing and validation, and focusses more on verifying the aggregated object detection capability of PDSs against user requirements in PUE Scenarios (PR5A-driven).

2.8 Tier 1 : Separation of Test Methodology and Test Levels

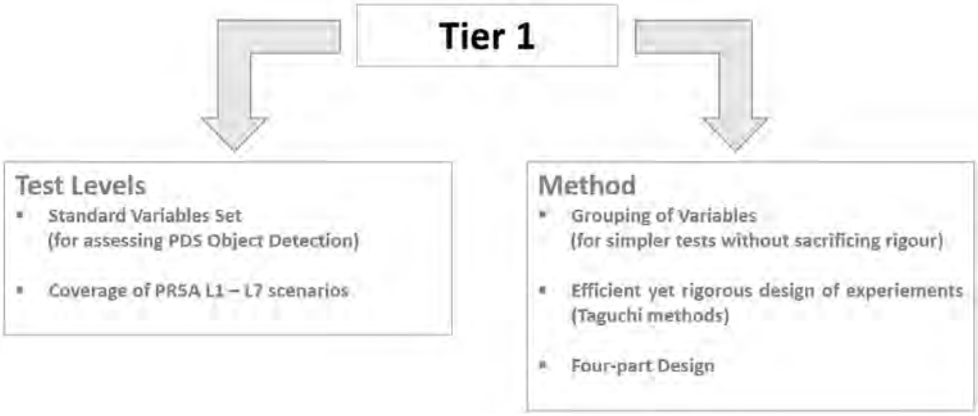


Figure 26 – Separation of the Tier 1 work into Test Levels and Methodology.

The body of work presented thus far for Tier 1 can be separated into two parts:

1. **Test Levels**
   This is the section of the work that includes the proposed Standard Variables Set (section 2.1.3) and the PR5A scenarios (L1 – L7) that are currently covered (section 2.3).

2. **Methodology**
   This covers the methods that translate the Test Levels into actual design of experiments and a test program.

At the time of writing, it is important to note that the Test Levels proposed here are by no means the final definitive prescribed test levels. Further evolution and refinement of these Test Levels is anticipated in future subsequent phases of this work that may or may not involve ACARP and / or Mining3.

3. Tier 2 - Intelligence Layer Validation

3.1 Overview

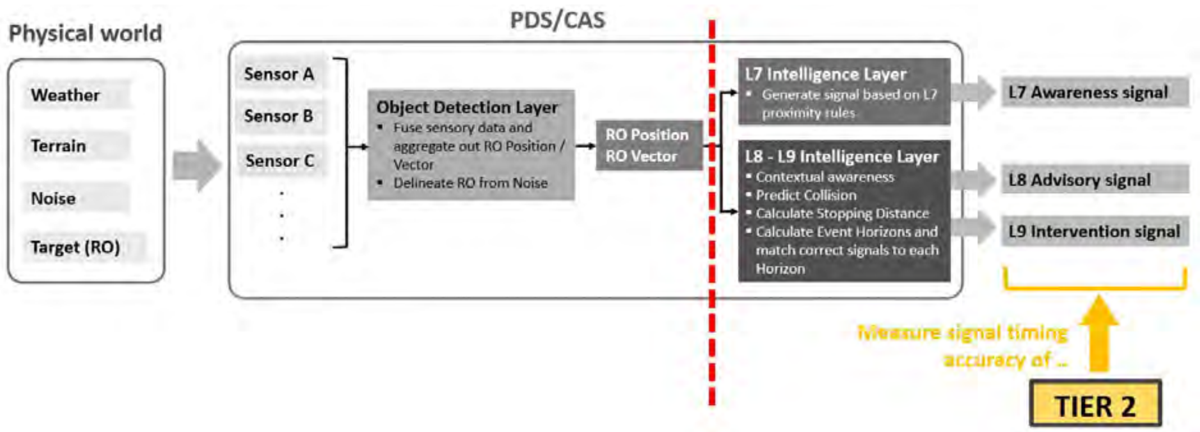


Figure 27 – Recap : Tier 2 Testing in the context of the PDS Operating Model.

Tier 2 will focus on assessing PDS units against Fundamental Performance Failure Mode 2. As a pre-requisite, the PDS unit being tested under Tier 2 will need to already have passed Tier 1 i.e. the PDS has been verified to be competent / accurate in locating and measuring the Target in the standard operating environment. Tier 2 will not involve environmental, terrain, and noise variables as these only affect the PDS Signals through the accuracy of the RO Localization, which is already treated in Tier 1. The overarching aim of Tier 2 is to validate the PDS Intelligence Layer's signal output in a limited set of choreographed test scenarios.

3.2 Design of Tests

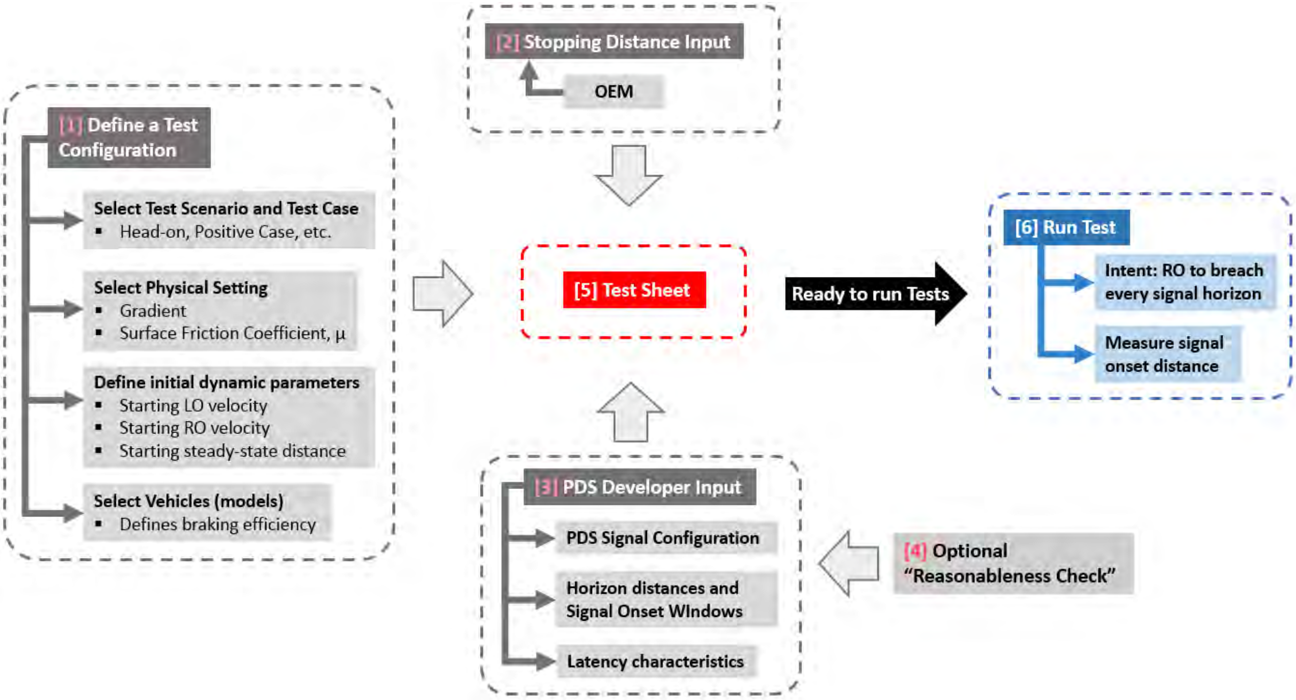


Figure 28 – Basic format to the design of tests in Tier 2

The basic format to the design of the Tier 2 tests is illustrated in the block diagram above. Each block is briefly summarized below, and further explained in sections 3.4 to 3.8.

1. **Define Test Configurations**
   The test scenario, test case, the physical location, and the vehicles involved (RO and LO) are selected / defined.

2. **Stopping Distance Input**
   The stopping distance of the vehicle(s) is to be derived based on the test speed parameters (defined in #1 above) and the vehicle's stopping performance. This report recommends that the vehicle OEM provides this Stopping Distance value.

3. **PDS Developer Input**
   The PDS developer shall provide horizon line distances that correspond to the various L7 – L9 PDS signals that are to be generated.

4. **Optional "Reasonableness Check"**
   This is a quick check on whether the values supplied by the PDS developer in #3 above pass a "sanity check". This compares said values against a set of baselines developed through first principles, and provides the potential user with a point of reference against which to assess the soundness of a PDS unit "on paper".

5. **Test Sheet**
   The Test Sheet, a.k.a. the "Marking Sheet", fully defines the test, including the space-time windows (called Signal Onset Windows) within which the PDS signals need to be generated during each test.

3.3 Tier 2 Measured Response

The measurement of concern in Tier 2 is the timing accuracy of the firing of PDS signals in relation to the defined Signal Onset Windows for a particular test (Figure 29), i.e. making sure the correct signals are generated at the correct time in the context of an unfolding Positive Event. Assessing how these generated signals translate into an interface to the operator (and vehicle), and how effective these interfaces are, is beyond the scope of the current project.

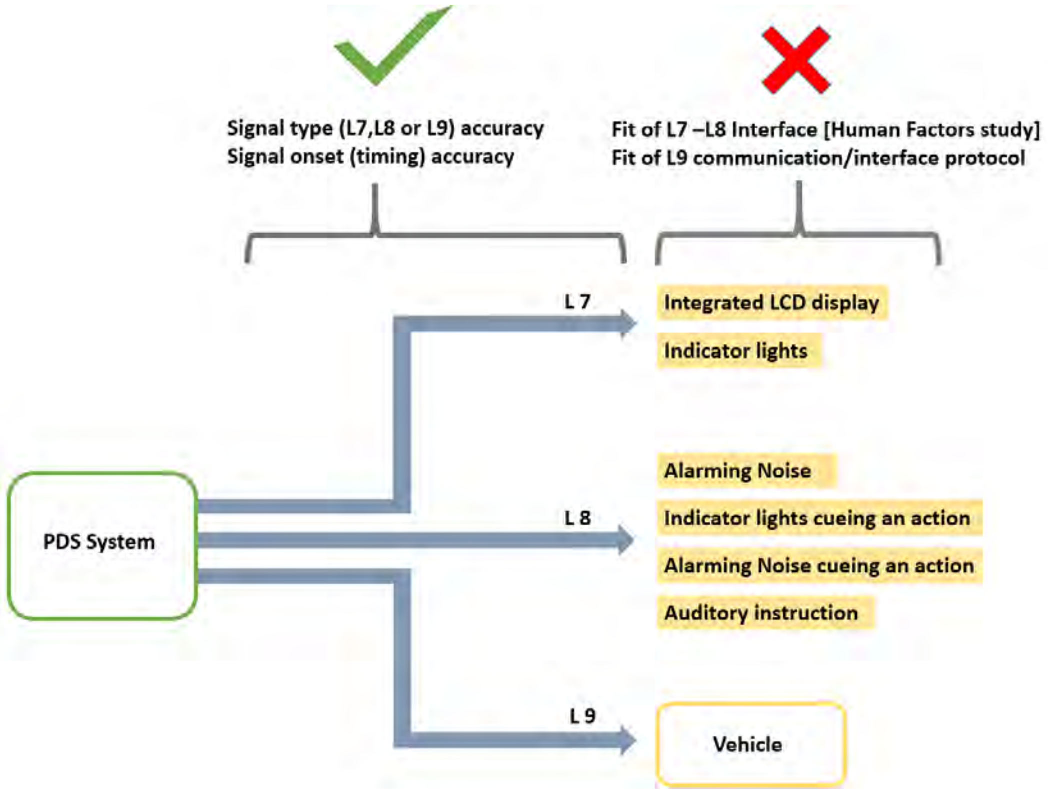


Figure 29 – What response is measured and assessed in Tier 2 (within scope), and what isn't (out of scope).

3.4 Defining Test Configurations

3.4.1 Treatment of Positive and Negative Events

In the context of Tier 2 testing,

- Positive Events refer to scenarios where LO and RO are on course to collision if both maintain current speeds and vectors
- Negative Events refer to the opposite: LO and RO are NOT on course to collide if both maintain current speeds and vectors.

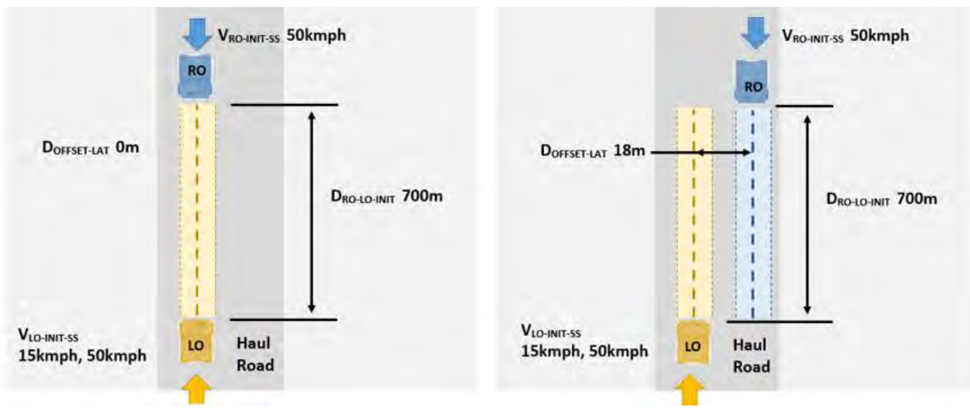


Figure 30 – Positive event (left) and Negative event (right)

The following test cases are proposed (the significance of which is explained in Section 3.10):

1. **Clear Positive Case** – A scenario where two vehicles are clearly headed for interaction (eg. Straight head-on)
2. **Edge Positive Case** – A scenario where two vehicles are headed for interaction but marginally so (eg. Misjudged clearance)
3. **Clear Negative Case** – A scenario where two vehicles are clearly not headed for interaction (e.g. passing head-on with sufficient clearance).
4. **Edge Negative Case** - A scenario where two vehicles are NOT headed for interaction but only marginally so (eg. passing head-on but with minimal clearance).

3.4.2 Scenarios and Configurations

As with Tier 1, the proposed Tier 2 group of tests will cover the PR5A in-line and parallel vehicle scenarios. The four base scenarios outlined in Section 2.3 above will again be used in Tier 2.

The four base scenarios (covering L1 – L7) and the four test cases (from Section 3.4.1 above) combine to give 16 unique Test Scenarios (4 X 4 = 16).

It is recommended that only one speed for both RO and LO is tested for each of the 16 unique scenarios, the reason being that different speed conditions only serve to affect the object detection capability of the PDS unit, which by design would already have been validated in Tier 1. The highest speed typical to most open cut sites is the recommended speed level in this case (50kmph).

Static condition for the RO is also recommended for the FORWARD FRONT A and REVERSE REAR base scenarios. This translates to 24 unique Test Configurations, as outlined below in from Figure 31 to Figure 35.

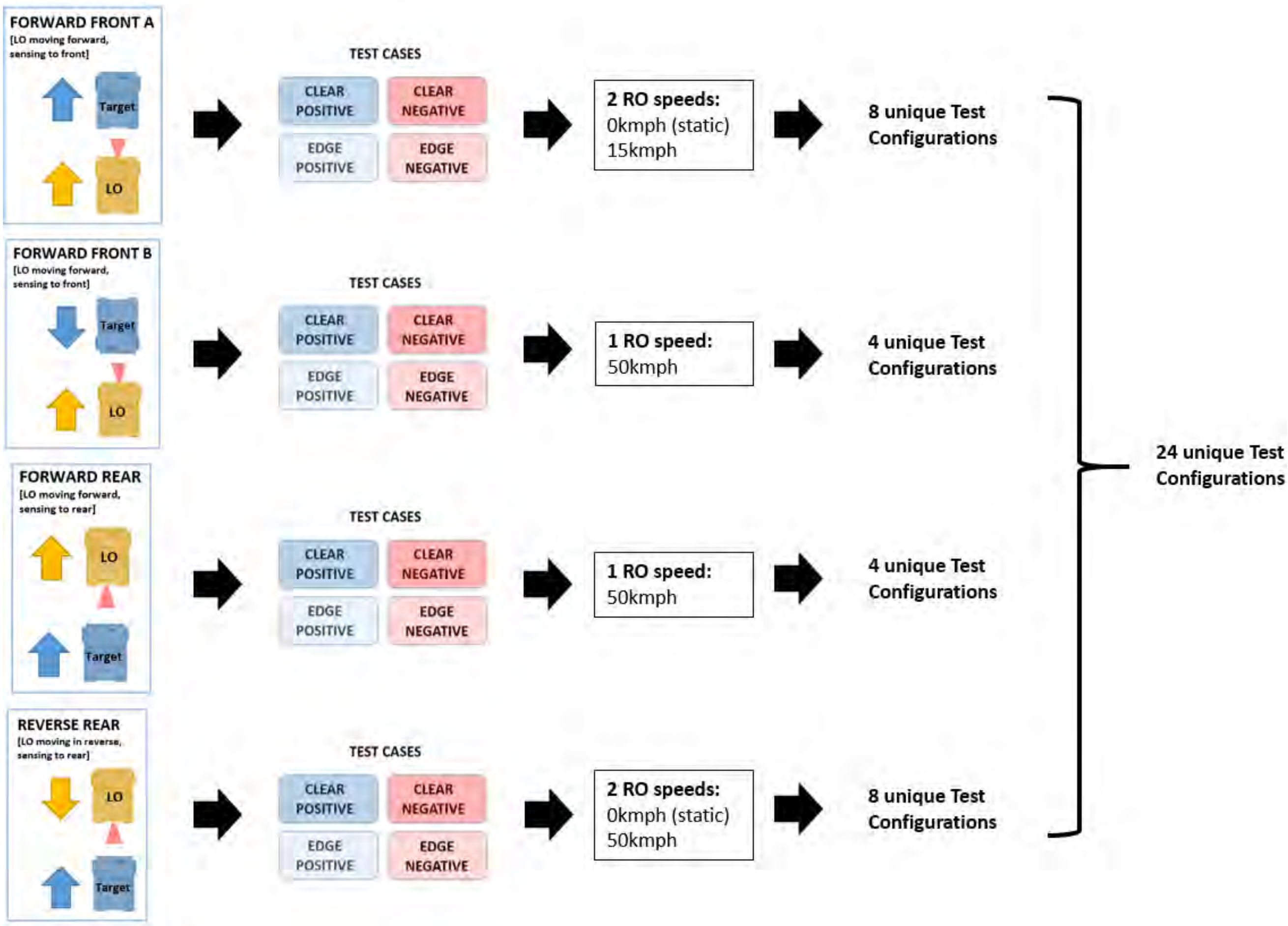


Figure 31 – Derivation of Test Scenarios from Base Scenarios and Test Cases.

FORWARD FRONT A

Config	D_{OFFSET_LAT} (m)		$V_{RO\text{-}INIT\text{-}SS}$ (kmph)
1	Clear	0	0
2	Positive	0	15
3	Clear	18	0
4	Negative	18	15
5	Edge	7	0
6	Positve	7	15
7	Edge	11	0
8	Negative	11	15

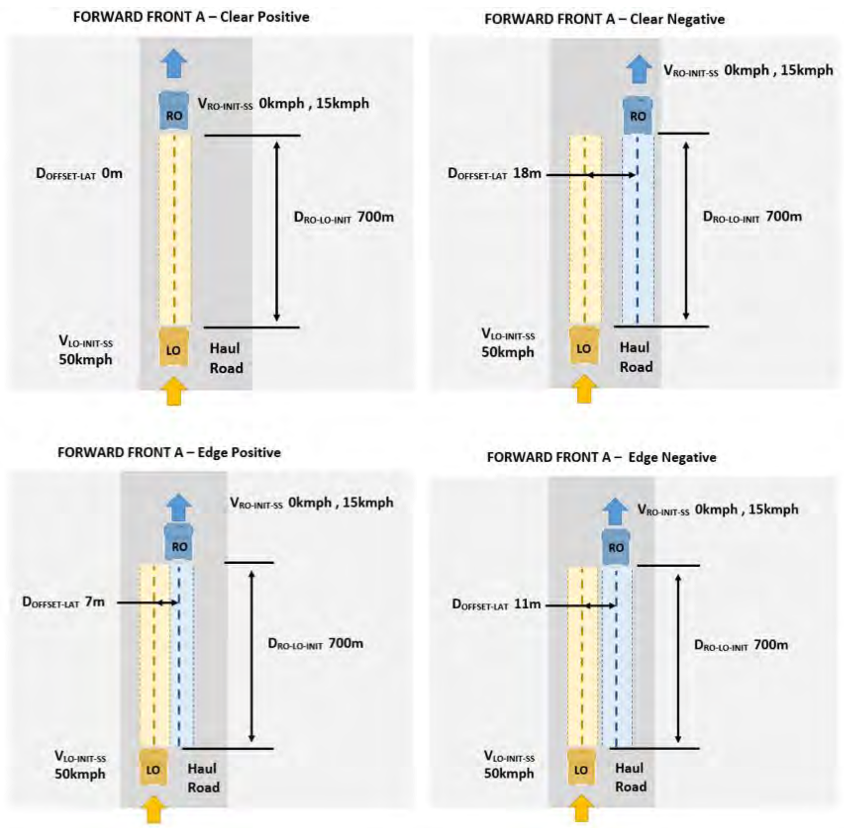


Figure 32 – Proposed Test Configurations for FORWARD FRONT A.

FORWARD FRONT B

Config	D_{OFFSET_LAT} (m)		$V_{LO\text{-}INIT\text{-}SS}$ (kmph)
9	Clear Positive	0	50
10	Clear Negative	18	50
11	Edge Positive	7	50
12	Edge Negative	11	50

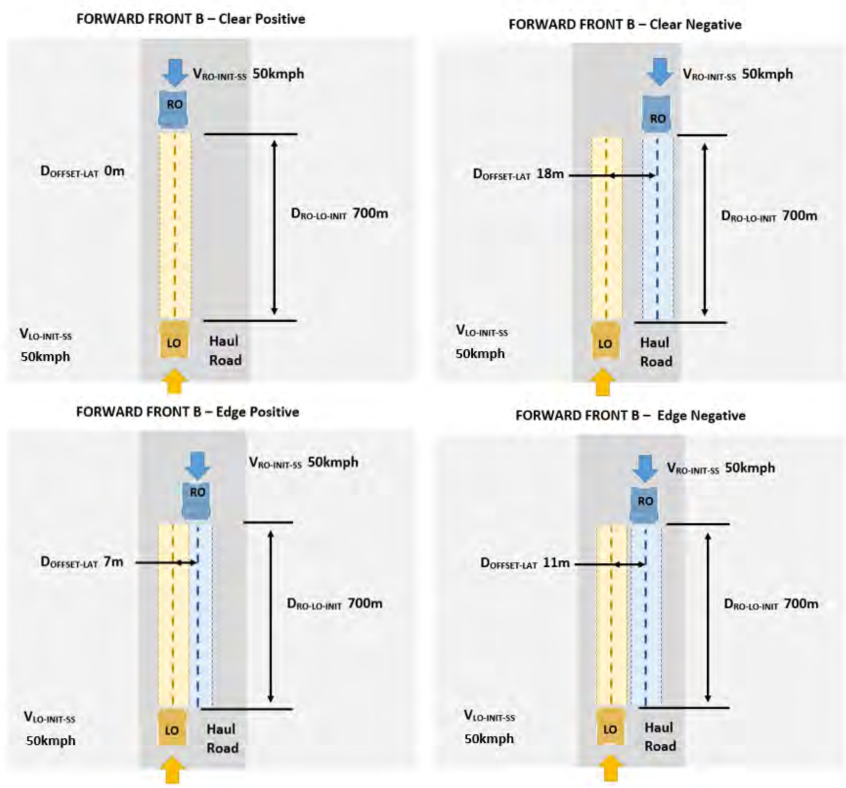
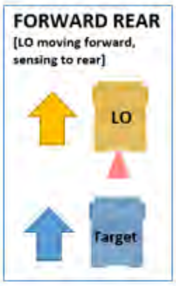
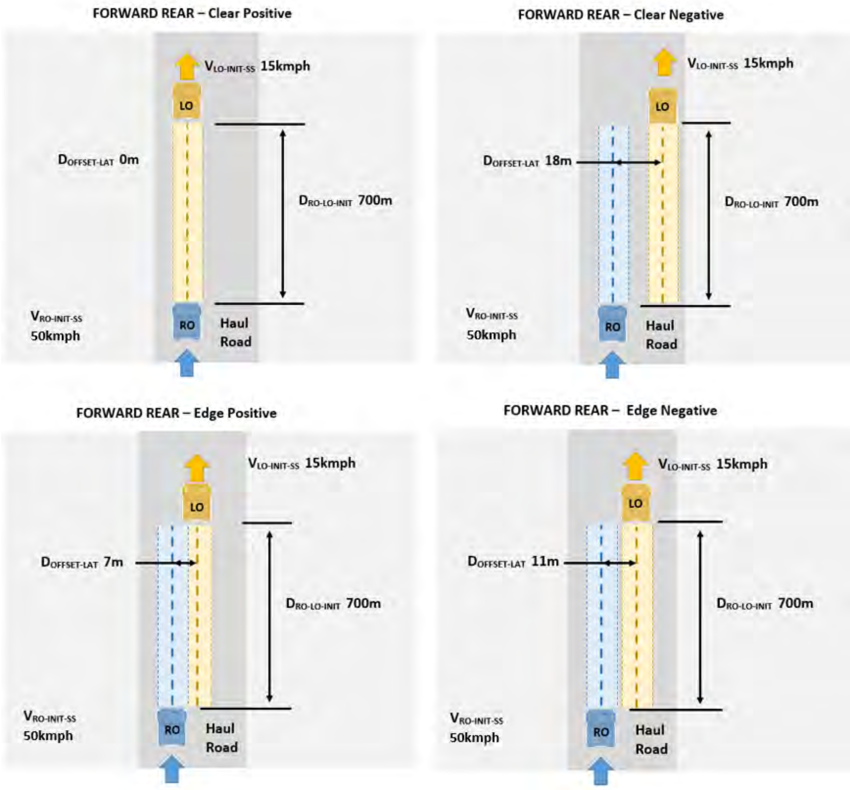


Figure 33 – Proposed Test Configurations for FORWARD FRONT B

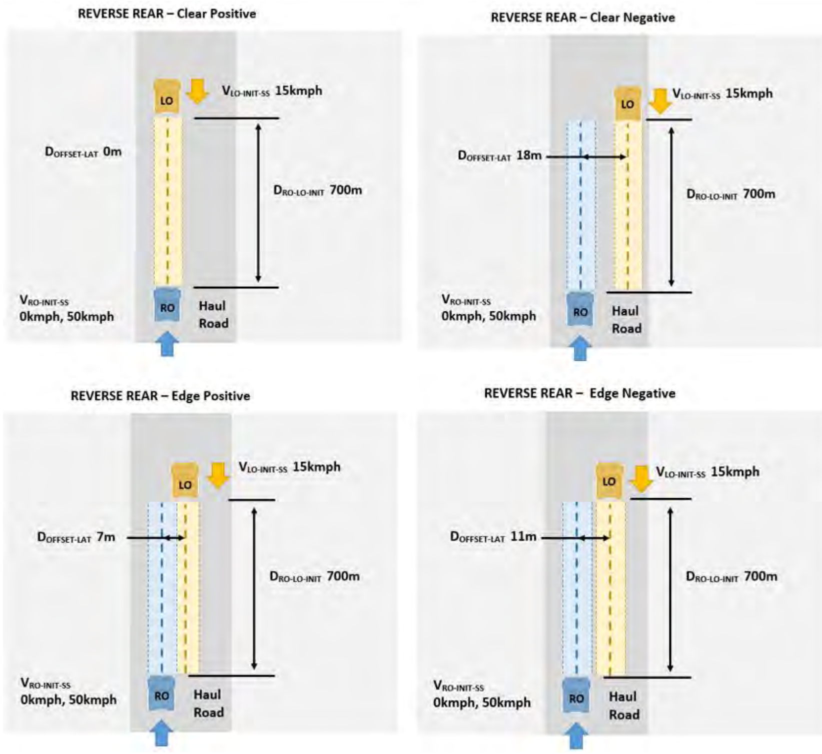




FORWARD REAR

Config		D_{OFFSET_LAT} (m)	$V_{RO\text{-}INIT\text{-}SS}$ (kmph)
13	Clear Positive	0	50
14	Clear Negative	18	50
15	Edge Positive	7	50
16	Edge Negative	11	50

Figure 34 – Proposed Test Configurations for FORWARD REAR.



REVERSE REAR

Config		D_{OFFSET_LAT} (m)	$V_{RO\text{-}INIT\text{-}SS}$ (kmph)
17	Clear	0	0
18	Positive	0	50
19	Clear	18	0
20	Negative	18	50
21	Edge	7	0
22	Positve	7	50
23	Edge	11	0
24	Negative	11	50

Figure 35 – Proposed Test Configurations for REVERSE REAR.

3.5 Stopping Distance Input

Stopping Distance is the distance required to stop a vehicle that is travelling at a certain speed once the brakes are fully actuated. It is a function of vehicle speed, gradient, braking efficiency and road surface-to-tire coefficient of friction, amongst other parameters. Where testing is concerned, the Stopping Distance to be used should be supplied by the vehicle OEM. It is either calculated and supplied directly by the OEM, or the OEM provides unambiguous equations or curves pertinent to that particular machine model that allow for the determination of the Stopping Distance based on the vehicle speed, road conditions, and gradient.

3.6 PDS Developer Input

3.6.1 PDS Signal Configuration

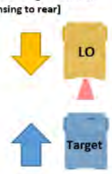
Base Scenario		ACTIONS				AWARENESS
		STOP	AVOID	SLOW	+VE COMMs	RO Position
FORWARD FRONT A [LO moving forward, sensing to front] 	L7 – Awareness					X
	L8 - Advisory	X		X		
	L9 - Intervention	X				
FORWARD FRONT B [LO moving forward, sensing to front] 	L7 – Awareness					X
	L8 - Advisory	X		X		
	L9 - Intervention	X				
FORWARD REAR [LO moving forward, sensing to rear] 	L7 – Awareness					X
	L8 - Advisory	**Not Available** *[This scenario cannot be resolved by an L9 or L8 system (for LO), only L7 control is available. However, calculation of Horizons 1- 3 (potentially fewer horizons) is still required in order to determine Horizon 4 (which the L7 signal is matched to)]*				
	L9 - Intervention					
REVERSE REAR [LO moving in reverse, sensing to rear] 	L7 – Awareness					X
	L8 - Advisory	X		X		
	L9 - Intervention	X				

Table 6 – PDS Signal Configuration Table

The PDS Signal Configuration table (Table 6) is to be specified by the PDS supplier. This table captures a PDS unit's full functional capability, as advertised, against the four base scenarios.

3.6.2 Horizon Distances and Signal Onset Windows

Event Horizons represent a set of lines in front of a moving LO demarcating points in space-time, on approximately which the PDS Signals are triggered when the RO is at said Horizon Line. The horizon lines are dynamically derived in real-time, and subsequently shrink or expand out as a function of the instantaneous closing velocities between LO and RO.

The Signal Onset Window is the space bounded by the Signal Onset Line and the Horizon Line within which the corresponding PDS signal for that Horizon line needs to be generated during an unfolding Positive Event. Where Window size is concerned, highly accurate and precise PDS units are able to specify tighter and smaller windows (and thereby scoring higher in the Reasonableness Check in Table 10).

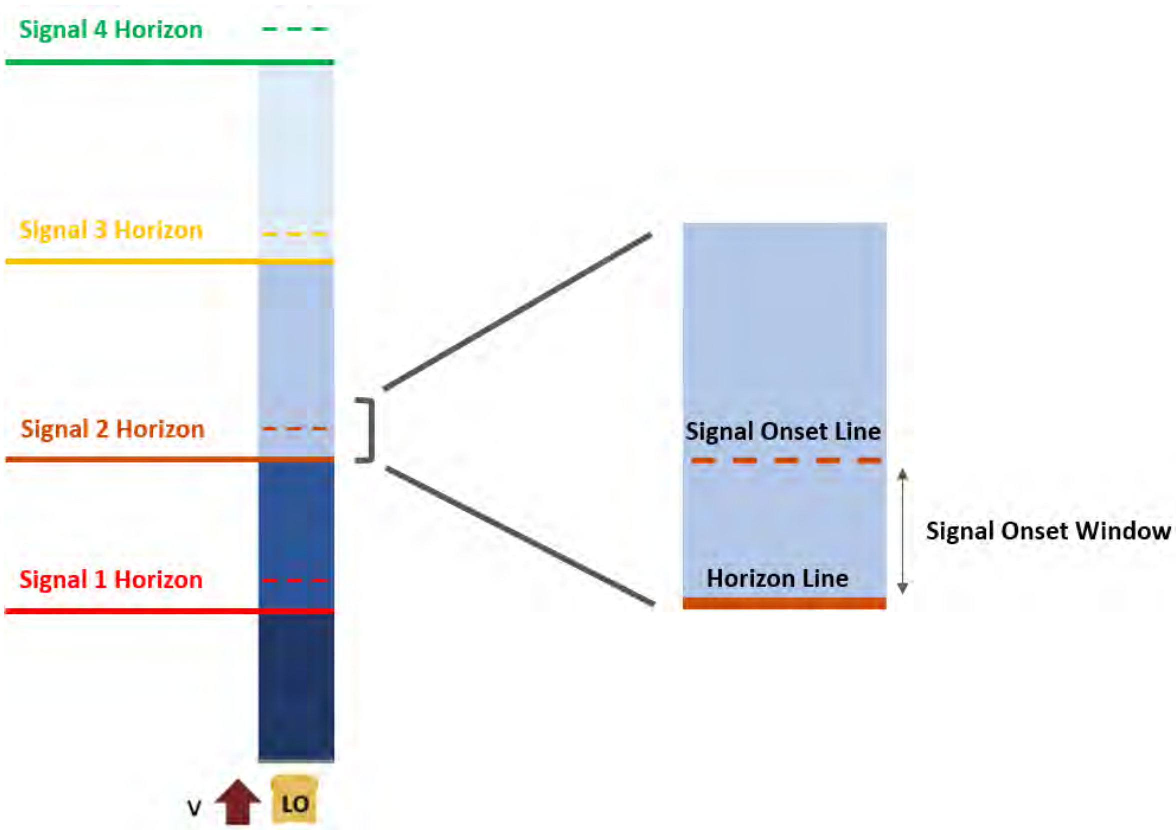


Figure 36 – Horizon Distances and Signal Onset Windows

For a given test configuration (any one of the Test Configurations proposed in Section 3.4, with speeds, vehicles defined), the PDS Supplier is to provide the Horizon specifications for each PDS signal to be generated. This includes the Horizon line and the Signal Onset Line for each PDS Signal.

For reference: Stopping Distance (from OEM)	**36.1 (m)**		
Stand-off Distance[1] (specified by End User)	**5.0 (m)**		
	Signal Type	**Specification (Distance out from LO)**	
Signal 1 Horizon (specified by PDS supplier)	L9 STOP	Horizon 1 Line	45.6 (m)
		Signal 1 Onset Line	65.0 (m)
Signal 2 Horizon (specified by PDS supplier)	L8 STOP	Horizon 2 Line	99.8 (m)
		Signal 2 Onset Line	119.2 (m)
Signal 3 Horizon (specified by PDS supplier)	L8 SLOW	Horizon 3 Line	153.9.(m)
		Signal 3 Onset Line	173.4 (m)
Signal 4 Horizon (specified by PDS supplier)	L7 AWARENESS	Horizon 4 Line	242.8 (m)
		Signal 4 Onset Line	262.3 (m)
…	…		
…	…		

Table 7 – PDS Supplier Input for Horizon and Signal Onset Lines for a given Test Configuration

3.7 "Reasonableness Check" (Optional)

3.7.1 "Horizon 1"

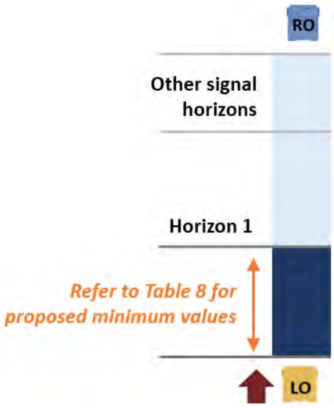


Figure 37 – Horizon 1

Horizon 1 is a proposed abstract construct which will be used as a baseline in the Reasonableness Check in Table 10. Table 8 below lists the proposed values for Horizon 1 according to each Base Scenario. See Table 9 for a graphical depiction of each Horizon 1 definition.

Base Scenario		Proposed Horizon 1 definition
Forward Front A  	The LO is moving forward, the RO (Target) is in front of the LO, moving in the same direction as the LO.	If RO is stationary: $D_{STOP-LO} + D_{STANDOFF}$ If RO is moving: Minimum allowable standoff for moving vehicles (defer to site rules, but typically 2-3 haul truck lengths)
Forward Front B  	The LO is moving forward, the RO (Target) is in front of the LO, and moving in the opposite direction as the LO.	If RO is stationary: $D_{STOP-LO} + D_{STANDOFF}$ If RO is moving: $[D_{STOP-LO} + D_{STANDOFF}]$ $+$ $[D_{STOP-RO} + D_{STANDOFF}]$ *[note: in absence of V2V link, assume RO is the vehicle model with the worst stopping performance of all vehicles on site]*
Forward Rear  	The LO is moving forward, the RO (Target) is at the rear of the LO, and moving in the same direction as the LO. *[LO at risk of being rear-ended by RO]*	Minimum allowable standoff for moving vehicles (defer to site rules, but typically 2-3 haul truck lengths)
Reverse Rear  	The LO is moving in reverse, the RO (Target) is at the rear of the LO, and moving in the opposite direction.	If RO is stationary: $D_{STOP-LO} + D_{STANDOFF}$ If RO is moving: $[D_{STOP-LO} + D_{STANDOFF}]$ $+$ $[D_{STOP-RO} + D_{STANDOFF}]$ *[note: in absence of V2V link, assume RO is the vehicle model with the worst stopping performance of all vehicles on site]*
$D_{STOP-LO}$ = LO Stopping Distance $D_{STOP-RO}$ = RO Stopping Distance		$D_{STANDOFF}$ = Standoff Distance

Table 8 - Proposed values for Horizon 1 (measured from LO) depending on the Base Scenario

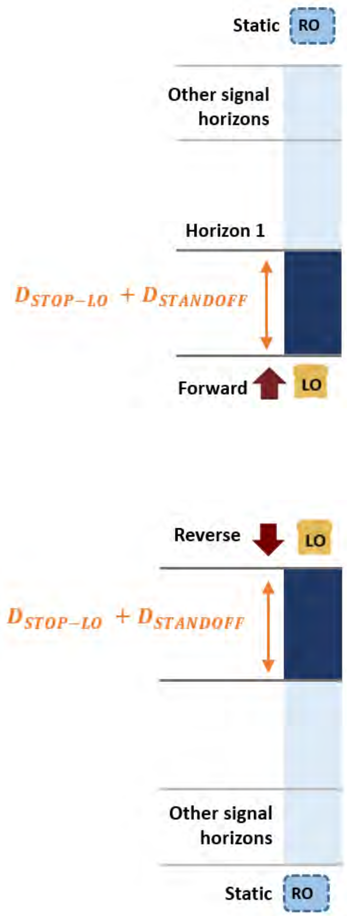
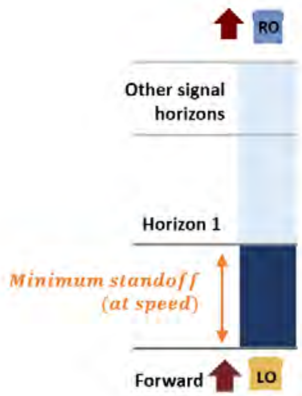
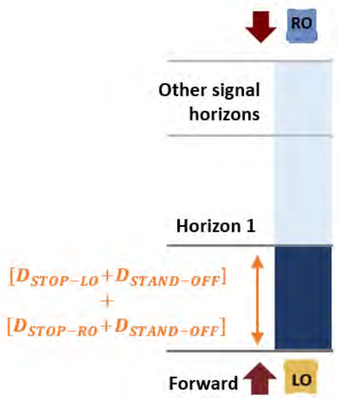
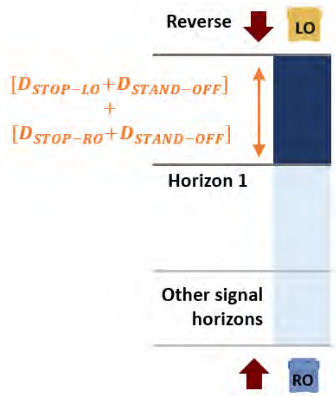
<table>
<tr>
<th>Static RO</th>
<th>FORWARD FRONT B
[LO moving forward, sensing to front]
</th>
<th>FORWARD FRONT B
[LO moving forward, sensing to front]
</th>
<th>FORWARD REAR
[LO moving forward, sensing to rear]
</th>
<th>REVERSE REAR
[LO moving in reverse, sensing to rear]
</th>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</table>

Table 9 – Graphical representation of Horizon 1 definitions for each Base Scenario

The Reasonableness Check provides a quick independent assessment of the PDS unit's signal horizons (provided by the PDS supplier) against proposed baselines. This baseline set outlined in Table 10 below. The Human Response Time (HRT) used is 2.5 seconds. Please see Appendix 5.1 for a treatment of **Human Response Time (HRT)**.

For L7 and L8 signals, the Response Window (as will be referred to below in Table 10) is defined as either of the following:

a. The distance between the Signal Horizon Line and the Signal Onset Line of the preceding signal, as illustrated in Figure 38 (left), or
b. If the PDS unit does not have L9 STOP capability, and the signal horizon in question is the first signal horizon out from the LO, the Response Window is then the distance between the Signal Horizon Line and Horizon 1, as illustrated in Figure 38 (right). (Horizon 1 is defined in Table 8),

Figure 38 – Response Window Definitions

Signal Type	Proposed Baselines	Reasonableness Score	
Generic L7	$\boldsymbol{Response\ Window_{Time\ Domain} \geq\ 2\ X\ HRT}$ *[The L7 signal is likely to be the first PDS signal received by the operator indicating a change in the operator's environment (i.e. presence and location of the RO). Operator likely to appreciate additional time to digest and incorporate the new information into his/her mental model of the environment and decide on a response. Hence a larger response time allowance is proposed for this signal.]*	3	If $Response\ Window \geq\ 2\ X\ HRT$
		2	If $Response\ Window <\ 2\ X\ HRT + SOW$
		1	If $Response\ Window <\ 1\ X\ HRT + SOW$
Generic L8	$\boldsymbol{Response\ Window_{Time\ Domain}\ =\ 1\ X\ HRT}$ *[Assuming continuum of awareness following on from L7 signal onset, operator is able to react in an alert manner to an advisory signal, hence 1 X HRT is deemed appropriate.]*	3	If $2\ X\ HRT\ \geq\ Response\ Window \geq\ 1\ X\ HRT$
		2	If $Response\ Window >\ 2\ X\ HRT$
		1	If $Response\ Window <\ 1\ X\ HRT$
L9 STOP	***Signal Horizon Line > Horizon 1 (as defined in** Error! Reference source not found.**)*** *[In addition to the stopping Distance and Stand-Off Distance, the Horizon Line for L9 STOP may need to incorporate an extra buffer to account for uncertainty associated with both the Machine (Machine Response Time variability) and the PDS (object detection error, latency, etc.).]*	3	If Signal Horizon Line > *Horizon 1*
		2	n/a
		1	If Horizon Line ≤ *Horizon 1*
Signal Onset Window (SOW)	***SOW size ≤ 1 second (time domain)*** *Ideally, the smaller the better.*	3	If $SOW\ \leq\ 1.0\ s$
		2	If $1.0\ s < SOW < 3.0\ s$
		1	If $3.0\ s\ \leq\ SOW$
Note: To switch from Time domain to Distance domain, multiply Time domain value with $\boldsymbol{V_{CLOSING}}$ (closing velocity between LO and RO)			

Table 10 – Proposed Baselines and "Reasonableness Score" definitions.

A "3" score is ideal, while a "2" score is acceptable. The PDS unit with only "3" and "2" scores should proceed with testing. Any component of the PDS Supplier's input sheet that scores a "1" should raise alarm bells with regards to the robustness of the PDS unit and the intelligence rules, and should create a point of discussion between all stakeholders around why low score was achieved and ways to mitigate the situation. It is recommended that a PDS unit with a score of "1" in any component should not be allowed to proceed with testing.

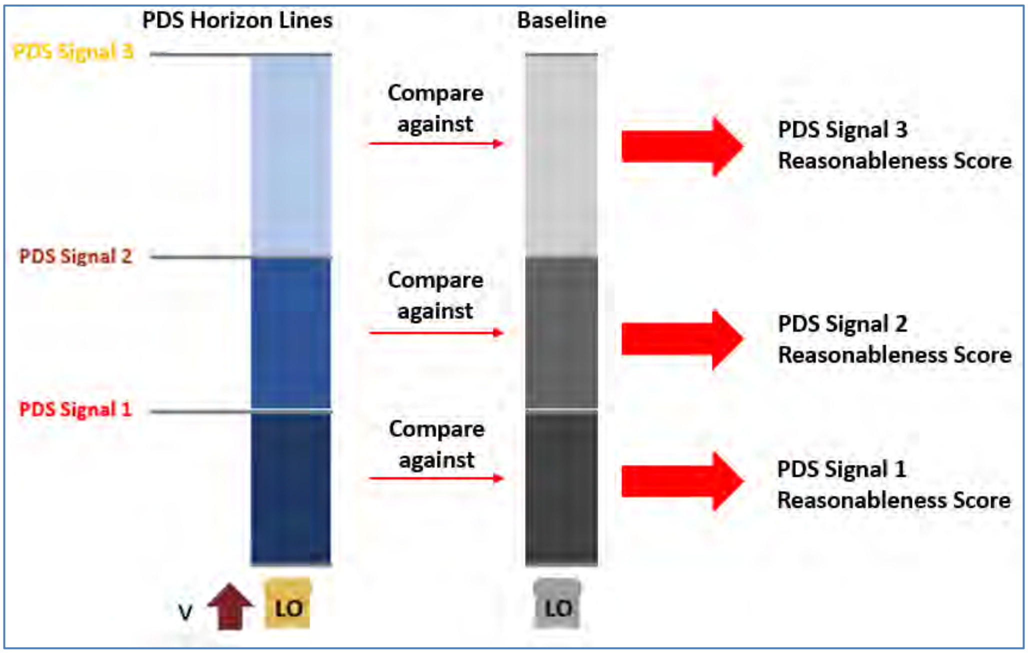


Figure 39 – Generating a Reasonableness Score for a set of PDS Signals

3.8 Signal Result Classification

Along with the definitions of Signal Onset Windows above, a set of Signal Success/Failure definitions are proposed below. Any signal generated will fall under one of the five definitions below.

Signal Success Definition	**True Positive**	Signal is generated within stipulated signal window during a positive event
	True Negative	Signal is NOT generated during a negative event
Signal Failure Definition	**Mis-timed (Too Early)**	Signal is generated before Onset line.
	Mis-timed (Too Late)	Signal is generated after breach of Horizon line.
	False Negative	Signal is NOT generated during a positive event
	False Positive	Signal is generated during a negative event

Figure 40 –Proposed Signal Result Classification

3.9 Test Sheet Development (Example)

The Test Sheet is developed based on the provided information (as per block diagram in Figure 28). An example is provided below, tracing the Test Sheet development path starting with the Test Configuration (Section 3.9.1) through to the Test Sheet itself (Section 3.9.5).

3.9.1 Example: Test Configuration

Configuration 1 is used as an example (see Figure 32). All data filled in below for Gradient and Coefficient of Friction are examples only.

Configuration (From Test Design Matrix in Figure 32**)**	Config 1
Configuration	Forward Front A (Head-on)
Test Case	Positive
Lateral offset, $D_{OFFSET-LAT}$ (m)	0
LO initial velocity, $V_{LO-INIT-SS}$ (kmph)	50
RO initial velocity, $V_{RO-INIT-SS}$ (kmph)	0
Closing Velocity, $V_{CLOSING}$ (kmph)	50
Steady state starting distance apart (m)	700
Gradient	0%
Surface coefficient of friction	0.68
LO Vehicle Model	Model XX
RO Vehicle Model	Model YY

Table 11 – Example Test Configuration

3.9.2 Example: Stopping Distance Input:

LO Stopping Distance supplied by OEM (m)	36.1m
RO Stopping Distance supplied by OEM (m)	n/a (as RO is stationary)

Table 12 – Stopping Distance Input

3.9.3 Example: PDS Supplier Input

For reference: Stopping Distance (from OEM)	**36.1 (m)**		
Stand-off Distance[1] (specified by End User)	**5.0 (m)**		
	Signal Type	**Specification (meters out from LO)**	
Signal 1 Horizon (specified by PDS supplier)	L9 STOP	Horizon 1 Line	45.6
		Signal 1 Onset Line	65.0
Signal 2 Horizon (specified by PDS supplier)	L8 STOP	Horizon 2 Line	99.8
		Signal 2 Onset Line	119.2
Signal 3 Horizon (specified by PDS supplier)	L8 SLOW	Horizon 3 Line	153.9
		Signal 3 Onset Line	173.4
Signal 4 Horizon (specified by PDS supplier)	L7 AWARENESS	Horizon 4 Line	242.8
		Signal 4 Onset Line	262.3

Table 13 – PDS Supplier Input

[1]*Stand-Off Distance is a safety buffer specified by the site/ End User.*

3.9.4 Optional “Reasonableness Check”

Reasonableness Score is calculated on the PDS Supplier Input, based on the proposed baseline in *Table 10.*

For reference: Stopping Distance (from OEM)	**36.1 (m)**					
Stand-off Distance (specified by End User)	**5.0 (m)**					
	Signal Type	**Specification (from PDS supplier)**			**Reasonableness Score (determined as per *Table 10*)**	
			Distance (m)	**Time-domain (s)**		
Signal 1 Horizon	L9 STOP	Horizon Line	45.6	n/a	3	**45.6** > (36.1 + 5)
Signal 2 Horizon	L8 STOP	Response Window	34.8	2.5	3	2 X HRT ≥ **2.5** ≥ 1 X HRT
		SOW	19.4	1.4	3	1.4s ≤ 1.5s
Signal 3 Horizon	L8 SLOW	Response Window	34.8	2.5	3	2 X HRT ≥ 2.5 ≥ 1 X HRT
		SOW	19.4	1.4	3	1.4s ≤ 1.5s
Signal 4 Horizon	L7 AW	Response Window	69.4	5	3	5s ≥ 2 X HRT
		SOW	19.4	1.4	3	1.4s ≤ 1.5s

Table 14 – “Reasonable Check” Table

The PDS supplier, in this example case, has passed the Reasonableness Check, with none of its components scoring “1”.

3.9.5 Test Sheet

The Test Sheet is an extension of the PDS Supplier Input Sheet, where extra columns are added to the right for the recording and classifying of results for each test run. The classification of results will follow the classification scheme proposed in Section 3.8.

	Signal Type	**Specification (m)**		**Test 1**		**Test 2**	
				Recorded Signal Onset (m)	**Result Classification**	**Recorded Signal Onset (m)**	**Result Classification**
Signal 1	L9 STOP	Horizon 1 Line	45.6	55.7	True Pos	44.8	Mis-timed (too late)
		Signal Onset Line	65.0				
Signal 2	L8 STOP	Horizon 1 Line	99.8	121.2	Mis-timed (too early)	115.2	True Pos
		Signal Onset Line	119.2				
Signal 3	L8 SLOW	Horizon 1 Line	153.9	170.5	True Pos	Signal did not come on	False Negative
		Signal Onset Line	173.4				
Signal 4	L7 AW	Horizon 1 Line	242.8	260.4	True Pos	250.7	True Pos
		Signal Onset Line	262.3				

Table 15 – Test Sheet with fictitious results over two runs

The number of replicate tests shown in Table 15 above is two. This report recommends a minimum of two runs to establish the repeatability of the results. (See Appendix 5.2 for a treatment of number of runs versus confidence interval)

The Test Sheet is expected look different across different PDS suppliers with different PDS Signal Configurations.

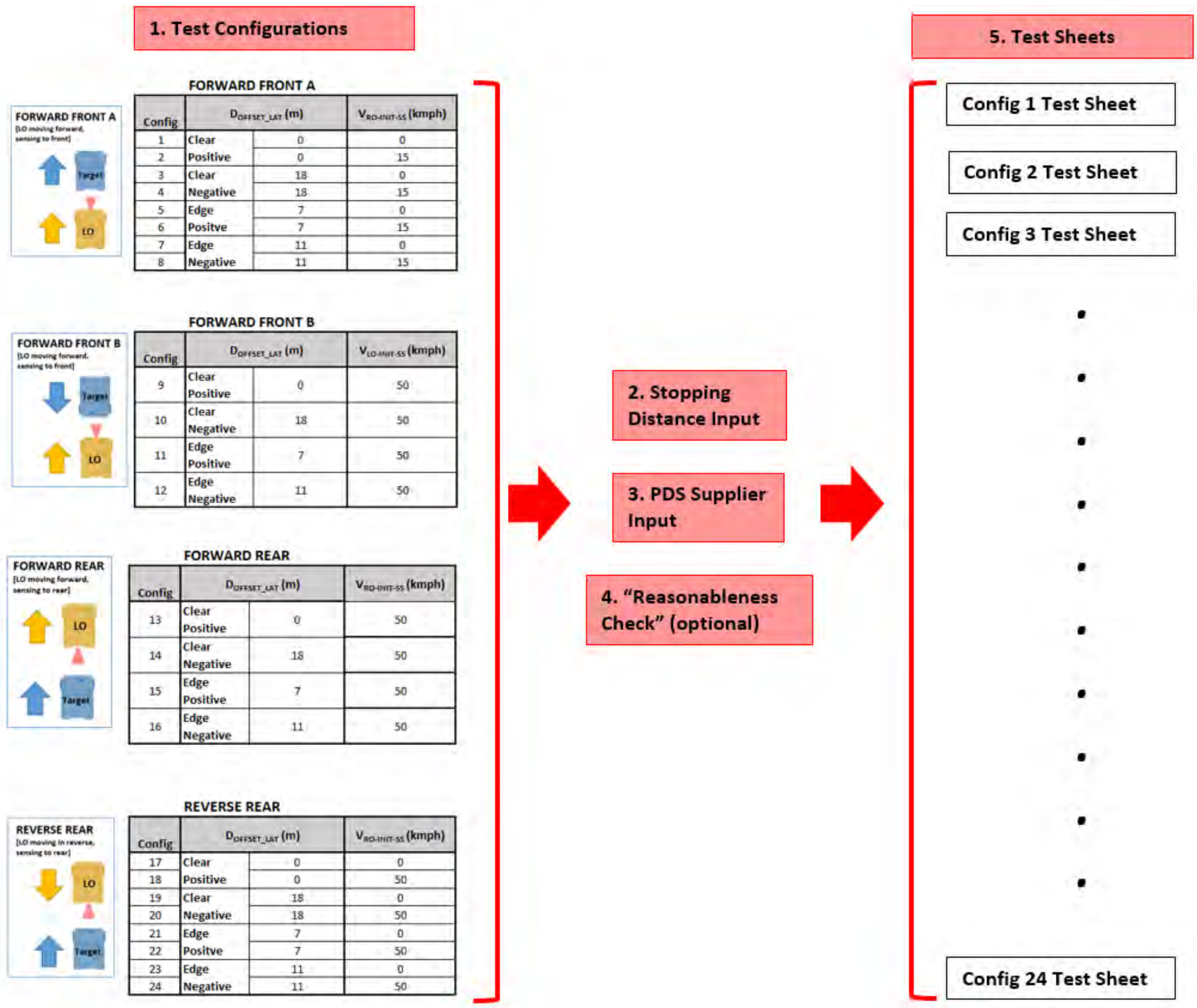
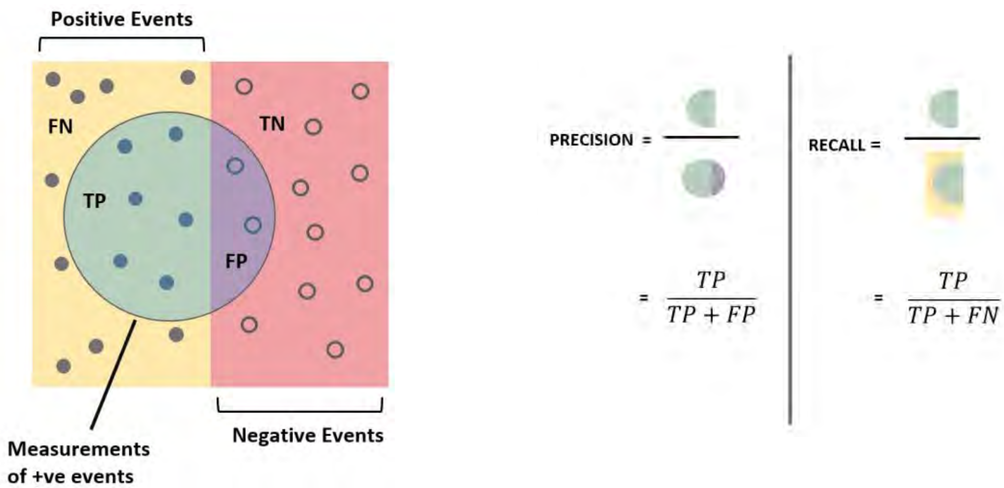


Figure 41 – High-level summary of the Test Sheet development process.

3.10 Tier 2 Performance Metrics



$$\text{PRECISION} = \frac{TP}{TP + FP} \qquad \text{RECALL} = \frac{TP}{TP + FN}$$

Figure 42 – Precision and Recall definitions

The test framework presented above, with the positive and negative cases tested, is designed provide us with two very useful metrics: Precision and Recall. Precision and Recall are functions of True Positives, True Negatives, False Positives, and False Negatives. They are commonly used where evaluating artificial intelligence constructs is concerned (rules-based classifiers, pattern recognition, etc.).

They provide a more nuanced interpretation of results as opposed to simple binary Pass/Fail percentages, and are deemed appropriate in the evaluation of PDS performance.

In particular, a PDS's Precision and Recall performances for Edge Cases (Edge Positives and Edge Negatives) will be informative, and can be interpreted in a number of ways depending on the mine's/user's specific use case. Just as an example, if a site has adequate lane separation (e.g. berms separating lanes), edge negative cases may be anticipated to be rare occurrences, possibly making it acceptable if the PDS system alarms frequently (although falsely) in Edge Negative cases during testing.

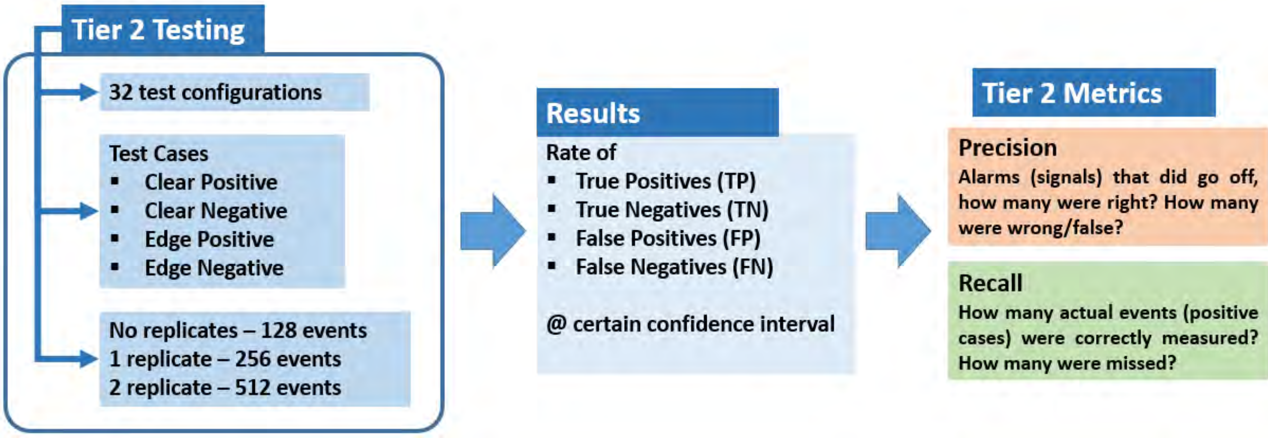


Figure 43 – Tier 2 Performance Metrics

Precision and Recall are usually inversely linked. Brain surgery provides an illustrative example of the trade-off: "*Consider a brain surgeon tasked with removing a cancerous tumor from a patient's brain. The surgeon needs to remove all of the tumor cells since any remaining cancer cells will regenerate the tumor. Conversely, the surgeon must not remove healthy brain cells since that would leave the patient with impaired brain function. The surgeon may be more liberal in the area of the brain she removes to ensure she has extracted all the cancer cells. This decision increases Recall but reduces Precision. On the other hand, the surgeon may be more conservative in the brain she removes to ensure she extracts only cancer cells. This decision increases Precision but reduces Recall. That is to say, greater Recall increases the chances of removing healthy cells (negative outcome) and increases the chances of removing all cancer cells (positive outcome). Greater Precision decreases the chances of removing healthy cells (positive outcome) but also decreases the chances of removing all cancer cells (negative outcome).*" **('Precision and Recall', n.d.)**

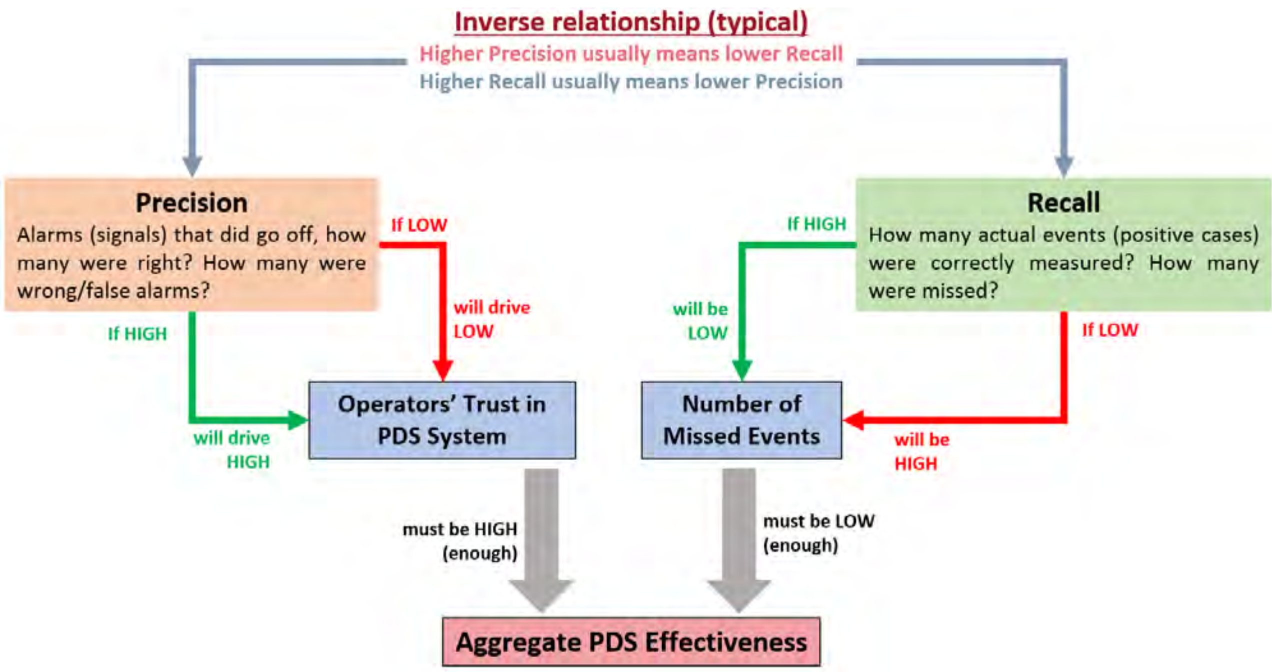


Figure 44 – The relationship between Recall, Precision and the final aggregate PDS effectiveness

In the context of PDS systems (Figure 44), having a high Recall will mean few real (positive) events slip through the net, but may also mean that the system errs on the side of caution and picks up on negative events as well, leading to a high rate of false alarms (low Precision) and subsequent loss of Operator Trust in the system (operator desensitization, creates negative behaviours). Conversely, prioritizing a high Precision may mean setting unambiguous criteria/cut-offs for what constitutes a Positive case (clear positives), which may cause the system to not pick up on borderline (fuzzy) positive cases (where interaction was still going to happen) in order to reduce risk of false alarming.

It is the authors' view that the eventual (aggregate) effectiveness of a PDS unit is ultimately a not-so-simple function of Precision and Recall, as we have tried to illustrate in the diagram above. Some questions which Figure 44 raise include

1. What is the (target) minimum Precision rate, below which the Operator mistrusts the system?
2. What is the (target) minimum Recall rate, below which the PDS system actually decreases overall safety due to an unacceptable number of missed events? (this question is pertinent if the operator trusts the system and comes to depend on the system fully).

Striking a correct balance between Recall and Precision is important. Although this project will provide the platform for measuring both metrics, determining the minimum acceptable or optimal rates for Precision and Recall for PDS systems are currently beyond the scope of the current project, and may involve an umbrella of studies involving human factors and risks analysis statistics.

3.11 Tier 2 Physical Test Requirements

Table 16 below summarizes the proposed physical location requirements and the equipment that would be required to execute the Tier 2 body of work as proposed above.

Physical Location Requirements	Vehicles Required	Data Acquisition Method	
		Baseline Measurement (Ground Truth)	**PDS Response Measurement**
Large Flat Area 1000m X 100m minimum.	2 Haul Trucks ▪ Local Object ▪ Remote Object	**For static objects:** Robotic Total Station, On-ground pre-surveyed demarcation **For dynamic objects:** Visual odometry (pre-surveyed demarcation + drone top-down footage) RTK GPS installed on all dynamic objects (will require RTK base station or at least a mobile base station)	Some options: **a) Logging interface to PDS unit:** This can be an RS232 port on the PDS module, with a simple serial output for real-time live output (target position). Logging will be done to a laptop via a serial monitor/logger. For dynamic testing (moving vehicles involved), will need to be time-synced with Baseline Logging module (e.g. all synced to International Atomic Clock). **b) Post-test download:** Again for dynamic testing, time sync required with Baseline Logging module.

Table 16 - Proposed location and equipment requirements for Tier 2 body of test

4. Conclusions

4.1 Limitations of the proposed set of tests

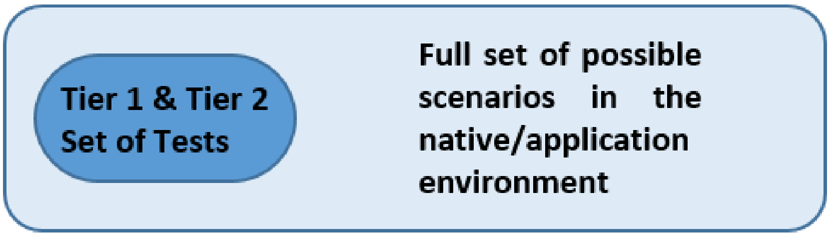


Figure 45 – The limits of controlled testing of products that will be deployed in complex environments

It is important to recognize the limitations of the proposed body of tests in Tier 1 and Tier 2. The scenarios that will eventually be covered (once the test scenarios are expanded beyond the inline L1 – L7 sets) are idealized scenarios, which by design should provide a fairly reliable indication of a PDS unit's robustness and adequacy. However, the reality is that the sheer number of combinations and permutations possible with vehicle arrangements and environmental parameters means that there will always be yet-unknown specific scenarios that could throw "curved balls" at PDS units, which could cause malfunctions, no matter how advanced these products may be engineered. This is a fundamental challenge in attempting to test and commission products whose functionality are contingent on successful operation within, and interaction with, a highly complex environment.

A framework for Learning and Knowledge Capture (driven by all stakeholders) is extremely critical as this will ensure that performance failures in the application environment (when they do occur) is converted into information that helps drive the development of the next generation of improved and more robust products while simultaneously reducing the set of "unknown unknowns" of the operating environment.

4.2 ACARP Next Phase

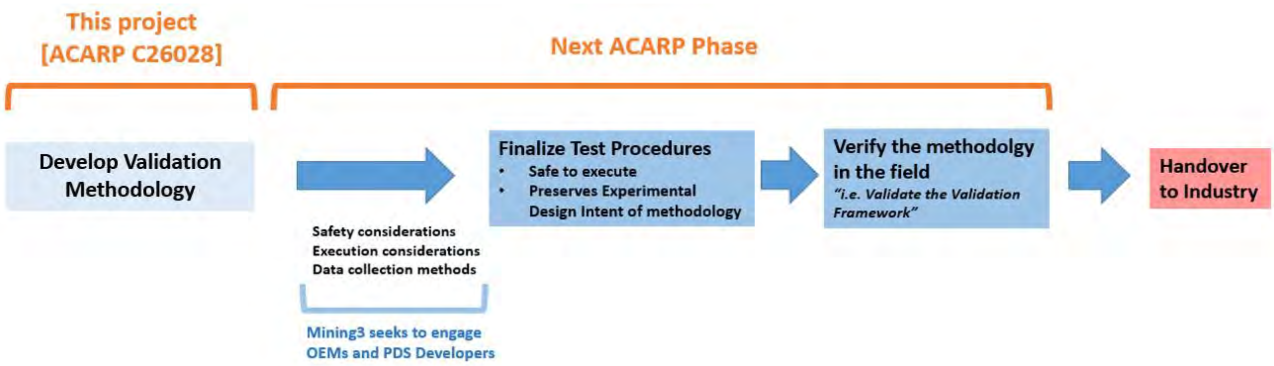


Figure 3 – Roadmap of the current project leading into the next proposed ACARP phase.

As of writing, the next ACARP project is currently under planning, and will involve translating and finalizing the proposed test procedures in this body of work into a safely executable field test program that preserves the original rigour of the methodology. Mining3 will seek engagement with expert volunteers from the industry to assist with this process. Importantly, the next phase will also involve field verification of the proposed test program, including logistics of setting up the tests and executing them. Gaps and weaknesses of the current methodology are to be identified, and the methodology is expected to be fine-tuned and improved as a result.

5. Appendices

5.1 Human Response Time [PROPOSED]

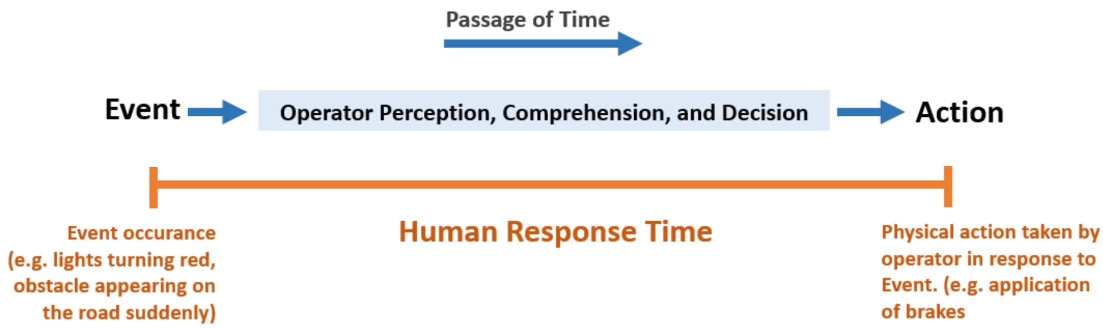


Figure 46 - Human Response Time, as defined in this body of work, encompasses the time from the occurrence of the Event, up till the moment that Action is initiated by the operator.

AASHTO (American Association of State Highway and Transportation Officials) uses 2.5 seconds as the human perception-reaction time for the application of brakes following an external cue (e.g. change of traffic lights). This value is then employed in estimating both stopping sight distances and other kinds of sight distances in road design and traffic light placement. The value of 2.5 seconds is based primarily around the work of Johansson and Rumar (1971).

Recent studies have checked the validity of 2.5 seconds as the design perception-reaction time:

1. Four recent studies have shown maximums of 1.9 seconds as the braking perception-reaction time for an 85th percentile time and about 2.5 seconds as the 95th percentile time (9,10,11,12).

	85th percentile	95th percentile
Gazis et al.	1.48s	1.75s
Wortman et al.	1.80s	2.35s
Chang et al.	1.90s	2.50s
Sivak et al.	1.78s	2.40s

Table 18 – Results of four recent studies by Gazis et. al., Wortman et al., Chang et al., Sivak et al.

	"Surprise"	"Expected"
95th percentile	2.45 s	0.72 s

Table 17 – Study by Lerner on two types of driver response.

2. A very recent literature review by Lerner and his associates (1995) includes a summary of brake PRT (including brake onset) from a wide variety of studies. Two types of response situation were summarized: (1) The driver does not know when or even if the stimulus for braking will occur, i.e., he or she is surprised, something like a real-world occurrence on the highway; and (2) the driver is aware that the signal to brake will occur, and the only question is when. Again the "worst" reaction time of the two types was 2.45s (95th percentile), again agreeing closely with 2.5s time.

[Note that the state of alertness of the drivers in each of these studies above are not explicitly discussed. It is assumed that all drivers involved were reasonably alert, and that fatigue as a variable that influenced response time was not investigated.]

The Human Response Time value recommended by this report is 2.5 seconds, assuming a reasonably alert driver. The fatigue dimension to human response time is not treated currently, but may be a relevant component in future revisions of this work due to the increasing proliferation and adoption of fatigue monitoring devices for mine vehicle operators at the time of writing.

5.2 Number of Runs VS Confidence Interval

As per conventional wisdom, the bigger the sample size the higher the confidence in the results/conclusions. The challenge is always finding the correct balance between scientific rigour and what is practically achievable. On the basis of reporting the results of Tier 2, a 95% confidence interval is recommended as this is the industry-standard for ascertaining that a hypothesis is true (in this case, the hypothesis being the PDS system is reliable to X%). Assume we can assign a simple Success/Failure (binary) outcome to each test, and assume four events per test (four horizons that were breached for each test). Table 19 below illustrates the various reliability values that can be quoted for a different number of failure cases against a different number of replicate runs for Tier 2. This exercise illustrates the challenge to balancing out practicality and scientific rigour, and to illustrate the reliability figures we can quote against the number of replicates.

Assume:

- **24 unique tests and 4 events per test (four Signal Events)**
- **Binomial distribution for failures**

The calculated Reliability values uses the Wilson Score for 95% confidence in the prediction.

# of replicates	# of Tests	# of Events (4 events per test)	# Failures	0 (Failure Free)	3	5	7	12
1 Run	24	96	Reliability (with 95% certainty)	96.9%	93.3%	90.2%	87.3%	80.4%
2 Runs	48	192		98.5%	96.7%	95.1%	93.7%	90.2%
3 Runs	72	288		99.0%	98.3%	97.6%	96.8%	95.1%
4 Runs	96	384		99.2%	98.3%	97.6%	96.8%	95.1%

Table 19 – Reliability values that can be quoted at 95% confidence interval for different number of failures against a different number of replicate runs for Tier 2

6. References

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