University of Southern Queensland
Faculty of Health, Engineering & Sciences

Development of Comparative Test Protocols for the Assessment of Autonomous Tractor Performance

A dissertation submitted by

Logan Torrance

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Abstract

As autonomous and semi-autonomous tractors (ASAT) become more prevalent and affordable within the agricultural industry, various standards that outline both the safety and design principles for ASATs have been developed. Current features on late model tractors inform most of the major components that would be required for an autonomous tractor – with these technologies ultimately providing a pathway from basic automation to full autonomy.

While such standards ensure certain levels of safety and/or performance are achieved, there are currently no universally accepted documents or testing protocols that assess the field-readiness or the level of performance/maturity of (semi-)autonomous tractors. Therefore, this project aims to develop ASAT testing protocols and to assess the performance of current tractor technology, relative to the suggested requirements.

Building upon existing research and standards of the mining, transport and agricultural sectors, a list of expected operations that an ASAT should be expected to perform was compiled, prior to developing test procedures to exploit certain operations and/or protocols. A John Deere 6120R case study was then implemented, to assess the appropriateness of test procedures and the performance of a market-ready ASAT.

The project presents recommendations for the introduction of universally accepted, independent testing procedures to ensure ASATs meet accepted levels of performance and field-readiness, pertaining to awareness and perception, automated tractor guidance, headland management and operational safety. The project also assessed the maturity and performance of existing tractor technologies, relevant for autonomous and semi-autonomous farming operations. Implementing this scoring method, the 6120R case study performed well across a number of elements, obtaining an overall mark of 8.3/10. The tractor benefitted from advanced headland management and operational safety protocols, while lacking in-depth perception and awareness practices – ultimately limiting its driverless capabilities.

While procedures were outlined for obstacle detection and avoidance systems, these protocols could not be tested due to limitations of available machinery. Therefore, further work should involve assessing the practical implementation of perception systems, prior to presenting these recommended tests to tractor manufacturers for feedback and refinement – thereby accelerating acceptance and uptake of these tests.

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Certification of Dissertation

I certify that the ideas, designs and experimental work, results, analyses and conclusions set out in this dissertation are entirely my own effort, except where otherwise indicated and acknowledged.

I further certify that the work is original and has not been previously submitted for assessment in any other course or institution, except where specifically stated.

L. TORRANCE

[redacted]

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Abbreviated Terms

ASAM – Autonomous or Semi-Autonomous Machine

ASAT – Autonomous or Semi-Autonomous Tractor

ATG – Automated Tractor Guidance

ATTA - AutoTrac Turn Automation

CAE – Centre for Agricultural Engineering

DTM – Digital Terrain Mapping

GNSS – Global Navigation Satellite System

GPS – Global Positioning System

HAAM – Highly Automated Agricultural Machinery

LOA – Level of Autonomy

ODD – Operational Design Domain

PADS – Precision Agriculture Data Sets

PAFR – Performance, Ability and Field-Readiness

PFDS – Precision Farming Data Sets

PTO – Power Take-Off

USQ – University of Southern Queensland

Chapter 1

Introduction

1.1 Background

Today's modern agricultural industry dictates that greater emphasis be placed on efficiency and optimisation, thereby improving productivity and output (Blackmore et al 2004). With a $5.8 billion decrease to the total national farming income, from 2018 to 2019 (Sullivan 2019), agricultural enterprises are under increased economic pressure to maintain viability. These businesses are thereby pressured to employ more efficient farming practices. Consequently, recent years have witnessed the emergence of highly automated and/or fully autonomous tractors and machinery, in an attempt to reduce overheads and improve productivity.

To maximise 'economies of scale', farms have been forced to increase in size (Duffy 2009). In turn, this necessitates tractor operators to perform monotonous tasks over prolonged periods of time; for example, steering in a straight line for long distances, whilst continually monitoring machine and implement performance. Given such tasks require a sustained degree of concentration, operator fatigue is becoming a more prevalent issue, with the potential to cause injury to both persons and machinery. By replacing human operators with highly automated or autonomous systems, these risks can be minimised.

As automated machinery is becoming more wide-spread and affordable within the agricultural industry, standards to ensure safety and performance of highly automated agricultural machinery (HAAM) have been developed; ISO 18497:2018 outlines the safety and design principles for HAAM. Although highly automated, these vehicles still require supervision from an operator. However, for a machine to be truly *autonomous*, constant supervision should no longer be required (Levinson 2017).

1.1.1 Development of Automated Tractor Systems

Given the requirement for larger farming operations, in addition to maximisation of machinery performance and land optimisation, automation lends itself to agricultural environments due to simple, monotonous tasks that also require high degrees of precision.

With the advent of the Global Position System (GPS), Rockwell International Corporation developed the first application of precision agriculture – yield monitoring of combine harvesters in 1995 – whereby the volume of crop harvested could be recorded against a particular co-ordinate within a field (Marsh 2018). This allowed farmers to develop yield maps, thereby highlighting areas of poor or fertile soil.

John Deere built upon the progress of Rockwell International when it released the first version of GPS AutoSteer in 1996, relying on their StarFire GPS receiver to dynamically control the steering of the tractor. This system was refined further, prior to the release of AutoTrac in 2002. Encompassing a 'terrain compensation module', AutoTrac could steer the tractor in a straight line, regardless of contours of the ground (Mayfield 2016).

Since then, technologies have been developed and refined, thereby improving the efficiency and productivity of farming operations. Such technologies include more advanced tractor guidance; variable rate technologies (allowing different rates of fertiliser, seed or chemicals to be applied according to a pre-defined application map); drive-by-wire functionalities (allowing speed, steering and transmission to be computer-controlled); engine optimisation and performance monitoring; automated field operations (such as adjusting and optimising implement settings and performing automated headland turns); machine-to-machine communications (including leader-follower technology); situational awareness (such as altering path to avoid flattening crops using visual guidance) and process monitoring (including 'on-the-go' analysis of crop parameters).

With 90% of Australian farmland being farmed using precision agriculture (Mayfield 2016), focus has now turned to the development of autonomous and semi-autonomous tractors (ASAT). The Japanese heavy-equipment company, Kubota, have already prototyped and implemented small, driverless tractors and harvesters (Michal 2018), while John Deere and Case IH have both released driverless tractor concepts (Baillie et al 2017), with Deere showcasing a new concept late last year – a one-axle, 500 kilowatt, fully-electric, driverless tractor (Comtoise 2019).

1.1.2 Operational Design Domain

Environments where an autonomous vehicle is expected to operate can be classified into two categories: structured or unstructured. Depending on the amount of 'freedom' given to the machine, together with how defined the operating environment is, determines the amount and sophistication of autonomous technology required by the vehicle – the greater the freedom, the less defined the environment is and the more advanced the technology must be. To avoid autonomous machinery manufacturers investing large economic, technical and labour resources to develop an 'all-encompassing' autonomous system, the concept of an 'operation design domain' (ODD) was introduced. This concept allows manufacturers to precisely define the conditions in which their machines are intended to operate. Consequently, the basic taxonomy of HAAM design domains can be separated into two categories, as per their operational environments: unstructured and structured.

Within an unstructured environment, the machine can operate in a multitude of scenarios and locations, using 'long-term' strategies and task planning, while also being able to deal with imminent or unexpected issues. Within this domain, the HAAM is expected to perform complex operations within fields such as setting start points for a field operation, optimising and monitoring implement performance and is not constrained to pre-programmed 'tramways' or paths within the field. Finally, being an unstructured environment, the task is not fixed and the machine is expected to perform a variety of operations and implement basic level intuition. Such examples of tasks within an unstructured environment may include: filling up with chemicals or seeds; travelling on roads to access fields; initialising, undertaking and completing field work and returning to a 'home station' for refuelling or maintenance.

Conversely, structured environments require limited automation, given a tightly defined operating scope. This domain requires a HAAM to operate within well-defined environments with minimal requirements for 'long-term' problem-solving and intuition; most tasks relate to resolving imminent, low-order situations such as maintaining speed; changing gears under loads; automated controls of 3-point hitch and hydraulic valves and basic-level obstacle detection. For structured environments, the tractor has minimal requirement for intuition and will typically halt and alert the operator should an unexpected scenario or obstacle be identified. Typical tasks for a HAAM operating within a structured environment include: driving up and down fields, following pre-programmed paths; following exact procedures when approaching a headland; alerting the operator when an unexpected scenario occurs or once a task has been completed.

1.2 Application of Research

The expected outcome of this research is to establish relevant and comprehensive testing protocols for comparative assessment of autonomous tractors. Given there are no current performance standards applicable to autonomous tractors, this research aims to produce independent recommendations for new industry standards.

The benefits of this research are three-fold:

- An open and transparent process is developed to assess and compare the field-readiness of autonomous machinery before being released.
- Farmers can make informed choices regarding the purchase of autonomous tractors from an unbiased source.
- This work will ultimately inform globally-accepted, standardised testing of autonomous machinery in agriculture.

1.3 Project Aim

Drawing from previous research on HAAM (outlined within ISO 18497) and autonomous vehicles (outlined within both SAE J3016 and ISO 17757), the research will consolidate and expand upon these principles. Therefore, this project is expected to deliver highly relevant, comparative testing procedures to assess the field readiness and performance of an autonomous or semi-autonomous tractor.

1.4 Project Objectives

The objectives of this research are as follows:

A. Determine machine requirements relative to existing standards and capabilities

B. Develop a series of tests to assess a machine relative to standards and requirements and assess the testing methodology and relevance with respect to standards

C. Pilot the developed testing procedures by evaluating a John Deere 6120R with ASAT capabilities

D. Develop a recommended assessment and grading system to convey information from tests in a standardised and concise format.

Chapter 2

Review of Literature

2.1 Summary

The purpose of the following literature review is to analyse and evaluate issues pertaining to autonomous vehicles and machinery, together with their safety and specific performance objectives. Although the research and development of autonomous tractors continues to grow, there appears to be no universally-accepted standards or tests that manufacturers can comply with. Current research on automated machinery delivers pertinent results (albeit somewhat disparate) from a relatively new area of development. While individual research conducted is comprehensive, no over-arching connections have been established in an attempt to standardise autonomous farm machinery. It should be noted that some sections within this review have been extracted from a literature review completed as part of ENG4110 Assignment 3.

2.2 History

Published research on autonomous agricultural machinery dates back to 2001 (Blackmore et al 2001), yet there is an absence of recent research specifically conducted for the requirements and standards of autonomous tractors. Blackmore was a prominent researcher in taxonomising control systems architecture for autonomous tractors during the embryonic stages of industry development (Blackmore et al 2004). However, his initial research has been rendered somewhat out-dated – being superseded by technological developments of John Deere (through the creation of iTEC and AutoTrac Turn Automation (ATTA) – a system that allows a range of tractor functions to be automated through GPS co-ordinates), Kubota (who prototyped small autonomous tractors and combines in 2017 (Michal 2018)) and other leading tractor manufacturers.

Furthermore, due to lack of consumer demand and reluctance to implement new, radical technology on farms (primarily due to legal and safety implications) (Rovira-Más 2010), research involving fully-autonomous, row-crop tractors moved at a relatively slow pace. Since the successful introduction of driverless cars, interest in autonomous farm machinery has reignited (BigAg 2018). However, researchers acknowledge that fully operational autonomous machinery (particularly at the commercial level) continues to be in its developmental stages and further work must be undertaken to realise the practical viability of implementation in real-world applications (Emmi et al 2014; Baillie et al 2018).

2.3 Fundamentals of Autonomous Tractors

2.3.1 Control Architecture

The behavioural characteristics and fundamentals of autonomous tractors are detailed within research conducted by Baillie et al (2018), Vougioukas (2005) and Blackmore (2002), with the latter outlining the required behaviours of a driverless tractor, presented below in Table 2.1.

Table 2.1: Operational behaviours for autonomous tractors

Behaviours	***Description***
Explore	A behaviour that extracts information from the unknown local environment to populate the GIS.
Implement Task	A behaviour that is executed by the attached implement whilst carrying out the assigned task.
Refuelling	A specialised form of navigation back to a base station.
Navigation	The process of moving safely to a required position at a given time.
Route Planning	The static process (once only) that analyses all the a priori information to determine the waypoints of a route to the destination.
Detailed Route Planning	The dynamic process of identifying the best route to the next waypoint (being modified by information from *Object Tracking*).
Object Tracking	The dynamic process of tracking the closest object to the tractor.
Watching and Waiting	The tractor is doing nothing. The sensors and communications wait for input.
Self-Check	A process that runs all the time in the background. It checks to see if all the parameters of the tractor are nominal. It keeps a log file and reports abnormalities.
Safety	Consists of different levels according to the existing situation.
Request to Start	The behaviour from power up of the tractor and before it moves into any other mode. All systems are reset and checked before continuing.
Request to Stop	This behaviour indicates that the system is ready for power off. It will be a terminal behaviour requiring that the power be shut off. During this process, the tractor may also put all the mechanical components into a safe neutral position.

For a fully-autonomous tractor to perform effectively in a working environment, the above ‘low-level behaviours’ must be executed when required and should change depending on the situation and/or task performed. Consequently, the developed testing procedures should exploit and assess a number of the above behaviours.

Vougioukas expanded upon these basic principles to develop a state-based diagram of the required control system. Both pieces of research underline the magnitude of complexity involved within an autonomous tractor and the need for effective communication of information between control agents. This allows a system to operate purely from the input of information that correlates directly to a specific behaviour. Such a behaviour network is presented in Figure 2.1 below (Vougioukas et al 2005). As a result, testing procedures should aim to exercise all states required to complete various field operations, in addition to assessing the performance of interconnecting protocols/control agents.

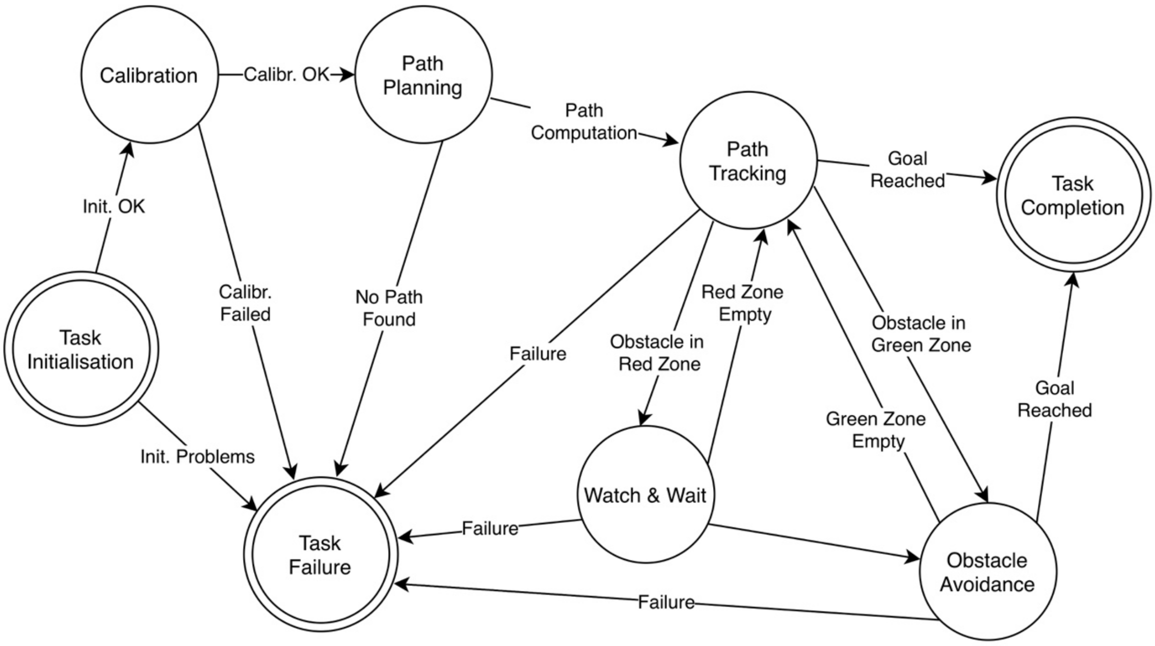


Figure 2.1: State-based diagram outlining behaviours and transitional requirements

While Blackmore and Vougioukas focus on the information-processing of the control system, Eaton et al (2008) research the concepts of 'Precision Farming Data Sets' (PFDS) and 'Precision Agriculture Data Sets' (PADS) in order to categorise various parameters involved in precision farming operations. Given PFDS encompass the permanent parameters of the field/farm environment (such as field boundaries and contour maps), PADS relate to the everchanging parameters of the field/crop itself (for example, soil and environmental conditions). It is common for farmers to manually configure PFDS by dictating field boundaries and contours – parameters that, once initiated, can be left alone. PADS, however, are typically recorded during harvest or spraying operations and are stored for later analysis (such as strategic crop-planning and variable-rate application maps).

2.3.2 Performance Objectives

Effective comparative testing criteria for autonomous tractors should include clear and specific performance objectives. Since 1920, the Nebraska Tractor Test is still the only standardised test available for assessment of mechanical capabilities of tractor performance, complying with codes outlined by the Organisation for Economic Co-operation and Development (Nebraska Tractor Test Laboratory 2019). The purpose of this test allows the comparison of functions between different makes and models of tractors. The testing procedure disseminates technical information, such as fuel consumption, power per weight ratio, hydraulic capabilities and sound level. Grisso et al (2009) emphasise the importance of correct selection and specification of tractors to ensure continued viability of farming enterprises.

However, the Nebraska Tractor Test only focusses on assessing mechanical tractor performance, without assessing usability or control capability. Although not universally accepted, Desai (2012) builds upon these usability requirements through the inclusion of row-width adaptation, manoeuvrability and ‘operate-by-wire’ capabilities of row-crop tractors.

Blackmore et al (2004) recommend the following attributes be exhibited by an ASAT when operating in small-scale farming environments:

- Behave in a safe manner, even when partial system failures occur
- Capable of being co-ordinated with other machines
- Exhibit long-term sensible behaviour
- Receive instructions and communicate information
- Ability to carry out a range of useful tasks

Further refining the aforementioned attributes, Baillie et al (2017), outline the following technological features that represent key components for tractor autonomy:

- Automated tractor guidance
- Variable-rate technology
- Drive-by-wire functionality
- Sensing (Perception)
- Performance optimisation
- Path planning
- Machine-to-machine communication
- Process monitoring
- Telematics
- In-field communications
- Data infrastructure

From the above literature, it can be deduced that although there are specific comparative tests for mechanical tractor performance, together with outlines/recommendations for autonomous tractor attributes, there are currently no published tests that consolidate both aspects.

2.4 Implementation of Autonomy within Car Industry

In drawing parallels with the car industry, where an increasing number of vehicles are equipped with greater levels of autonomous functions, the development of commercially-viable autonomous tractors is following suit (More 2019). According to the Society of Automotive Engineers, driving automation can be classified into six distinct levels – ranging from Level 0 (providing warnings and momentary assistance only) to Level 5 (providing complete driverless capabilities in all conditions) (SAE International 2018). A graphical representation of this recommended categorisation (SAE J3016) can be viewed below in Figure 2.2.

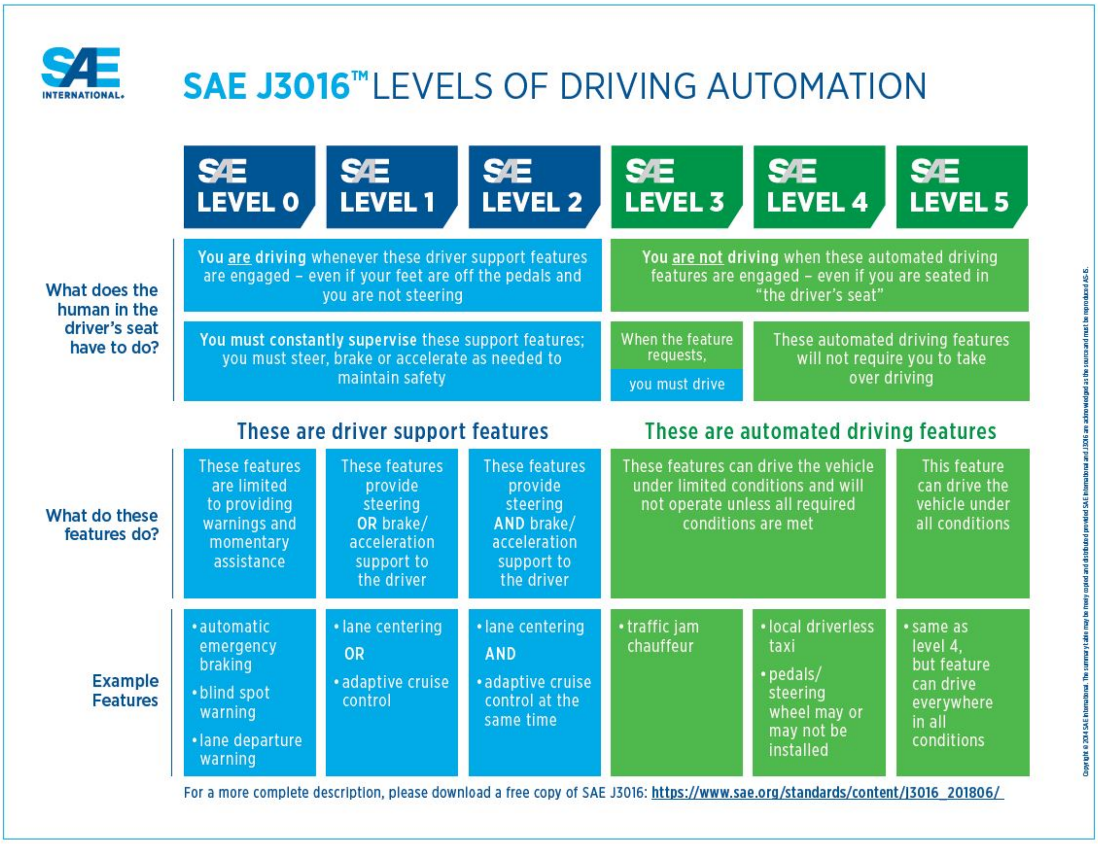


Figure 2.2: Graphical representation of SAE J3016 (SAE International 2018)

J3016 provides a useful framework for ascertaining levels of driving automation. However, it would be necessary for autonomous tractors to comply with Level 4 or above to meet the required level of automation to be considered 'autonomous'. With best-in-class John Deere tractors equipped with AutoTrac Turn Automation (ATTA) (with the ability to steer, adjust throttle and control the implement, prior to performing an automated end-of-row turn, albeit with required human confirmation), the current Level of driving automation for farming machinery is at SAE Level 3. To advance to Level 4, the tractor must be able to operate with no human intervention (i.e. no human confirmation required prior to executing a headland turn).

A further categorisation of operational features is included within the U.S. Department of Transport's Framework for Automated Driving System (Thorn et al 2018). Incorporating aspects from J3016, an evaluation matrix assesses the various autonomous driving systems against current technologies. This enables a succinct and comprehensive overview of included functions within the autonomous system – a system that this project will hopefully implement to present the results of the comparative tests. Figure 2.3 shows the results of the *Toyota Guardian* driving system – which scores a mark of 4:7 – with the '4' indicating Level 4 of SAE J3016 and '7' representing the number of autonomous functions, from a total of 16. By presenting the test results as two digits, an understanding of the vehicle's autonomous capabilities can be quickly ascertained and understood.

ADS Feature and Tactical and Operational Manoeuvres X = Demonstrated ? = Speculated	**Commercially Available? (Y/N)**	**Level of automation (SAE 1-5)**	Parking	Maintain Speed	Car Following	Lane Centring	Lane Switching/Overtaking	Enhancing Conspicuity	Merge	Navigate On/Off Ramps	Follow Driving Laws	Navigate roundabouts	Navigate Intersection	Navigate Cross Walk	Navigate work Zone	N-Point Turn	U-Turn	Route Planning
Toyota Guardian	N	4		X	X	X	X	X		X	X							

Figure 2.3: Example of evaluation matrix used to assess the Toyota Guardian software (Thorn et al 2018)

However, Brown and Laurier (2017) highlight the dangers of autonomous systems within the automated car industry. Their research investigates the pitfalls of auto-pilot systems, including an over-reliance on the system and consequential de-skilling of the driver. While the paper focusses on applications within the automotive industry, such concepts can also be applied to agricultural machinery.

The automation required to operate road vehicles is further simplified through the refinement of the ODD. While the vehicle must be attentive in recognising potential threats (such as pedestrians, slowing of traffic and avoiding miscellaneous obstacles), the operating environment, as a whole, is expected to remain fixed and predictable – driving on roads within a well-defined/documented, structured environment (Barker 2015). This allows technology to focus primarily on accurately following a pre-determined path and obstacle avoidance, without the need to adapt to ever-changing landscapes or control the vehicle/implement under challenging conditions – present within agriculture and mining applications.

2.5 Implementation of Autonomy within Mining Industry

Given the scale and longevity of mining operations, autonomy lends itself well to this sector. Spurred by efficiency and productivity, with reduced attention to outlay costs, mining companies have been able to capitalise upon the benefits offered by automated and autonomous operations (Towers-Clark 2019).

In practice, BHP states autonomous blast-hole drilling operations have increased productivity by 25%, whilst reducing maintenance costs by more than 40% (BHP 2019). The company also reports an 80% reduction in haul truck incidents and an autonomous rail network that can transport 270 million tonnes of iron ore annually (BHP 2019).

While such companies are adopting more automated/autonomous operations, hybrid practices (whereby human operators work alongside automated machines) are also becoming more prevalent within the workplace (Brooks 2018). These operations allow a single operator to control multiple machines, or allow repetitive tasks to be managed by the machine while the operator focusses on higher-level tasks. Such an example of a wide-scale hybrid system is Rio Tinto's operation centre, based in Perth, Western Australia. Within the centre, operators are able to oversee various automated operations across the Pilbara region from one, centralised location (seen in Figure 2.4) (Rio Tinto 2020). Additionally, a more individual example of hybrid systems within the mining industry includes the interaction of human excavator drivers with autonomous haul trucks (Figure 2.5). For the purposes of this project, both 'hybrid' and 'semi-autonomous' control modes will be explored/exploited and assessed.

Figure 2.4: Rio Tinto's Operations Centre (ABC News 2019)

Figure 2.5: Loading of autonomous haul truck (AUS HeavyQuip Journal 2019)

Operating environments evident in mining industries are also be applicable to the agricultural sector. Such similarities include scale of operations, delicate manipulation of powerful and heavy machinery, exposure to dust and climatic conditions, execution of monotonous tasks and the mantra of 'larger equipment resulting in greater efficiency'. Ultimately, autonomous systems employed in mining and agricultural environments must be able to adapt to continually changing landscapes, with the main sources of navigation being provided by pre-defined digital terrain maps (DTM).

2.5.1 ISO 17757:2019

One of the main ISO standards that governs the automation and autonomous vehicular operations within the mining industry is ISO 17757:2019 – "*Earth-Moving Machinery and Mining – Autonomous and Semi-Autonomous Machine System Safety*" (International Organization for Standardization 2019). This standard outlines the various systems and performance metrics required by an autonomous or semi-autonomous machine (ASAM) in order to operate safely within a mining environment, including interactions with other objects/personnel within its vicinity, possible hazards, machine controls and associated protocols. Such systems are outlined below:

- Braking performance of a manned machine is measured by the time taken from actuation of the brake pedal until the machine comes to a complete halt. Conversely, braking time of an ASAM is determined by the time taken from receiving the 'brake' command to complete stopping of the machine.

- Steering system requirements within the standard refer extensively to ISO 5010:2019 (*Earth-Moving Machinery – Steering Requirements*). However, attention is drawn to the periodic checking of steering capabilities, performed either autonomously or by the operator. These checks are undertaken according to a pre-determined risk-assessment and the period/method of checks are adjusted to suit the risk environment. Should the steering system fail to meet the criteria of the self-test, the machine should enter a safe/idle state.

- Protocols when dealing with adaptations to environmental conditions are also contained within the standard. Provided changes to the operating environment are within identified constraints, the ASAM should be able to adapt accordingly. Methods of adaptation may include automated or manual changes to: operating speeds, disabling of certain operations, restricting areas of operation, or other adjustments that ensure safe operation of ASAM.

- Various requirements and risks associated with ASAM navigation systems are also highlighted within the standard. The navigation system should be able to use absolute or relative positioning methods to navigate either a predetermined or dynamically determined path to accomplish the ASAM's objective. When operating within its specified environment, the machine must be able to maintain a heading and speed. The machine should also be able to detect if it satisfies the specific requirements and accuracy of the task (in other words, have a closed-loop feedback system). If the accuracy exceeds the acceptable threshold, the ASAM should halt and enter a safe/idle state. Risks that may present an issue to navigation primarily stem from inaccurate local or absolute positioning and orientation, imprecise navigation control, poor path-planning or inaccuracies within the DTM.

- Positioning and orientation systems are also discussed – highlighting particular risks (such as collisions with other machines, damage to the ASAM itself and incorrect/misaligned DTM), failure modes and requirements of such systems. Failure modes identified within the standard include:
    - Inaccurate absolute positioning (using global positioning systems)
    - Inaccurate relative positioning (using local positioning systems)
    - Inaccurate orientation
    - Inaccurate registration to DTM
    - Inability to determine position, orientation or registration

  Furthermore, the standard requires the ASAM to be aware of the positioning system status (including error probability and precision of measurements) and to enter a safe/idle state, should the system operate with insufficient precision or accuracy.

Additionally, the standard includes a form to verify conformity to the specified requirements of the standard. Performance is recorded and *"Complete"* is inserted into the right-hand column with the successful completion of the test. *"See document number …"* can be added, as required, for the provision of additional information. This style of documentation will be implemented to record results of the developed testing procedures. An extract of the ISO 17757 Check List can be viewed below:

Clause	Requirement	Conformance check list
	After an ASAM is placed in the halted state, operator intervention shall be required to restart machine motion.	
4.2.3	When risk assessment shows a need, ASAMS shall be equipped with an additional remote stop system which is distinct from the all-stop system specified in 4.2.2.	

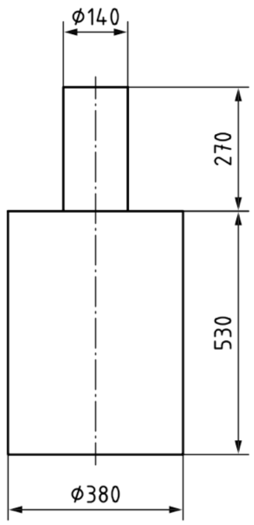
Figure 2.6: Extract of Conformance Check List

2.6 Current Standards and Tests for HAAM

One of the most pertinent documents currently available relates to ISO Standard 18497:2018 (International Organization for Standardization 2018). Released in 2018, this standard details required safety measures to be implemented by HAAM. The purpose of this document is to specify safety parameters and outline verification and validation processes associated with the relevant safety systems. The standard also provides valuable information pertaining to specific safety protocols (for example, 'loss of communication' and 'engine fault' procedures). A further value of ISO 18497 relates to the identification of failure modes and possible risks to the system (for example, occluded obstacles and difficult environmental/weather conditions). The standard also outlines three different types of safety standards, categorised as follows, where Type-C takes precedence:

- Type-A – Basic design (hardware and software) and safety standards pertaining to general aspects
- Type-B – Generic safety requirements (including surface temperatures, safe distances, interlocking devices and guards)
- Type-C – Machinery specific standards for particular machines

Moreover, ISO 18497 details the specific verification procedures necessary to conduct accurate tests that wholly comply with the standard. Such specifications include testing on flat, paved surfaces; recording of date, time and climatic conditions and the use of a standardised test object (as outlined in Figure 2.7 below, showing two different sized cylinders mounted one atop the other) when testing the obstacle detection capabilities of the machine:



a) the dimensions given by the figure to the left (dimensions in mm).

b) test obstacle shall be filled with water to represent the composition of the human body.

c) material shall be plastic, e.g. polyethylene with a matte surface.

d) the colour shall be olive green with matte surface

Figure 2.7: Test object specification to be used as an 'obstacle' during testing (International Organization for Standardization 2018)

Furthermore, the standard also highlights safety requirements of HAAM – particularly for hybrid systems where the operator remains inside the cab. Attention is focussed on the protocols and requirements involved when the operator assumes control and overrides the automated control system. Within the document, the means for enabling and disabling highly automated operations are to be:

- Easily identifiable
- Readily accessible – including remote emergency stops for driverless scenarios
- Guarded against unintentional actuation

Expanding upon these principles, the standard also dictates that overriding of HAAM functions must also be permitted by deliberate activation of controls, such as steering, braking and implement control (including PTO, hydraulics and 3-point hitch).

Additionally, ISO 18497 outlines methods for verification and testing of a HAAM which will be implemented when designing the test procedures. To comply with the standard, testing of automated functions can be achieved through the following means:

- <u>Inspection</u>
  Using human senses, with no reliance on specialised inspection equipment

- <u>Practical tests</u>
  Testing the machine in both normal and abnormal operating conditions, implementing three modes of practical testing:
  - Fault-injection testing (such as disconnecting hardware)
  - Endurance testing (completing the same test repeatedly)
  - Performance testing (determining the performance of the HAAM using predefined metrics for measurable outcomes)

- <u>Measurement</u>
  Comparing documented parameters against actual, measured values

- <u>Simulation</u>
  Modelling the machine and subjecting it to simulated operating conditions prior to verifying results using actual data from practical testing

- <u>Observation during operation</u>
  Observing the functions of the machine for correct operation with rated payload, overloaded scenarios and in challenging environmental conditions

- <u>Examination of circuit diagrams and software</u>
  Executing a structured walkthrough and/or review of technical diagrams and documentation (including software code) of the HAAM

2.7 Safety Aspects of Autonomous Tractors

As autonomous tractors and associated safety issues are still in the developmental stage, published statistics relating to autonomous tractor accidents are not widely available. However, a correlation may be established with respect to industrial robot accidents. Vasic and Billard (2013) identify a range of incidents deemed harmful to the operator within the industrial workplace. Their research broadly corresponds to the risks identified within ISO 18497 (including crushing, impact and entanglement hazards). Vasic and Billard's research also outlines the percentage break-down of personnel injuries when working with robots; with 72% of injuries affecting the operator, while programming and maintenance workers account for the remainder.

Vasic and Billard's findings also include a taxonomy of accidents involving robots within the industrial workplace, as detailed in Figure 2.8.

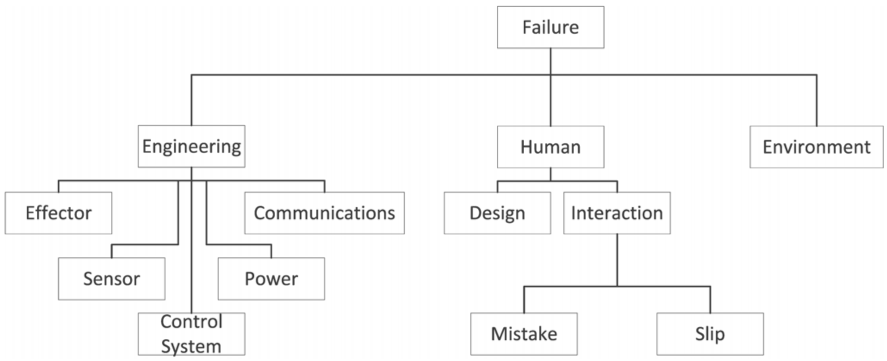


Figure 2.8: Taxonomy of failure mechanisms with respect to human-robot interactions (Vasic and Billard 2013)

Consequently, the comparative tests (developed within later sections of this report) should focus on subjecting the ASAT to the above failure modes, prior to recording the subsequent results – allowing for comparison between various ASATs.

The importance of safety between humans and robots is reiterated within the research of Heinzmann and Zelinsky (2003), where safety guidelines are outlined as follows:

Requirement 1: Designed so humans and robots can safely co-exist in the workplace

Requirement 2: Human operator must fully comprehend and predict motion of the robot

Requirement 3: Collision with a human should not result in serious injury

The article also covers 'motion bandwidth limits' (similar to defining the ODD) – whereby the motion of the robot is reduced when travelling in certain directions. This allows for predictability of the robot's motion and consequently, permits the operator to take evasive action to avoid collision.

2.8 Graphical Summary of Literature

The above literature review, focussing on the automation practices implemented within the aforementioned industries, can be summarised by the following Venn Diagram (Figure 2.9). It should be noted that all sectors lacked applied, standardised testing procedures and relied on a rigidly defined ODD which may not be applicable across the entire sector.

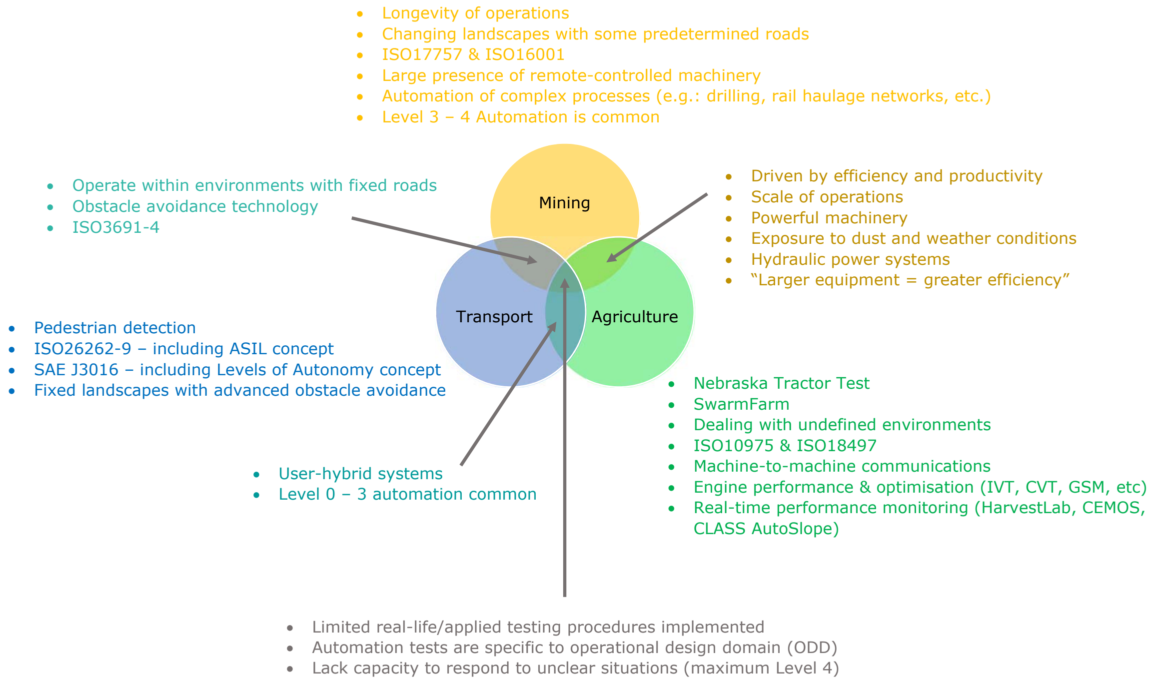


Figure 2.9: Venn diagram summarising literature and relationships between sectors

2.9 Knowledge Gap & Study Justification

Upon reviewing the literature, there was an opportunity to compare and analyse the tests currently available for tractors, HAAM and autonomous cars. Given 'fully autonomous tractors' are not currently included within the scope of ISO 18497 nor SAE J3016, a significant knowledge gap exists. Therefore, the focus of this project will endeavour to research and develop testing protocols and recommend standards for the safe and effective operation of autonomous and semi-autonomous tractors (ASAT).

Based on the literature review, it is considered the project is both achievable and valid. Findings derived from this research will benefit the agricultural industry in providing comparative tests to ascertain levels of performance for ASAT – benefiting both tractor manufacturers and purchasers of such equipment.

Chapter 3

Methodology

This chapter shall comprise the conceptualisation, development and analysis of the proposed comparative test protocols for the assessment of ASAT performance. The information within this chapter shall draw upon information gleaned from the literature review to both comply and build upon existing standards and knowledge. The testing protocols developed within this section will inform the execution of experimental tests within Chapter 4.

3.1 Research Focus

The project draws from the research and current standards of the transport, mining and agricultural industries, whilst employing similar and feasible methodologies. In doing so, this section outlines the research aim, prior to defining the scope of the investigation.

3.1.1 Research Aim

The aim of the conducted research is to develop standardised, comparative testing protocols in order to assess the performance and functionalities of ASAT. Analysis of the developed protocols will ensure validity and appropriateness of the test. Ultimately, the outcomes of the research will allow individuals to ascertain levels of practical suitability of ASATs, prior to deployment on farms.

3.1.2 Research Scope

Due to the holistic nature of this project and HAAM/ASATs in general, the scope of this research is narrowed sufficiently to allow comprehensive testing and analysis. To accomplish this, the ODD is restricted and specific use cases identified.

3.1.2.1 Refinement of Operational Design Domain

As outlined within Chapter 1.1.2, the ODD of HAAM/ASAT can be categorised into either structured or unstructured environments. Given the limited time, labour and resources allocated for this dissertation, in addition to the maturity of current ASAT technology, the decision was made to conduct the research using machinery functioning within a structured environment. This ensures a definitive list of testing protocols (based on expected tasks) that can be executed in a specific, standardised and repeatable format. Operating in a structured environment, the tractor shall be provided with relevant PFDS prior to execution of automated field operations – including designation of field boundaries, headland areas, track bearing/spacing, maximum in-field speed and maximum turning speed/angle.

3.1.2.2 Actions to be Performed within a Structured Environment

As a result of performance testing protocols being limited to 'Structured Environments' ODD, a list of expected operations that the tractor should be expected to perform, must be compiled (drawing from research by both Blackmore et al (2004) and Baillie et al (2017)). Such operations are to include tasks that a tractor would typically perform in routine broad-acre farming operations. To ensure repeatability and standardisation of the tests, testing procedures shall be kept simplistic and will avoid reliance on exclusive testing areas (such as earthen embankments, large concreted areas or specific soil composition).

3.2 Project Methodology

Given the scope of the research, the methodology of the project is decomposed into the following tasks/stages:

1. Fully define and detail ODD for proposed testing procedures

2. Ascertain a list of tasks that an ASAT should be capable of performing within the specified ODD, grouped according to operational functions of a tractor

3. Determine criteria for a successful test protocol

4. Determine required metrics and test procedures to measure performance of each task

5. Compare test procedures against criteria developed in Stage 3

6. Restrict list of tasks and procedures based on current ASAT available

7. Implement test procedures using CAE ASAT as a case study

8. Refine test procedures by incorporating lessons learned from case study

9. Present recommended test procedures for assessing ASAT performance

These tasks are outlined in greater detail within the next section.

3.3 Task Analysis

3.3.1 Fully Defining ODD

As outlined previously, the ODD for the testing of ASAT will be restricted to a 'Structured Environment'. Within this setting, limited automation is required (thereby simplifying test procedures) as the machine is to operate within a structured, fixed and well-defined environment. This ODD will therefore assume the following:

- The path of the tractor is pre-programmed – either a linear heading or a DTM
- The tractor follows exact, pre-programmed procedures when approaching the headland
- Operator moves the tractor into and out of the field and initialises implement prior to activation of automated system
- The tractor alerts the operator once the task has been completed or if an unexpected scenario occurs (including engine alerts, detection of obstacles, requests to take control and general machine faults)

3.3.2 Ascertaining Tasks to be Completed by ASAT

The list of tasks must include scenarios that the tractor is expected to perform within typical field operations and present within a *structured environment* ODD. Such operations may include:

- Perception
- Automated tractor guidance (ATG)
- Headland management
- Overriding of autonomous operations

These operations are expanded upon within the following pages, with associated tasks and requirements listed under these operational headings. It should be stressed that although more tasks could be listed, the practices are limited to operating within the aforementioned ODD.

3.3.2.1 Perception

Perception and safe operation of the ASAT relates to the machine's ability to understand both its own operation and the environment it is working within. Much of this operation relies on the machine being able to sense its environment through the use of real-time data collecting equipment (such as GPS, cameras and sensors). Consequently, the effect of impeding such systems by simulating challenging environments shall also be examined – as per Blackmore's autonomous tractor attributes (2004).

- Self-perception
  - Changing gears to maintain speed under load
  - Know location and orientation within field
  - Know boundaries of field
  - Awareness of machine operational status (including fault checking)

- Obstacle detection
  - Detect static and dynamic obstacle in driving and turning path
  - Detect static and dynamic obstacle in implement working width
  - Effectiveness of traction control – including ability to determine if the tractor is stuck/bogged or skidding
  - Detection of earthen obstacles, including berms, ruts, ditches, rocks
  - Detect impact with unforeseen obstacle

- Obstacle avoidance
  - Smallest detectable obstacle at a certain distance
  - Braking reaction time (following protocol of ISO 17757)
  - Compliance of warning and alert systems in relation to ISO 18495 and ISO 17757

- Effects of Environmental Conditions

  Detection of static and dynamic ISO 18497 obstacle in machine path under the following conditions:
    - Rainfall
    - Mist/fog/snowfall
    - Dust cloud
    - Sun glare
    - Poor light conditions (such as night-time)
    - Obscured sensors due to mud/dust/water/ice

3.3.2.2 Automated Tractor Guidance

One of the main operations a row-crop tractor is expected to perform, relates to the traversing of fields whilst performing various operations. Consequently, ATG has been developed to guide the tractor using pre-programmed pathways. While ATG may be effective in favourable conditions, the technology will also be subjected to more challenging environments within these testing procedures.

- Path Following
    - Linear headings
    - Curves and custom paths
    - Accuracy
    - Repeatability
    - Ability to perform in both forward and reverse directions

- Performance of ATG under various conditions, including:
    - Implement loading
    - Unbalanced load
    - Undulating terrain
    - Independent braking

3.3.2.3 Headland Management

Once the tractor travels the length of a field, it must be able to slow down, raise the implement, turn around, align with the next pass and re-engage the implement. While functions like ATG allow for navigating a pre-determined path, headland management solutions (such as John Deere's ATTA) must be implemented to allow the tractor to work across the entire field. Other, more basic, parameters will also be tested to allow comparison of the tractor's mechanical turning constraints.

- Lifting and lowering of implements
- Ability to adjust ground speed
- Ability to engage/disengage PTO
- Ability to engage/disengage differential lock
- Turning and aligning with next path
- Ability to execute various turning procedures (such as lightbulb, skip-row, P-turn, etc.)
- Required headland width
- Turning circle
- Maximum steering angle

3.3.2.4 Overriding of Autonomous Operations

While automation of tractor procedures can be viewed as both beneficial and safe, there are occasions where the operator must assume control to avoid potential collisions, preserve the health of the machine or during miscellaneous events where manual control must be exercised. Additionally, the ASAT must be able to alert the operator about engine faults or deteriorating performance of the machine.

- Disabling of automated systems, including:
    - ATG
    - Headland management procedures
    - Automated field operations
    - PTO
    - Cruise control
    - All-stop / Emergency stop

- Engine fault alerts and alarms
    - Low fuel
    - Oil pressure
    - Hydraulic oil levels
    - Engine temperature
    - Ambient temperature
    - Loss of load/implement

- Associated fail-safe protocols for the above points – particularly for hybrid-systems where user input or intervention is typically required

3.3.3 Criteria for Successful Test Protocol

In order to develop precise test protocols, criteria must be established to measure the success of a test procedure. Consequently, a test protocol shall include the following attributes:

Repeatable: The test shall be able to be repeated to ensure accuracy of results and ability to be conducted at different locations.

Measurable: The test shall assess metrics that are easily measured, in order to provide numerical and qualitative results that can be compared.

Applicable: The test shall accurately and precisely assess the relevant performance metric to ensure components of typical tractor operations are tested.

Attainable: The test shall be easily completed and not require exclusive or extensive resources to perform the assessment.

Succinct: The test shall be straight-forward in nature, focussing on the relevant performance metric, and be able to be completed within an acceptable timespan.

Pertinent: The test shall be able to remain current and appropriate as technology of ASAT advances.

Safe: The test shall ensure risk is at a manageable level for the operator, test assessors and the ASAT itself.

Once each test procedure is determined, the above criteria will be applied to ensure the test is valid for the specific operation being assessed.

3.3.4 Test Procedures to Measure Performance of each Task

This section will outline the test procedures required to measure the performance of the ASAT against each task. A comprehensive risk assessment can be viewed in the following sub-chapter (Sub-Chapter 3.5).

3.3.4.1 *Perception* Test Procedures – ***TEST A***

- SELF-PERCEPTION
    - **Changing gears to maintain speed under load (TEST A.1)**
      The tractor will be travelling at a set speed, prior to engagement of a field cultivator (or similar implement) to provide a resistance force – thereby compelling the tractor to alter the transmission to maintain the set ground speed.

    - **Know location and orientation within field (TEST A.2)**
      The tractor's positioning system will be referred to whilst moving across a field (both laterally and longitudinally) **(TEST A.2-i)**.

      Additionally, the tractor will be turned in a circle to ensure the positioning system updates orientation appropriately **(TEST A.2-ii)**.

    - **Know boundaries of field (TEST A.3)**
      The tractor shall be set on a 'collision course' with a virtual boundary and the actions recorded **(TEST A.3-i)**.

      The same test will be executed in a manual control mode and actions recorded **(TEST A.3-ii)**.

      Additionally, passable yet non-arable boundary protocols will be assessed by driving through such areas – the implement should disengage yet the tractor shall continue through the area **(TEST A.3-iii)**.

    - **Awareness of machine operational status (TEST A.4)**
      The tractor shall alert the operator to any faults within the control system, such as disconnected hardware or uninitialized/uncalibrated software. To test this, components of the control system (such as cameras, sensors, global positioning receivers or implement harnesses) will be disconnected and the tractor started **(TEST A.4-i)**.

      Additionally, the machine shall be able to remain in a safe, idle state until a command is given by the operator **(TEST A.4-ii)**.

- OBSTACLE DETECTION

    - **Detect static and dynamic obstacle in driving and turning path (TEST A.5)**

      An obstacle (manufactured according to ISO 18497 *specifications) shall be placed in front of the tractor's driving path and the distance measured from the object to the stopped tractor* (**TEST A.5-i**).

      The same obstacle shall then be placed in the tractor's headland turning path and the distance measured from the object to the stopped tractor (**TEST A.5-i**).

      The obstacle shall then be dragged (upright, using a rope or similar technique, at a speed comparable to a human walking) in front of the tractor's driving path and the distance measured from the object to the stopped tractor (**TEST A.5-iii**).

      The same set-up shall then be used in the tractor's headland turning path and the distance measured from the object to the stopped tractor (**TEST A.5-iv**).

    - **Detect static and dynamic obstacle in implement working width (TEST A.6)**

      Repeat **TEST A.5** (**TEST A.5-i** *through* **-iv**) *using a tractor and implement (connected by either the draw-bar or* 3*-point hitch). The implement working width shall be configured within the ASAT control system prior to commencement of the test. Should the implement make contact with the obstacle, the result is considered a 'fail'.*

    - **Effectiveness of traction control (TEST A.7).**

      The tractor shall be subjected to muddy or slippery environments whereby the tractor is expected to get bogged, skid or slip. This test shall be conducted in wide, open fields and the assessor shall halt the test if the ASAT is not making progress in escaping the challenging situation (unable to make traction) or is causing excessive damage to the test site (such as creation of deep ruts etc.) (**TEST A.7-i**).

      The tractor will then be subjected to a half-and-half scenario where one half of the tractor is experiencing wheel slip, while the other side retains traction (to assess automatic locking of differential) (**TEST A.7-ii**).

- Detection of earthen obstacles (TEST A.8)

  The tractor will be set on a 'collision course' with small berms, ditches and rocks with similar appearance/colour to the surrounding ground.

  NOTE: *It is the responsibility of the operator/assessor to exercise judgement in whether the tractor is permitted to continue driving over an obstacle, should the system not recognise it as an hazard.*

- **Detect impact with unforeseen obstacle (TEST A.9)**

  The tractor shall be forced to collide with an obstacle (by either obscuring the cameras or sensors, or presenting the machine with an obstacle it cannot detect) and the outcome recorded once collision occurs.

- OBSTACLE AVOIDANCE

  - **Smallest detectable obstacle at a certain distance (TEST A.10)**

    The tractor will be presented with various sizes of obstacles until the system can no longer detect the object. Gleaned from ISO 18497*, the obstacles will be painted matte 'olive green', positioned* 10 m *from the front of the tractor (long-side vertical), on a uniform, level surface – such as a bitumen or dirt road, concrete surface or grassy field. The dimensions of the obstacle start at* 500 x 400 mm *and decrease* 50 mm *each iteration; for example:*

    500 x 400 mm (largest obstacle)

    450 x 350 mm

    ...

    150 x 50 mm (smallest obstacle)

    The smallest size of obstacle, successfully detected, will then be recorded.

  - **Braking reaction time (following protocol of ISO 17757) (TEST A.11)**

    Following the protocols outlined within ISO 17757*, the braking reaction time is the time taken from the control system sending the 'brake' command (or operator actuating the brake pedal/emergency stop) until the machine comes to a complete stop. Although* ISO 17757 *recommends the test be conducted at* 40 km/h*, the speed will be adjusted to* 12 km/h *due to the typically lower field speed of tractors compared to mining haul trucks. While most field operations occur at speeds of* 8-9 km/h *(Powell 2019), a higher speed will be used during testing to allow for a greater factor of safety.*

- **Compliance of warning and alert systems (TEST A.12)**
  In relation to ISO 18495 *and* ISO 17757*, the ASAT shall be equipped with visual and audible alarms. Visual indicators (such as coloured strobe lights) must be visible from a safe distance, from any side of the ASAT* **(TEST A.12-i)**

  Audible alarms should be used for critical faults, requiring operator intervention, yet also recommended for engine start, pre-movement and when reversing. **(TEST A.12-ii)**

- EFFECTS OF ENVIRONMENTAL CONDITIONS

The test obstacle from ISO 18497 *shall be positioned in front of the tractor's driving path and the distance from the obstacle to the stopped tractor will be measured under the following simulated conditions:*

- **Rainfall (TEST A.13-i)**
  Test is performed during a rainfall event or water hoses/sprinklers are used to simulate rainfall

- **Mist/fog/snow (TEST A.13-ii)**
  Test is performed during misty/foggy/snowfall conditions or translucent material is placed over cameras and sensors to limit visibility.

- **Dust cloud (TEST A.13-iii)**
  Test is performed during misty/foggy/dusty conditions or a garden blower is used to disperse fine soil or dust particles into the air immediately in front of the tractor.

- **Sun glare (TEST A.13-iv)**
  Test is performed during sunrise or sunset, with the tractor directly facing the sun. Should this prove impractical, flashlights are to be shone into the cameras and sensors.

- **Poor light conditions (TEST A.13-v)**
  Test is performed at night-time (after 'golden-hour' and twilight), using only the lights of the tractor (typically used during night-time operations) to illuminate the area.

- **Obscured sensors from environmental conditions (TEST A.13-vi)**
  Test is performed with the following items smeared or covering the sensors and cameras: mud, dust, water, ice (or where temperatures do not permit freezing, translucent sandwich bags or 'cling film' can be used instead).

3.3.4.2 ***Automated Tractor Guidance*** **Test Procedures –** ***<u>TEST B</u>***

The following tests are to be conducted on either a flat, fine tilth field or a large concreted area, with an accurate (± 10 mm) method of marking where the tractor has travelled. Such methods of marking could include a sand-trail dropper, chalk marker, scratching the surface with a single-tined implement, spray paint or using the tyre tracks themselves.

- PATH FOLLOWING

  - **Linear headings (TEST B.1)**
    The tractor is provided with a start point and a heading prior to driving down the specified line. Once complete, the tractor drives the same path, yet in the opposite direction. Accuracy is calculated by determining the distance difference between the two passes. **(TEST B.1-i).**

    The tractor is then driven to a distant area of the test site before the test is repeated on the same path and the measurements re-recorded. The repeatability of the system is calculated by determining the difference between the first set of data (from TEST B.1-i*) and the second.* **(TEST B.1-ii).**

  - **Curves and custom paths (TEST B.2)**
    Similar to TEST 2.1.1*, except the paths are pre-programmed curves. It is left to the assessor to decide how extreme the curves are, yet should be kept under 120°. Once programmed, the test protocols are to follow* TEST B.1-i *and* TEST B.1-ii. **(TEST B.2-i** and **TEST B.2-ii).**

  - **Ability to follow path both forward and in reverse (TEST B.3)**
    The tractor shall complete TEST B.1-i *and* TEST B.2-i *but in reverse gear. If required, the operator shall change the 'travel direction' within the ASAT control system.* **(TEST B.3-i** and **TEST B.3-ii).**

- PERFORMANCE OF ATG UNDER VARIOUS CONDITIONS

Similar to TEST B.1-i, the tractor will travel the length of the field (recording the accuracy based on the control-system's guidance monitor), yet be subjected to the following conditions:

  - **Load (TEST B.4)**
    The tractor will be connected to a chisel plough (or an implement that provides similar resistance), before being driven along the pre-defined track. The load should be balanced, therefore the implement shall have all tines/chisels in working order and/or be symmetrically configured.

  - **Unbalanced load (TEST B.5)**
    Similar to TEST 2.2.1*, except the load is to be unbalanced. To accomplish this, chisels/tines shall be disabled from one half of the implement, while the other side remains engaged.*

  - **Undulating terrain (TEST B.6)**
    The tractor will be driven over a line of sandbags (filled to provide a cross section area of 130 x 370 mm*) at varying angles of incidence to simulate a range of undulation severity:* 90°, 75°, 60°, 45°, 30°, 15° *and parallel (with one side of the tractor riding on the sandbags).*

  - **Independent braking (TEST B.7)**
    The tractor will be driven down the specified track, however independent braking will be applied to determine the effect of unequal wheel speeds/torque. This simulates occasions where the operator has to manually adjust wheel speeds due to spinning of the rear wheels (and when locking of the differential is unavailable) or front axle steering is impractical.

3.3.4.3 *Headland Management* Test Procedures – ***<u>TEST C</u>***

- HEADLAND OPERATIONS

  - **Lifting and lowering of implements (TEST C.1)**
    The tractor shall raise and lower the implement, via either the 3-point linkage **(TEST C.1-i)** *or hydraulic controls* **(TEST C.1-ii)**, *as it enters and exits the headland respectively.*

  - **Ability to adjust ground speed (TEST C.2)**
    The tractor shall adjust its ground speed accordingly to allow the tractor to perform a U-turn before accelerating once aligned with the next pass.

  - **Ability to engage/disengage PTO (TEST C.3)**
    The tractor must be able to both engage and disengage the PTO as it enters and exits the headland.

  - **Ability to engage/disengage differential lock (TEST C.4)**
    The tractor must be able to both disengage and engage the rear-wheel differential lock as it enters and exits the headland respectively.

  - **Turning and aligning with next path (TEST C.5)**
    The tractor (or at least, the implement) must successfully align with the next pass by the time the ASAT exits the headland. An example is outlined below in Figure 3.1:

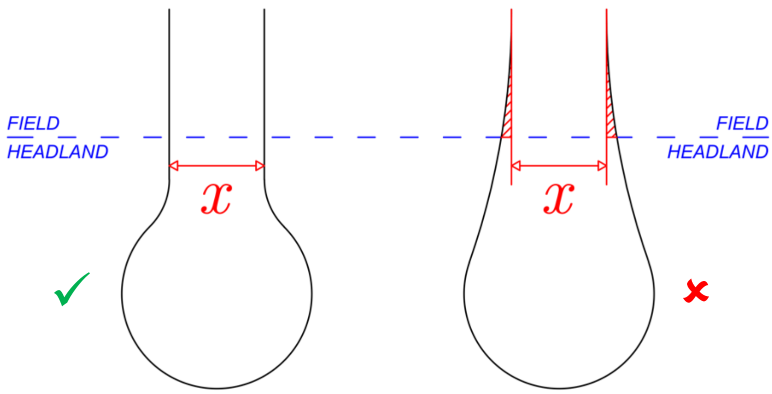


Figure 3.1: Correct and incorrect alignment with subsequent pass

- **Ability to execute various turning procedures (TEST C.6)**
  The tractor shall allow various formats of turns to be conducted within the headland, depending on turning circle, headland width, implement length and requirement of balanced drafts. Such turning formats include: lightbulb turns, P-turn and skip-row (outlined below in Figure 3.2):

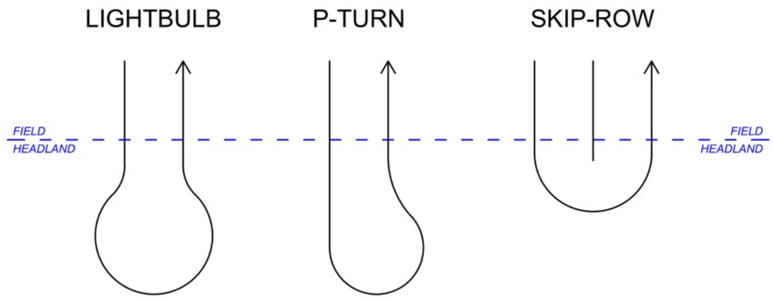


Figure 3.2: Examples of different turning formats

- **Required headland width (TEST C.7)**
  The required headland width will be calculated based upon the length and width of the implement, the jack-knife angle of the tractor-implement connection, and type of turn being executed.

- MECHANICAL TURNING CONSTRAINTS

    - **Turning circle (TEST C.8)**

      The turning circle of the tractor will be calculated by determining the distance between the centre of the turn and the centre of the outermost front wheel, as illustrated in Figure 3.3. To achieve this, the position of the front right wheel is marked before executing a 180° left turn. Once aligned with the initial marker, another marker is placed at the same wheel before measuring the distance between markers. The width of the front wheel is subtracted before the distance is divided by two to yield the turning radius.

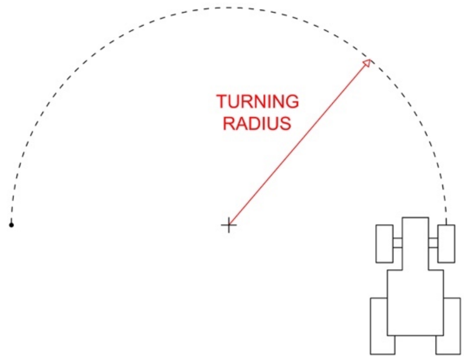


Figure 3.3: Illustration of a tractor's turning radius

    - **Maximum steering angle (TEST C.9)**

      The maximum steering angle is calculated by measuring the angle the wheel makes with the chassis of the tractor (equal to the supplementary angle of the front wheel in relation to the rear wheels). Figure 3.4, below, summarises this measurement:

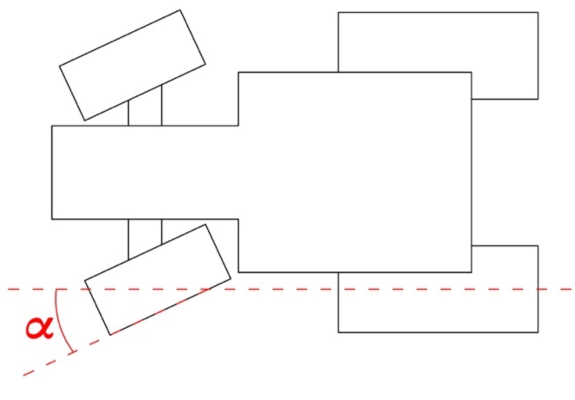


Figure 3.4: Maximum steering angle

3.3.4.4 *Overriding Autonomous Operations* Test Procedures – ***TEST D***

In accordance with ISO 18497, the machine shall allow the operator to override the ASAT system unhindered. Additionally, the machine shall also be aware of its operational status and implement procedures in response to engine faults, alerts and alarms.

- ENABLING/DISABLING OF AUTOMATED SYSTEMS

Each component of the ASAT will be assessed against the following criteria for both enabling and disabling each system (As per ISO 18497*):*

A. Easily identifiable
B. Readily accessible
C. Guarded against unintentional actuation

The relevant systems shall be enabled from a safe, idling position and disabled whilst autonomous systems are operational and/or the ASAT is in motion.

- **Automated tractor guidance** **(TEST D.1)**
- **Headland management procedures** **(TEST D.2)**
- **Automated field operations** **(TEST D.3)**
- **PTO** **(TEST D.4)**
- **Cruise control** **(TEST D.5)**
- **Obstacle detection and avoidance** **(TEST D.6)**
- **All-stop / Emergency stop** **(TEST D.7)**

- ENGINE FAULT & ALERT MANAGEMENT

The ASAT shall be aware of various engine faults and have fail-safe protocols defined for each of the following alarms or faults:

- **Low fuel level** **(TEST D.8)**
- **Oil pressure** **(TEST D.9)**
- **Hydraulic oil levels** **(TEST D.10)**
- **Engine temperature** **(TEST D.11)**
- **Ambient temperature** **(TEST D.12)**
- **Loss of load/implement** **(TEST D.13)**

The procedure for the above tests will be executed by inspecting the manufacturer's datasheet and/or user's manual for the particular machine (in compliance with ISO 18497:2018 Section 5.2 – *Verification Methods).*

3.3.4.5 *Parameters of Testing*

For each test, certain measurements or qualitative data must be collected to allow comparison between different brands and models of ASAT. For each test, both the results and a brief description, comment or pertinent observations shall be recorded – similar to the procedures outlined in ISO 17757. Table 3.1, below, summarises each measurement (including units of measurement) required for each test:

Table 3.1: Required parameters for each test

TEST	REQUIREMENT	MEASUREMENT
TEST A: PERCEPTION		
A.1	Changing gears to maintain speed	Maximum change of speed when load is applied (km/h)
A.2-i	Know location within field	Do the latitude and longitude measurements update to match the current position of tractor? (✓/✗) If so, what is the resolution of the measurement? (Number of decimal places*)
A.2-ii	Know orientation within field	Does the heading measurement match with the direction of the tractor and does it update as the tractor performs a 360° turn? (✓/✗) If so, what is the resolution of the measurement? (Number of significant digits)
A.3-i	Protocols when approaching virtual boundary of a field (under ASAT control)	Does the tractor stop before crossing the boundary threshold? (✓/✗) If so, what are the protocols?
A.3-ii	Protocols when approaching virtual boundary of a field (under manual control)	Does the tractor stop before crossing the boundary threshold? (✓/✗) If so, what are the protocols?
A.3-iii	Protocols when approaching virtual, non-arable boundary of a field	Does the tractor disengage the implement, prior to crossing the boundary? (✓/✗) If so, what are the protocols?
A.4-i	Detection of faults within hardware and software	Can the tractor detect non-operational hardware when disconnected or uncalibrated? Can the tractor be set into an autonomous mode while faults are present? (✓/✗)
A.4-ii	Maintain safe, idle state	Once the tractor has entered a safe state (either manually enforced or from a fault), can it maintain a safe state until a command is given from the operator? (✓/✗)
A.5-i	Detecting static obstacles in driving path	Distance from stopped tractor to obstacle, once obstacle detected (m)
A.5-ii	Detecting static obstacles in turning path	
A.5-iii	Detecting dynamic obstacles in driving path	
A.5-iv	Detecting dynamic obstacles in turning path	
A.6-i	Detecting static obstacles in implement driving path	
A.6-ii	Detecting static obstacles in implement turning path	
A.6-iii	Detecting dynamic obstacles in implement driving path	
A.6-iv	Detecting dynamic obstacles in implement turning path	
A.7-i	Testing of traction control – fully bogged or spinning	Does the tractor engage certain measures to free itself? If not, can it successfully enter a safe, idle state? (✓/✗)
A.7-ii	Testing of traction control – half bogged or spinning	

* for reference, 7 decimal places provides 11.1 mm of accuracy, while 8 decimal places allows for 1.11 mm

A.8	Detect earthen obstacles	Can the tractor successfully identify and avoid collision with berms/ditches/rocks etc? (✓/✗) If so, what is the detection distance? (m)
A.9	Detect impact with unforeseen obstacles	Does the tractor halt once collision with an obstacle, undetected by cameras/sensors, is detected? (✓/✗)
A.10	Smallest detectable obstacle	What is the smallest detectable obstacle the tractor can recognise (dimensions of smallest, pre-defined obstacle recorded)
A.11	Braking reaction time	Time taken from full application of brake pedal (or activation of emergency stop) to complete stopping of the machine (sec)
A.12-i	Compliance of visual indicators	Can the visual indicators be viewed at a safe distance, from any side of the tractor? (✓/✗)
A.12-ii	Compliance of audible alarms	Can the audible alarms be heard at a safe distance, from any side of the tractor? (✓/✗)
A.13-i	Effect of rainfall on obstacle detection	Distance from stopped tractor to obstacle, once obstacle detected (m)
A.13-ii	Effect of mist/snow/fog on obstacle detection	
A.13-iii	Effect of dust on obstacle detection	
A.13-iv	Effect of sun glare on obstacle detection	
A.13-v	Effect of poor lighting conditions on obstacle detection	
A.13-vi	Effect of obscured sensors/cameras on obstacle detection	
TEST B: AUTOMATED TRACTOR GUIDANCE		
B.1-i	Accuracy of linear heading paths	Error distance between passes (cm)
B.1-ii	Repeatability of linear heading paths	
B.2-i	Accuracy of curved/custom paths	
B.2-ii	Repeatability of curved/custom paths	
B.3-i	Accuracy of linear heading paths when driven in reverse	
B.3-ii	Accuracy of curved/custom paths when driven in reverse	
B.4	Accuracy of ATG under balanced load conditions	Error distance reported on tractor control system monitor (cm)
B.5	Accuracy of ATG under unbalanced load conditions	Error distance reported on tractor control system monitor (cm)
B.6	Accuracy of ATG when driven over undulating terrain	Error distance reported on tractor control system monitor (cm)
B.7	Accuracy of ATG when independent braking is applied	Error distance reported on tractor control system monitor (cm)

TEST C: HEADLAND MANAGEMENT		
C.1-i	Automated lifting and lowering of implement using 3-point linkage	Can the tractor automatically lift the implement using the 3-point linkage? (✓/✗)
C.1-ii	Automated lifting and lowering of implement using hydraulic controls	Can the tractor automatically lift the implement using hydraulic controls? (✓/✗)
C.2	Automatic adjustment of ground speed	Can the tractor control its ground speed when performing a headland turn? (✓/✗)
C.3	Automated control of PTO	Can the tractor enable/disable the PTO during automated operations? (✓/✗)
C.4	Automated control of differential lock	Can the tractor enable/disable the rear-wheel differential lock during automated operations? (✓/✗)
C.5	Automated headland turn	Can the tractor perform an automated headland turn and align with the next pass? (✓/✗) If so, what is the distance between the aligned implement and the headland boundary? (m)
C.6	Execution of various turning formats	Can the tractor perform various automated turning formats? (✓/✗) If so, what formats?
C.7	Required headland turning width	Minimum headland width required to complete a U-turn of the tractor and implement? (m)
C.8	Turning circle of tractor	Distance between centre of the turn and centre of outermost front wheel (m)
C.9	Maximum steering angle	Angle of the front wheel in relation to the tractor chassis (degrees)
TEST D: OVERRIDING OF AUTONOMOUS OPERATIONS		
D.1	Manually overriding ATG	Are the manual measures for overriding the system: Easily identifiable? (✓/✗) Readily accessible? (✓/✗) Guarded against unintentional activation? (✓/✗)
D.2	Assuming control of automated headland management	
D.3	Assuming control of automated field operations	
D.4	Assuming control of automated PTO control	
D.5	Manually overriding cruise control	
D.6	Manually overriding obstacle detection and avoidance	
D.7	Activation of 'all-stop'/emergency stop	
D.8	Awareness of low fuel levels	Can the tractor determine if fuel is critically low? (✓/✗)
D.9	Awareness of low oil pressure	Can the tractor determine if the oil pressure is lower than expected? (✓/✗)
D.10	Awareness of low hydraulic oil levels	Can the tractor determine if hydraulic oil levels are low? (✓/✗)
D.11	Awareness of excessive engine temperatures	Can the tractor determine if the engine is overheating? (✓/✗)
D.12	Awareness of extreme ambient temperatures	Can the tractor determine if the ambient temperature exceeds normal operating temperatures? (✓/✗)
D.13	Awareness of load/implement loss	Can the tractor determine if the load or implement has been lost? (✓/✗)

The above table provides the basis for the testing checklist and recording of performance. Once the tests are refined, this table shall be converted into a document, suitable for use by an assessor.

3.3.5 Comparing Test Procedures Against Criteria

This section will compare the test procedures outlined in Chapter 3.3.4 against the protocol testing criteria, developed within Chapter 3.3.3. The following table (Table 3.2) will summarise the success of each test, and where required, a comment regarding the performance or requirements of the procedure.

Table 3.2: Assessment of Test Procedures against Protocol Criteria

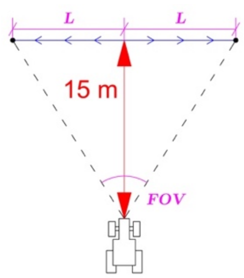
Test	Repeatable	Measurable	Applicable	Attainable	Succinct	Pertinent	Safe	**VERDICT**	Comments
A.1	✓	✓	✓	✓	✓	✓	✓	✓	
A.2-i	✓	✓	✓	✓	✓	✓	✓	✓	
A.2-ii	✓	✓	✓	✓	✓	✓	✓	✓	
A.3-i	✓	✓	✓	✓	✓	✓	✓	✓	Care should be taken to ensure the 'virtual' boundary provides no actual danger to the ASAT or operator, should the machine cross the threshold.
A.3-ii	✓	✓	✓	✓	✓	✓	✓	✓	Care should be taken to ensure the 'virtual' boundary provides no actual danger to the ASAT or operator, should the machine cross the threshold.
A.3-ii	✓	✓	✓	✓	✓	✓	✓	✓	
A.4-i	✓	✓	✓	✓	✓	✓	✓	✓	
A.4-ii	✓	✓	✓	✓	✓	✓	✓	✓	
A.5-i	✓	✓	✓	✓	✓	✓	✓	✓	Emergency stop must be easily accessible, should the tractor fail to detect the obstacle.
A.5-ii	✓	✓	✓	✓	✓	✓	✓	✓	As above.
A.5-iii	✓	✓	✓	✓	✓	✓	✓	✓	As above.
A.5-iv	✓	✓	✓	✓	✓	✓	✓	✓	As above.
A.6-all	×	✓	✓	×	✓	✓	✓	×	Given the varying widths of farming implements, the test is deemed non-repeatable nor attainable. Consequently, the test shall be redesigned to avoid reliance on non-standardised implement widths.
A.7-i	×	✓	✓	✓	✓	✓	✓	✓	As muddy conditions cannot be accurately repeated, the assessor must use their discretion to ensure the tractor is subjected to conditions where it is expected to get bogged.
A.7-ii	×	✓	✓	✓	✓	✓	✓	✓	As above.
A.8	×	✓	✓	×	✓	✓	✓	×	While applicable, it is expected that the operator has surveyed the field for such obstacles prior to enabling the ASAT.
A.9	✓	✓	✓	✓	✓	✓	✓	✓	The obstacle shall be subjected to situations where an impact is certain. As a result, the object should be robust and an emergency stop must be accessible, should the tractor fail to detect the obstacle.
A.10	✓	✓	✓	✓	✓	✓	✓	✓	
A.11	✓	✓	✓	✓	✓	✓	✓	✓	Assessor should exercise caution when performing the braking tests
A.12-i	✓	✓	✓	✓	✓	✓	✓	✓	
A.12-ii	✓	✓	✓	✓	✓	✓	✓	✓	
A.13-i	✓	✓	✓	✓	✓	✓	✓	✓	Assessor shall NOT stand in driving path while simulating environmental conditions. Emergency stop must be easily accessible, should the tractor fail to detect the obstacle.
A.13-ii	✓	✓	✓	✓	✓	✓	✓	✓	As above.
A.13-iii	✓	✓	✓	✓	✓	✓	✓	✓	As above.
A.13-iv	✓	✓	✓	✓	✓	✓	✓	✓	As above.
A.13-v	✓	✓	✓	✓	✓	✓	✓	✓	As above.
A.13-vi	✓	✓	✓	✓	✓	✓	✓	✓	As above.
B.1-i	✓	✓	✓	✓	✓	✓	✓	✓	
B.1-ii	✓	✓	✓	✓	✓	✓	✓	✓	
B.2-i	✓	✓	✓	✓	✓	✓	✓	✓	
B.2-ii	✓	✓	✓	✓	✓	✓	✓	✓	
B.3-i	✓	✓	✓	✓	✓	✓	✓	✓	
B.3-ii	✓	✓	✓	✓	✓	✓	✓	✓	
B.4	✓	✓	✓	✓	✓	✓	✓	✓	
B.5	✓	✓	✓	✓	✓	✓	✓	✓	
B.6	✓	✓	✓	✓	✓	✓	✓	✓	
B.7	✓	✓	✓	✓	✓	✓	✓	✓	

C.1-i	✓	✓	✓	✓	✓	✓	✓	✓	Attachment to an implement is optional – test can be conducted using no implement.
C.1-ii	✓	✓	✓	✓	✓	✓	✓	✓	As above, however hydraulic valves are to be closed/bypassed if no implement is used.
C.2	✓	✓	✓	✓	✓	✓	✓	✓	Manual control shall be exercised, should the tractor not slow down to a suitable speed, prior to turning.
C.3	✓	✓	✓	✓	✓	✓	✓	✓	Attachment to an implement is optional – test can be conducted using no implement, however, PTO guard must be in place.
C.4	✓	✓	✓	✓	✓	✓	✓	✓	
C.5	✓	✓	✓	✓	✓	✓	✓	✓	
C.6	✓	✓	✓	✓	✓	✓	✓	✓	
C.7	×	✓	×	×	✓	✓	✓	×	Given the number of variable parameters, the test is deemed too complex to achieve.
C.8	✓	✓	✓	✓	✓	✓	✓	✓	
C.9	✓	✓	✓	✓	✓	✓	✓	✓	
D.1	✓	✓	✓	✓	✓	✓	✓	✓	
D.2	✓	✓	✓	✓	✓	✓	✓	✓	
D.3	✓	✓	✓	✓	✓	✓	✓	✓	
D.4	✓	✓	✓	✓	✓	✓	✓	✓	
D.5	✓	✓	✓	✓	✓	✓	✓	✓	
D.6	✓	✓	✓	✓	✓	✓	✓	✓	
D.7	✓	✓	✓	✓	✓	✓	✓	✓	
D.8	✓	✓	✓	✓	✓	✓	✓	✓	No attempts shall be made to run the tractor empty of fuel.
D.9	✓	✓	✓	✓	✓	✓	✓	✓	No attempts shall be made to run the tractor with insufficient oil pressure.
D.10	✓	✓	✓	✓	✓	✓	✓	✓	No attempts shall be made to run the tractor with low hydraulic levels.
D.11	✓	✓	✓	✓	✓	✓	✓	✓	No attempts shall be made to manually overheat the tractor.
D.12	✓	✓	✓	✓	✓	✓	✓	✓	The tractor shall not be tested out-with its specified ambient operating temperatures.
D.13	✓	✓	✓	✓	✓	✓	×	×	While applicable, it is assumed the operator has correctly attached the implement and included safety chains.

From the above table, it can be deduced that the majority of the tests pass the attributes required by a standardised, comparative test. Of the four procedures that did not pass, two failed due to testing scenarios that were outside the ODD (Test A.8: *Detection of Earthen Obstacles* and Test D.13: *Loss of Load/Implement*) while the remaining two related to testing protocols that were dependent on the parameters of an unspecified/non-standardised implement (Test A.6: *Detection of Obstacles in Implement Working Width* and Test C.7: *Required Headland Width*). However, Test A.6 can be redefined, using the field-of-view to allow the operator to determine suitability of the ASAT. The redefined test is as follows:

Field-of-view for obstacle detection (TEST A.6)

The ISO 18497 *obstacle shall be placed* 15 m *from the front of the tractor and offset laterally until the ASAT can no longer detect the obstacle. The offset distance will be measured and the field-of-view (FOV) calculated as shown in Figure 3.5:*



$$FOV = 2 \cdot \tan^{-1}\left(\frac{L}{15}\right)$$

Figure 3.5: Diagram and equation for calculating FOV

3.3.6 Restricting Tests Based on Available ASAT

As limited technology and machinery are available for use in this dissertation, the aforementioned tests are limited to ensure pertinent test procedures can be successfully executed.

USQ CAE currently possesses two John Deere tractors: a 4066R utility tractor (Figure 3.6) and a 6120R row-crop tractor (Figure 3.7). For the purposes of this dissertation, the 6120R is used as a case study, due to more advanced autonomous capabilities and appropriateness to the study (as row-crop tractors are more common within farming businesses, compared to utility tractors). Additionally, the 6120R has been configured with a *StarFire 6000 GNSS Receiver* and 900 MHz RTK radio receiver, connected to CAE's Real-Time Kinematic (RTK) base station. John Deere's ATTA was also activated within the tractor control system – allowing semi-autonomous headland turns to be executed.

Figure 3.6: John Deere 4066R utility tractor

Figure 3.7: John Deere 6120R row-crop tractor

As no 'fully-autonomous' tractors are available for testing, the following tests have been omitted from the list compiled in Section 3.3.4:

- Obstacle Detection (A.5, A.6 & A.12)
- Obstacle Avoidance (A.9 & A.10)
- Effects of Environmental Conditions (A.7 & A.13)
- Overriding Obstacle Detection/Avoidance (D.6)

While the above tests cannot be evaluated within this dissertation, due to current lack of obstacle detection technology, it is recommended that future studies (having access to tractors with greater autonomy) build upon, implement and analyse the effectiveness of such testing procedures.

3.4 Resource Analysis

The resources required for the successful completion of this project are outlined below in Table 3.3. Financial costs are also included, to ascertain the fiscal requirements of the research. It should be noted that CAE already owns the machinery, implements and land, with the main expenses being attributable to items being used in the testing itself.

Table 3.3: Resource Requirements

Resource	Cost	Source
Test area	Owned	CAE
ASAT (6120R)	Owned	CAE
Chisel plough	Owned	CAE
Traffic cones to limit access to test area	Owned	CAE
Diesel (25 litres)	$30	Project (fuel station)
Row marker	$20	Project (to fabricate)
Sandbags	$17	Project (Bunnings)
Survey Marking Paint	$7	Project (Bunnings)
GoPro Hero 4	Owned	Student
Tape measure	Owned	Student
High-visibility vest	Owned	Student
Laptop	Owned	Student
Sundries	$10	Project/Student
Total:	**$84**	

With the total cost of the project being under $100, the financial requirements of the research are considered relatively affordable. Furthermore, most items purchased (with the exception of the diesel) have uses beyond this dissertation.

3.4.1 Row Marker

For the purposes of this dissertation, a simple, single-tined implement was used to score the ground where the tractor has driven. While any implement with a single chisel or tine could be used, the decision was made to employ a pointed length of round-bar steel, inserted through the draw-bar, to accurately mark the travelled path. Being free to slide up and down within the holes of the draw-bar, this system ensures a narrow line is scored into the ground using a constant downwards pressure. The simple design guarantees the marker can be easily replicated and ensures standardisation of the test procedures.

While not crucial, an eye-bolt and string are included on the end of the marker to allow the operator to 'engage' or 'disengage' the marker from the cab, (by lifting it up when not in use). The design can be viewed below in Figure 3.8:

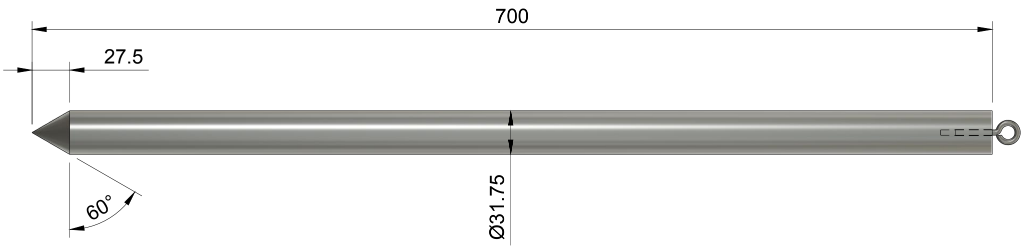


Figure 3.8: Row marker to be inserted vertically through the draw-bar (*units in millimetres*)

Other designs of the row marker included a spring-loaded drag arm and a steel 'tooth' being connected to the draw-bar via a rigid compression spring. The spring-loaded drag arm design involved a length of material with a tooth on one end being connected to the tractor body via a hinge – allowing the tractor to traverse uneven terrain without the tooth losing contact with the ground. This design also incorporated a range of locations for mounting the loading spring, to adjust the amount of downwards pressure. This design was discarded due to the 'lever effect' of the long drag arm – whereby small rotational/steering movements by the tractor would be exaggerated by the length of the drag arm – thereby generating amplified error measurements. This design can be viewed below in Figure 3.9, where the drawbar is shown in green.

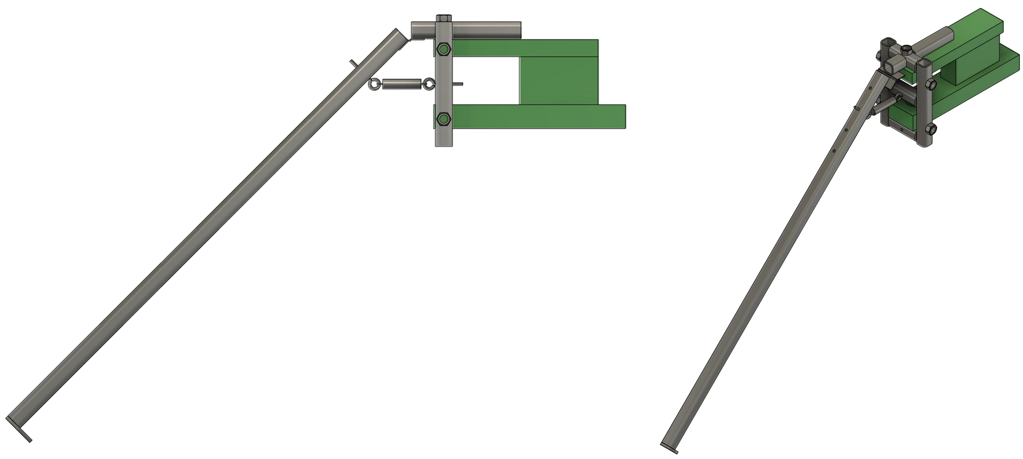


Figure 3.9: Drag-arm row marker

The subsequent design involved a compression-spring being dragged along the ground, with a steel tooth being attached to the end of the spring. This design eliminated the 'lever effect' of the previous design, and allowed adjustment of the spring's height to provide varying amounts of downwards pressure. Similar to the previous design, this concept involved attachment to the draw-bar through clamping bolts. This design was not employed, primarily due to its complex nature not complying with the 'Attainable' metric, as outlined within *Criteria for a Successful Test Protocol* (from Section 3.3.3). The proposed design can be illustrated in the below Figure 3.10:

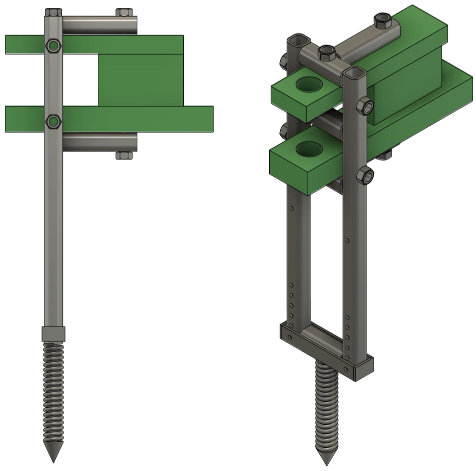


Figure 3.10: Drag-spring row marker

Consequently, the first, simple spike design (as per Figure 3.8), was selected due to its accuracy (given a point-of-contact directly below the drawbar) and simplicity (thereby allowing ease of replication). For instances where the testing procedures may be conducted on hard ground, a chalk-marker, sand dropper or concrete scoring device is recommended.

3.5 Preparation of Trial Case Study

This section illustrates the various pieces of equipment and resources implemented within the tests, and how they are configured within the testing environment.

3.5.1 Configuring Semi-Autonomous Capabilities on 6120R

Delivered in March 2020, the 6120R was initially fitted with no automated functions. To equip the tractor for semi-autonomous capabilities, a John Deere SF6000 GNSS receiver was first mounted atop the cab to provide ATG capabilities. By connecting this system to the CAE RTK base station, the tractor is able to operate with a reported repeatability accuracy of ± 2.5 cm. Deere's Intelligent Total Equipment Control (iTEC) was then installed by the local dealership to allow programming of automated field operations and programmed implement control. Once iTEC was successfully configured, ATTA was activated (via a product activation key) to allow autonomous headland turns. By implementing a combination of ATG, iTEC and ATTA, the tractor can successfully travel the length of the field in a straight line, raise the implement, execute a headland turn (180° turn), lower the implement and continue – all without operator input.

Figure 3.11: Deere 6120R used within tests, with a SF6000 Receiver mounted atop the cab

Automated Tractor Guidance was also calibrated before testing – following Deere's automatic procedure to calibrate the 'Terrain Calibration Module'. The tractor was parked in one location and data recorded, before realigning the tractor in the same location but facing the opposite direction and re-recording the results. This ensured mitigation of GPS receiver mounting errors and minute anomalies in tyre pressure etc.

3.5.2 Configuration of PFDS

Precision Farming Data Sets (PFDS) must be programmed prior to successful operation of the ASAT. For these tests, PFDS include defining the: field and headland boundaries; track bearings; travel speeds and turning speeds and headland/field operations. Field and headland boundaries were defined by driving the perimeter of the test area before applying an offset of 16 metres to the north-west and south-east edges to create headlands. The completed map can be viewed below in Figure 3.12:

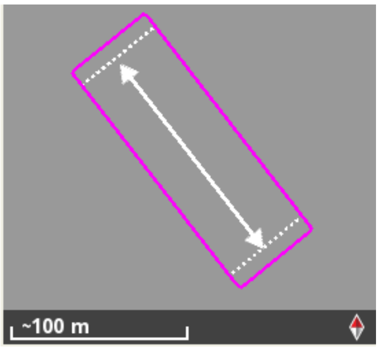


Figure 3.12: Computer generated field map (showing headland boundaries)

To program the headland protocols, sequences were defined for raising and lowering the implement. For the purposes of testing, a sequence called 'Raise Implement' would raise the rear hitch, before disengaging the differential lock and front wheel drive; 'Lower Implement' would execute the opposite. These protocols were then assigned to entering and exiting the headland, together with entering/exiting non-arable interior boundaries. Finally, field and turning speeds, together with 'turn aggressiveness' were set at the required values. Operational speeds for this project were set at 7 km/h for in-field travel, as recommended by Powell (2019), while headland turns were executed at 4 km/h – the speed at which an operator would typically/safely turn a machine with a raised implement, as per Worksafe Queensland (2018). The 'Start Turn' value was left at the default value (0.0 m), but could be adjusted to suit the particular implement and/or turn geometry. Figure 3.13 summarises the automated headland turn protocols that were programmed into the control system.

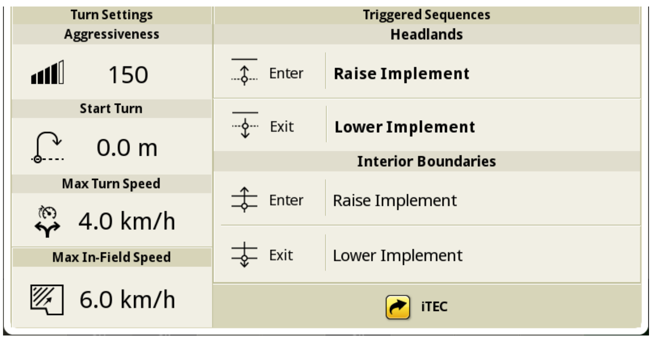


Figure 3.13: Screenshot of the automated headland management system

3.5.3 Test Area

The test area was selected as the CAE Rear Field, behind P9, at USQ Toowoomba Campus. Given the field was flat and had no immediate use, all tests were performed in one location – including execution of various tillage operations.

The ground of the test site was severely compacted due to lack of farming operations and recent construction of a bird cage (with construction equipment further compacting the soil). For instances where a fine-tilth soil was required – such as tests requiring the path to be marked with a marking spike – a small area of the test site was cultivated before project testing could commence.

To ensure the newly erected bird netting would not interfere with satellite signals, a preliminary signal test was executed. This involved monitoring the percentage of data packets collected as it travelled along the field. Furthermore, radio, Wi-Fi and cellular reception was also tested using a number of different methods. All tests concluded that the bird netting did not noticeably interfere with electromagnetic signals required for ASAT operation.

An aerial view of the test site (including the cultivated section) can be seen below in Figure 3.14.

Figure 3.14: Aerial view of test site, showing cultivated area in the lower half

To limit pedestrian access to the test site, warning signs were placed on all main entrance gates to inform individuals about the presence of autonomous tractor operations. While an operator was in the cab at all times, danger to pedestrians was further reduced by restricting access to the site, should the ASAT and/or operator fail to notice a human in the path of a tractor. These signs were printed on laminated A4 paper and can be viewed below in Figure 3.15:

Figure 3.15: Warning sign placed on all main entrances

For instances where a pedestrian was located in the test zone (such as a supervisor or spotter), they were to wear a high-visibility vest and ensure visual and/or audible contact was maintained with the tractor operator.

3.5.4 Chisel Plough / Field Ripper

To provide balanced and unbalanced loading conditions for certain tests, a chisel plough and field ripper were used. A nine-shank chisel plough was used to provide a balanced drag force, while a duck-foot field ripper was modified to produce an unbalanced/offset load on the three-point linkage (accomplished by removing two of the four shanks). Ideally, a single chisel plough was to be used for both tests; however, given the labour involved in removing four to five chisel shanks, the decision was made to simply remove two duck-foot shanks instead.

Due to severely compacted soil, the duck-foot ripper did not have sufficient ground-penetrating force (due to a larger cutting surface); consequently, the ripper was used in the cultivated section of the field to ensure sufficient loading. The heavily compacted soil also dictated that the sway-block be engaged to minimise side-to-side motion of the implement when working through heavy soils.

Images of the chisel plough, duck foot ripper and sway-block can be viewed on the following page.

Figure 3.16A-B: Nine-shank chisel plough to provide a balanced load

Figure 3.17A-B: Duck-foot ripper (noting two shanks removed) to provide unbalanced load

Figure 3.18: Sway-block (circled) engaged on rear hitch

3.5.5 Row Marking Spike

To record the travelled path of the machine, the designed marking spike was manufactured and installed on the tractor. Due to lack of appropriately-sized materials, a bushing was inserted to correctly fit the drawbar hole for the spike shaft. This reduced the tolerances between the drawbar and spike (minimising measurement variances caused by a loose fit), while also allowing for a smoother sliding motion. Figure 3.19 illustrates the final row-marking assembly:

Figure 3.19: Installed row marking spike

3.5.6 Sandbag Berm

To ensure the 'undulating terrain' was standardised and repeatable, a berm was constructed using hessian sandbags (with overall dimensions of 130 mm high by 10 m long). To ensure ease of replication, the sandbags were filled with dry dirt before being lightly compacted (by walking on them) prior to driving over them with the ASAT. The completed berm, used in the testing, can be viewed below in Figure 3.20:

Figure 3.20: Sandbag berm

The sandbags were aligned parallel to the field track bearing (142°/332°), before the track bearing was updated to suit each approach angle of Test B.6. Consequently, the sandbags were traversed at bearings of 52°, 22°, 352°, 337° and 322° for the approach angles of 90°, 60°, 30°, 15° and 0° respectively.

Upon completion of initial/'pilot' testing, it was deduced that the sandbags were not providing sufficient undulation for the ASAT to traverse. Consequently, a more aggressive contour bank was used for the second iteration of testing. While a berm could have been constructed by piling earth in a straight line, the CAE irrigation bays (constructed in the Front P9 Field) were implemented instead, due to the high degree of soil compaction and multiple contour banks located adjacent to each other. For reference, an elevation survey of the berm was conducted, to ascertain the following cross-section:

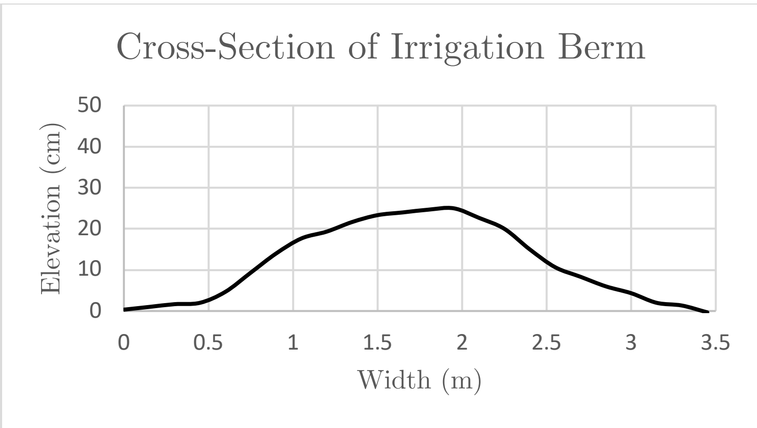


Figure 3.21: Cross-section of the P9 Irrigation Bays

An aerial image of the test site can be viewed below in Figure 3.22.

Figure 3.22: Aerial view of irrigation bays, with human for scale

3.6 Determining ATG Accuracy

Accuracy of the AutoSteer system was determined through the use of the marking-spike and/or logging the GNSS error data from the screen of the control system. For instances where the row-marking spike could not be utilised due to towing of an implement (Tests B.4, B.5 and B.6), error data was collected by logging the output of the control system.

Ideally, a standalone error-measuring system would have been implemented, to provide empirical evidence (such as separate GPS data or laser/visual markers). However, as tests must not rely on complicated or specialised equipment, it is assumed that the error logged by the control system is sufficiently accurate. This error value (situated at the top of the guidance page) can be viewed in Figure 3.23 below.

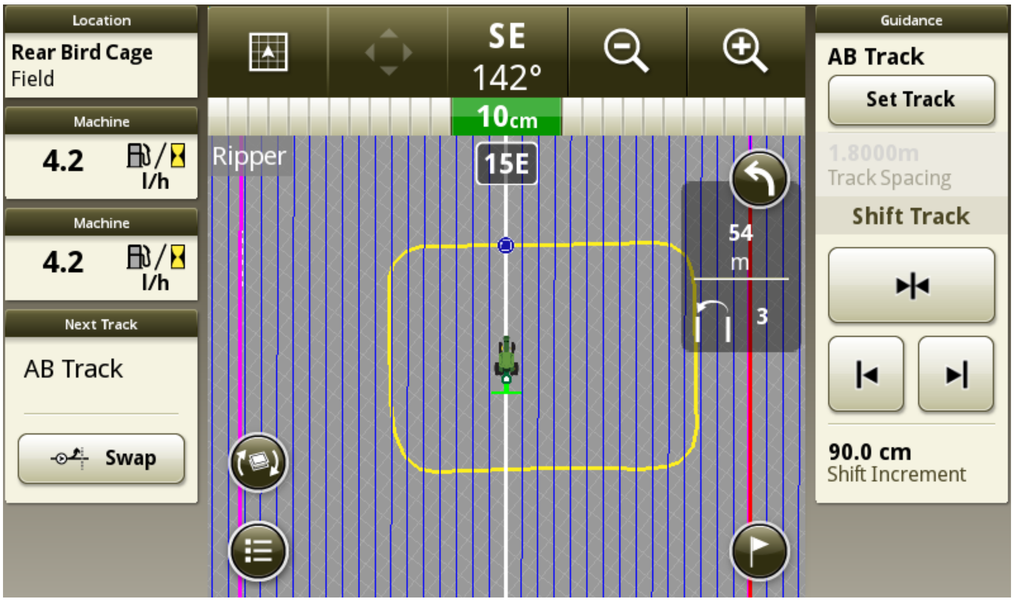


Figure 3.23: Guidance page, showing the error value as 10 cm off track

To log the data, John Deere was first approached to ascertain if ATG error values could be presented on the CANBUS – thereby allowing a CAN-Trace software to log the relevant values. Due to strict intellectual property protocols, Deere was unable to assist. Consequently, the decision was made to record the values on a video camera and log them manually by reviewing the footage at a later time.

Given its high resolution, fast frame-rate, rugged construction and wide field of view, a GoPro Hero4 was selected as the camera for recording the control screen. By mounting the camera above and behind the operator (as per Figure 3.24), the GoPro was able to capture the control screen, the surrounding environment and any operator actions (illustrated in Figure 3.25). This video footage also serves as a basis for experimental evidence, whilst also allowing review of test results.

Figure 3.24: Cab of 6120R, with the GoPro mounted on the rear windscreen

Figure 3.25: GoPro field of view - recording both interior and exterior environments

3.7 Risk Assessment

As tests were conducted on USQ CAE property, the CAE risk assessment protocol was implemented within this project. This matrix is outlined below in Figure 3.26:

	PROBABILITY	A Insignificant No Injury 0 - $5 k	B Minor First Aid $5 - $50 k	C Moderate Med Treatment $50 - $100 k	D Major Serious Injury $100 - $250 k	E Catastrophic Death > $250 k
1	Almost Certain (1 in 2)	**M**	**H**	**E**	**E**	**E**
2	Likely (1 in 100)	**M**	**H**	**H**	**E**	**E**
3	Possible (1 in 1,000)	**L**	**M**	**H**	**H**	**H**
4	Unlikely (1 in 10,000)	**L**	**L**	**M**	**M**	**M**
5	Rare (1 in 1,000,000)	**L**	**L**	**L**	**L**	**L**

CONSEQUENCE

Figure 3.26: Probability and Consequence (Wellbeing/Economic) Risk Assessment Matrix

The USQ Recommended Action Guide is as follows:

E – EXTREME RISK:	Task <u>must not</u> proceed.
H – HIGH RISK:	Special procedures required. Approved by VC only.
M – MEDIUM RISK:	A risk management plan is required.
L – LOW RISK:	Manage through routine procedures.

The following table (Table 3.4) outlines the potential safety risks present in the execution of the research task, together with residual risks, once mitigative strategies are implemented.

Table 3.4: Potential safety risks and relevant management strategies

Scenario	Risk	Risk Level	Mitigation Strategy	Residual Risk
Malfunction of ASAT control system	Vehicle collision; Pedestrian injury; Vehicle rollover; Damage to property	H (D3)	Monitor autonomous system while operating. Operator should intervene and apply brakes, should ASAT behave unexpectedly. Emergency stop easily accessible.	L (B4)
Unauthorised pedestrian entering test area	Vehicle collision; Pedestrian injury	H (D3)	Implementation of safe operating practices. Only authorised people to enter test area. Operator shall be aware of people within test vicinity.	L (B4)
Chisel plough set too deep during load tests	Failure of shear bolts; Excessive stress on plough frame; Stalling of tractor	M (A2)	Monitoring of plough depth and audible exertion of engine. Ensure human operator is trained on safe operating practices	L (A3)
Testing of tractor turning circle and traversing sandbags	Tractor rollover; Damage to property; Operator injury	H (C3)	Tractor shall slowly perform the turn test, controlled manually. Sandbag berm will be filled to an acceptable height. Operator shall approach sandbags slowly and with caution.	L (A4)

NOTE: *The submitted USQ Risk Management Plan can be viewed in Appendix E.*

While not required by USQ CAE, the risk assessment was expanded to include risks that may affect attainment of project objectives in general – not just risks affecting the wellbeing of individuals and/or assets (as previously explored). Therefore, project risks were assessed as per the previous grading system, yet potential consequences were to reflect downtime, instead of impact to wellbeing or financial standing (as per Figure 3.27 below).

CONSEQUENCE (Lost Time)

	PROBABILITY	A Insignificant < 1 Day	B Minor < 1 week	C Moderate < 1 Month	D Major 1 – 3 Months	E Catastrophic Project unable to be completed
1	Almost Certain (1 in 2)	**M**	**H**	**E**	**E**	**E**
2	Likely (1 in 100)	**M**	**H**	**H**	**E**	**E**
3	Possible (1 in 1,000)	**L**	**M**	**H**	**H**	**H**
4	Unlikely (1 in 10,000)	**L**	**L**	**M**	**M**	**M**
5	Rare (1 in 1,000,000)	**L**	**L**	**L**	**L**	**L**

Figure 3.27: Probability and Consequence (Downtime) Risk Assessment Matrix

Similar to the previous risk assessment, potential project risks and their respective mitigative strategies are outlined in the following table (Table 3.5):

Table 3.5: Potential project risks and relevant management strategies

Scenario	Risk	Risk Level	Mitigation Strategy	Residual Risk
Health complications (ranging from common cold to severe injury or illness)	Loss of productivity; Unable to produce usable concepts/ideas; Unable to type	H (C3)	Avoid contact with contagious individuals. Monitor personal health. Work on progressing project when possible. Eat well and exercise often.	M (C4)
Family emergency	Loss of productivity due to emotional distraction	H (C3)	Work on progressing project when possible. Keep up-to-date with overseas family members.	M (B3)
File corruption and/or IT failure	Loss of progress; Loss of data; Complete loss of dissertation file	E (E2)	Save frequently and to different devices. Upload regularly to cloud storage. Create new document iterations for large changes.	M (E4)
Disintegration of working relationship with USQ CAE	Denial of testing grounds; Loss of access to ASAT; Potential loss of supervisor.	H (E3)	Maintain amicable bond with all CAE staff. Appreciate the inputs that CAE offers. Communicate and act with respect and gratitude.. Contingency plans for alternative test areas. Obtain access to another ASAT.	L (E5)
ASAT technical issues	Unable to perform practical tests; ASAT unable to be accurately assessed.	E (D2)	Liaise with John Deere dealership to troubleshoot any major technical issues. Obtain access to another ASAT. Accrue sufficient practical driving time.	M (A2)
Force majeure (e.g. pandemic, flood, bushfires, cyclones)	Unable to perform practical tests; Complete loss of dissertation file	M (E4)	Save frequently and to different devices. Upload regularly to cloud storage. Obtain access to another ASAT. Contingency plans for alternative test areas.	M (C4)

Chapter 4

Experimental Testing & Results

4.1 Chapter Overview

This chapter outlines the experimental process to successfully implement and assess the proposed test protocols. All procedures followed the testing protocols outlined within the methodology section, employing the same test identification and measurement conventions.

As per Chapter 3.3.6, certain tests were excluded due to limited available technology. Tests that were appropriate for use in this dissertation are presented in a simple, easy-to-comprehend format – as presented within Appendix B.

Upon successful completion of testing, results are presented in Section 4.2 of this chapter for later analysis and discussion. Each test also includes additional commentary regarding set-up of the test, relevant observations and issues/notes regarding the testing methodology. These observations are analysed in Chapter 5 for refinement and eventual recommendation of testing protocols.

4.2 Test Results

Following the procedures outlined in Chapter 3.3.4, results from each test were first recorded in the test documentation (Appendix B) prior to being detailed as follows.

A-Series Tests – Perception Results

A.1 Maximum change of speed when load applied

By continually engaging and disengaging the implement at 6 km/h, the tractor was able to be loaded multiple times in one pass of the field. Engagement depth was approximately 250 mm in very compacted soil. By implementing reactive measures (such as selecting lower gears, increasing throttle and automated clutch controls), the onboard computer was able to minimise the effect of loading/unloading the machine.

<u>Maximum change of speed:</u> 0.5 km/h under harsh loading conditions.

A.2-i Latitude and longitude readings match current position of tractor

Observing the output of the tractor's control system, both latitude and longitude measurements update to match the current position of the machine's StarFire GNSS unit. Given lack of permanent survey markers (certain points that have been verified by other methods to produce locations with exact co-ordinate values), the test could only assess the resolution of the measurement and its ability to update to suit the tractor's current position.

<u>Latitude and longitude readings update to match the current position of tractor:</u> ✓
<u>Resolution of measurement:</u> 7 decimal places (equivalent to $\pm$ 1.11 cm)

A.2-ii Heading value updates as tractor executes a 360° turn

Observing the tractor's control system output, the heading value updates to match the current direction of the machine. While the main guidance screen presented the bearing to a whole integer, a sub-menu would allow the bearing to be presented to one decimal place.

<u>Heading value updates to match the current bearing of tractor:</u> ✓
<u>Resolution:</u> 1 decimal places (equivalent to 3600 increments per revolution)

A.3-i Tractor stops before crossing field boundary (under ASAT control)

To allow the tractor to cross the field boundary, the headland width was reduced from 16 m to 10 m – ensuring the tractor would overshoot the boundary when executing a headland turn. While both an error message (Figure 4.1) and two stages of audible alarms were implemented to alert the operator of an upcoming threshold breach, the tractor did not stop and continued to execute the turn regardless (Figure 4.2). Consequently, the operator was required to undertake evasive manoeuvres to avoid a potential collision. By failing to stop when no input was given, the tractor appears to have no 'dead-man' protocols when executing this operation.

<u>Tractor stops before crossing field boundary:</u> ✖

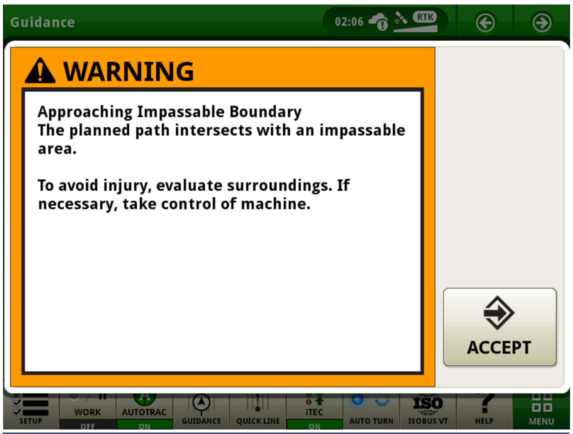


Figure 4.1: Potential collision warning message

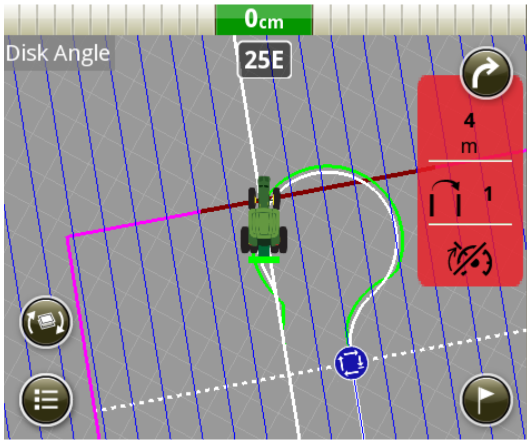


Figure 4.2: ASAT executes turn regardless

A.3-ii Tractor stops before crossing field boundary (under manual control)

To simulate the operator breaching the field threshold, the tractor was driven through the field gate with the tractor still engaged in 'field mode' – with automated systems idling but not engaged (similar to when executing a headland turn). The tractor failed to alert the operator to a potential boundary breach with no audible or visual alarms involved.

<u>Tractor stops before crossing field boundary:</u> ✖

A.3-iii Tractor raises implement when entering non-arable area

A non-arable, interior boundary was created in the middle of the test field (Figure 4.3) and the tractor driven through under ASAT control. When travelling through this area, the machine executes the pre-specified protocols (in this case, the same as when entering a headland – raising and lowering the implement – as per Figure 3.13 in Chapter 3.5.2) whilst maintaining the current ATG bearing and travel speed.

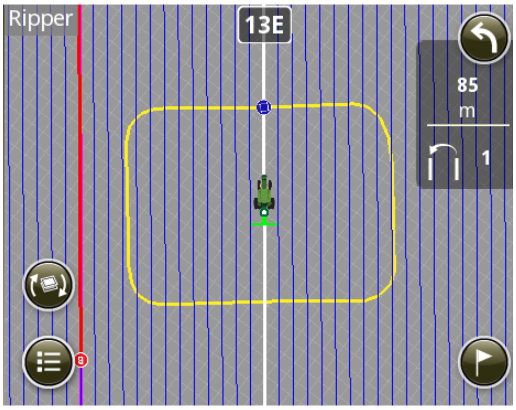


Figure 4.3: Tractor operating within non-arable area

<u>Tractor raises implement when entering non-arable area:</u> ✓

A.4-i Detect non-operational hardware when disconnected/uncalibrated Autonomous mode locked-out while faults are present

For this test, the StarFire6000 GNSS Receiver was disconnected (as per Figure 4.4) and the faults analysed. An error message was displayed and most ASAT operations (such as ATG, ATTA and awareness of field boundaries) were unable to be engaged (Figure 4.5). iTEC (automated field controls) was still operational, yet required the operator to manually press buttons to action the automated sequences.

<u>Detect non-operational hardware when disconnected/uncalibrated:</u> ✓
<u>Autonomous mode locked-out while faults are present:</u> ✓

Figure 4.4: Disconnected SF6000 Receiver

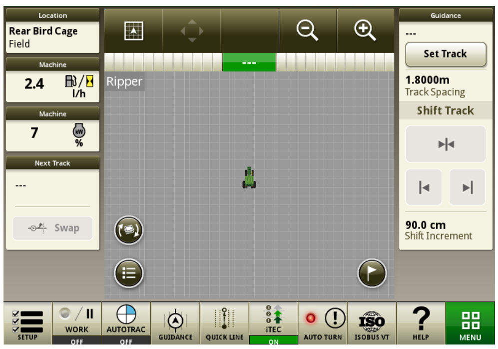


Figure 4.5: Unable to engage ATG or ATTG

A.4-ii Maintain a safe state until a command is given from the operator

The tractor can only operate autonomously when in gear (either forward or reverse). When in 'neutral' or 'park', the tractor does not move and remains in a safe, idle state. The tractor only becomes mobile and permits automated operation when the driver moves the gear selector (Figure 4.6) to forward or reverse. The gear selector itself is designed to 'fail-safe' – the selector paddle is spring-loaded to return to the neutral position if knocked out of 'park' or a gear, and stays in the desired gear by means of a detent that requires deliberate force to engage. Once in gear, the operator must manually initialise ATG, iTEC and ATTA by pressing the respective buttons on the control screen.

<u>Maintain a safe state until a command is given from the operator:</u> ✓

Figure 4.6: Gear selector (in the spring-loaded 'neutral' position)

Tests A.5 – A.10 (inclusive) omitted as per Chapters 3.3.5 and 3.3.6

A.11 Stopping time from 12 km/h

This test was conducted on both compacted grassy ground and cultivated loose soil. The chisel plough was attached on the rear hitch (to provide a load), yet not engaged in the soil. Both the 'clutch and brake' (engine clutch and brakes were engaged simultaneously) and 'brake only' (whereby the tractor would automatically engage the clutch) methods were used, and the time taken to come to a complete stop was deduced from the GoPro time stamps. All brake test produced the same stopping time of less than one second.

<u>Stopping time from 12 km/h:</u> $<$ 1 second

B-Series Tests – Automated Tractor Guidance Results

B.1-i Accuracy of linear heading paths

Tests were conducted on both compacted and cultivated soil. Following the methodology, each test was executed by driving the same path in each direction and measuring the difference between each pass (as per Figure 4.7). The row-marking spike was very effective on the compacted soil, yet tended to 'trench' on the finer tilth soil – resulting in inaccurate measurements. Consequently, measurements were taken from tests conducted on the compacted soil.

Figure 4.7: Measuring the error between passes to deduce accuracy

<u>Accuracy of linear heading paths:</u> 2 cm

B.1-ii Repeatability of linear heading paths

After performing the accuracy tests, a period of time was allowed to elapse, before returning to repeat the same tests in the same location. Differences between accuracies were then recorded. Although conducted in compacted soils, the various markings began to merge into one trench due to the repeated scoring of the ground. Three separate test tracks were used to ensure 'trenching' was kept minimal, however an accurate measurement proved difficult to obtain. Consequently, the width of the resulting trench was used as the final measurement.

<u>Repeatability of linear heading paths:</u> < 2 cm

B.2-i Accuracy of curved/custom paths

Curved paths were generated by recording the path travelled by the tractor under manual control. While multiple paths were generated (as per Figure 4.8), the shallower curves (located to the right) were used as they were recorded on the narrow section of cultivated soil – allowing the track to be marked using the row marker.

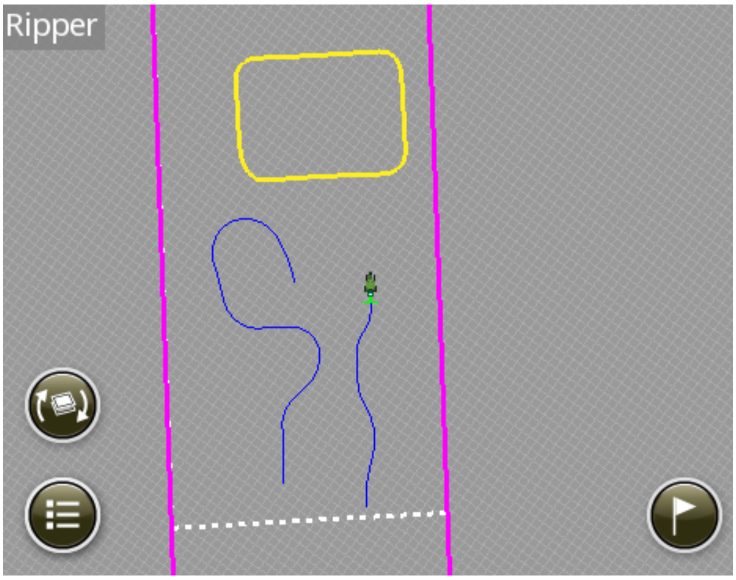


Figure 4.8: Guidance page showing both custom tracks

Completing the tests, it was observed that the sharper the turn, the lower the accuracy (witnessed in Figure 4.9 and 4.10), with gentle curves and straight sections of the path having an improved accuracy (as in Figure 4.11).

Figure 4.9: Accuracy of curved paths (with superimposed path marks)

Figure 4.10: Accuracy of curved paths (without superimposed path markings)

Figure 4.11: Marked path of a more gentle curve

As seen in the above figures, issues arose with trenching – due to both the finer soil and multiple passes. Where separate paths (evident within Figure 4.9 and 4.10) could not be determined, the width of the trench would be measured instead (seen in Figure 4.11).

Accuracy of curved/custom paths: 13 cm (maximum variance)

B.2-ii *Repeatability of curved/custom paths*

By travelling the same custom path after a period of time had elapsed, the repeatability could be determined. While the accuracy of the paths remained poor during aggressive turns, the repeatability was surprisingly accurate. Measurement issues continued to arise due to trenching – merging the tests into one wide line. Consequently, the width of each trench was used as the final measurement.

Accuracy of curved/custom paths: < 3 cm

B.3-i *Accuracy of linear heading paths when driven in reverse*

The tractor was driven to the area in which Test 2.1.1-A was performed, and set in the reverse gear. Given the integrated tractor control system, no inputs/changes were required by the operator to specify the direction of travel.

During the first 20 metres of driving in reverse, the error was approximately $\pm$ 30 cm, however, after the initial error, the tractor path appeared to stabilise at $\pm$ 2 cm. Instead of aggressively turning to the line, the ASAT slowly approached the line with minimal overshoot (similar to an over-damped response).

It was also observed that the ATG would time-out after 45 seconds when driven in the reverse gear – requiring the operator to stop the tractor and drive forwards, prior to re-engaging AutoSteer and commence reversing again.

Accuracy of linear heading paths when driven in reverse: 2 – 30 cm

---

B.3-ii Accuracy of curved/custom paths when driven in reverse

Similar to the previous test, accuracy of the ASAT when driven in reverse was lacking – with errors ranging from $\pm$ 14 cm on the straighter sections to $\pm$ 47 cm on the apex of curves. Figure 4.12 below shows the variance between a straight section (observed in the upper half of the image, towards the tractor) and the beginning of a curved section (located towards the bottom of the photo). The right-hand path was the control run (forward direction), while the left was driven in reverse. Similar to Test 2.1.3-A, the ATG timed-out after 45 seconds in reverse.

Figure 4.12: Comparison of forward vs reverse accuracy

Accuracy of curved/custom paths when driven in reverse: 14 – 47 cm

B.4 Accuracy of ATG under balanced load conditions

To simulate a balanced load on the rear three-point hitch, a chisel plough was engaged to a depth of 275 mm in heavily compacted soil. To further load the tractor, periodic engagement of the tool was trialled – engaging the tool for 10 metres before raising it for 3 metres. Even under severe loading conditions (whereby the tractor executed various reactive procedures to avoid stalling, such as automatically engaging the differential lock, dropping to a lower gear, increasing engine speed, etc.), accuracy of the ATG was not severely affected – with a maximum variance of only 2 cm.

<u>Accuracy of ATG under balanced load conditions:</u> 2 cm

B.5 Accuracy of ATG under unbalanced load conditions

Unbalanced loading was provided by engaging a duck-foot ripper with half of the tines removed. Similar to Test 2.2.1, the implement was periodically engaged and disengaged, and the response monitored. This test was originally conducted on heavily compacted soil, yet engagement of the shanks proved difficult. Therefore, the test was conducted in cultivated soil and engaged to a depth of 350 mm. Regardless, the tractor was able to maintain a reasonable accuracy, with a maximum variance of 7 cm.

<u>Accuracy of ATG under unbalanced load conditions:</u> 7 cm

---

B.6 Accuracy of ATG when driven over undulating terrain

Upon creating the sandbag berm, using compacted dirt from the test field, the tractor was then programmed with relevant bearings to intersect the berm at the required angles. The berm was driven over at 4 km/h and the maximum ATG variance recorded. Results can be viewed below in Table 4.1:

Table 4.1: Accuracy of ATG over Undulating Terrain (Sandbag Berm)

Angle of Approach	Max Error
90°	1 cm
60°	1 cm
30°	2 cm
15°	2 cm
0°	0 cm

Due to the minimal undulation offered by the sandbag berm, testing advanced to the second, more ‘aggressive’, iteration of undulation testing – using contour banks of the irrigation bays in P9 Front Field. Speed remained at 4 km/h and the ATG paths were adjusted to suit the orientation of the contour banks. The results are recorded below in Table 4.2.

Table 4.2: Accuracy of ATG over Undulating Terrain (Irrigation Bays)

Angle of Approach	Max Error
90°	1 cm
60°	11 cm
30°	8 cm
15°	6 cm
0°	2 cm

<u>Accuracy of ATG when driven over undulating terrain:</u> See Table 4.2 above.

B.7 Accuracy of ATG when independent braking is applied

Once the tractor was aligned with the path and travelling with an error value of 0 cm, independent braking was applied by depressing either the left or right wheel brake. This was completed in a periodic nature – depressing the relevant brake pedal for 10 to 20 seconds before releasing. A considerable force was applied, but not to the extent to cause the tractor to vibrate or become excessively loaded. While initial errors reached 6 cm, the ASAT was able to implement reactive measures (by steering in the opposite direction to the braked wheel) to reduce the error to 2 cm. Upon releasing the brake, the tractor experienced some degree of over-steering/overshoot – allowing the error to approach 9 cm. However, after 5 seconds, the tractor was again, fully aligned with the track.

<u>Accuracy of ATG when independent braking is applied:</u> 6 – 2 cm

C-Series Tests – Headland Management Results

To assess Tests C.1 to C.4, iTEC and ATTA control screens (Figure 4.13-A/B) were analysed and abilities of the ASAT noted. Such functions can be assigned to control buttons on the armrest, or to procedures when entering or exiting headlands. A number of abilities also had various options available – these are listed within each test.

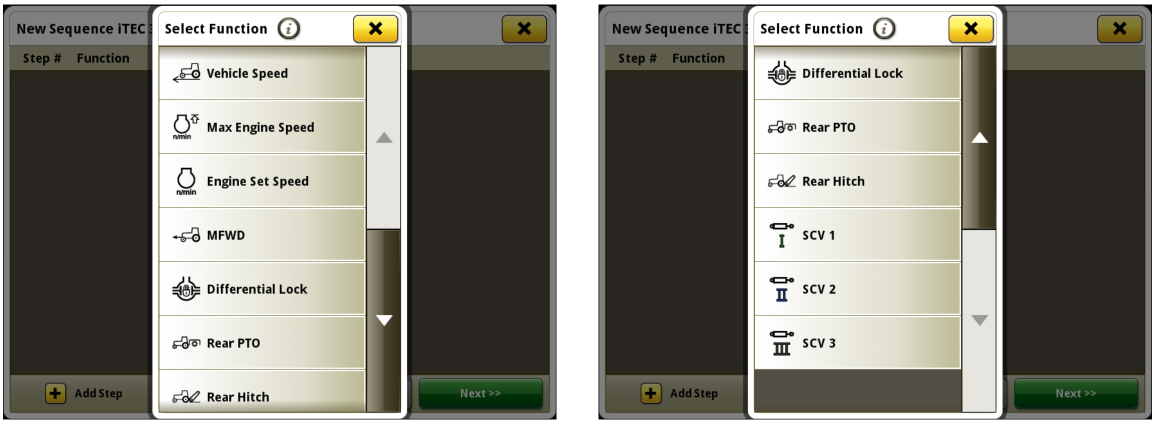


Figure 4.13-A/B: Automated functions available on the 6120R

C.1-i *Automated lifting and lowering of implement using 3-point linkage*
Verdict: ✓
Options available: Raise, Lower, Fast Lower

C.1-ii *Automated lifting and lowering of implement using hydraulic controls*
Verdict: ✓
Options available: Extend, Retract, Float

C.2 *Automatic adjustment of ground speed*
Verdict: ✓
Options available: 0.8 – 42 km/h

C.3 *Automated control of PTO*
Verdict: ✓
Options available: On, Off

C.4 *Automated control of differential lock*
Verdict: ✓
Options available: Auto, On, Off

While the tractor can perform automated headland turns, options are available for fine-tuning the turn itself, through adjustment of *Turn Aggressiveness* and *Start of Turn* (Figure 4.14).

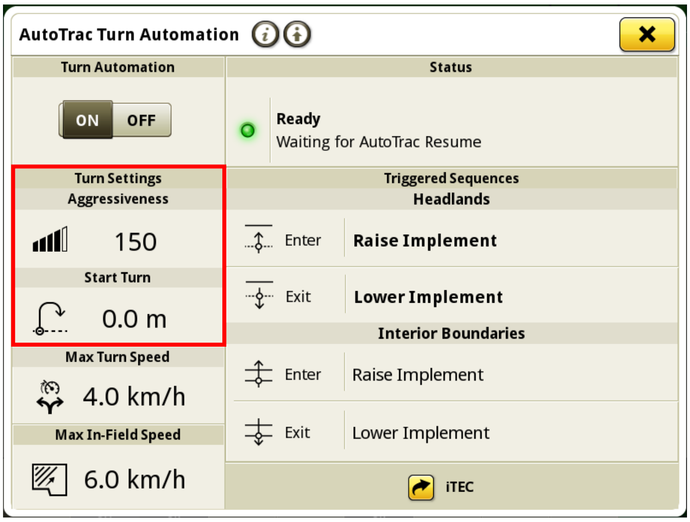


Figure 4.14: Automated headland turn settings (outlined in red)

Turn Aggressiveness determines how sharp the ASAT is allowed to turn, while automatically limiting the 'aggressiveness' based on the turning radius, implement size and steering angle of the tractor. This setting could be adjusted in a sub-menu, as illustrated in Figure 4.15 below:

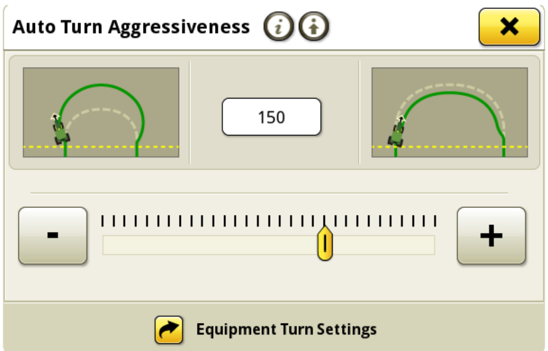


Figure 4.15: 'Turn Aggressiveness' settings

Start of Turn allows the operator to specify when the tractor can begin the turn in relation to the headland boundary – either before or after the boundary is crossed.

<u>Perform an automated headland turn and align with next pass:</u> ✓

C.6 *Perform various turning formats to suit various implements*

Turning formats are determined automatically by the ATTA software to ensure pre-specified *turning radius* and *angle of turn* limits are not exceeded (Figure 4.16). The default turning format is a lightbulb turn (Figure 4.17), however, the operator is able to specify the turn direction and number of rows skipped (Figure 4.18); the software then determines the suitable turning format to achieve the desired result. The control screen displays two paths – the blue one for the path of the tractor and green one for the expected implement travel path. The system also uses the width of the implement to determine if any portion of the implement will collide with the field boundary.

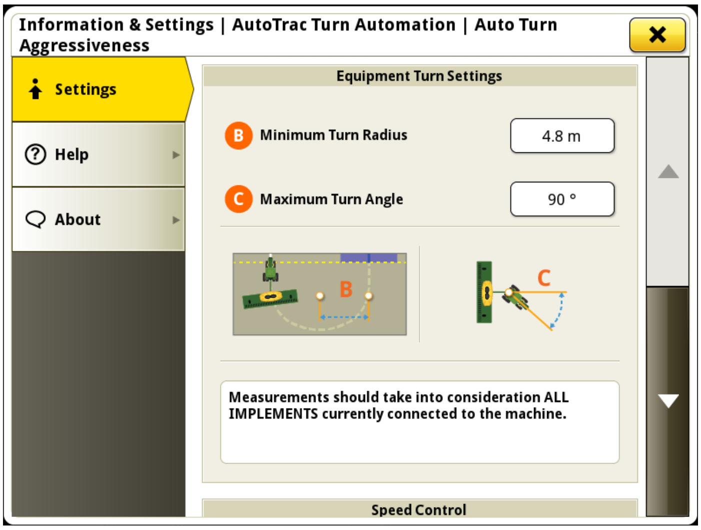


Figure 4.16: Specifying turning constraints

Figure 4.17: ATTA lightbulb turn to the left, skipping one row

Figure 4.18: ATTA elongated turn to the left, skipping five rows

<u>Perform various turning formats to suit various implements:</u> ✓

C.8 Turning circle of tractor

The turning circle of the tractor was first determined by aligning the front right wheel of the tractor with the edge of the cultivated section before executing a 180° turn. However, given the turning geometry, the tractor did not complete the turn (fully facing the opposite direction) prior to reaching the edge of the cultivated section. This is illustrated in Figure 4.19 below:

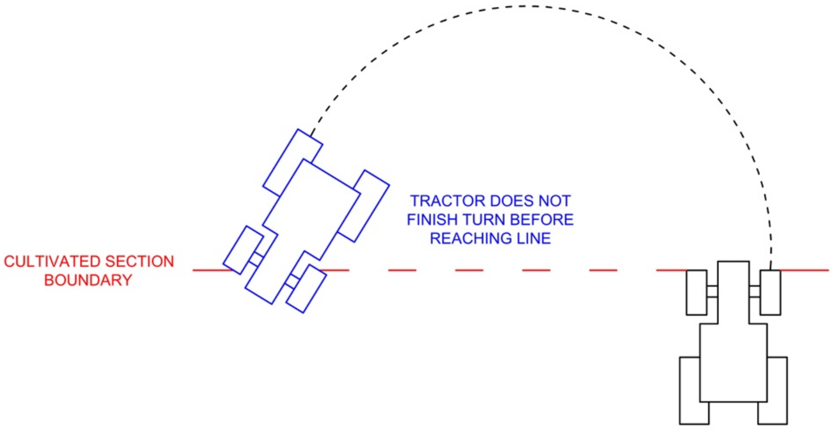


Figure 4.19: Incomplete turn during 'Turning Circle' tests

Consequently, the test was revised to record the turning circle diameter, before dividing by two to produce the turning radius. Driving in a circle at 3 km/h, with the wheel locked fully to the left, the circle produced by the front right wheel was marked with surveying paint on the ground. Once a complete 360° turn was executed, the diameter was measured with a tape measure. A turning diameter of 9.6 m was recorded, producing a turning radius of 4.8 m.

<u>Turning radius of tractor:</u> 4.8 m

C.9 Maximum steering angle

By measuring the angle between the front and rear wheels, the maximum steering angle was determined. Upon turning the wheel to the far left, a straight edge was held against both tyres and the angle between them measured. The set-up (before being held against the centre of each tyre) can be viewed below in Figure 4.20, with Figure 4.21 showing the measurement being taken (with the straight edges held against the centre of both tyres).

Figure 4.20: Layout of straight edges

Figure 4.21: Straight edges being held against centre of each tyre
Inset: Protractor measurement reading 45°

As the protractor was configured in a 'complementary' mode (whereby 0° would represent perpendicularity of one edge to another), the steering angle was determined by subtracting the measurement from 90°. With the protractor reading 45°, the maximum steering angle was therefore calculated as 45°.

<u>Maximum steering angle:</u> 45°

D-Series Tests – Overriding Autonomous Operations Results

D.1 Manually overriding ATG

For the ATG to be successfully activated, the operator must first ensure the tractor is in the correct gear – either forward or reverse. The AutoTrac button on the control screen must then be pressed to initialise the system, before pressing the physical button on the control arm to engage the ATG. Each step of activation is illustrated by means of a pie graph, illustrated below in Figure 4.22:

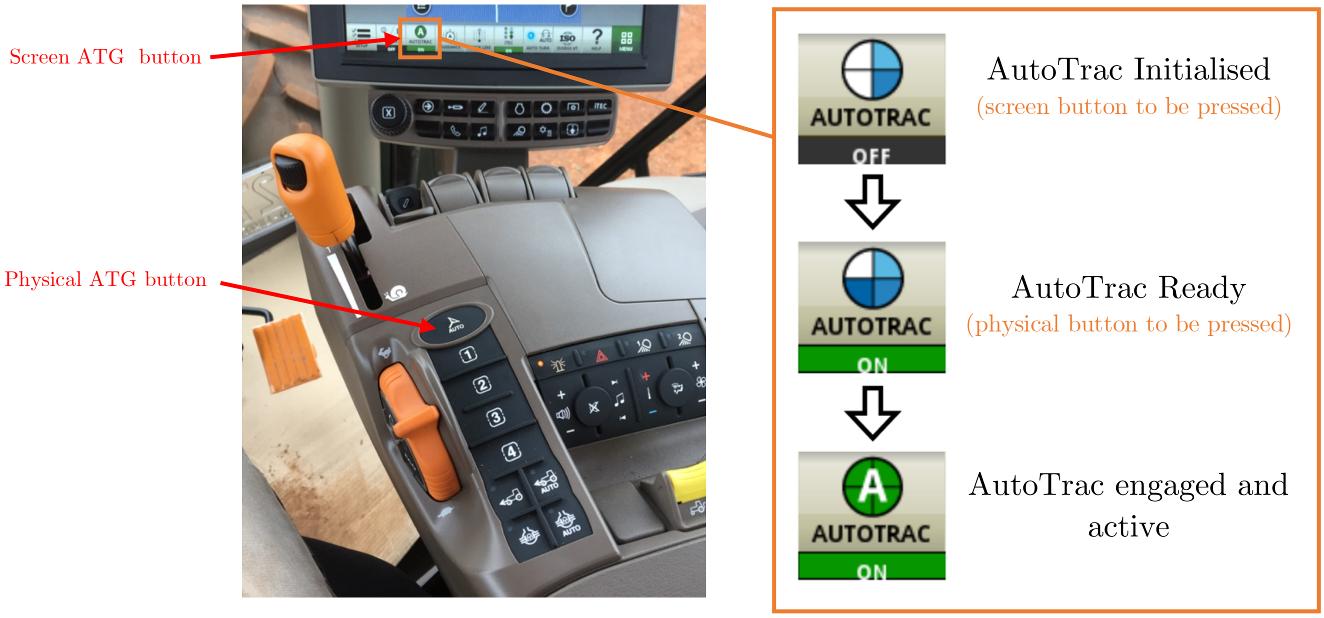


Figure 4.22: Steps to enable ATG

The ATG can be overridden by pressing the ATG button on the screen or slightly turning the steering wheel. This may present a problem if the wheel is knocked accidentally – as even a minute turn disables the system. Another method of overriding the ATG is placing the tractor in neutral or park (as in Figure 4.23). When overridden, an alarm sounds and the pie graph reverts to ¾ complete. The ATG can be re-engaged by pressing the physical ATG button.

Figure 4.23: Disengaging ATG by placing the gear into neutral

<u>Verdict:</u> Identifiable ✓ Accessible ✓ Guarded ✗

D.2 Assuming control of automated headland management

Automated headland management can be overridden by pressing either the 'Auto Turn' or iTEC buttons on the control screen – with iTEC disabling both ATTA and automated field operations (such as entering non-arable boundaries). Deere also included 'panic mode' – whereby ATTA is disabled when the operator turns the steering wheel. This may be beneficial if an imminent collision is to be avoided and the operator does not have time to find and press on-screen buttons. The 'Auto Turn' on-screen button also acts as a status light – showing if the system is active (blue or green), off (grey) or presenting a fault (red or orange), witnessed in Figure 4.24.

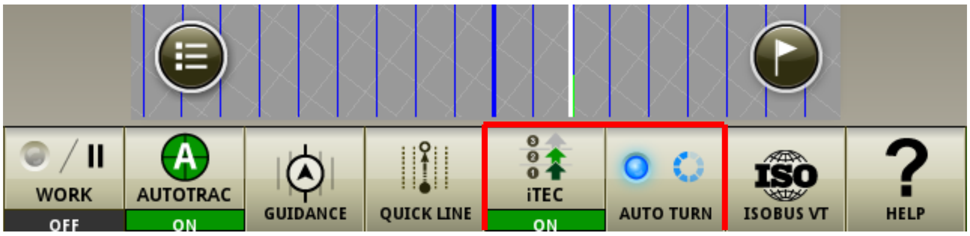


Figure 4.24: iTEC and ATTA (outlined) engaged and active

<u>Verdict:</u> Identifiable ✓ Accessible ✓ Guarded ✓

D.3 Assuming control of automated field operations

iTEC – responsible for automated field operations – can be engaged and disengaged through pressing the on-screen button (as per previous Figure 4.24). Additionally, actuating the manual controls for the rear hitch, PTO or hydraulic valves overrides the automated commands.

<u>Verdict:</u> Identifiable ✓ Accessible ✓ Guarded ✓

D.4 Assuming control of automated PTO control

For automated PTO operations, the operator must engage the PTO 'master switch' (Figure 4.25), prior to assigning control to the ASAT. The switch itself is protected from accidental activation by requiring the operator to push down and forward simultaneously. The master switch is disabled by tapping the spring-loaded toggle backwards in a single motion. Consequently, automated PTO operations are disabled by disengaging the bright yellow master switch.

Figure 4.25: PTO master switch

<u>Verdict:</u> Identifiable ✓ Accessible ✓ Guarded ✓

D.5 Manually overriding cruise control

Given the 6120R is a row-crop tractor, field speed is maintained through setting the throttle and travel speed controls (Figure 4.26). To reduce the field speed, the throttle and/or travel speed controls can be slid backwards – this will reduce the tractor to a slow crawl, yet will not stop. To fully stop, the gear selector (Figure 4.27) must be moved into the neutral or park positions. Alternatively, depressing the brake pedal will automatically engage the clutch and bring the tractor to a stop from any speed.

Figure 4.26: Speed and throttle controls
(top left: speed control, bottom centre: throttle)

Figure 4.27: Gear selector
(not engaged in any gear)

<u>Verdict:</u> Identifiable ✓ Accessible ✓ Guarded ✓

D.7 Activation of 'all-stop'/emergency stop

Although no exclusive emergency stop exists, shifting the gear selector into the neutral position (as per Figure 4.27) can disable most automated operations (such as ATG and ATTA) whilst also bringing the tractor to a stop. Depressing the brake pedal is able to quickly stop the tractor while ensuring ATG and ATTA are not disabled – useful for avoiding wildlife or moving obstacles. While turning the ignition off may be considered an emergency stop, this was not tested due to fears of machine damage.

Verdict: Identifiable ✗ Accessible ✓ Guarded ✓

D.8 Awareness of low fuel level

Referring to Page 30A-7 of the 6120R user manual, the fuel gauge will flash when the level of fuel enters the reserve range. The ASAT, however, will not stop the engine – it will only advise the operator to fill the tank and continue to run until dry. The control system is able to display fuel use statistics, such as fuel use per hour, time until empty and the fuel use per acre. These can be viewed in the Machine Monitor screen, as below, in Figure 4.28:

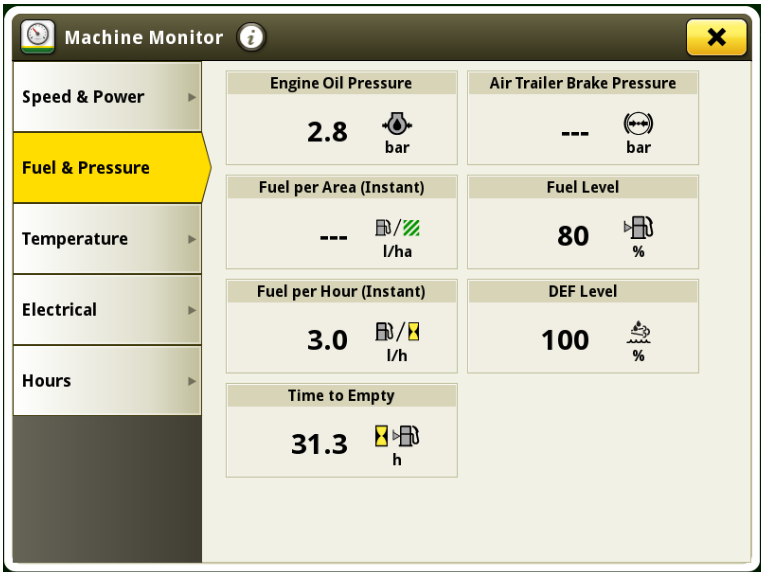


Figure 4.28: Machine monitor for fuel levels and oil pressure

Awareness of low fuel level: ✓

D.9 Awareness of low oil pressure

Similar to fuel levels, the ASAT will detect abnormal oil pressures (readout shown in the previous Figure 4.28) but will not shut the engine down – it is the operators responsibility to monitor alarms and faults, and where required, stop the engine. The user manual advises that the operator checks oil levels regularly using the dipstick and must not start the engine if levels are below the minimum threshold.

Awareness of low oil pressure level: ✓

D.10 Awareness of low hydraulic oil level

The 6120R is able to measure temperature of the hydraulic oil, yet is unable to measure hydraulic oil levels. Referring to the operator manual, hydraulic/transmission oil levels are checked manually through a sight-glass. Additionally, no alarms will sound if hydraulic oil levels reach a critical level – such as when hydraulic leaks deplete the oil reservoir. Given both the hydraulics and transmission rely on the same oil reservoir, major issues could potentially arise.

Awareness of low hydraulic oil level: ✗

D.11 Awareness of excessive engine temperature

Coolant levels, correlating to the engine temperature, are continually monitored by the machine (see Figure 4.29). Similar to other readings, the ASAT will not take action if excessive engine temperatures are reached and will only alert the operator to take corrective measures.

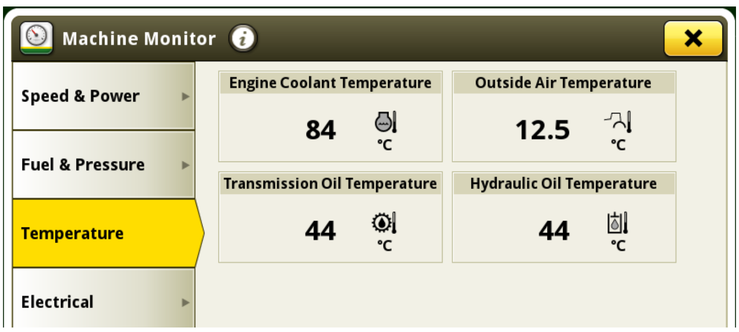


Figure 4.29: Machine temperature readouts

Awareness of excessive engine temperature: ✓

D.12 Awareness of extreme ambient temperatures

The 6120R can measure the outside air temperature and displays the reading in the machine monitor sub-menu (see Figure 4.42 above). Page 50J-4 of the 6120R's user manual also outlines the pre-programmed cold-weather starting protocols – whereby the tractor cannot be driven while the transmission is too cold. When the '*Transmission Warm-up Routine*' is active, the ASAT prevents the drive system from engaging. Warm-up times vary from 95 to 245 seconds (from -8°C to -30°C respectfully). For warm climates, engine cooling protocols are implemented, as per Test D.11.

<u>Awareness of excessive ambient temperatures:</u> ✓

---------- Completion of Testing ----------

Note: As outlined within Chapter 3.3.6, the following tests were omitted from this project due to lack of obstacle detection technology:

- Obstacle Detection (A.5, A.6 & A.12)
- Obstacle Avoidance (A.9 & A.10)
- Effects of Environmental Conditions (A.7 & A.13)
- Overriding Obstacle Detection/Avoidance (D.6)

Chapter 5

Analysis of Testing Procedures & Machine Performance

5.1 Chapter Overview

This section explores the analysis of results obtained from field-testing. Within each section, both the appropriateness of the procedure and performance of the case study will be summarised. Once current test protocols are analysed and refined, the final testing procedures, together with a suitable grading system, will be presented.

A summary of 'Test Appropriateness' and 'Machine Performance' is included in Appendix C. Both summaries implement a scoring method of *Poor*, *Moderate* or *Good*.

5.2 A-Series Tests – Perception

A.1 Maximum change of speed when load applied

Being able to implement reactive measures to ensure the tractor continues at the set speed when engaging and disengaging heavy loads, the case study can successfully adapt to loaded applications. The test itself, particularly when executed in a cyclic nature, ensures the machine can both acknowledge and respond to changes in loading. Reactive measures were automatically implemented by the tractor to prevent stalling and/or damage to the transmission – illustrating the ASAT's ability to be aware of the situation and knowledge of reactive measures for self-preservation.

However, it is recommended that a 'percentage change' in speed be implemented, rather than an absolute value. This allows the assessor to perform the test at various speeds, or at speeds relevant to the application of the ASAT (for example, deep tillage is performed at slower speeds when compared to planting or harrowing).

Appropriateness of Test: Moderate   Performance of 6120R: Good

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A.2-i   *Latitude and longitude readings match current position of tractor*
A.2-ii   *Heading value updates as tractor executes a 360° turn*

As a basis for precision-agriculture, the tractor must be aware of its position at all times while operating in the field. While some applications require the tractor to travel in accurate, straight lines (such as inter-row cultivation and fertilizer side-dressing), modern farming systems such as application maps and yield monitoring require the machinery to know absolute positions within the field. By knowing the position of the tractor on a global scale, data can be shared between platforms and machinery – allowing DTM, application-rate data and 'location flags' to be recorded using a universally accepted positioning system.

As 'smart farming' becomes more accessible in the commercial marketplace, being able to accurately log application rates, yield data, field boundaries and the general position of the tractor, operations are made more efficient and holistic through the synchronisation of location data (both PFDS and PADS).

The tests themselves were easy to implement and produced pertinent results, with sub-two centimetre accuracy (confirming the manufacturer's quoted performance). Ideally, surveyed location markers would be implemented to 'cross-check' the StarFire 6000 location data. Nonetheless, repeatability tests (B.1-ii and B.2-ii) were designed to assess the ASAT's ability to return to the same position.

Appropriateness of Test: Good   Performance of 6120R: Good

A.3-i Tractor stops before crossing field boundary (under ASAT control)

To avoid damage to property or machinery, an ASAT should be expected to stop prior to crossing an unpassable field boundary. This test assessed the protocols when the ASAT crosses a field boundary under automated control. For this case study, the tractor failed to stop before breaching the field boundary. Although two stages of alarms sounded, there was no apparent 'dead-man protocol' and the tractor continued regardless – thereby producing a 'fail-unsafe' situation.

Ultimately, the test is deemed extremely pertinent – if the general control system malfunctions, a high-level control protocol should be actioned to stop the tractor crossing the field boundary. Ideally, the ASAT should always revert to a 'fail-safe' mode if a critical error is encountered (such as crossing a field boundary, loss of load or excessive roll/pitch angles). Only when an operator has acknowledged the potential collision, should the tractor continue to execute the manoeuvre.

Appropriateness of Test:	Good	Performance of 6120R:	Poor

A.3-ii Tractor stops before crossing field boundary (under manual control)

Similar to Test A.3-i, the tractor implemented no protocols to avoid an imminent collision with the field boundary. While it could be argued that the tractor is operating outside of its ODD, a certain level of awareness may be advantageous – whether it be an audible, haptic or visual alarm to alert the operator of a potential collision.

Given the popularity of hybrid systems currently available within the agricultural industry – where the ASAT drives the length of the field and the operator performs the headland turn and implement management – an additional layer of safety would be beneficial, particularly in fatigued or distracted situations.

While not as crucial as stopping the tractor under ASAT control, alerting the operator to a potential boundary breach would be advantageous in the reduction of fatigue and/or skill-related incidents.

Appropriateness of Test:	Moderate	Performance of 6120R:	Poor

A.3-iii Tractor raises implement when entering non-arable area

With some fields containing non-arable areas (such as natural waterways/depressions, contour banks, poor drainage and/or poor soil composition), it may be necessary to disengage the implement while travelling over such areas. Given the capability of modern DTM/PFDS to capture field boundaries (exterior and interior), guidance tracks and non-arable areas, the ASAT must be able to use this information by disengaging and re-engaging the implement whilst continuing on the original bearing.

The case study allowed the operator to program dedicated sequences for such instances – allowing 'non-arable boundaries' to have different procedures to that of the 'headland boundaries'. For this project, the 6120R successfully disengaged the implement while travelling through a virtual non-arable area.

Appropriateness of Test:	Good	Performance of 6120R:	Good

A.4-i Detect non-operational hardware when disconnected/uncalibrated Autonomous mode locked-out while faults are present

To exploit the 'Engineering' failure mechanism of Vasic and Billard's *Taxonomy of Failure Mechanisms* (outlined in Chapter 2.7 and below in Figure 5.1), the worst case scenario was tested by completely disabling the StarFire 6000 Receiver.

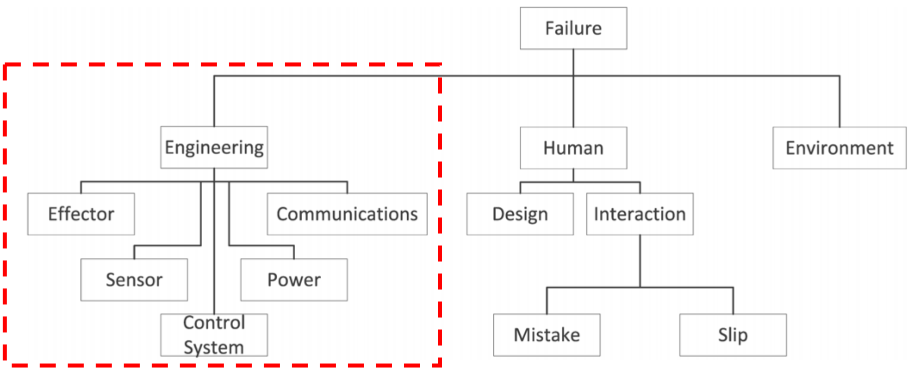

Figure 5.1: Taxonomy of failure mechanisms, with the engineering branch highlighted (Vasic and Billard 2013)

Once disconnected, operations requiring location data (ATG and ATTA) could not be engaged. However, should the hardware be disconnected whilst moving, the tractor would display and sound an error message, but would not stop – thereby 'failing-unsafe'. Similarly to Test A.3, the 6120R case study appears to have no 'dead-man' or 'fail-safe' protocols when a critical error arises. Consequently, this aspect should be highlighted within the user manual to avoid reliance on a protocol that is designed for emergency-stop situations.

While ATG and ATTA were locked-out while faults were present, automated field operations such as iTEC were still operational, albeit requiring the operator to press buttons to initiate the automatic sequences. Furthermore, should iTEC become inoperative, all functions can still be controlled manually. This allows the tractor to still remain operational, even if ASAT features are disabled.

Appropriateness of Test:	Good	Performance of 6120R:	Moderate

A.4-ii Maintain a safe state until a command is given from the operator

Given the tractor can only operate (semi-)autonomously when set manually (as opposed to electronic initiation) in the forward or reverse gear, it can be deemed that the tractor remains in a safe state until the operator gives the command. Accidentally engaging the gear is avoided by having the gear selector spring-loaded into a neutral position – requiring the operator to purposefully push the selector into forward or reverse.

As noted in previous tests, the tractor is unable to place itself into a safe state should it be faced with a (potentially) critical situation. Therefore, while not 'failing-safe', the ASAT is capable of remaining in a safe state until issued a command to move.

Appropriateness of Test:	Good	Performance of 6120R:	Good

A.11 Stopping time from 12 km/h

This test was originally developed to assess the reaction time of the tractor – by acknowledging the presence of an obstacle, determining that evasive action (braking) is required and bringing the tractor to a halt. However, given the lack of on-board obstacle detection technology, the stopping time (under manual braking) was recorded instead.

Disregarding the reaction time of the operator (braking time was calculated from actuation of brake pedal to tractor stopping), the braking performance of the tractor was notable – with the machine coming to a complete stop within one second – both with and without the use of the clutch (equal to a deceleration of at least 3.33 m/s^2).

This trial also assessed the performance of the auto-clutch, whereby depressing the brake pedal automatically disengages the clutch, allowing smooth acceleration and deceleration using only the brake pedals. The auto-clutch is also implemented in situations where a different gear range must be used for the automatic transmission – allowing the operator to specify the desired field speed, without the need to dictate the exact gear or gear range.

Appropriateness of Test:	Good	Performance of 6120R:	Good

Summary of Perception Testing

Overall, the tests continued to satisfy the 'Criteria for Successful Test Protocol' (Chapter 3.3.3) and produced pertinent results, relevant for deducing the field readiness of ASATs. Tests accurately assessed the tractor's awareness of both itself and its location within a field, whilst also ensuring the machine could act in a safe manner when hardware was non-operational or a command had not been given.

Tests revealed that the 6120R has not been programmed with 'fail-safe' or 'dead-man' protocols – whereby an operator must be present at all times to execute reactive measures. By implementing such protocols, distraction and fatigue-based incidents may be reduced, thereby minimising damage to machinery/property and operator injury. By not entering a safe state when a critical fault arises (such as the ASAT crossing a field boundary or hardware becoming inoperative while driving), the driverless capabilities of the tractor are limited.

However, by not relying exclusively on highly-automated functions, the tractor can still be operated manually should such systems become inoperative. Ultimately, the commercial viability of a tractor is dependent on the usability of the machine: should the operator be unable to use the ASAT due to complex practices (that may not work), they are unlikely to use it. Therefore, the 'field readiness' of the tractor is dependent on machinery that operates as expected, is robust enough to handle the challenges of agricultural field work and does not hinder farming operations, should the system fail (i.e. autonomous functions are not a critical failure point of the machine).

5.3 B-Series Tests – Automated Tractor Guidance

B.1-i *Accuracy of linear heading paths*
B.1-ii *Repeatability of linear heading paths*

Both the accuracy and repeatability tests produced results that were in keeping with what was expected. Given the StarFire 6000 Receiver was connected to an RTK Base Station, repeatability accuracy was commensurate with that claimed by John Deere as 2.5 cm (with these tests indicating a repeatability of < 2 cm).

Accuracy and repeatability of ASAT operations are imperative in modern precision agriculture – whereby inter-row cultivation, side-dressing and double planting require highly accurate and repeatable guidance technologies.

While the row-marking spike was effective at measuring instantaneous accuracy (by comparing one pass against another), there may be merit in completing the test whilst also observing overall accuracy (to determine how accurate a path is, along the length of a field). This may be accomplished through the use of a string line, surveyed reference-points or a laser-plane. Irrespective of the method used, it may be apparent that a similar set of results is obtained. Furthermore, use of a laser-plane would contradict the testing criteria of '*Attainable*' – by requiring the use of expensive or exclusive equipment.

Appropriateness of Test:	Good	Performance of 6120R:	Good

B.2-i *Accuracy of curved/custom paths*
B.2-ii *Repeatability of curved/custom paths*

While accuracy of the curved paths was poor (< 13 cm), repeatability of the paths was reasonably accurate (< 3 cm). The tractor appeared to struggle with sharper turns, while better accuracy was achieved on gentle curves.

As most large-scale row-crop farming operations occur in large rectangular fields, ASAT manufacturers may not be concentrating on developing accurate curve-tracking. However, the tractor was able to navigate winding turns, together with performing a 180° turn, arguably more efficiently/accurately than a human operator. The repeatability accuracy of the curves far exceeds the absolute accuracy – with the tractor following approximately the same track as the first pass.

Although lacking accuracy, the curve-tracking system appears to exhibit high levels of precision and repeatability. This result allows the tractor to operate with a regular error, albeit deviating from the desired track. Although a margin of error is apparent, the regularity of the movement can be tolerated (i.e. existing tram-tracks will be adhered to).

Appropriateness of Test:	Good	Performance of 6120R:	Moderate

B.3-i *Accuracy of linear heading paths when driven in reverse*

When driven in reverse, the ATG appeared to lack accuracy – similar to an over-damped system, the ATG's reaction speed to an increasing error was poor (30 cm error), yet managed to maintain a consistent error value (2 cm) once settled. When driven in reverse from a starting error of 0 – 2 cm (simulating driving through a crop with ATG previously engaged), the ASAT was able to maintain a straight line while reversing. This would allow accurate reversing through a crop when an obstacle is encountered or should the implement require re-setting.

This test ultimately assesses the control systems ability to operate under different steering dynamics – changing the machine from front-axle to rear-axle steering with the operator having no need to change any control settings. Consequently, the test results indicate limited functionality when reversing.

Appropriateness of Test:	Moderate	Performance of 6120R:	Good

B.3-ii *Accuracy of curved/custom paths when driven in reverse*

Given the poor ATG accuracy when negotiating curved paths in the forward direction (Test B.2-i), together with low reversing accuracy (Test B.3-i), it is to be expected that the errors of each component would compound to result in scant accuracy of ATG when manoeuvring around curved paths in reverse.

Instances where this would impact the usability of the tractor would, again, relate to the need to re-set the implement while working the field or to avoid an obstacle. Similar to Test B.2, it is likely ASAT row-crop tractors would be configured for linear-heading fields and consequently, may lack the curve-tracking technology required to accurately navigate curves (in both forward and reverse).

Overall, having the ability to accurately reverse down a curved track, particularly for a tractor designed for front-axle steering, is a positive feature. As ASAT technology becomes more sophisticated, it is anticipated that curve-tracking capabilities would improve, allowing tractors to navigate fields that have not been configured in a rectangular shape.

Appropriateness of Test:	Moderate	Performance of 6120R:	Poor

B.4 Accuracy of ATG under balanced load conditions

As row-crop tractors are fundamentally designed to pull implements, this test was designed to provide a resistance force to monitor the effects of load on the ATG accuracy. Coupled with Test A.1 (to assess change in speed), this test ensured high ATG accuracy is not dependant on 'no load' scenarios and can maintain accuracy as the implement is engaged at a working speed.

As expected, ATG accuracy produced similar results to that of an unloaded scenario (Test B.1). Providing both a uniform resistance force and some degree of unforeseen/minor offset loading (as the ripper encounters patches of both loose and compacted soils), executing tillage operations allowed real-world testing of the ASAT to ensure practical field-readiness.

Furthermore, by implementing reactive procedures, as discussed in Test A.1, the ATG accuracy remained unaffected – illustrating the ASAT's ability to react to one issue (self-preservation and maintaining field speed), without negatively affecting another (ATG accuracy). Therefore, there may be merit in designing a test to force the tractor to sacrifice performance of one task to accomplish another – such as raising the implement slightly should the tractor almost stall or sacrifice field speed to allow a lower gear (higher torque) to be implemented.

Appropriateness of Test:	Good	Performance of 6120R:	Good

B.5 *Accuracy of ATG under unbalanced load conditions*

In particular instances, such as disengaging half of a planting implement to obtain a half-swath, unbalanced loading may occur. This test provided abnormally high offset loading by use of a duck-foot ripper with only the right-hand shanks engaged. Despite excessive offset loading, the accuracy of the ATG remained satisfactory, with the tractor steering against the direction of the unbalanced load. Figure 5.2 below shows the effect of offset loading – a clockwise rotational moment is produced as a result of the half-engaged implement (red arrow), resulting in the tractor steering to the left (pink arrow) to maintain straight line travel (blue arrow).

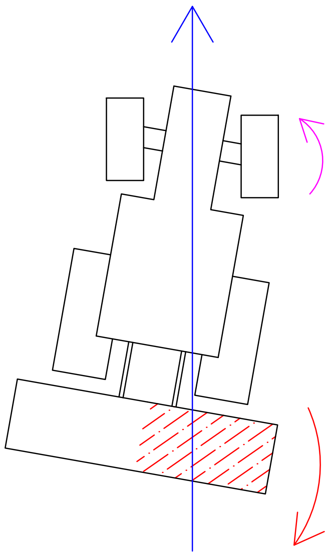

Figure 5.2: Effects and reactive measures caused by offset loading

This test also exploits the ASAT's ability to recognise the machine's yaw rate (as the tractor canted/drifted to the right while continuing to move forward) and correct the steering as necessary. Test B.6 (on the following page) exclusively assesses the tractor's ability react to changing pitch and roll rates using the 'Terrain Calibration Module'; while similar reactive protocols to yaw rates are assessed in Test B.7 (Reaction to Independent Braking).

Appropriateness of Test:	Good	Performance of 6120R:	Good

While use of the sandbags ensured uniformity and repeatability of the test, the degree of undulation offered was insufficient to fully exploit the tractor's ability to implement reactive measures. Results from the second iteration of testing (using contour banks) provided results with greater variance, whist allowing the tractor to apply reactive steering as it traversed the 'rolling' nature of the contour bank (instead of an abrupt/aggressive 'bump' offered by the sandbag tests). The irrigation berm also offered a more substantial obstruction, of 250 mm, instead of the sandbag's 130 mm and allowed greater rolling and pitching motions of the tractor. Ultimately, implementing the contour banks provided a more realistic scenario and should be recommended for future testing.

Various approach angles were implemented to provide a range of motions as the tractor traverses the contour bank, ranging from purely pitch (perpendicular angle of incident) to a purely roll motion (parallel angle of incident).

The ultimate objective of this trial was to assess the performance of the ASAT's 'Terrain Calibration Module'; whereby internal sensors calculate the pitch, roll and yaw of the machine to provide a 'true' position of the tractor's drawbar. Figure 5.3, below, highlights this – whereby the StarFire GNSS receiver would normally produce a location directly below the receiver (Position 1), instead of at the tractor's 'true centreline' (Position 2).

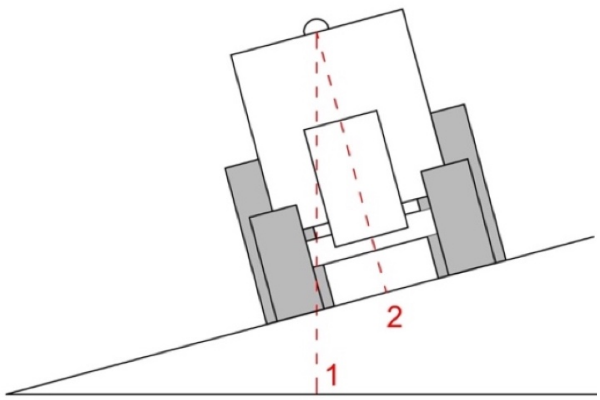

Figure 5.3: Terrain Calibration producing 'true' location of tractor

By utilising in-built inclinometers and accelerometers, the system can calculate the actual position of the tractor, relative to the terrain it is traversing (Position 2 of Figure 5.3 above). This ensures the path of the tractor remains unaffected by undulations by 'folding'/'wrapping' the pathways over inclines, berms and contours.

This is illustrated in Figure 5.4 (below), where the right-hand diagram shows terrain calibration's ability to ensure equal track spacing up the incline.

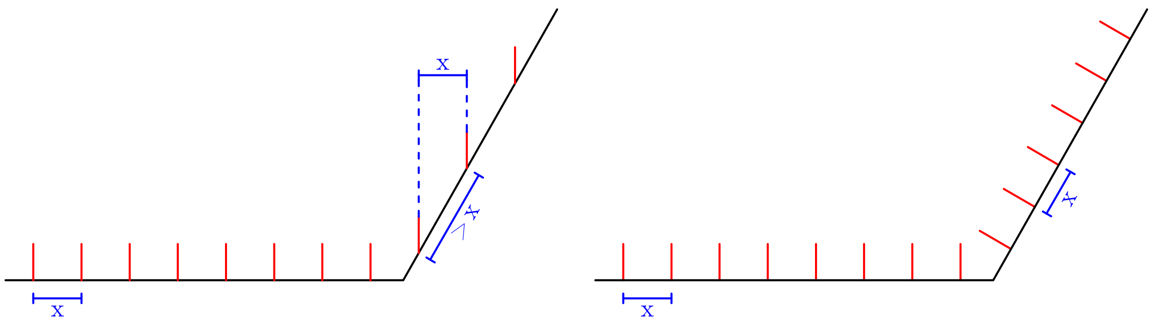

Figure 5.4-A/B: Track spacings without (left) and with (right) Terrain Calibration

Ultimately, the high degree of accuracy illustrates the tractor's ability to adapt to various slopes and undulations through use of terrain compensation systems. Future testing may choose to further exploit the Terrain Calibration Module by driving the tractor along a constant side slope and/or driving the tractor along an incline where a roll-over situation may occur (i.e. 'Can the tractor determine if a slope is too steep?').

Appropriateness of Test:	Good	Performance of 6120R:	Good

B.7 Accuracy of ATG when independent braking is applied

This test was designed to assess the effectiveness of the ATG under conditions where one rear wheel rotates faster than the other – such as the operator implementing independent braking to steer the tractor (if insufficient downwards pressure is available on the front wheels) or to offset the 'drifting' effect caused by severely unbalanced loads.

As observed, the tractor experienced a small amount of overshoot in the opposite direction when independent braking was released, thereby highlighting the fact that the tractor was indeed implementing reactive measures to counteract the difference in rear wheel speeds.

Upon completion of this test, it was deduced that the applied brake force could not be accurately determined. Therefore, it is recommended that the assessor exert maximum pressure on the brake pedal to obtain the greatest effect.

Appropriateness of Test:	Good	Performance of 6120R:	Good

Summary of Automated Tractor Guidance Testing

Overall, the tests performed as expected, with no or minor modifications. However, some tests may benefit from more uniform procedures to increase reproducibility of results – such as outlining the required drag force in Tests B.4, the offset load/distance in Test B.5, and the braking force in Test B.7.

Test B.6 could be expanded to encompass more undulations per iteration, together with producing an appropriate method to 'ground-truth' the terrain calibration system (such as using a row-marker to score the travelled path).

Ultimately, these tests represented the largest collection of quantitative data and therefore, care was taken in the methodology stage to ensure testing procedures were as uniform/repeatable as possible. However, upon completion of testing, it was realised that some areas could be improved to ensure greater repeatability. For example, a particular load or implement engaged to load the tractor to a certain percentage of its maximum engine power for Tests B.4 and B.5. Given the procedure base allowed adequate exploration of concepts and assessment of abilities, it is recommended that future research develops and establishes quantifiable criteria for each test. This may require further instrumentation to ensure tests are both repeatable and standardised (for example, use of draft sensors to ensure correct loading is applied or utilisation of certain implements and/or weight sleds).

Furthermore, testing methodology of Test B.6 may dictate that the tractor must travel along an incline of 10° (for example), with the assessor responsible for achieving this. Finally, Test B.7 could be made more repeatable by using a force sensor between the operator's foot and brake pedal to apply a specific braking force.

In summary, the tests could assess the ATG performance of the ASAT in a variety of typical farming situations. In applications requiring high degrees of accuracy and repeatability, operators and manufacturers must ensure the proclaimed accuracy can be achieved in both ideal conditions and practical situations.

5.4 C-Series Tests – Headland Management

C.1-i	*Automated lifting and lowering of implement using 3-point linkage*
C.1-ii	*Automated lifting and lowering of implement using hydraulic controls*
C.2	*Automatic adjustment of ground speed*
C.3	*Automated control of PTO*
C.4	*Automated control of differential lock*

Results from the above tests were obtained directly from the user's manual and iTEC programming screen. The functions listed, represent those an operator would be expected to use whilst controlling an implement. Additionally, as almost all the controls in the 6120R are control-by-wire, many functions can be executed simultaneously and with no need of an operator (when implementing ATTA, functions are executed automatically – following a prespecified sequence, as programmed by the operator).

With the exception of manual initiation, the 6120R can automatically operate all controls that an operator could (assuming the operator specifies the required actions and/or values). It should be noted, however, that although functions may be automated, they may not include autonomous adjustment by the tractor itself. For example, the ASAT will not slow down to turn a sharp corner, nor will it adjust the engagement depth of the implement should loading become excessive – aspects that a human operator may be able to gauge and adjust accordingly. Nonetheless, these issues may be classed as outside the ODD and therefore vetoed (as it is the operator's responsibility to specify PFDS, such as turning speed and engagement depth). However, automated control of the rear differential lock was able to include a certain degree of autonomy – engaging when the rear wheels begin to slip relative to each other and disengaging when turning corners, travelling at speed or using independent braking.

Given the primary function of a tractor is to power/move an implement along a field, the executed tests are deemed of utmost importance. By implementing a simple 'yes/no' criteria, function performance is easily recorded and allows simple comparison of abilities.

Appropriateness of Tests:	Good	Performance of 6120R:	Good

C.5 *Perform an automated headland turn and align with next pass*
C.6 *Perform various turning formats to suit various implements*

While ATG and automated implement control (such as iTEC) have been operational for some time, automated headland-turning is deemed relatively new technology. Being able to execute various operations for entering and exiting the headland, together with turning and aligning with the next pass, levels of necessary technology must be mature enough to execute safely and correctly.

Upon provision of the turning radius, angle of turn and turning speed, the tractor was able to automatically produce a turning profile to follow, once reaching the end of the field. The aggressiveness of the turn could also be adjusted – with lower values having a more pronounced 'lightbulb'-shaped turn. A less aggressive turn requires a larger headland width to complete a lightbulb turn, while a higher aggressiveness results in sharper turns and reduced headland requirements.

Implement alignment could be adjusted through the alteration of the 'Start of Turn' value. Independent of the turn aggressiveness, this allows the implement to be aligned 'sooner' or 'later', before entering or exiting the headland. This value also affects required headland widths by simply shifting the turning path towards or away from the headland boundary.

While controlling the ASAT's position may be straightforward, Deere's ATTA allows the system to extrapolate the implement's expected position. This is highlighted below in Figure 5.5, with the blue line representing the tractor's planned path and the green line representing the expected path of the implement.

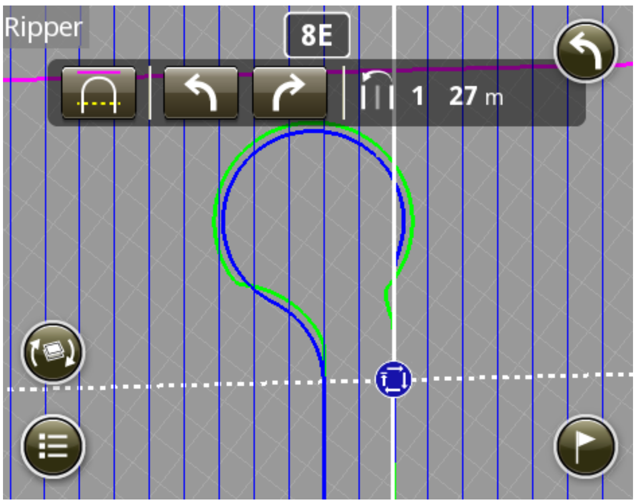

Figure 5.5: Planned tractor path (blue) and expected implement path (green)

Additionally, the system is also able to apply a perpendicular offset (equal to the width of the implement) to the expected implement path. Should any portion of this offset path (edge of the implement) intersect with the field boundary (as per Figure 5.6 and 5.7 below), a collision alarm is sounded.

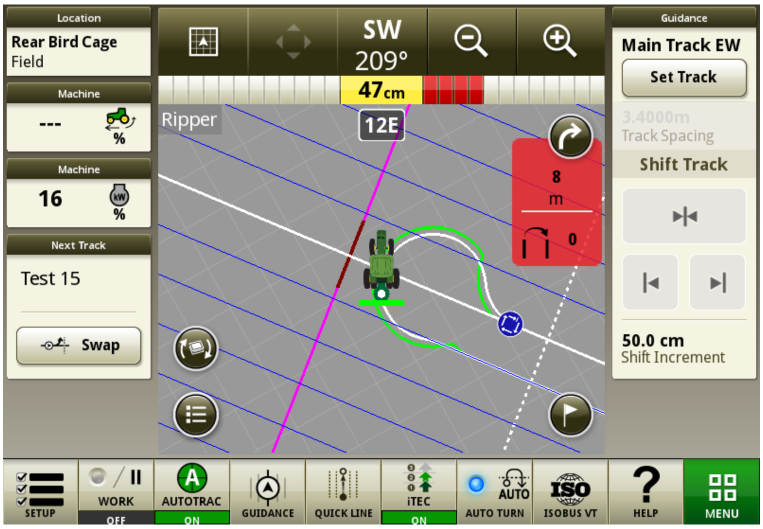

Figure 5.6: Planned turning path of the tractor, showing the area of a potential field boundary collision. *The red text box (top right of inner screen) is displayed after the collision alarm is sounded*

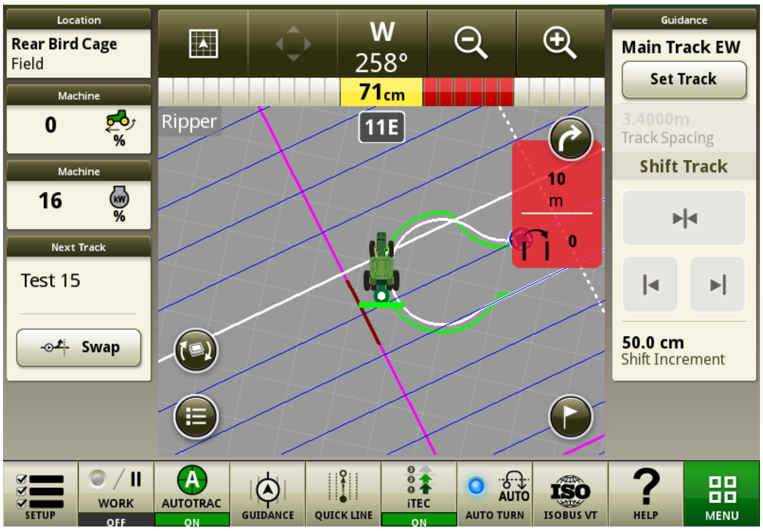

Figure 5.7: Implement collision with field boundary (noting the tractor avoids collision with the boundary)

This highlights the maturity of ATTA technology currently available on the 6120R – being able to both plan the path of the tractor, but also analyse/predict how tractor movements affect the path of the implement. The control system also disables ATTA when an implement profile is not specified (outlining implement parameters such as width, working point and connection type), further minimising the risk of property damage due to incorrect use or setup of the software.

While the control system is able to perform automated headland turns, it is unable to plan turns within a certain/constrained headland boundary. Currently, the technology can perform a headland turn and successfully align with the next pass; however, it must have ample space to execute this turn. Given the tractor possesses no ability to stop when approaching a field boundary (outlined in Test A.3), the tractor will perform the same format of turn, regardless of available headland space or possible collisions. Therefore, it may be deduced that the tractor has been 'hard programmed' with a turning algorithm and cannot adjust the turning format to suit available turning spaces. The sole consequence of this limitation requiring a larger headland width – areas which can be driven before or after working the main length of the field.

Appropriateness of Tests:	Good	Performance of 6120R:	Good

C.8 Turning circle of tractor
C.9 Maximum steering angle

While starting Test C.8 against the edge of a cultivated area provided a realistic scenario, it proved difficult to obtain an accurate measurement of a 'complete turn' (with the tractor facing 180° to the original bearing). Results varied depending on the starting position of the tractor, when the steering wheel was turned and the speed at which the wheel was turned to full lock. However, by starting the test whilst driving in a continuous circle, the tractor's minimum turning circle was accurately deduced.

While both tests assess the manoeuvrability of the tractor, each test can inform different parameters of the turning geometry. The steering angle determines how severe a turn can be, while the turning radius outlines how tight a tractor can turn – taking into account both the steering angle and wheel-spacing of the machine.

Appropriateness of Tests:	Good	Performance of 6120R:	Good

Summary of Headland Management Systems

With in-field automated operations (such as iTEC and ATG) becoming more mature, functional abilities of ASATs now focus on automatic execution of headland operations. Overall, testing procedures performed as expected, yet future tests could exploit the ASAT's ability to manoeuvre within a restricted headland area.

Requiring extensive set-up and programming by the operator, John Deere's ATTA is powerful enough to execute nearly all tractor functions when navigating a headland. Although somewhat intricate to initialise, the implementation of a 'fail-safe' protocol (by disabling ATTA when no implement profile is specified), together with an intuitive troubleshooting menu (outlining steps required to remedy particular issues), ensures errors due to incomplete programming are minimised.

For Tests C.1 to C.4, simple yet effective testing procedures ensure results are easily understood and allow clear comparison between ASATs' abilities to automatically control implements.

As per Tests C.5 and C.6, the ability of the ASAT to extrapolate and predict the path of the implement is to be commended. However, as outlined within 'Perception Testing', the tractor could benefit from 'dead-man'/'fail-safe' protocols when a tractor or implement collision with a field boundary is imminent. For farming operations where a lesser-skilled/experienced operator may be in the cab, being able to accurately predict a collision with a field boundary would be highly beneficial – especially when connected to wide loads, where judging the edge of the implement may prove challenging.

Ultimately, headland management systems, such as John Deere's ATTA, provide a firm basis for driverless capabilities of an ASAT. Given the current level and maturity of ASAT technology, a tractor is able to drive the length of the field and perform automated headland turns, with no need for operator input (excluding obstacle avoidance and reactive measures). Therefore, although relatively simple, these tests are deemed highly pertinent for both assessing (semi-)autonomous performance and determining the field-readiness of such systems.

5.5 D-Series Tests – Overriding Autonomous Operations

D.1 *Manually overriding ATG*
D.2 *Assuming control of automated headland management*

For both ATG and headland management systems, the ability to quickly locate and override the automated function is imperative – whether to avoid an obstacle in the field or prevent a collision with a field boundary.

Consequently, these tests drew upon information outlined in ISO 18497, ensuring manual override of functions are identifiable, accessible and guarded from accidental activation. For both Test D.1 and D.2, manually overriding the automated systems is accomplished by either moving the steering wheel, placing the machine in neutral or pressing the on-screen buttons; the first two options may be useful in a 'panic situation', where action is required immediately (turning the wheel will simultaneously disable ATG/ATTA and also turn the tractor, while placing the machine into neutral gear immediately stops the tractor, disables ATG/ATTA and enters a safe idle state, as per Test A.4-ii).

Given the on-screen buttons are relatively small and difficult to locate without looking at the screen (i.e. no physical/haptic buttons are available), use of the steering wheel or gear selector allows the operator to easily identify and access the manual override. However, although identifiable and accessible, there is an inherent lack of 'guarding' the manual override. Should the steering wheel be turned slightly, ATG and ATTA are disabled and a brief audible alarm sounds. The threshold at which the ATG is disabled can be adjusted to allow a greater tolerance of steering wheel movement.

In summation, having the ability to manually override functions that control direction and speed of the tractor is crucial for safe operation of hybrid system ASATs.

Appropriateness of Tests:	Good	Performance of 6120R:	Good

D.3 Assuming control of automated field operations

For all field operations, functions can be overridden by manually actuating the respective control. As the 6120R is a control-by-wire machine, multiple inputs can be used to control a single tractor function (such as hydraulic valves, PTO and 3-point hitch). However, by prioritising operator controls, manually overriding automated field operations/functions is both identifiable and accessible.

This may also prove beneficial for altering implement parameters as the tractor travels the length of the field, such as adjusting engagement of the implement as soil/crop density fluctuates.

The ability for automated field operations to be completely overridden is also of paramount importance. While the entirety of the system cannot be overridden in a 'panic scenario' (by turning the steering wheel or placing the gear into neutral when overriding ATG/ATTA), the system can still be disabled through pressing a single on-screen button.

Overall, the ability to manually override automated field operations (particularly for machine-operator hybrid systems), is essential for assessing the field-readiness of commercially ASATs.

Appropriateness of Test:	Good	Performance of 6120R:	Good

D.4 Assuming control of automated PTO control

Given the danger associated with PTO shafts, automated PTO control can only be enabled once the master switch is engaged in the cab. Given the location and actuation process (pressing down and forwards simultaneously to engage; flicking back to disengage) of the PTO switch, the method of overriding is deemed to satisfy the ISO 18497 safety criteria.

Appropriateness of Test:	Good	Performance of 6120R:	Good

D.5 Manually overriding cruise control

Ground speed on the 6120R is maintained by setting the engine speed and throttle levers to the desired position. The 6120R is equipped with Deere's 'Infinitely Variable Transmission' – allowing the engine speed to rev at any desired value and travel at any speed (in increments of 0.1 km/hr). Speed can be maintained by engaging automatic transmission mode – whereby the tractor determines the required engine speed and gear to maintain a constant velocity, with no need for operator input. Consequently, the 6120R does not have a dedicated 'cruise control'.

Regardless, the ASAT should have overriding procedures available for stopping the tractor or adjusting the field speed. For the case study, this is accomplished through adjusting the speed or throttle levers, placing the gear into neutral or maintaining pressure on the brake pedals (which can be used in 'panic situations').

While no button or switch is available for setting the field speed, adjustment of vehicle speed is intuitive, with most ASATs having a system similar to the 6120R – pushing a lever forward accelerates the tractor and pulling back slows it down. Given its instinctive nature, adjustment of the ASAT field speed satisfies ISO 18497 safety criteria.

Appropriateness of Test:	Good	Performance of 6120R:	Good

D.7 Activation of 'all-stop'/emergency stop

Pertinent for ASATs involving high levels of autonomy, this test was included to provide operators/supervisors with the ability to pause or shut down the entire system, as quickly as possible, in an emergency situation. Ideally, the ASAT should include an easily identifiable button that disables all automated/autonomous operations and places the machine into a safe, idle state.

Given the 6120R is only semi-autonomous, the operator is expected to implement relevant proactive measures to ensure no emergency situation arises in the first place. Although depressing the brake pedals can quickly bring the tractor to a stop (assessed in Test A.11), this action does not disable automated functions. However, by placing the gear into neutral, automated functions are disabled, machine motion is stopped and the tractor can maintain a safe state.

Appropriateness of Test:	Good	Performance of 6120R:	Moderate

D.8	*Awareness of low fuel level*
D.9	*Awareness of low oil pressure*
D.10	*Awareness of low hydraulic oil level*
D.11	*Awareness of excessive engine temperature*
D.12	*Awareness of extreme ambient temperatures*

For the above tests, the ASAT was aware of various temperatures and levels, and would trigger alarms if excessive values were reached.

However, for all tests, the 6120R would not take corrective action (or shut down) should the operator fail to act on these warnings or alarms. Conversely, it could be reasoned that this scenario lies outside the ODD and remains the operator's responsibility to ensure correct levels and temperatures are maintained at all times, and to act on such warnings accordingly.

For ASATs involving higher levels of autonomy (particularly driverless tractors), the ability to monitor and act upon abnormal temperatures and levels is imperative to preserve the health and performance of the machine. Ideally, should an anomalous condition be encountered, the machine should stop and enter a safe state, before alerting the operator or supervisor.

Given the 6120R is designed for human-machine hybrid conditions, it can be deduced that displaying an error/warning message satisfies the test criteria of 'being aware of abnormal machine conditions'. However, for the ASAT to be classed as driverless (and/or not require continual supervision), a 'successful' result may involve the tractor executing relevant self-preservation measures by itself.

Appropriateness of Test:	Good	Performance of 6120R:	Good

Summary of Overriding Autonomous Tractor Operations

As human-machine hybrid systems become more advanced and popular within the agricultural marketplace, methods to override autonomous operations should remain identifiable, intuitive and accessible.

Testing procedures yielded relevant and pertinent results – highlighting functions where manual override abilities may be lacking (such as the absence of a dedicated emergency stop button). Furthermore, for ASATs with greater levels of autonomy, the machine should be expected to implement reactive measures to preserve both its health and performance.

Unlike previous tests that presented the lack of 'fail-safe' protocols, manual override of critical functions ensured an operator faced with a 'panic scenario' could safely bring the tractor to a stop or overrule automated operation (e.g. overriding ATG and ATTA by turning the steering wheel).

Ultimately, all operations of the 6120R can be overridden though manual/deliberate actuation of controls. Consequently, the machine also complies with ISO 18497 (*Chapter 4.6: Overriding of Highly Automated Operation*). Again, this is beneficial in a situation where the operator does not have time to locate the 'Disable' button on the control screen – thereby allowing even an inexperienced operator to override automated procedures.

5.6 Refining Test Procedures

Upon completing an initial analysis of testing, it was deduced that some tests could be refined, through increasing the repeatability or relevance of the testing procedures.

For tests requiring the engine to be loaded – such as Test A.1 (*Change of Speed when Load Applied*), Test B.4 (*ATG Accuracy under Balanced Load*) and Test B.5 (*ATG Accuracy under Unbalanced Load*) – a more repeatable and scalable procedure would enhance the testing protocols. Consequently, these tests should aim to load the engine to a certain percentage of its maximum power output. Given the tractor can directly display the power output as a percentage (as per Figure 5.8), this alteration to the methodology is deemed achievable. Furthermore, by loading the tractor to a certain percent of the tractor's output, this test allows for 'self-scaling' – producing a similar effect for both large and small tractors. Therefore, for 'loaded' situations, the tractor should be loaded to 75% or more.

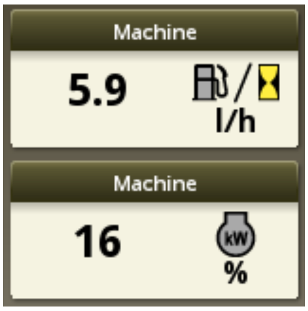

Figure 5.8: Control screen displaying power output as a percentage

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For tests involving accuracy and repeatability (in particular: Test A.2-i – *Latitude and longitude match current position of tractor*), it would be beneficial to compare the GPS output of the tractor against a known marker. By comparing the value of the ASAT's coordinates against those of the survey pin/location, an absolute error value can be produced.

Although requiring extensive preparation and set-up, this test would also produce pertinent results for validating/'ground-truthing' the ASAT's ability to know its exact position. While this may work in theory, issues may arise when trying to align the GPS receiver directly above the survey pin – thereby affecting the error measurement. Ultimately, these test procedures may be superfluous, given confirmation of GPS accuracy is widely researched and documented using previously validated means.

Furthermore, as discussed in the analysis of Test B.1-i (*Accuracy of linear heading paths*), overall accuracy should also be determined. Given the use of advanced/exclusive equipment is to be avoided, a simple string-line could be strung between the beginning and end of the path, with the maximum variance between the travelled path and stringline being recorded as the 'overall accuracy' value. Alternatively, surveyed location markers may also be used as reference locations to deduce accuracy at pre-determined points along the travelled path.

As outlined within the analysis of Test B.5 (*ATG Accuracy over undulating terrain*), further dedicated testing should be undertaken to assess the performance of the ATG when the tractor is driven along a constant incline. While a 'pure roll' motion was obtained in initial testing by driving over the berm in a parallel manner, a certain amount of roll was reduced by the tractor's suspension system. To counteract the effect of independent front-axle suspension, the tractor should be driven along a constant slope. Figure 5.9, below, shows the exaggerated effect of independent suspension on both a berm and constant incline.

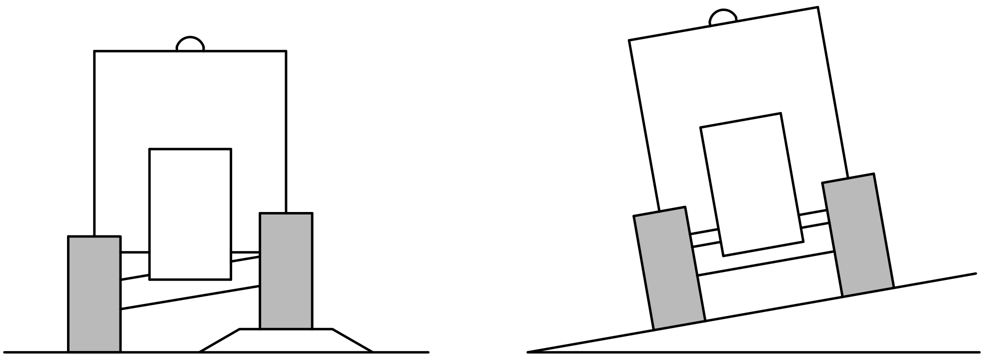

Figure 5.9: Influence of independent suspension reduced on constant inclines

By conducting the test on a constant incline, this would allow full exploitation of the terrain calibration module. Additionally, a constant incline may be more appropriate for a practical scenario (with farming along inclines being more common than driving over berms/contours). Therefore, the test should be redefined by driving the tractor along a constant incline, recording accuracy of the ATG as it travels.

While additional testing may be implemented for assessing the ASAT's ability to detect critical roll/pitch angles, it is assumed situations like this lie outside the scope of ODD – with the operator ensuring the environment is suitable for ASAT operation prior to engaging automated/autonomous functions.

With reference to the analysis of Test C.5/C.6, testing revealed the ability of the ASAT to extrapolate the working width and location of the implement – triggering the same collision alarm as if the tractor were to cross the field boundary. Given this is both highly applicable and pertinent to the safe operation of an ASAT, a dedicated test is included in the final/recommended testing procedures. Similar to Test A.3-i/ii, this test assesses whether the ASAT stops before the implement crosses the field boundary. This will require the operator to program the parameters/dimensions of the implement and adjust the headland turning circle until only the implement (not the tractor) collides with the boundary.

Test A.11 (*Stopping time from 12 km/h*) is refined further through the assessment of stopping mechanisms. As discussed in many of the aforementioned tests, methods to override the tractor in a 'panic situation' should be made available. Ideally, the operator should be able to instinctively override ASAT functionality without spending time locating the override mechanism.

For the purposes of refining Test A.11, modes/methods to bring the tractor to a complete stop within a panic situation are also examined and may correlate to the result of Test D.7 (*Activation of emergency stop*). For example, stopping the ASAT by placing the tractor in neutral may have a stopping time of 2 seconds, while activation of an emergency stop can halt the machine in 1 second. Consequently, the refined procedure includes listing the 'stopping methods' and time taken to bring the tractor to a standstill in the shortest period of time.

Building upon a combination of 'Tractor Perception' and 'ATG Performance', an additional test is developed to assess the ASAT's ability to stop if the position or heading error becomes too great. Upon completion of Test B.2-i (*Accuracy of curved/custom paths*) and B.3-ii (*Accuracy of curved paths when driven in reverse*), it was observed that significant errors can result while ATG remains engaged.

Therefore, to prevent damage to property, machinery or crop, the ASAT is assessed on its ability to stop operations, should positioning errors become excessive or cross a predefined threshold. This test may be undertaken as part of Test B.2-i or B.3-ii (where sizable positioning errors are most likely to occur). Should the error exceed 50 cm or an 'operator-defined limit', the ASAT should stop moving and enter a safe state for successful completion of this test.

5.7 Recommended Test Procedures

5.7.1 Overview

During testing, it was apparent that the order and grouping of test procedures could be improved to allow greater comprehension and appreciation of results. The refined tests continue to use an alpha-numerical system, thereby allowing ease of assessment and discussion of results.

The tests are reclassified into four subcategories:

Test A: Perception and Awareness

Test B: Automated Tractor Guidance

Test C: Headland Management

Test D: Operational Safety

Sub-tests are also allocated their own test (e.g. Test A.2-ii will become Test A.3). Furthermore, tests are reordered to allow the most pertinent ones to be assessed first, with less critical tests (deduced from practical testing) being presented thereafter.

Additionally, the refined/new testing procedures (outlined in Chapter 5.6) are implemented within these new recommended tests.

For the purposes of this project, certain tests pertaining to *Obstacle Detection and Avoidance* were omitted. Consequently, the addition of a fifth test (Test E) will be required (and therefore recommended for future research) to complete the entirety of the testing procedures.

5.7.2 Finalised Procedures

The following procedures are recommended to assess both the capabilities and field readiness of an ASAT.

Test A: Perception and Awareness

A.1 Tractor stops before crossing field boundary (under ASAT control)

A.2 Tractor stops before crossing field boundary (under manual control)

A.3 Tractor stops before implement crosses field boundary (under ASAT control)

A.4 Tractor stops when positioning errors become excessive

A.5 Latitude and longitude readings match current position of tractor

A.6 Heading measurement updates as tractor executes 360° turn

A.7 Percentage change of speed when load is applied

A.8 Awareness of low fuel level

A.9 Awareness of low engine oil pressure

A.10 Awareness of low hydraulic oil level

A.11 Awareness of excessive engine temperature

A.12 Awareness of extreme ambient temperature

Test B: Automated Tractor Guidance

B.1 Accuracy of linear paths

B.2 Repeatability of linear paths

B.3 Accuracy of ATG under balanced load conditions

B.4 Accuracy of ATG under unbalanced load conditions

B.5 Accuracy of ATG when driven across a constant incline

B.6 Accuracy of curved/custom paths

B.7 Repeatability of curved/custom paths

B.8 Accuracy of linear paths when driven in reverse

B.9 Accuracy of curved/custom paths when driven in reverse

B.10 Accuracy of ATG when independent braking is applied

Test C: Headland Management

C.1 Perform an automated headland turn and align with next pass

C.2 Perform various turning formats to suit different implement profiles

C.3 Tractor performs required action/s when entering non-arable area

C.4 Automated adjustment of ground speed

C.5 Automated lifting and lowering of implement using 3-point linkage

C.6 Automated lifting and lowering of implement using hydraulic controls

C.7 Automated control of PTO

C.8 Automated control of differential lock

C.9 Turning circle (radius) of tractor

C.10 Maximum steering angle

Test D: Operational Safety

D.1 Maintain a safe state until a command is given by the operator

D.2 Detect non-operational hardware

D.3 Lock-out autonomous functions while faults are present

D.4 Activation of emergency stop

D.5 Manual override of ATG

D.6 Assuming control of automated headland management

D.7 Assuming control of automated field operations

D.8 Assuming control of automated PTO operation

D.9 Manual override of cruise control

D.10 Stopping time from 12 km/h (listing methods to stop the tractor)

Assessment metrics and parameters remain unchanged from the initial version of testing, with the final/recommended *Test Document* presented in Appendix D.

5.8 Recommended Grading System

This sub-chapter will present the recommended system used for grading test results. By condensing raw tests results into a score/mark/grade, results are summarised in a simple, yet comprehensible, format. Similar to the 'Energy Star' rating on domestic appliances and white goods (whereby efficiency is presented on a numerical scale), the developed system allows ease of comparison between ASAT capabilities.

Two options exist for grading the performance of ASAT abilities, employing the use of either a rubric/criteria or an equation to directly input numerical performance values. The following sub-sections outline the recommended grading system (and where applicable, the measures to satisfy a certain level of performance).

5.8.1 Grading of A-Series Tests

The majority of Test A (with the exception of A.5 – A.7) consists of pass/fail tests. Depending on the test, more marks are assigned to the completion of 'higher-level' ASAT competencies. The designation of marks for each test is summarised below:

A.1 Crossing boundary under ASAT control	4 marks	(4/2/0 for stopping/acknowledging/fail)
A.2 – A.4 Manual control/implement collision Excessive positioning errors	3 marks	(3/1/0 for stopping/acknowledging/fail)
A.8 – A.12 Levels and pressures	1 mark	(1/0 for pass/fail)

For Tests A.5 - A.7, marks are determined using the following criteria:

Table 5.1: Test A.5 Criteria

Decimal Places	8 – 7	6	< 6
Theoretical accuracy (accuracy at equator)	1 – 11 mm	111 mm	> 111 mm
Mark	**2**	**1**	**0**

With typical precision-agriculture operations operating at substantial levels of precision (sub-10 cm), the decision was made to penalise accuracies above this threshold by awarding no marks. For finer tolerances offered through premium GPS receivers and/or access to RTK technology, accuracy is substantially increased and consequently, a higher mark shall be awarded.

Table 5.2: Test A.6 Criteria

Decimal Places	1	0	No awareness of heading
Theoretical accuracy (increments per revolution)	3600	360	-
Mark	**2**	**1**	**0**

Given the tractor must have an appreciation of its direction and bearing of travel (particularly when using a 'Start Point and Bearing' method to produce an ATG track), a suitable bearing accuracy must be employed. While a measurement with no decimal places would provide a suitable reading, a higher resolution ultimately provides a finer tolerance, and therefore, shall be allocated a higher mark.

Table 5.3: Test A.7 Criteria

Change of Speed	$< 20\%$	$20 - 50\%$	$> 50\%$
Mark	**3**	**1**	**0**

Given the complexity involved when selecting a lower gear, increasing engine speed, and the potential implementation of other reactive procedures (as witnessed during initial pilot testing), a higher mark is allocated to the successful maintenance of field speed with minimal disruption. To achieve full marks, the maximum change in speed must be less than 20% (equivalent to 1.2 km/h change in speed if travelling at 6 km/h).

Consequently, for the 12 tests (A.1 to A.12), a maximum mark of 25 can be achieved. This mark is then converted to a score out of 10 – accomplished by converting the score to a percentage before dividing by 10, or simply **multiplying the total marks by 0.4**.

For example, a score of 22/25 is presented as 8.8/10.

5.8.2 Grading of B-Series Tests

While pre-specified criteria (similar to Tables 5.1 – 5.3) could have been implemented for the grading of the B-Series Tests, the decision was made to employ an equation-based method to allow accurate and true representation of the ATG results.

To simplify the grading process, the following equation was applied to all results:

$$\text{Grade} = 0.95^{(\text{ERROR} - 50)} - 2.8 \qquad \text{(Eqtn 1)}$$

This equation accepts the ATG error (in centimetres) as an input and outputs the corresponding resultant grade – with an error of 0 cm producing a grade of ten, with an error of 30 or above producing a zero or negative result (negative results are recorded as a zero). Parameters of the equation were adjusted to suit the 0 – 10 grading and 0 – 30 cm error values, with the resulting grade recorded to one decimal place.

While a linear equation could have been implemented, a 'power function' is recommended to amplify and discriminate the error results. This allows the consequence of error to be more at the higher accuracies (as an deviation of $\pm$ 1 cm at a required 2 cm accuracy represents 50% error, while only 4% at 25 cm). Therefore, a greater discrepancy is required at higher levels of precision, as errors are more significant at lower ranges. The following figure summarises the grading curve produced from the above equation.

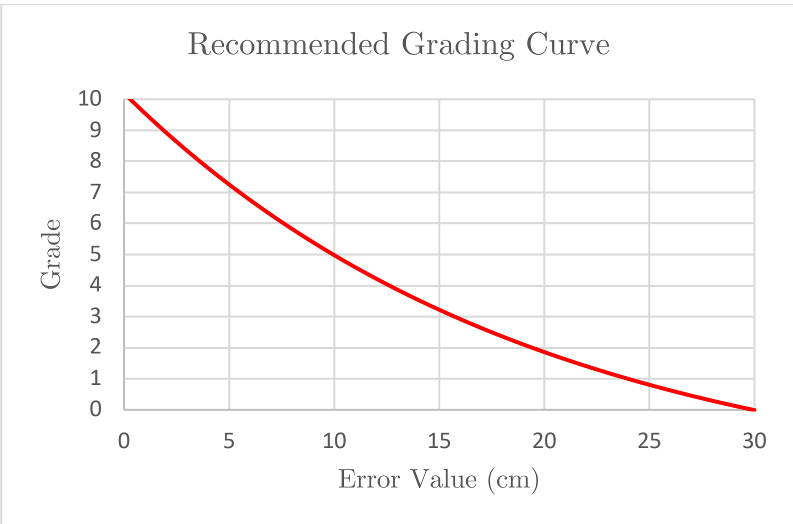

Figure 5.10: Recommended Grading Curve (using Eqtn 1)

Upon completion of grading individual tests, the **marks are totalled** (with a maximum of 100), **before multiplying by 0.1** to produce an overall grade for ATG performance.

5.8.3 Grading of C-Series Tests

Similar to the grading of A-Series Tests, a range of marks are awarded for the successful completion of ASAT abilities during headland operations. These are summarised as follows:

C.1 Automated headland turn	5 marks	(5/0 for pass/fail)
C.2 Adjustment of turning format	3 marks	(3/0 for pass/fail)
C.3 & C.4 Non-arable headland and ground speed	2 marks	(2/0 for pass/fail)

For Tests C.9 and C.10, the following criteria was implemented to produce a grade when provided with a certain turning radius or steering angle. All other tests (C.5 – C.8) are graded with a mark of 1 or 0 for a 'pass' or 'fail' respectively.

Table 5.4: Test C.9 Criteria

Turning Radius	< 5 m	5 – 10 m	> 10 m
Mark	**2**	**1**	**0**

Given most tractors in the marketplace now feature advanced steering systems (such as John Deere's 'Variable Ratio Steering'), tractors are able to manoeuvre within increasingly restricted areas. Consequently, maximum marks are awarded for a turning radius less than 5 m, with no marks provided for a radius greater than 10 m.

Table 5.5: Test C.10 Criteria

Steering Angle	> 60°	45 – 60°	< 45°
Mark	**2**	**1**	**0**

For similar reasons to that of Test C.9 – row-crop and utility tractors are becoming increasingly manoeuvrable. For example, the latest John Deere 5R model tractor possesses a turning angle of 60° (John Deere 2018). To ensure competitive comparisons, a steering angle of 60° or greater shall warrant full marks, while angles less than 45° obtain a mark of 0.

Individual **marks are totalled** (maximum of 20), **before multiplying by 0.5** to produce the overall grade for Headland Management ability and performance.

5.8.4 Grading of D-Series Tests

Each test was awarded three marks for the successful and safe overriding of autonomous operations. Tests D.1 – D.3 are prescribed three or zero marks for a pass/fail, while Tests D.4 – D.9 are awarded three marks for satisfying all ISO 18497 criteria (one mark each for: *Identifiable*, *Accessible* and *Guarded*). Additionally, Test D.10 (Stopping Time) is marked using the following criteria:

Table 5.6: Test D.10 Criteria

Stopping Time	< 1 sec	1 – 2 sec	> 2 sec
Mark	**3**	**2**	**0**

Upon completion of awarding individual marks, the overall grade is calculated by **summing each test** (maximum of 30) **and multiplying the result by 0.3**.

5.8.5 Presentation of Grade

Once a grade was awarded for each test series, the overall grade for ASAT performance, ability and field-readiness (PAFR) is presented – accomplished by presenting the results as follows (where the letters 'A' to 'D' represent the mark out of 10 for each test series):

$$A : B : C : D$$

For marks where more than one decimal place is recorded, the mark is rounded to one decimal place. For marks including only a single integer (with no decimal places), no decimal place is included.

It is recommended that future tests (such as the inclusion of Test-Series E) continue implement this notation to ensure continuity and clarity.

5.8.6 Grading 6120R Case Study

Test A: Perception and Awareness

A.1	Tractor stops before crossing field boundary (under ASAT control)	**2/4**
A.2	Tractor stops before crossing field boundary (under manual control)	**0/3**
A.3	Tractor stops before implement crosses field boundary (under ASAT control)	**2/3**
A.4	Tractor stops when positioning errors become excessive	**2/3**
A.5	Latitude and longitude readings match current position of tractor	**2/2**
A.6	Heading measurement updates as tractor executes 360° turn	**2/2**
A.7	Percentage change of speed when load is applied	**3/3**
A.8	Awareness of low fuel level	**1/1**
A.9	Awareness of low engine oil pressure	**1/1**
A.10	Awareness of low hydraulic oil level	**0/1**
A.11	Awareness of excessive engine temperature	**1/1**
A.12	Awareness of extreme ambient temperature	**1/1**
		17/25 **6.8/10**

Test B: Automated Tractor Guidance

B.1	Accuracy of linear paths	**2 cm**	**8.9**
B.2	Repeatability of linear paths	**2 cm**	**8.9**
B.3	Accuracy of ATG under balanced load conditions	**2 cm**	**8.9**
B.4	Accuracy of ATG under unbalanced load conditions	**7 cm**	**6.3**
B.5	Accuracy of ATG when driven across a constant incline	**2 cm**	**8.9**
B.6	Accuracy of curved/custom paths	**13 cm**	**3.9**
B.7	Repeatability of curved/custom paths	**3 cm**	**8.3**
B.8	Accuracy of linear paths when driven in reverse	**2 cm**	**8.9**
B.9	Accuracy of curved/custom paths when driven in reverse	**14 cm**	**3.5**
B.10	Accuracy of ATG when independent braking is applied	**4 cm**	**7.8**
			74.5/100 **7.5/10**

Test C: Headland Management

C.1	Perform an automated headland turn and align with next pass		**5/5**
C.2	Perform various turning formats to suit different implement profiles		**3/3**
C.3	Tractor performs required action/s when entering non-arable area		**2/2**
C.4	Automated adjustment of ground speed		**2/2**
C.5	Automated lifting and lowering of implement using 3-point linkage		**1/1**
C.6	Automated lifting and lowering of implement using hydraulic controls		**1/1**
C.7	Automated control of PTO		**1/1**
C.8	Automated control of differential lock		**1/1**
C.9	Turning circle (radius) of tractor	**4.8 m**	**2/2**
C.10	Maximum steering angle	**45°**	**1/2**
			19/20 **9.5/10**

Test D: Operational Safety

D.1	Maintain a safe state until a command is given by the operator		**3/3**
D.2	Detect non-operational hardware		**3/3**
D.3	Lock-out autonomous functions while faults are present		**3/3**
D.4	Activation of emergency stop	**I A G**	**2/3**
D.5	Manual override of ATG	**I A G**	**2/3**
D.6	Assuming control of automated headland management	**I A G**	**3/3**
D.7	Assuming control of automated field operations	**I A G**	**3/3**
D.8	Assuming control of automated PTO operation	**I A G**	**3/3**
D.9	Manual override of cruise control	**I A G**	**3/3**
D.10	Stopping time from 12 km/h	$<$ **1 sec**	**3/3**
			28/30 **9.3/10**

Combining the four grades together, the PAFR mark for the John Deere 6120R case study was as follows:

6.8 : 7.5 : 9.5 : 9.3

Using this grading system, it can be easily deduced that the 6120R lacks certain perception and awareness capabilities, whilst performing competently in regards to automated headland operations and machine operational safety.

Chapter 6

Discussion

6.1 Chapter Overview

This chapter both summarises and discusses the results from testing and their respective implications for both the project and potential future work.

Implementation of a Deere 6120R case study allowed practicality of test procedures to be assessed, whilst also informing the PAFR of currently available, ‘best-in-class’, ASATs. While it is hoped this project will inform the basis of universally accepted ASAT test protocols, future work and industry inputs are required to reach the desired level of commercial acceptance.

Finally, the testing procedures, and respective results obtained from the 6120R are analysed with respect to the original project objectives (as outlined in Chapter 1.4). Each objective is outlined and discussed within the following sections.

6.2 Achievement of Project Objectives

Research was conducted against the aim of fulfilling certain, pre-defined, project objectives (as outlined in Chapter 1.4). By retaining focus on these objectives, pertinence of the research was maintained – allowing valuable insights to be deduced.

6.2.1 Objective A: Determine Machine Requirements

Current standards, performance objectives and safety aspects of ASATs and autonomous functions were outlined within Chapter 2 (Review of Literature). Analysis of standards across multiple industries (agriculture, mining and transport) were also discussed to gain an understanding of current knowledge and how (semi-)autonomous machinery is assessed and/or standardised across a range of applications and industries. By doing so, it was ensured that research delivered by this project built upon, and did not contradict, current research and published works.

By implementing a literature review, tasks that a typical 'field-ready' ASAT should be expected to perform were deduced. For tasks that were not exclusively detailed, the control architecture of an ASAT was referenced, in order to produce tasks that would exploit certain behaviours or protocols. While the review of literature revealed certain requirements of ASATs/HAAMs, together with recommended testing procedures in both mining and agricultural sectors, no 'standardised' list of expected tractor tasks was available. However, by referencing aspects of ISO 18497, ISO 17757, together with fundamentals of ASATs (including control architecture and performance objectives), high-level objectives were used to define lower-order tasks that exploited both the performance and abilities of a field-ready ASAT.

Furthermore, the list of expected ASAT tasks developed within this project may be referred to as a foundation for future work/research. This list can also be used as a 'blue-print' for the testing of other metrics, or as a 'check-list' when comparing low-level abilities of a tractor (not limited to ASATs).

Ultimately, the main insight drawn from this Project Objective is related to the limited documentation available that specifically lists tasks correlating to ASAT PAFR. Given the broad nature of tractor tasks, this was to be expected. However, by limiting the ODD and outlining the four main categories of ASAT operations, tasks could be outlined in a simple yet logical pattern. Drawing from Blackmore and Baillie's research in relation to abilities and control architecture of an ASAT, tasks were developed to observe such fundamentals and behaviours.

6.2.2 Objective B: Develop Series of Tests

Once expected ASAT tasks were determined, tests were designed to exploit various behaviours and protocols within the control system. Each category was broken-down into individual tests that would implement various aspects of the control system to complete the desired task. Some tests were quite basic in nature (such as a pass or fail mark for automated field speed abilities) while others were reliant on numerous systems, working in parallel, to achieve a complex task (such as ATTA or driving across an incline).

Procedures were developed using practical knowledge, however many tests also relied upon Blackmore's and Baillie's research into control architecture and performance objectives respectively. A practical understanding was beneficial when designing tests to exploit certain objectives/behaviours – for example, driving across an incline to exploit the ASAT's 'Terrain Compensation'.

Although 60 tests were initially developed, the pertinence of them (in relation to both the John Deere 6120R case study and relevance to assessing ASAT PAFR) was limited. However, by implementing a predetermined 'criteria for a successful test', testing was made more achievable (number of tests was reduced to 39) and practical (tests were restricted to suit the current PAFR of the case study).

Upon completion of initial analysis, procedures were refined to ensure observations and recommendations from initial testing could be addressed and implemented – thereby increasing relevance and confirming the tests exploited the desired ASAT element.

Insights drawn from satisfying this Project Objective include:

- Sufficiently refining ODD to allow creation of tests based on tasks to be performed in a 'structured environment' to allow relevance across a variety of farm/operating environments.
- Creation of 'successful test criteria' was valuable to ensure tests meet the required specifications (such as relevant, repeatable and safe) and thereby allow limiting of the total number and/or detail of tests.
- Implementation of a numbering system ensured tests were easily identified – particularly once re-categorised into an alpha-numerical system.
- Development of a standardised/universal format of testing proved challenging when attempting to include all important aspects of an ASAT

6.2.3 Objective C: Pilot Testing using John Deere 6120R

Pilot Testing

Upon developing testing procedures and criteria, the PAFR of a John Deere 6210R was then assessed. While set-up of ASAT functionalities was labour and time-intensive, the tractor was successfully configured and programmed with the relevant information.

Following the testing procedures developed in Chapter 3.3.4 (*Test Procedures to Measure Performance*), tests were conducted and results recorded. Pilot testing provided valuable insights into the performance of not only the 6120R, but also the appropriateness of test procedures themselves.

While procedures were initially 'screened' in Chapters 3.3.5 and 3.3.6, practical implementation of tests revealed areas requiring improvement or further refinement to ensure the desired system component was being exploited. For example, while use of a singular berm/contour bank provided a source of undulation, full exploitation of the machine's terrain compensation could not be achieved. Tests were then adjusted (by driving the tractor along a constant incline) to directly work the compensation module.

Through the execution of practical testing, the process/methodology of assessing ASAT abilities could also be analysed. Most tests followed a natural progression; for example, the operator could complete various tests by simply viewing one display (Tests A.8 – A.12 and Tests C.2 – C.8 may be completed by viewing the dashboard or CommandArm display) or by driving the tractor within an open area (A.5, A.6, D.1, D.2 and D.9). Additionally, with the exception of B-Series Tests (involving ground-truthing), the assessor could remain in the cab while executing tests – thereby improving ease, comfort and the ultimate up-take/acceptance of testing.

Overall, by implementing an initial screening process, the majority of tests were able to satisfy the criteria for a 'successful test' before being applied in practice. Given the comprehensive standard of the criteria, it was expected that practical implementation would produce compliant/compatible results. As anticipated, pilot testing ultimately confirmed the procedures' appropriateness to assess ASAT PAFR.

Performance of 6120R

By implementing a practical/real-life case study, test procedures and their respective results can be observed against currently available technologies. In addition to assessing the appropriateness of test procedures, the implementation of a John Deere 6120R case study also outlines the performance of said machine.

With PAFR scores of 6.8 : 7.5 : 9.5 : 9.3, it is apparent that both the perception and tractor guidance systems lack performance, while marks for headland management and operational safety are significantly better. Focussing on the A-Series Tests (*Perception and Awareness*), the tractor lacks numerous 'fail-safe' protocols. Should the operator (or lack thereof) fail to implement a reactive procedure (even when the tractor registers a potential collision hazard), the 6120R fails to stop/enter a safe state and instead, continues the task. While acknowledging a potential collision and sounding an alarm is significant, it should be considered equally important that the ASAT halts operation prior to damage occurring. This suggests that although the technology has approached a semi-advanced level of maturity (witnessed in the C and D-Series Tests), it still lacks the 'intuition' required for safe, fully-driverless operation.

Furthermore, the 6120R appears to lack the ability to manoeuvre about curved or custom paths – ultimately affecting the grade of the B-Series Tests. While larger row-crop tractors are mainly used for straight-row scenarios, the ability for the tractor to traverse curved paths may be equally important – particularly when the compact size of the 6120R lends itself to smaller spaces, where fields can be oddly-shaped. While performance of the tractor's curve-tracking may be poor, the ability for the case study to adapt to undulations and inclines was commendable (further boosting the appeal for farmers who may have small, undulating fields or fields on an incline). Moreover, due to the high repeatability scores of all ATG tests, it can be deduced that the 6120R would be well suited for applications requiring high levels of season-to-season precision (such as controlled-traffic farming, side-dressing of fertiliser or inter-row cultivation).

Overall, the 6120R performed very well throughout most testing procedures – scoring an average mark of 8.3/10. While the abilities of the tractor were present and of a high complexity (such as advanced headland management systems), some aspects of ASAT performance were deficient – primarily relating to the machine's ability to 'fail-safe' and enter a safe state if a collision is detected yet no reactive measures are implemented. Testing the full functionality of the tractor in a 'driverless' format was limited, given the lack of obstacle detection and avoidance systems.

6.2.4 Objective D: Develop Recommended Grading System

Upon completion of pilot testing to confirm and/or refine testing protocols, the finalised/recommended test procedures were then presented. A grading system was then developed to convey the test results in an easy to understand format, prior to rating the 6120R's PAFR using this grading system.

As ASATs become more popular in the commercial marketplace, a system to convey the ability, safety and performance of such tractors, in a standardised, easy to comprehend format, will become ever more important. Similar to the *Energy Star* rating on whitegoods or the *Fuel Consumption* labels on new vehicles, the grading system put forward in this paper aims to standardise the comparison process between different makes and models of ASATs – benefitting not only the consumer, but tractor manufacturers as well.

Through creation of the grading system, it was realised that although these tests may be sufficient for the purposes of this dissertation (in determining the PAFR of a 6120R and satisfying the project objectives), the execution of further pilot testing/case studies, together with the input and guidance from tractor manufacturers, industry partners and additional research institutes would prove invaluable to the uptake of such standardised testing. Inputs from these sources would also provide a more comprehensive perspective as to what would ultimately influence the PAFR of an ASAT. Furthermore, obtaining insights and advice from industry may also allow refinement of the grading system itself – such as applying weightings on each test, or re-classifying the rating curve used for B-Series Tests.

Overall, insights drawn from achieving this Project Objective relate primarily to the potential limitations of industry uptake due to lack of liaising with stakeholders and manufacturers. This would allow a more rounded and universal perspective on what abilities and levels of performance should be expected of a field-ready ASAT, together with how marks are awarded. Ultimately, this paper provides a foundation to initiate future work by allowing industry stakeholders to build upon, veto or refine the recommended grading systems.

6.3 Limitations

Primary limitations of this research relate to the amount and maturity of technology available for this project.

Although an advanced, highly-automated tractor, the 6120R was designed to be used within a hybrid (human-machine) scope. ASAT functions provided by this tractor ultimately aim to assist the operator, rather than replace them. Consequently, higher-levels of driving autonomy were unable to be assessed – such as obstacle detection and avoidance protocols. Overall, the machine provided a suitable case study (given its ability to operate within the 'Structured Environment' ODD) to allow implementation of the developed test procedures.

A further limitation as a result of time/resource requirements involves the testing of only one case study. While tests were successfully executed using a John Deere 6120R, no additional case studies were employed to test the reproducibility of results when assessing a different make or model of tractor. A further effect of these limits relates to the use of non-standardised implements. Given the lack of standardised equipment used throughout testing (such as weight or resistance sleds) reproducibility of results may be impacted – particularly for tests involving a balanced or unbalanced load.

Additionally, test procedures were only executed by the developer of the tests, and did not assess the test's usability or effects of using a 'third-party' assessor (an individual who is competent in operating a tractor, but has no experience with experimental testing).

Environmental conditions were also unable to be tested due to limited time and travel restrictions. All testing was conducted during temperate June/July days in a dry, flat field. Therefore, effects of rain, mud, sub-zero temperatures (including ice, frost and freezing of fluid lines) and soil conditions were unable to be examined, with regards to impacting the repeatability of test procedures and/or reproducibility of results.

Finally, concepts produced and inferences drawn from the research were produced by the author's personal understanding and perspectives. With the ultimate aim of introducing standardised, comparative testing protocols, further input from tractor manufacturers, industry partners, research institutes and other organisations/third-parties may be required to eliminate the effects of partiality or personal opinion – particularly reviewing the list of 'expected ASAT abilities' and the recommended grading system.

6.4 Further Work

To provide a comprehensive procedure for assessing the PAFR of a (semi-)autonomous tractor, further work is recommended (based on the previously outlined limitations), before universally acknowledged and accepted tests can be delivered.

As discussed throughout this paper, the 6120R was limited in its capability to detect and avoid potential obstacles in the field. Consequently, the scope exists to expand the recommended tests and/or develop a fifth testing procedure (i.e. Test E) to fully assess the ASAT's obstacle detection and avoidance protocols. Moreover, some tests may expand upon the exploitation of 'fail-safe' protocols – such as protocols when no operator is detected on the seat, when engine/machine parameters exceed certain thresholds, or when a programmed turning speed exceeds a safe limit.

Further refinement of both the testing protocols and grading scheme is also recommended to mitigate the effects of potential bias and/or personal perspectives and understanding. By presenting this paper to numerous tractor manufacturers and industry stakeholders, insights can be provided from a commercial standpoint, while further reducing subjectivity of competitors.

Additionally, further case studies and different assessors should be employed in order to assess both the repeatability of tests and reproducibility of results when the trials are conducted by a third-party and/or using a different machine.

It is also advocated that standardised implements be used or developed to ensure uniformity across tests with no reliance on particular implements being dragged through specific soil types – for example, use of a weight sled or draft gauge to confirm the load on the drawbar.

The developed procedures should also be assessed across a range of climatic conditions. To ensure pertinence for industry-wide/global uptake, the tests should produce similar results, regardless of the environment. Therefore, it may prove beneficial to execute Tests A – D (and potentially the future Test E) across a variety of weather/operating conditions – such as rain, snow, ice, muddy fields, concreted areas and sub-zero temperatures.

Chapter 7

Conclusion

7.1 Chapter Overview

This chapter summarises key findings of the research, together with presenting recommendations based upon the completed testing and analysis. Conclusions are drawn from all aspects of the project and respective recommendations presented for both further work and the implementation of potential industry-wide standards.

7.2 Key Findings

Conclusions and key findings drawn from this project are summarised as follows:

- Absence of existing research and literature pertaining to the consolidation of standards, expected abilities and performance metrics for the safe and practical applications of ASATs.

- Refinement of the ODD is crucial for the in-depth assessment of ASATs. By restricting the operational environment in which a semi-autonomous tractor can function, pertinent abilities were deduced and relevant tests created.

- Machine requirements can be categorised into four succinct categories, relating to: perception and awareness; automated tractor guidance; headland management and operational safety.

- Development of a recommended grading system allows PAFR results to be conveyed in a straightforward and concise manner.

- Implementation of a practical case study ensured testing procedures were suitable for the accurate assessment of ASAT PAFR. Not only did these tests provide confirmation of test appropriateness, PAFR of the 6120R case study was also deduced.

- The John Deere 6120R scored a PAFR mark of 6.8 : 7.5 : 9.5 : 9.3. This score outlined the ASAT's lack of in-depth perception and awareness practices. However, it also highlighted the machine's comprehensive headland management abilities and operational safety protocols.

- PAFR test results show the 6120R exhibits promising/'enabling' elements of fully-autonomous technology, yet is ultimately limited in its driverless capabilities due to its current lack of obstacle detection and 'fail-safe' protocols.

7.3 Recommendations

Upon completion of this project, the following recommendations are proposed:

- Present the developed testing protocols and grading system to tractor manufacturers, industry partners, and relevant stakeholders, to obtain meaningful feedback and possible refinements to accelerate uptake of independent '*USQ Tractor Test*' test procedures.

- Explore opportunities to further exploit 'fail-safe' protocols of the ASAT.

- Develop and pilot-test 'E-Series Tests' to assess Obstacle Detection and Avoidance protocols.

- Complete testing using additional ASATs from a range of manufacturers to assess the repeatability of tests, using machines with varying levels of PAFR.

- Execute testing in a variety of environmental conditions using 'third-party' assessors, who have had no experience with the development of these test procedures.

- Repeat tests using standardised equipment and instrumentation that can be easily sourced or manufactured to ensure reproducibility of tests and results.

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Appendix A – Project Specification

ENG4111/ENG4112 Research Project

Project Specification

For:	Logan Torrance
Title:	Development of testing protocols to assess the performance of autonomous tractors in order to ascertain suitability prior to deployment on farms.
Major:	Mechatronic
Supervisors:	Craig Baillie Peter Brett Justine Baillie
Enrolment:	ENG4111 – ONC S1, 2020 ENG4112 – ONC S2, 2020
Project Aim:	Develop standardised, comparative testing protocols to assess the performance and functionalities of autonomous tractors to ascertain levels of practical suitability.
Programme:	**Version 1, 15th March 2020**

1. Assimilation of literature; review relevant testing protocols for automation and robotic machinery (drawing from agricultural, transport and mining standards). Identify gaps or refinements to current standard testing protocols and procedures for testing autonomous tractors.
2. Develop testing methodology including relevant performance criteria of protocols. Ensure available equipment can be used to satisfy testing protocols. Confirm/submit risk assessment with USQ WH&S.
3. Assemble/procure instrumentation and equipment; commission USQ/CAE 4066R autonomous tractor and establish tractor testing site.
4. Undertake a preliminary safety and performance evaluation prior to testing on available equipment to maximise potential outcome in results.
5. Conduct performance testing (using available equipment) according to test protocols and collate data for analysis.
6. Undertake analysis and evaluation of performance metrics. Assess the appropriateness of test protocols and performance metrics against the project objectives and adjust/recommend changes, if necessary. Develop a recommended grading system to convey information of tests in a standardised and concise format

If time and resources permit:

7. Testing of additional tractors as case studies to allow comparison between models.
8. Expand tests to allow assessment of wider operational design domains.

Appendix B – Initial Test Documents

As outlined within Chapters 3.3.4 – 3.3.6, the following tests will be performed and the results recorded within the following assessments (whereby required metrics are included on the right-most side of the page, with space underneath each test to record notable observations).

Test A: Perception

A.1	Maximum change of speed when load applied	______	km/h
A.2-i	Latitude and longitude readings update to match the current position of tractor.	☐✓ ☐✗	
	Resolution of measurement.	______	d.p.
A.2-ii	Heading measurement updates as tractor executes a 360° turn.	☐✓ ☐✗	
	Resolution of measurement	______	d.p.
A.3-i	Tractor stops before crossing field boundary (under ASAT control)	☐✓ ☐✗	
A.3-ii	Tractor stops before crossing field boundary (under manual control)	☐✓ ☐✗	
A.3-iii	Tractor raises implement when entering non-arable area	☐✓ ☐✗	
A.4-i	Detect non-operational hardware when disconnected or uncalibrated.	☐✓ ☐✗	
	Autonomous mode locked-out while faults are present.	☐✓ ☐✗	
A.4-ii	Maintain a safe state until a command is given by the operator	☐✓ ☐✗	
A.11	Stopping time from 12 km/h	______	sec

Test B: Automated Tractor Guidance

B.1-i	Accuracy of linear heading paths	______	cm
B.1-ii	Repeatability of linear heading paths	______	cm
B.2-i	Accuracy of curved/custom paths	______	cm
B.2-ii	Repeatability of curved/custom paths	______	cm
B.3-i	Accuracy of linear heading paths when driven in reverse	______	cm
B.3-ii	Accuracy of curved/custom paths when driven in reverse	______	cm
B.4	Accuracy of ATG under balanced load conditions	______	cm
B.5	Accuracy of ATG under unbalanced load conditions	______	cm
B.6	Accuracy of ATG when driven over undulating terrain	90° ______	cm
		60° ______	cm
		30° ______	cm
		15° ______	cm
		0° ______	cm
B.7	Accuracy of ATG when independent braking is applied	______	cm

Test C: Headland Management

C.1-i	Automated lifting and lowering of implement using 3-point linkage	☐✓ ☐✗
C.1-ii	Automated lifting and lowering of implement using hydraulic controls	☐✓ ☐✗
C.2	Automatic adjustment of ground speed	☐✓ ☐✗
C.3	Automated control of PTO	☐✓ ☐✗
C.4	Automated control of differential lock	☐✓ ☐✗
C.5	Perform an automated headland turn and align with next pass	☐✓ ☐✗
C.6	Perform various turning formats to suit various implements If so, what formats are available?	☐✓ ☐✗
C.8	Turning circle of tractor	________ m
C.9	Maximum steering angle	________ deg

Test D: Overriding of Autonomous Operations and Self-Preservation

For tests D.1 – D.7, the controls must be Identifiable, Accessible and Guarded

The methods of overriding ASAT control must also be recorded

D.1	Manually overriding ATG	I☐ A☐ G☐
D.2	Assuming control of automated headland management	I☐ A☐ G☐
D.3	Assuming control of automated field operations	I☐ A☐ G☐
D.4	Assuming control of automated PTO control	I☐ A☐ G☐
D.5	Manually overriding cruise control	I☐ A☐ G☐
D.7	Activation of 'all-stop'/emergency stop	I☐ A☐ G☐
D.8	Awareness of low fuel level	☐✓ ☐✗
D.9	Awareness of low oil pressure	☐✓ ☐✗
D.10	Awareness of low hydraulic oil level	☐✓ ☐✗
D.11	Awareness of excessive engine temperature	☐✓ ☐✗
D.12	Awareness of extreme ambient temperatures	☐✓ ☐✗

Note: Some tests have been omitted from this list, as outlined within Sub-Chapter 3.3.6

Appendix C – Summary of Test Appropriateness & Machine Performance

TEST	DESCRIPTION	TEST APPROPRIATENESS	MACHINE PERFORMANCE
TEST A: PERCEPTION			
A.1	Maximum change of speed when load applied	MODERATE	GOOD
A.2-i	Latitude and longitude readings update to match the current position of tractor.	GOOD	GOOD
A.2-ii	Heading measurement updates as tractor executes a 360° turn.	GOOD	GOOD
A.3-i	Tractor stops before crossing field boundary (under ASAT control)	GOOD	POOR
A.3-ii	Tractor stops before crossing field boundary (under manual control)	MODERATE	POOR
A.3-iii	Tractor raises implement when entering non-arable area	GOOD	GOOD
A.4-i	Detect non-operational hardware when disconnected or uncalibrated.	GOOD	MODERATE
A.4-ii	Maintain a safe state until a command is given by the operator	GOOD	GOOD
A.11	Stopping time from 12 km/h	GOOD	GOOD
TEST B: AUTOMATED TRACTOR GUIDANCE			
B.1-i	Accuracy of linear heading paths	GOOD	GOOD
B.1-ii	Repeatability of linear heading paths	GOOD	GOOD
B.2-i	Accuracy of curved/custom paths	GOOD	MODERATE
B.2-ii	Repeatability of curved/custom paths	GOOD	MODERATE
B.3-i	Accuracy of linear heading paths when driven in reverse	MODERATE	GOOD
B.3-ii	Accuracy of curved/custom paths when driven in reverse	MODERATE	POOR
B.4	Accuracy of ATG under balanced load conditions	GOOD	GOOD
B.5	Accuracy of ATG under unbalanced load conditions	GOOD	GOOD
B.6	Accuracy of ATG when driven over undulating terrain	GOOD	GOOD
B.7	Accuracy of ATG when independent braking is applied	GOOD	GOOD

TEST	DESCRIPTION	TEST APPROPRIATENESS	MACHINE PERFORMANCE
TEST C: HEADLAND MANAGEMENT			
C.1-i	Automated lifting and lowering of implement using 3-point linkage	GOOD	GOOD
C.1-ii	Automated lifting and lowering of implement using hydraulic controls	GOOD	GOOD
C.2	Automatic adjustment of ground speed	GOOD	GOOD
C.3	Automated control of PTO	GOOD	GOOD
C.4	Automated control of differential lock	GOOD	GOOD
C.5	Automated headland turn	GOOD	GOOD
C.6	Execution of various turning formats	GOOD	GOOD
C.8	Turning circle of tractor	GOOD	GOOD
C.9	Maximum steering angle	GOOD	GOOD
TEST D: OVERRIDING OF AUTONOMOUS OPERATIONS			
D.1	Manually overriding ATG	GOOD	GOOD
D.2	Assuming control of automated headland management	GOOD	GOOD
D.3	Assuming control of automated field operations	GOOD	GOOD
D.4	Assuming control of automated PTO control	GOOD	GOOD
D.5	Manually overriding cruise control	GOOD	GOOD
D.6	Manually overriding obstacle detection and avoidance	GOOD	GOOD
D.7	Activation of ‘all-stop’/emergency stop	GOOD	MODERATE
D.8	Awareness of low fuel levels	GOOD	GOOD
D.9	Awareness of low oil pressure	GOOD	GOOD
D.10	Awareness of low hydraulic oil levels	GOOD	GOOD
D.11	Awareness of excessive engine temperatures	GOOD	GOOD
D.12	Awareness of extreme ambient temperatures	GOOD	GOOD

Appendix D – Final/Recommended Test Documents

Test A: Perception and Awareness

A.1	Tractor stops before crossing field boundary (under ASAT control)	☐✓ ☐✗	
A.2	Tractor stops before crossing field boundary (under manual control)	☐✓ ☐✗	
A.3	Tractor stops before implement crosses field boundary (under ASAT control)	☐✓ ☐✗	
A.4	Tractor stops when positioning errors become excessive	☐✓ ☐✗	
A.5	Latitude and longitude readings update to match the current position of tractor. Resolution of measurement.	☐✓ ☐✗ ______	 d.p.
A.6	Heading measurement updates as tractor executes a 360° turn. Resolution of measurement	☐✓ ☐✗ ______	 d.p.
A.7	Percentage change of speed when load applied	______	%
A.8	Awareness of low fuel level	☐✓ ☐✗	
A.9	Awareness of low oil pressure	☐✓ ☐✗	
A.10	Awareness of low hydraulic oil level	☐✓ ☐✗	
A.11	Awareness of excessive engine temperature	☐✓ ☐✗	
A.12	Awareness of extreme ambient temperatures	☐✓ ☐✗	

Test B: Automated Tractor Guidance

B.1	Accuracy of linear heading paths	______	cm
B.2	Repeatability of linear heading paths	______	cm
B.3	Accuracy of ATG under balanced load conditions	______	cm
B.4	Accuracy of ATG under unbalanced load conditions	______	cm
B.5	Accuracy of ATG when driven along constant incline	______	cm
B.6	Accuracy of curved/custom paths	______	cm
B.7	Repeatability of curved/custom paths	______	cm
B.8	Accuracy of linear heading paths when driven in reverse	______	cm
B.9	Accuracy of curved/custom paths when driven in reverse	______	cm
B.10	Accuracy of ATG when independent braking is applied	______	cm

Test C: Headland Management

C.1	Perform an automated headland turn and align with next pass	☐✓ ☐✗
C.2	Perform various turning formats to suit various implements	☐✓ ☐✗
C.3	Tractor performs required action/s when entering non-arable area	☐✓ ☐✗
C.4	Automatic adjustment of ground speed	☐✓ ☐✗
C.5	Automated lifting and lowering of implement using 3-point linkage	☐✓ ☐✗
C.6	Automated lifting and lowering of implement using hydraulic controls	☐✓ ☐✗
C.7	Automated control of PTO	☐✓ ☐✗
C.8	Automated control of differential lock	☐✓ ☐✗
C.9	Turning circle (radius) of tractor	________ m
C.10	Maximum steering angle	________ deg

Test D: Operational Safety

For Tests D.3 – D.8, the controls must be Identifiable, Accessible and Guarded

D.1	Maintain a safe state until a command is given by the operator	☐✓ ☐✗
D.2	Detect non-operational hardware when disconnected or uncalibrated.	☐✓ ☐✗
D.3	Autonomous mode locked-out while faults are present.	☐✓ ☐✗ ☐✓ ☐✗
D.4	Activation of 'all-stop'/emergency stop	I☐ A☐ G☐
D.5	Manual override of ATG	I☐ A☐ G☐
D.6	Assuming control of automated headland management	I☐ A☐ G☐
D.7	Assuming control of automated field operations	I☐ A☐ G☐
D.8	Assuming control of automated PTO control	I☐ A☐ G☐
D.9	Manual override of cruise control	I☐ A☐ G☐
D.10	Stopping time from 12 km/h	______ sec

Note: Some tests have been omitted from this list, as outlined within Sub-Chapter 3.3.6

Appendix E – USQ Safety Risk Management Plan

UNIVERSITY OF SOUTHERN QUEENSLAND

University of Southern Queensland

Print View

USQ Safety Risk Management System

Version 2.0

Safety Risk Management Plan

Risk Management Plan ID:	*Status:*	Current User:	Author:	Supervisor:	Approver:
RMP_2019_3242	*Approve*	i:0#.w|usq\x0069929	i:0#.w|usq\u8005380	i:0#.w|usq\mccarthc	i:0#.w|usq\u8007639

Assessment Title: 1007012 GRDC Future Farm Phase 2

Assessment Date:

Workplace (Division/Faculty/Section): R&I / CAE

Review Date: 31/03/2022 (5 years maximum)

Approver: *Peter Brett*

Supervisor: (for notification of Risk Assessment only) *Cheryl McCarthy*

Context

DESCRIPTION:

What is the task/event/purchase/project/procedure?	Development and supply of automated sensing technology to improve farmer confidence
Why is it being conducted?	funded research project by GRDC
Where is it being conducted?	various trial sited in Qld, NSW & WA, USQ ag field
Course code (if applicable)	
Chemical Name (if applicable)	

WHAT ARE THE NOMINAL CONDITIONS?

Personnel involved	Cheryl McCarthy, Alison McCarthy, Logan Torrance, Victor Skowronski, other USQ trained staff as directed
Equipment	construction equipment (soldering irons, drills etc), drones, sensors, tractors
Environment	mechatronics lab, field site/s
Other	
Briefly explain the procedure/process	team will develop and test sensing technology

Assessment Team - who is conducting the assessment?

Assessor(s): Majella Bathurst, Craig Baillie;

Others consulted: (eg elected health and safety representative, other personnel exposed to risks) *Logan Torrance, Alison McCarthy*

Risk Matrix

Probability	Insignificant No Injury 0-$5K	Minor First Aid $5K-$50K	Moderate Med Treatment $50K-$100K	Major Serious Injury $100K-$250K	Catastrophic Death More than $250K
Almost Certain 1 in 2	M	H	E	E	E
Likely 1 in 100	M	H	H	E	E
Possible 1 in 1,000	L	M	H	H	H
Unlikely 1 in 10,000	L	L	M	M	M
Rare	L	L	L	L	L

1 in 1,000,000					

Recommended Action Guide	
Extreme:	**E**= Extreme Risk – Task ***MUST NOT*** proceed
High:	**H** = High Risk – Special Procedures Required (Contact USQSafe) Approval by VC only
Medium:	**M**= Medium Risk - A Risk Management Plan/Safe Work Method Statement is required
Low:	**L**= Low Risk - Manage by routine procedures.

Risk Register and Analysis

	Step 1	*Step 2*	*Step 2a*	*Step 2b*	*Step 3*			*Step 4*				
	Hazards: From step 1 or more if identified	***The Risk:*** What can happen if exposed to the hazard without existing controls in place?	***Consequence:*** What is the harm that can be caused by the hazard without existing controls in place?	***Existing Controls:*** What are the existing controls that are already in place?	***Risk Assessment:*** Consequence x Probability = Risk Level			***Additional Controls:*** Enter additional controls if required to reduce the risk level	***Risk assessment with additional controls:*** Has the consequence or probability changed?			
					Probability	*Risk Level*	*ALARP*		*Consequence*	*Probability*	*Risk Level*	*ALARP*
	Example											
	Working in temperatures over 35^0 C	*Heat stress/heat stroke/exhaustion leading to serious personal injury/death*	*catastrophic*	*Regular breaks, chilled water available, loose clothing, fatigue management policy.*	*possible*	*high*	*No*	*temporary shade shelters, essential tasks only, close supervision, buddy system*	*catastrophic*	*unlikely*	*mod*	*Yes*
1	Wild fauna in external fie	Bite, envenomation	Major	Long pants & covered footwear; keep distance with animals, arachnids, etc	Rare	Low	☑					☐
2	Travel to field sites (vehic	Personal injury/death	Catastrophic	Ensure all drivers have a current license, use in-built safety measures, keep to speed limit, regular breaks. Follow the procedure listed in USQ Laboratory Safety Manual, Section 10.13.3 Vehicle Usage for Field Trips. USQ CAE Car booked following procedures.	Rare	Low	☑					☐
3	Using tools in workshop i	personal injury including burns, chemical exposure from soldering, etc.	Minor	observe all workshop safety protocols. Use PPE safety gear (glasses, gloves, etc).	Unlikely	Low	☑					☐
4	operation of drone	personal injury, damage to property e.g. powerlines, houses, cars, etc.	Major	only licenced operators to fly drones. All CASA regulations to be followed including min distances from powerlines, people, property etc.	Rare	Low	☑					☐
5	field work in middle of su	heat exhaustion, heat stroke, sunburn, dehydration	Catastrophic	wear appropriate clothing for the field work - light long sleeved shirt, broad brimmed hat, sunscreen, drink plenty of water/electrolytes, avoid extreme weather events (eg heat waves)	Rare	Low	☑					☐
6	Use of tractor to test equ	crush injuries from attaching plant, potential rollover or rolling of vehicle; PTO or implement entanglement resulting in injury to appendages, etc. Projectiles from rotary hoe/ fertilizer spreader injuring bystanders	Major		Rare	Low	☑					☐

				Operator to be trained/inducted by a competent operator and follow the SOP. Staff not engaged in machine operation to stand back min 5m in view of operator. Tractor is to be parked in gear with hand break applied when attaching implements as per SOP. Ensure travel speed of tractor matches surface conditions. PPE to be worn - gloves, safety glasses. Ensure PTO is switched off prior to (dis)connect. PTO guard to be attached. Secure or remove long hair, loose clothing/items. Bystanders to not stand directly behind rotary hoe/ spreader when operational.									
7	Working around dam/pu	drowning; ingestion of algae resulting in sickness; personal injury from moving parts	Major	Maintain a safe distance from dam wall (min 0.5m) so as not to fall in. No swimming allowed. Ladder on dam slope to assist entry/exit from dam if required. Ensure safety guards are in place on pumps. Personnel to be trained by experienced staff on pump use & dam safety. Use of buddy system.	Rare	Low	☑					☐	

Step 5 - Action Plan (for controls not already in place)

	Additional Controls:	Exclude from Action Plan: (repeated control)	Resources:	Persons Responsible:	Proposed Implementation Date:

Supporting Attachments

No file attached

Step 6 – Request Approval

Drafters Name:	*Majella Bathurst*	*Draft Date:*	*4/01/2019*
Drafters Comments:			

Assessment Approval: All risks are marked as ALARP ☐

Maximum Residual Risk Level: Low - Manager/Supervisor Approval Required ☐

Document Status: *Approve*

Step 6 – Approval

Approvers Name:	*Peter Brett*	*Approvers Position Title:*	
Approvers Comments:			

I am satisfied that the risks are as low as reasonably practicable and that the resources required will be provided.

Approval Decision: *Approve*	*Approve / Reject Date:* *11/03/2019*	*Document Status:* *Approve*