UNIVERSITY OF SOUTHERN QUEENSLAND

Review of Technologies, Regulations and Operating Standards for Field Based Autonomous Agricultural Machinery

GRDC Project Ref: USQ2006-004RTX

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Abstract

To inform the development of a Code of Practice (CoP) for Autonomous Machinery in Agriculture a review was undertaken to assess current technology developments and the status of standards and regulations informing the commercial release of this technology. Large equipment manufacturers including companies such as John Deere, Case New Holland, AGCO, CLAAS, Deutz Fahr and Kubota are progressively moving from automation to autonomy where machinery systems operate independently from human involvement. These developments occur at the component level and provide a pathway to autonomy where value is extracted as features and functionality on new models of machinery. A review of the technology landscape suggests that many of the enabling features for full autonomy are already present on recent model tractors with the exception of machine perception. The current level of technology availability suggests that autonomous technology is within reach of a commercial reality. In this regard non-technical considerations which inform the roll out of this technology is timely and include the obligations of manufacturers, dealers (including service agents), end users of the technology as well as standards and test protocols informing the safe operation of this equipment. New standards are currently being developed which will inform the commercial development of autonomous systems however there is a lack of information on performance expectations, testing protocols and assessment criteria for the infield application of autonomous machinery which requires further work. Similarly developments in agricultural autonomous machinery are limited by the absence of an agreed definition for the Operating Design Domain (ODD) which provides specifics on the operating environment and machinery requirements. Clarity on the ODD will help define technology requirements, the development of standards, expected performance and protocols for testing and assessment. Restricting the ODD to a structured operating environment will provide a progressive implementation of autonomy in agriculture. It is apparent from the transport sector that restricting the ODD has contributed to the roll out of driverless cars and that a controlled release of autonomous machinery on farm and under commercial use cases will greatly assist more broad scale / wider release of the technology. The CoP informed by this review, will provide the overarching structure to separate work such as the implementation of new standards, design specifications and test protocols that will facilitate the commercial release of autonomous machinery in Australian agriculture.

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1. Introduction

The Centre for Agricultural Engineering at the University of Southern Queensland has explored established standards and practices for autonomous land vehicles. These have been developed to assure acceptable performances in path following and operational safety. This investigation has contrasted current approaches in agriculture with other sectors to understand transferable merits in the approach. For agricultural applications, the means to evaluate fundamental expectations under prominent operational and environmental disturbances have been studied.

Systems are currently being trialled by leading manufacturers of tractors. Fundamental opportunities offered by increased system autonomy are frequently identified in performance terms such as consistent outcomes, labour savings and increased productivity. There are challenges posed by inconsistencies and unpredictability in the natural environment, such as terrain, events, mediums encountered, and the presence of personnel and animals.

Looking ahead, limiting technology factors are expected to diminish progressively through advancing techniques in machine sensory perception, machine learning, communications and big data, in particular. Future autonomous machine capability will confront increased complexity in the natural working environment. This expectation is reflected widely across application sectors of autonomous vehicles. A progressive capability index for autonomous vehicles is important for users and producers, and paves the ground for future operational expectations and safety standards.

2. Background

As highly automated agricultural machinery becomes more prevalent within the agricultural sector, performance and safety standards, together with codes of practice, continue to be developed and refined. With a multitude of industries implementing varying degrees of automation, developed standards and regulations appear pertinent for only a definitive industry. Whilst seemingly exclusive for certain applications or machinery, such standards are crucial for informing autonomous practices in other sectors. For the purposes of this document, standards and regulations have been summarised from the agricultural, mining and transport industries where there is perceived overlap.

Currently within the Australian Grains industry Grain Producers Australia is developing a Code of Practice (CoP) for autonomous machinery in agriculture. The autonomy COP stakeholder partners include:

- Grain Producers Australia (which includes participation of all representative state farming organisations)
- Tractor and Machinery Association of Australia (Including technical support of AGCO, CNH, John Deere, Kubota and Nufarm-Croplands)
- Society of Precision Agriculture Australia (Australia's lead independent national precision agriculture organisation)

The Code of Practice for Autonomy in Agriculture is being developed from work previously undertaken in the Mining Industry (Department of Mines and Petroleum, 2015). Participation on the working group has also provided a source of information for i) regulations and standards, ii) system operations and iii) operational risks relating to autonomous systems in agriculture.

3. Fundamentals of Autonomous Tractors

3.1. Operational Design Domain (ODD)

Environments where a highly automated agricultural machine (HAAM) 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 maturity 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 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 the field; initialising, undertaking and completing field work and returning to a 'home station' for refuelling or maintenance.

3.2. 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 1.

Table 1: Operational behaviours for autonomous tractors (Blackmore, 2002)

Behaviours	Description
Explore	A behaviour that extracts information from the unknown local environment to populate 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 several 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 1 on the following page. 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.

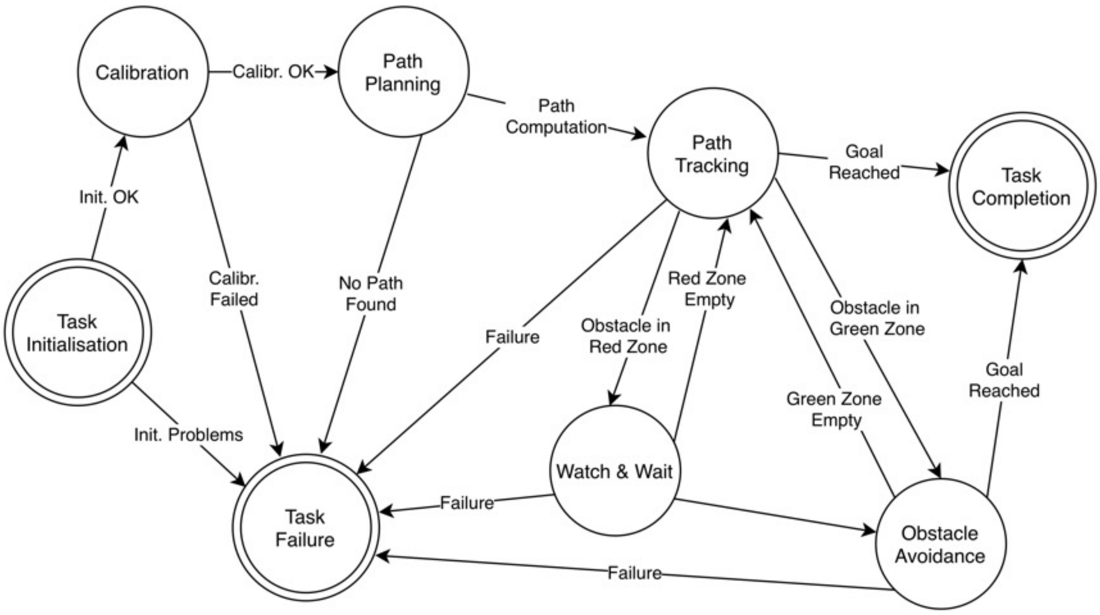


Figure 1: *State-based diagram outlining behaviours and transitional requirements*
(Vougioukas et al, 2005)

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 set 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 – items 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).

3.3. 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 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
- Performance optimisation
- Path planning
- Machine-to-machine communication
- Sensing (Perception)
- Process monitoring
- Telematics
- In-field communications
- Data infrastructure

From the above sources of 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.

4. Developments in Autonomous Machinery

This section reviews the advancements in automation to date made by six major tractor manufacturing companies and other companies that make 'bolt-on' solutions. The review is an update to the technology review in Baillie et al. (2017) and uses the same key areas for tractor autonomy as a framework for categorising existing automation technologies.

4.1. Tractor manufacturers

The technologies reviewed for the major tractor manufacturers include current and upcoming products, and on-going development activities, and pathways for future development. The products discussed in this section demonstrate the underlying technology in place to support tractor automation, though some of the products may, themselves, become obsolete under a new framework of tractor autonomy. The product developments for each manufacturer in the key technology development areas is summarised in Table 2 on the following pages.

Table 2: Technology and product development of the six major tractor manufacturers relating to autonomy.

Technology Pathway to Autonomy	Tractor Manufacturer					
	John Deere	CNH	AGCO	CLAAS	Same Deutz-Fahr	Kubota
Automated Tractor Guidance (i.e. GPS Autosteer)	AutoTrac™ (GPS autosteer)	Case IH Advanced Farming Systems (AFS) components (e.g. AccuGuide – GPS autosteer) NH Precision Land Management (PLM) components (e.g. Intellisteer™ – GPS autosteer)	Auto-Guide™ (GPS autosteer, *Fuse*®) Varioguide™ (GPS autosteer - Fendt)	GPS PILOT (GPS autosteer)	AGROSKY (GPS autosteer)	GPS autosteer
Headland Management System	AutoTrac™ Turn Automation	Headland Management Control	Variotronic™ (headland management system (Fendt))	GPS PILOT - AUTO TURN, TURN IN	AUTO-TURN	Headland Management Control
Variable Rate Technologies	JD Section Control (+ AutoTrac™) GreenStar™ Rate Controllers	Case IH AFS section and rate control (AccuControl, ISO Task Controller, Field-IQ ™) NH PLMR input control systems (IntelliRate™, ISO Task Controller, Field-IQ ™)	AgControl™ (section and rate control - *Fuse*®)	Section control and variable rate via S10 terminal ISARIA CROP SENSOR (red - infrared crop canopy sensing)	Section & Rate Control	GEOseedR (patterned seeding) GEOcontrol (section control) (*IsoMatch*) GEOspreader (precision spreading) (*IsoMatch*)
Drive by Wire Functionality	AutoTrac™ (GPS autosteer) ActiveCommand Steering (ACS™) TIA (Tractor Implement Automation)	AccuGuide™, Intellisteer™ Feedrate Control System NH Ground Speed Management (GSM)	"Steer-by-wire" in ChallengerR track series, from BEI Duncan Electronics; TwinTrac in Valtra S Series	GPS PILOT (GPS autosteer)	Via Agrosky - TopCon GPS autosteer system TIM (Tractor Implement Management)	Via GPS autosteer

Engine/Machine Performance Optimisation (i.e. IVT/CVT transmissions)	Infinitely Variable Transmission (IVT™) with PowerZero™ feature Active Terrain Adjustment™ (harvester - adjust fan speed & sieve openings with slope)	Continuously Variable Transmission (CVT) – with Active Stop Feedrate Control System NH TerraLock™ traction Management NH Ground Speed Management (GSM)	Continuously Variable Transmission (CVT)	CMATIC Continuously Variable Transmission (CVT) CEMOS for tractors	Continuously Variable Transmission (CVT)	K-VT transmission (CVT)
Machine Operation and Path Planning	Passive and active implement guidance	NH PLMR TrueGuide™ (Implement guidance and steering) & TrueTracker™ (active implement guidance and steering)	AGCO Smart Connect Fendt OptiNozzle		IMonitor XTend	
Machine to Machine Communications (i.e. leader/follower technology; tractor/implement interface and awareness)	Machine Sync (coverage map and guidance line sharing, logistics)					
Sensing – perception & situational awareness (crop referenced guidance; situation awareness – single machine operation/machine to machine/machine to crop	AutoTrac™ Vision (Machine vision crop referenced guidance) Active fill control (Automated trailer and truck filling with machine vision)	AFS RowGuide™ Cruise Cut and SmartSteer™ laser guidance (optical crop referenced guidance) IntelliFill™ (Automated trailer and truck filling with machine vision)		LASER & CAM PILOT (optical and machine vision crop referenced guidance) AUTO FILL (Automated trailer and truck filling with machine vision)	Driver Extended Eye Camera guidance system (blind spot, active human detection) Automatic trailer hitch coupling	

Sensing – process monitoring (crop sensing; process monitoring)	Grain yield and moisture sensor (including Active Yield calibration system) HarvestLab	HarvestCommand AFS Harvest Command™		ISARIA CROP SENSOR Variable rate harvesting systems		KSAS 'taste' and yield sensing (rice – yield/moisture)
Machine to back office communication "Telematics" (i.e. date recording and management; remote monitoring and control)	JDLink ™ Connect (mobile comms, optional satellite) data transfer to Operations Center	Case IH AFS Connect ™ (telematics) NH PLMR Connect ™ (telematics) ClearVU	AgCommand ™ (telematics) (*Fuse®*) AGCO Connect Fendt Logistics	TELEMATICS TONI (implement telematics) CLAAS Diagnostics System (CDS)	ISOXML for data recording; not remote	KUBOTA Smart Agri System (KSAS)
Infield Communications and Data Structure (3rd party info i.e. weather)	JD is an Onfarm Ready™ Partner *JD Field Connect ™ environmental monitoring (soil moisture, weather)* *JD Mobile Weather (tractor mounted weather sensor)*			365FarmNet		
Upcoming developments and concepts	Electro-mechanical transmission See and Spray CommandCab	Automation development framework			-	More KSAS functionality Agri-robo rice transplanter

4.1.1. John Deere

Guidance and steering control

John Deere's guidance range is called AutoTrac™, which features a range of steering solutions guided dominantly by GPS but also vision in some cases. The base functionality of AutoTrac™ is to follow guidance lines, but the system is also optionally capable of managing tractor and implement functions during turns (AutoTrac™ Turn Automation) as well as implement guidance for pull-type implements.

The NavCom (John Deere) Starfire™ guidance system (pictured in Figure 2 left) offers accuracies ranging from ± 15 cm on SF1 signal to ± 3 cm on the SF3 signal using the best satellite broadcast correction information. Real-time kinematic (RTK) positioning can be added to provide long-term, season-to-season repeatability of ± 2.5 cm. The guidance system also includes a Terrain Compensation Module (TCM) which detects and assesses roll, pitch and yaw of the vehicle to provide accurate ground positioning of the tractor on uneven terrain (see Figure 2 right).

***Figure 2:** Starfire 6000 guidance system and terrain compensation* *(John Deere, 2019)*

John Deere also offers a Mobile RTK modem which allows the machine to communicate with a cellular network instead of by radio RTK. This is primarily intended for use-cases where radio RTK signals are obscured by rolling hills or obstacles (Figure 3, following page).

Aftermarket steering solutions by John Deere include:

- AutoTrac™ Controller 300 — an integrated solution available for tractors with open or closed centre hydraulics.
- AutoTrac™ Universal 300 — a steering wheel modification that is available to the widest range of models and brands and is easily transferable between machines.

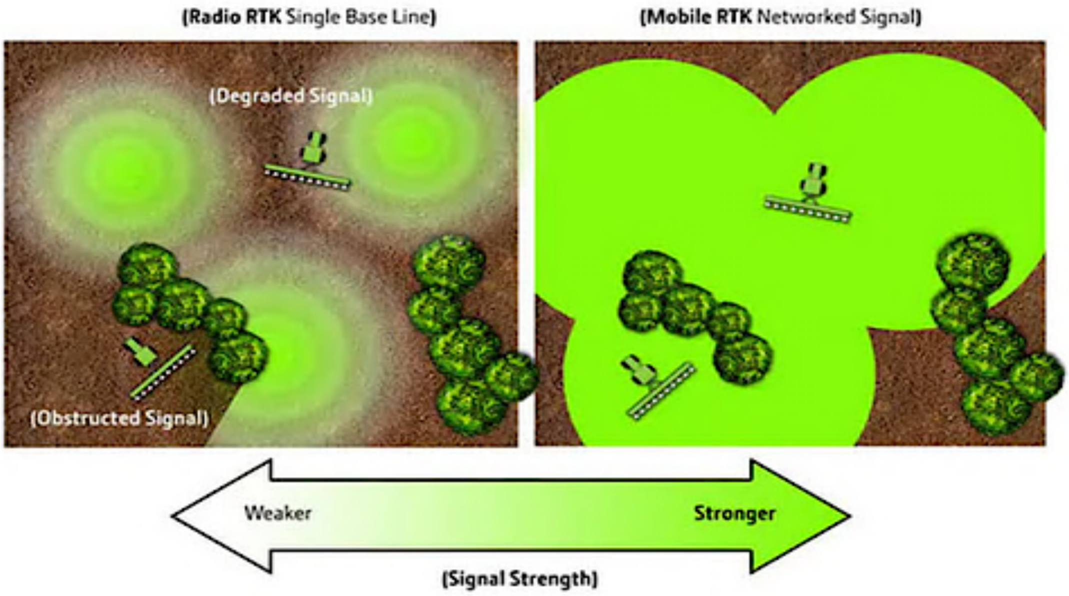


Figure 3: *Mobile RTK coverage using 3G/4G communications (John Deere, 2020)*

Headland management system

AutoTrac™ Turn Automation can reduce operator fatigue by controlling the steering, tractor speed, engaging/disengaging differential lock and PTO, and raising/lowering of implements during a turn sequence. Multiple forms of field boundaries are supported to facilitate automatic turns including headland boundaries where turns start and end and the exterior field boundary that the turn needs to occur within. The headland boundary can be set automatically using a constant offset or manually drawn. Internal passable and impassable boundaries can also be set with corresponding interior headlands.

Variable rate technologies

John Deere Section Control automatically controls the sections on an implement based on GPS data. The system switches sections off that are over previously applied areas or outside field boundaries. In addition to supported John Deere implements, the system is currently compatible with AEF ISOBUS Task Controller Section Control (TC-SC) compliant implements from other brands. Furthermore, the Greenstar™ Rate Controller allows displays to integrate with non-ISOBUS implements without requiring a second console in the cab.

Engine and machine performance optimisation

ActiveCommand Steering (ACS™) is John Deere's steering system designed to vary steering effort and lock-to-lock turn number depending on ground speed (John Deere, 2012). The system reduces the steering wheel resistance at low speeds to make headland turns easier and increases resistance at high speeds for better control on the road. The ACS™ also prevents over-steering when the operator makes a sudden steering reaction and eliminates steering wheel drift and slop.

Automatic transmission adjustment is also available through John Deere's Infinitely Variable Transmission (IVT™). IVT™ provides a seamless range of speeds with no clutching required to start or stop the tractor. IVT™ features an electronic communication between the engine and transmission that improves efficiency and productivity by adjusting settings based on engine load. The PowerZero™ feature enables a ground speed of zero to also be a target speed for instance when a tractor needs to remain stationary on an incline.

Automatic adjustment of combine harvesters to account for hill slopes is also available in John Deere Active Terrain Adjustment™ (ATA). The technology adjusts the combine's sieve and chaffer openings as well as the cleaning fan speed to minimise grain loss on inclines up to 16°.

Machine operation and path planning

John Deere has developed two forms of implement guidance to ensure that machine operation with implements is precise and reliable. Passive implement guidance uses a second Starfire™ receiver on the implement and the tractor changes its path as necessary to keep the implement on the desired line (Figure 4). Active implement guidance extends on this by utilising steerable implements to control both tractor and implement and keep all machines on the desired line where absolute precision is required.

Figure 4: *John Deere passive implement guidance (John Deere, 2019)*

Machine to machine communications

MachineSync enables multiple John Deere machines to coordinate and have GPS-based synchronisation of speed and steering for effective multi-vehicle operations. The primary use-case for MachineSync is between combines and tractors with chaser bins, where precision positioning of the vehicles relative to each other minimises harvest losses.

Communication protocols based on the ISOBUS standard have also been developed to allow for implement control of tractor operation (Tractor Implement Automation, or 'TIA'). Certified implements can communicate using ISOBUS Class 3 and additional proprietary messages to change a selection of tractor operating parameters including speed, acceleration, stopping (with the IVT transmission), hydraulics and power take-off (von Hoyningen-Huene, 2010). The system is typically most effective during processes that require frequent starting and stopping (such as baling). The TIA system can be augmented with sensors at the front of the tractor to inform speed control (von Hoyningen-Huene, 2010).

Sensing – perception and situational awareness

John Deere's sensing and perception products augment tractor guidance as well as harvesting operations. AutoTrac™ Vision uses a high-resolution front camera (see Figure 5) to detect early season crops and assist steering in fields that were planted without GPS guidance or for which guidance lines are otherwise unavailable. The detection software requires the crop to be at least 10 cm high for reliable vision detection.

Figure 5: *John Deere AutoTracTM Vision sensor (John Deere, 2019)*

Active Fill Control uses a stereo camera to track transport vehicles and controls the rotation and flap position of a harvester to optimise filling the trailers. The system reduces crop spillage to nearly zero in both day and night operation.

Sensing – process monitoring

Whilst yield monitors are standard on harvesters, John Deere have developed ActiveYield™ to automatically measure the weight of a known mass of grain and calibrate the mass flow sensor accordingly. The original calibration process involves taking a trailer load of grain over a weighbridge to obtain a calibration check weight, and so the on-the-go calibration of ActiveYield™ simplifies harvesting operations.

HarvestLab is a sensor that uses near-infrared spectroscopy to analyse constituents in harvested crops and silage in real-time. John Deere have deployed the HarvestLab sensor in two applications:

- Fitted on a forage harvester, HarvestLab analyses dry matter content for the adjusting length of cut to optimise silage fermentation and reduce silage additives. The sensor can also take real-time readings of crude protein, starch, crude fibre, sugar, crude ash and more.
- As a standalone mobile laboratory unit, the HarvestLab can be connected to a vehicle power outlet to provide feed quality analysis for optimising feed rationing and livestock health.

Telematics and infield communications

John Deere's telematics solutions for interacting with machine performance data and diagnostics is JDLink™. JDLink™ provides an interface for viewing machine location, fuel, seed and fertiliser for logistics planning and enables access to machine displays to check on work in progress. Dealers can also be allowed access to a remote connection to assist with diagnostic trouble codes, facilitate software updates on certain controllers, and obtain machine recordings for troubleshooting.

A field soil moisture and environmental monitoring solution is also available through John Deere Field Connect™. Data from the field station is accessible via a smartphone app to inform crop management decisions before and during a growing season.

Figure 6: *John Deere Field Connect™ (John Deere, 2019)*

Upcoming developments and concepts

Sensors — process monitoring: Weed detection on sprayers
John Deere subsidiary Blue River Technology is working on machine vision detection of weeds to improve herbicide use on-farm (Blue River Technology, 2018). An array of cameras (implement shown in Figure 7) feeds live images into computer processors mounted on the sprayer which classify weeds and mark locations for individual spray nozzles to target. The technology aims to reduce herbicide use by up to 90% and prevent resistance uptake in weeds. '*See and Spray*' technology is currently progressing towards farm-scale trials in 2020.

Figure 7: *See & Spray technology for John Deere sprayers (Blue River Technology, 2018)*

Telematics and infield communications: Remote access to tractor cab
John Deere premiered the Command Cab at Agritechnica 2019, a stand-alone cab with displays and controls designed for remote monitoring and operation of tractors (Figure 8). The envisaged use of the cab is for an operator to remotely monitor and control a fleet of autonomous vehicles using touchscreens and joystick to manually control vehicles as necessary. The Command Cab uses real-time weather data, machine settings, sensor data and camera feeds to give the operator all the information necessary to manage the machine remotely.

Figure 8: *John Deere CommandCab (Wordsworth, 2019)*

4.1.2. Case New Holland

Automation and precision technologies developed by Case New Holland (CNH) are available under the Case IH Advanced Farming Systems (AFS) and New Holland Precision Land Management (PLM) product lines.

Guidance and steering control

Both AFS and PLN guidance solutions (AccuGuide™ and Intellisteer™ respectively) are based on Trimble® hardware (AFS 372 GNSS Receiver) and satellite differential correction services (Omnistar®, CentrePoint™ RTX™ and RangePoint™ RTX™) that range from ± 20 cm accuracy all the way down to ± 4 cm accuracy and RTK correction available for ± 2.5 cm accuracy. Case IH has also released a cellular network-delivered solution (AFS RTK+) in the US and Canada which ensures a dependable signal provided the machine is in network range (Figure 9). T3 terrain compensation technology is also integrated which tracks the roll, pitch and yaw of the machine to further improve guidance accuracy on difficult terrain.

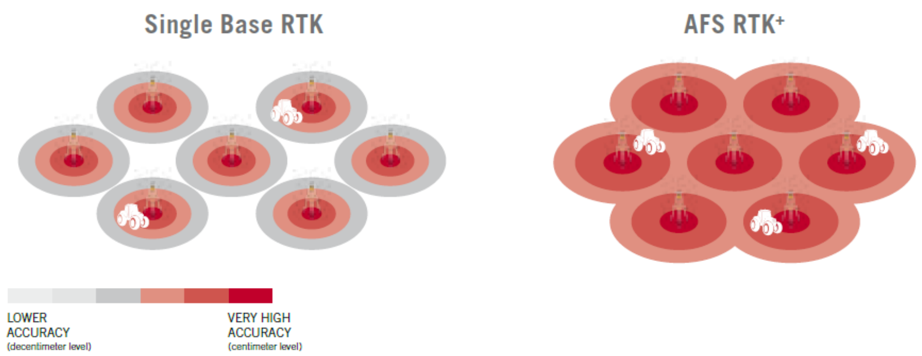


Figure 9: *CNH Mobile RTK Coverage visualisation compared to Radio RTK* (CNH Industrial, 2017)

Aftermarket steering solutions by CNH include:

- AutoPilot™ — a fully automatic solution that includes an antenna, steering sensor, controller and vehicle interface.
- EZ-Pilot™ — an electric motor drive that steers the wheel.
- AutoPilot™ Motor Drive (APMD) — The EZ-Pilot™ motor drive but with an added controller with terrain compensation technology for increased accuracy.

Headland management systems

Case IH and New Holland both offer headland management systems that manage implements during headland turns. The systems control transmission, engine speed, hitch position and electro-hydraulic valves to execute a turn sequence.

Variable rate technologies

AFS section and rate control and PLM IntelliRate™ products enable optimised spraying and planting by switching off sections over areas where product has already been applied or varying the application rate according to a prescription map. The systems also allow for boundaries to be manually set where sections will be automatically turned off when crossed.

The AFS and PLM product lines are also equipped with Field-IQ™ developed by Trimble™ (Trimble, 2020). Field-IQ™ is a crop input control system that allows for simultaneous variation of up to six different materials such as plant seeds, chemicals and fertilisers for optimised operations. The application rates can be manually adjusted on the go, set with a prescription map, or informed by readings from a GreenSeeker® crop sensor. The Field-IQ™ system also includes section control for up to 48 individual rows and boom height control which senses the distance from boom to the ground or crop canopy and automatically adjusts the boom height accordingly for even applications.

Engine and machine performance optimisation

Case IH and New Holland both offer a range of CVT transmissions (continuously variable transmission). An Automatic Productivity System (APM) then detects the current driving conditions and load and selects the optimal engine speed and gearbox ratio combination in response. Active Hold Control and Active StopStart (for Case IH and New Holland respectively) allow a tractor to be stopped and remain stationary on an incline under a heavy load.

New Holland Terralock™ traction provide automatic four-wheel drive and front/rear differential lock engagement. If in automatic mode, the FWD and differential lock only disengage when the steering wheel is turned to favour manoeuvrability over traction. The FWD and differential lock can also be disengaged only by braking or left as always disengaged.

New Holland achieves CVT-like performance in some powershift tractors with Ground Speed Management II (GSM II). GSM II uses a combination of data relating to engine load, forward speed and operator setting to adjust engine speed and transmission to maintain a fixed forward ground speed with optimal fuel economy.

Machine operation and path planning

Case IH and New Holland offer the AgGPS TrueGuide™ and AgGPS TrueTracker™ systems for implement guidance. TrueGuide™ is a passive guidance system in which the tractor steers to keep the implement on the desired path and requires a second GPS module to be installed on the implement. TrueTracker™ is the active variant that utilises implements with mechanical steering to follow exactly in the tractors path including on uneven terrain. Both forms of implement guidance can achieve similar levels of accuracy as the tractor for the installed GPS accuracy (down to ±2.5 cm).

Sensing – perception and situational awareness

The technologies developed for perception from CNH are applied in row guidance and harvesting optimisation. A mechanical Row Guidance System (sensor shown in Figure 10) can be fitted to corn headers to keep combines or forage harvesters on course. The two sensors detect the distance of the crop row to each sensor and then generate a guidance signal to keep the machine perpendicular.

A laser eye system is also available under the names Cruise Cut and SmartSteer™ which is mounted on the cab and detects the crop edges from a distance. The primary stated use-cases for laser guidance are in low-visibility conditions such as dusty environments or at night.

Figure 10: *New Holland mechanical row guidance sensors (New Holland Agriculture, 2020b)*

New Holland has developed a 3D camera system for monitoring bin fill on harvesters called IntelliFill™. The sensing system detects the trailer edge (see Figure 11) and controls the spout movement to optimally fill the trailer to the edges without spilling.

Figure 11: *New Holland IntelliFill™ imaging system (New Holland Agriculture, 2020a)*

Sensing – process monitoring

Case IH has combined a range of sensing technologies for optimising combine harvesting into a package called AFS Harvest Command™. The system reduces the amount of operator inputs to concave clearance, header position and grain tank unload. The automation system manages the sieve openings (upper, lower, pre sieve), cleaning fan speeds, rotor vane angle, rotor speed and ground speed to achieve a desired level of throughput, grain savings and grain quality.

Telematics and infield communications

AFS and PLM both use telematics software called Connect™ which provides functions such as fleet management and logistics, machine performance and security monitoring, maintenance alerts, viewing live machine dashboards and two-way messaging to machine operators.

Case IH also launched a cloud-based farm management information software (FMIS) platform called ClearVU in partnership with AgDNA (acquired by CNH in 2019). ClearVU is designed as a comprehensive solution with the ability to store and interpret equipment data, weather charts/forecasts, crop data, harvest records and financial information. The software is a step forward in the digitisation of agriculture and allows users to maintain and manage their farm all from one place. The software receives machine data from Case IH tractors via AFS Connect.

Upcoming developments and concepts

The autonomous tractor concept that Case IH showed in 2016 was a vision of a fully automated tractor. Case IH followed up on this concept by defining a staged approach to achieve full tractor autonomy (Figure 12). Case IH stated that only the first stage of automation (guidance) is widespread, and that Case IH is currently trialling higher stages of automation for tasks such as primary tillage and deep tillage in a pilot program that commenced in 2018.

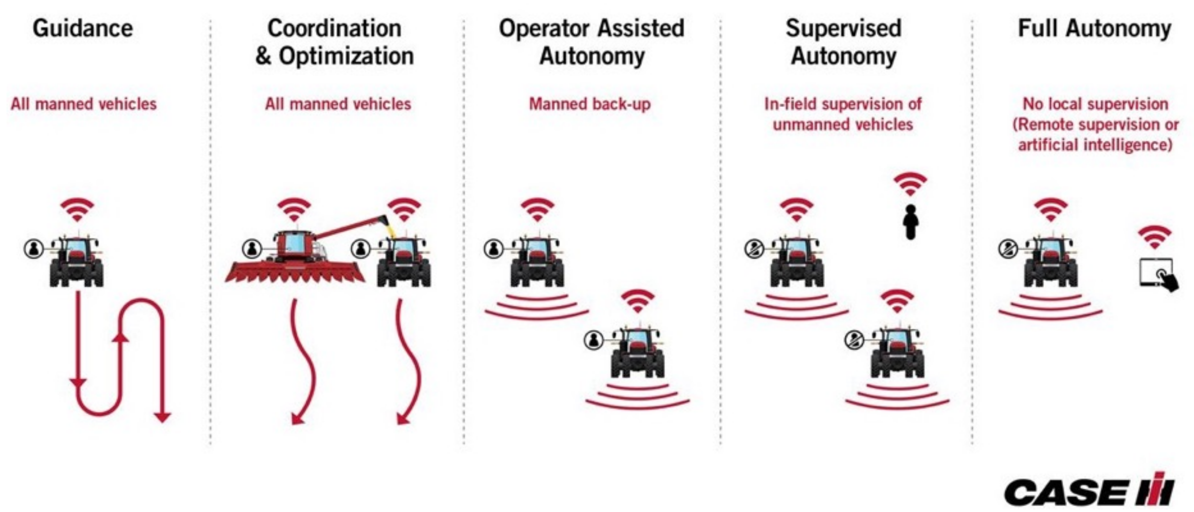


***Figure 12:** Case IH framework for developing automation* *(Case IH, 2018)*

4.1.3. CLASS

CLAAS precision farming and automation technologies are grouped under the label *'EASY'* — Efficient Agriculture Systems by CLAAS. EASY includes telematics machine networking, fleet management, remote services as well as software solutions for optimising application of fertilisers chemicals.

Guidance and steering control

CLAAS have utilised mechanical sensors, laser guidance and vision guidance in previous iterations of PILOT products, but today CLAAS guidance is based on GPS and labelled GPS PILOT. GPS PILOT is an integrated system installed into the steering hydraulics and incorporates sensors and a navigation controller. Various GPS corrections are available at different accuracies and prices including EGNOS, ONMISTAR and RTK.

GPS PILOT FLEX is the aftermarket solution by CLAAS that uses an electric steering wheel instead of hydraulic steering. The system can be uninstalled and reinstalled on CLAAS machines and machines from other manufacturers to provide the same functionality as the fixed GPS PILOT system.

CLAAS have also released a steering assistance product which provides a steering recommendation but does not control the machine. GPS COPILOT displays guidance via a lightbar or LED display (see Figure 13). The driver is still required to do the steering, and thus, the EGNOS guidance accuracy of ± 15-30 cm can be limited by the driver's skill.

Figure 13: *Lightbar display for GPS COPILOT guidance* (CLAAS, 2018)

Headland management systems

GPS PILOT also supports turn automation (AUTO TURN) which can be triggered on the workload headland or at a set boundary line. The TURN IN feature (released in 2017) allows the tractor to automatically turn into a track from angles up to 120° with high accuracy. TURN IN calculates the next optimal track to take across the field by accounting for machine alignment, steering lock and current speed. The driver can influence track selection by changing guidance parameters or directly intervening in the steering.

Variable rate technologies

CLAAS introduced automatic section control is managed by the ISOBUS terminal (such as the CLAAS S10 terminal) in ISOBUS functions. The terminal allows for control and adjustment of a range of ISOBUS attachments (CLAAS, 2016). The input to the section control can be based off of pre-generated prescription maps using yield maps, biomass measurement from remote sensing and soil maps (nutrient and/or conductivity), and CLAAS also supports on-the-go estimation of crop requirements using ISARIA crop sensor (see 'Sensing – process monitoring' section).

Engine and machine performance optimisation

CLAAS has developed a range of optimisation technologies under the umbrella term CEMOS originally for harvesters and then in 2019 for tractors (CLAAS, 2020b). The primary function of the CEMOS system for tractors is as a digital reference for operating procedure instead of a physical manual. The system recommends required ballasting and optimum tyre pressure and illustrates setting up implements (CLAAS is expanding the range of supported implements over time).

Once in operation, the CEMOS system also suggests optional drive parameters for optimal tractor efficiency or performance. If the settings are accepted, the system monitors work rate and diesel consumption and reports on the effectiveness of the suggested optimisations.

Sensing – perception and situational awareness

CLAAS offers vision and laser guidance as alternatives to GPS for specific use-cases. CLAAS CAM PILOT is offered primarily for forage harvesters and uses a 3D stereo camera to detect rows in three dimensions and provides a steering correction (see Figure 14 left). The CAM PILOT is activated using the AUTO PILOT button, as if it was using GPS, and the system is deactivated whenever the steering wheel is turned.

LASER PILOT uses electro-optical sensors mounted on the side of the cutter bar and uses pulses of light to scan the crop to generate a guidance signal (see Figure 14 right). The system is robust on sloped terrain and night-time operation.

Figure 14: *CLAAS CAM PILOT sensor operation and LASER PILOT visualisation*

(CLAAS, 2020b & CLAAS, 2020e)

CLAAS also implement 3D image analysis for directing the discharge chute of forage harvesters. CLAAS AUTO FILL controls the direction of the discharge chute towards the trailer (shown in Figure 15) which can run alongside the harvester or directly behind.

Figure 15: *CLAAS AUTO FILL operation* *(CLAAS, 2020a)*

Sensing – process monitoring

CLAAS offers the ISARIA CROP SENSOR to measure biomass and N index as an on-the-go data source for variable rate applications. The CROP SENSOR uses four LEDs for active lighting removing the reliance on daylight and the need for re-calibration during or after use (shown in Figure 16).

There are manual and automatic calibration options available for the measurement of N index. Manual calibration includes single-point and two-point methods where the user specifies the required N for a site (or two) and the system calculates the control curve for the application rate. In AUTO mode, only the desired average application rate and adjustment range need to be defined, and the system manages application rates from there.

Figure 16: *ISARIA sensor on front of CLAAS tractor* *(CLAAS, 2020c)*

CLAAS has also introduced an array of sensors that form part of a Variable Rate Harvesting™ (VRH) system that adjusts operating parameters of self-propelled combines and forage harvesters to maximise performance. Sensors integrated into self-propelled combines monitor moisture, yield, engine load, losses, grain distribution, blockages, ground slope, and thermal performance. The VRH system subsequently adjusts ground speed, rotor cover positions, fan speeds and sieve position to maximise outputs.

The VRH system for forage harvesters uses similar dynamic cooling and ground speed systems as the self-propelled combines but also uses a camera sensor and image analysis to: direct the unloading spout at the trailer, adjust horsepower output based on engine load, and stop intake if a large/damaging object is detected in front of the harvester.

Telematics and infield communications

CLAAS first used the term TELEMATICS to describe the digital transfer system which retrieves machine data from connected harvesters and tractors, but now TELEMATICS also describes CLAAS' software which visualises and analyses the machine data. In the TELEMATICS website or app, operators can:

- track the location and fuel consumption of each machine;
- document fields and activities that occur on each field; and
- analyse operating procedures and optimise logistics.

CLAAS Diagnostics System (CDS) is a system for diagnosing machine vaults using machine error messages and alarm signals. CLAAS have combined functionality of CDS with TELEMATICS to launch CDS REMOTE, a remote diagnostics tool that allows viewing of machine diagnostics and location data. CDS REMOTE also supports the link between operator and dealer by allowing maintenance and repair data to be sent directly to a CLAAS dealer.

4.1.4. AGCO

Guidance and steering control

AGCO has two guidance solutions available across its brands: Auto-Guide™ 3000 for Challenger, Massey Ferguson and Valtra tractors, and VarioGuide for Fendt. The GPS receivers can access EGNOS, RangePoint® RTX and CentrePoint® RTX for Trimble receivers on VarioGuide, TerraStar for NovAtel receivers on VarioGuide, OmniSTAR for Auto-Guide 3000 receivers, and RTK correction signals for all receivers delivered via radio or mobile network. Accuracies range from ± 30 cm to ± 2.5 cm depending on the subscription tier.

Headland management systems

The Variotronic™ headland management system allows drivers to define and store a timed sequence of actions to execute a turning manoeuvre. Up to 39 functions can be saved in the sequence including lifting and lowering implements and toggling cruise control, PTO, automatic steering, VarioGuide and more (Fendt, 2020b). The sequence can be initiated manually with the press of a button or automatically by Variotronic™- Automatic which links in to VarioGuide to detect when the sequence should trigger.

Variable rate technologies

AGCO offers a Rate & Section Control system for select sprayers which allows for simultaneous variable application of up to 5 products with control of 36 sections across the length of the boom. The system uses prescription maps which are generated before-hand, and AGCO also offers the TaskDoc® Pro software as a method for creating the maps (Fuse, 2020b).

Engine and machine performance optimisation

AGCO introduced Continuously Variable Transmission on its Fendt tractors in 1995.

Machine operation and path planning

AGCO have provided the ability to customise a second in-cab display with the Smart Connect app. The app is designed specifically for iPads and allows operators to customise interfaces with machine data such as engine, position and harvest metrics for easy access (see Figure 17, next page). The intent of the app is to present a large range of machine data accessible in the machine terminal in an intuitive way to improve machine monitoring.

Figure 17: *AGCO Smart Connect views of machine data (Fuse, 2020a)*

Fendt have released a smart spray nozzle system called OptiNozzle which uses an array of nozzles and selects the best nozzle (or combination of nozzles) to achieve a required drift reduction (Fendt, 2020a). The system automatically adjusts the nozzle configuration depending on the speed and the output level, resulting in a greatly expanded speed range when spraying (see Figure 18). The Fendt Rogator sprayer that incorporates the OptiNozzle also has TIM functionality, thus allowing the sprayer to adapt the speed and nozzle configuration to suit a desired output level and level of drift reduction.

Figure 18: *Fendt OptiNozzle spraying system (Fendt, 2020a)*

Telematics and infield communications

AGCO have released a range of software tools for supporting farm operations as listed on the Fuse Smart Technologies website (Fuse, 2020a).

AgCommand™ is a tool for remotely monitoring equipment and collecting machine data to assist the grower in optimising fleet performance. There is also an option for sharing the data with dealers to leverage their expertise in maintaining a fleet of machines.

AGCO Connect is a farm management system software that allows operators to remotely view and manage their fleets. Data streams visible in the software include fuel levels, current position, service hour counters and alerts, fault codes and diagnostic data, and in some cases machine documentation. The aim of the software is to improve work efficiency through logistics optimisation and providing early warnings of arising issues that could cause downtime for machines.

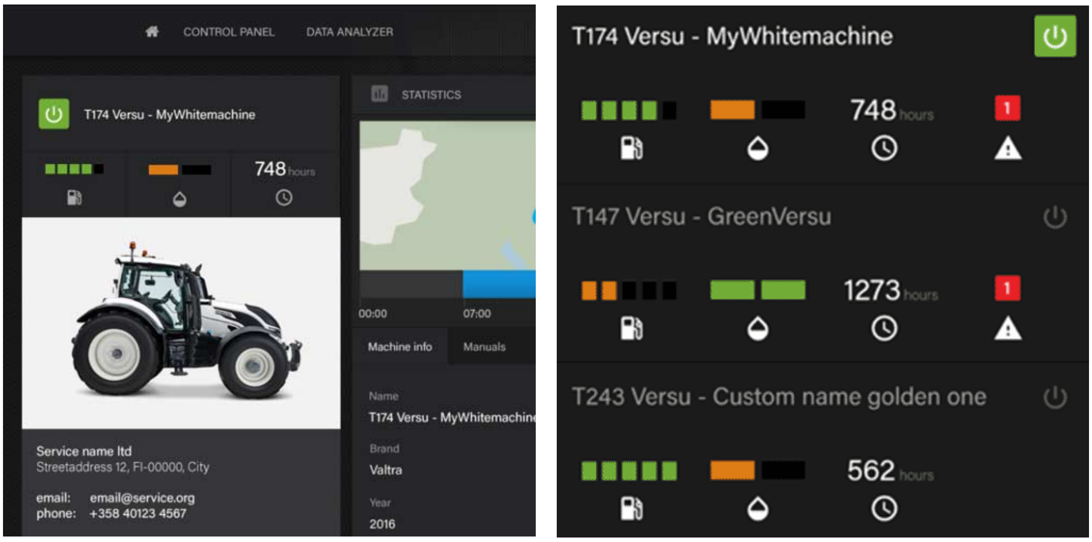


Figure 19: *AGCO Connect view of telematics (Fuse, 2020a)*

Fendt Logistics is an organising app to assist with coordination of collection trucks in harvesting operations. The app uses vehicle positions and collection truck capacities to forecast where and when the next collection team is required to take over to minimise empty runs and unnecessary waiting times for machines.

4.1.5. SAME Deutz-Fahr

Guidance and steering control

Same Deutz-Fahr (SDF) have both manual and automatic steering guidance products available through partnership with TopCon. The automatic steering systems use either an SRC40 receiver, which has optional upgrades for terrain compensation and a modem for receiving RTK data, or the SR20 receiver which has the terrain compensation and modem included. The receivers can receive EGNOS, OmniSTAR, TopNet Global D and RTK corrections.

SDF also have an aftermarket electric steering wheel option for automatic guidance – the AEF35. The steering wheel system links into the same receiver and other components as the hydraulic steering system and can achieve the same accuracy. The visual guidance system receives Autonom/GLONASS correction services and connects to an iMonitor in the cab to add manual guidance to the existing functionality of the iMonitor.

Headland management systems

The iMonitor3 incorporates an auto-turn system to perform turns on the headland. The system allows for manual selection of track and supports different patterns depending on the application.

Variable rate technologies

Section control is available through the iMonitor3 which supports up to 200 sections (Same Duetz-Fahr, 2019). The iMonitor3 also supports variable rate control with selected products.

Engine and machine performance optimisation

SDF offer continuously variable transmission (CVT) for their mid-range tractors which provide improved power take off, more efficient ploughing drive and lower engine speeds at high road speed.

Machine operation and path planning

The iMonitor3 provides an interface for ISOBUS attachments and implements made in line with the ISO 11783 standard. SDF is one of the core members of the Agricultural Industry Electronics Foundation (AEF) which aims to standardise communications between brands and improve compatibility (Same Duetz-Fahr, 2019). The iMonitor also support WLAN connection of a tablet device using the XTend app to act as a second display for expanded viewing of track guidance of ISOBUS functions.

SDF also supports Tractor Implement Management (TIM) which allows attached equipment to take control of certain tractor outputs such as ground speed to achieve optimal performance in the field.

Sensing – perception and situational awareness

A camera system has been developed to improve safety on larger machines and reduce accidents caused by lack of visibility in blind spots. The Driver Extended Eyes provide vision to reduce the number of blind spots for the driver, and also actively detect people in the camera view.

SDF further implemented cameras to detect the position of an attachment hook with respect to the tractor. An automatic trailer hitch coupling system can then determine the best path for the coupling and performs all appropriate movements (shown in Figure 20).

Figure 20: *Automatic trailer hitch coupling (Same Duetz-Fahr, 2013)*

Telematics and infield communications

SDF have released two communication modules to transmit telematics: the basic telematic module transmits to nearby smart devices via Bluetooth, and the communication telematic module transmits telemetry and task data from the monitor over internet connection back to the office. The SDF Fleet Management software can then be used to view and manage location and performance data. The software includes geofence alarms that can be set to trigger if a machine leaves a designated area.

4.1.6. Kubota

Guidance and steering control

The M7-2 tractors are Kubota's current flagship range, however the only information directly stated on GPS guidance for these tractors are that it has a range of corrections available including RTK. Kubota entered into a partnership with Smart Guided Systems (Business Wire, 2017) to bring guidance technology to Kubota's tractors, and it can be assumed that the same technology is behind the current generation such as the M7-2 tractor.

Headland management systems

Kubota flagship tractors are equipped with a Headland Management System which allows operators to store operating sequences for turning at the headland (Kubota, 2017). Loadable actions include adjusting tractor speed, lifting and lowering implements, and disengaging/engaging 4WD, PTO and Diff-Lock. A total of four sequences can be stored on the system.

Variable rate technologies

Kubota's GEOCONTROL can be enabled on the K-Monitor to use section control and variable rate control on supported Kubota ISOBUS implements. Variable rate applications can be linked to on-board sensors and as-applied maps can be saved though GEOCONTROL.

Kubota also creates implements that connect to the ISOBUS terminal and GEOCONTROL such as the GEOSPREAD system. GEOSPREAD is an ISOBUS 11783 compatible and AEF certified spreader with up to 14 sections that can reduce overlap in applied product. GEOseed® technology on precision drills manages the precise placement of seeds in parallel or diamond patterns (see Figure 21) to maximise the use of nutrients and solar energy and minimise water erosion and wind (Kubota, 2016).

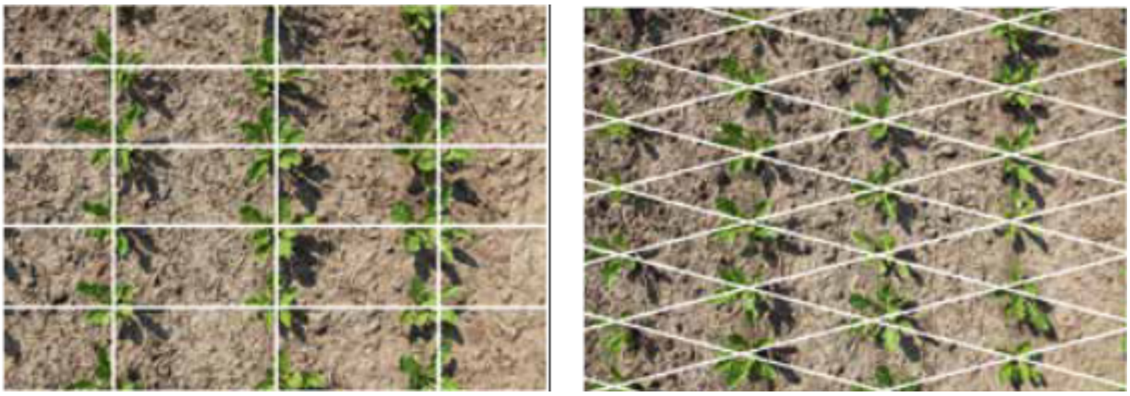


Figure 21: *GEOseed parallel or diamond planting pattern (Kubota, 2016)*

Engine and machine performance optimisation

Kubota's M7 series tractors are equipped with KVT (Kubota Variable Transmission).

Sensing – process monitoring

Kubota have developed a grain flow sensor for combine harvesters which measures yield and grain taste and links the readings to the current GPS location to generate variability maps (see Figure 22). The size of each tile in the yield and taste maps can be selected from 10, 15 or 20 sq. metres.

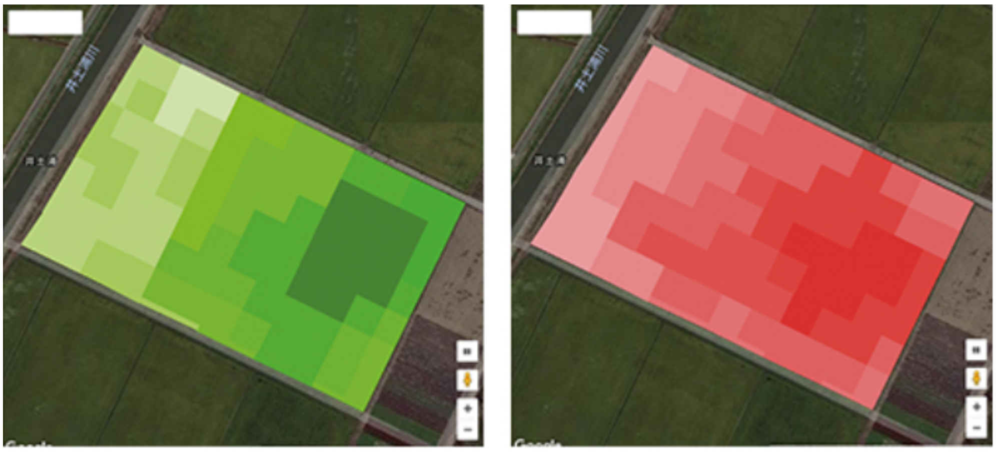


Figure 22: *Yield and taste maps from combine harvester grain sensor* *(Kubota, 2020a)*

Telematics and infield communications

Kubota equip selected machines with communication units so that location and operating information can be sent to the cloud. The Kubota Smart Agri System (KSAS) is a cloud-based management support service launched in 2014 which allows easy access to machine data so farmers can optimise their operations.

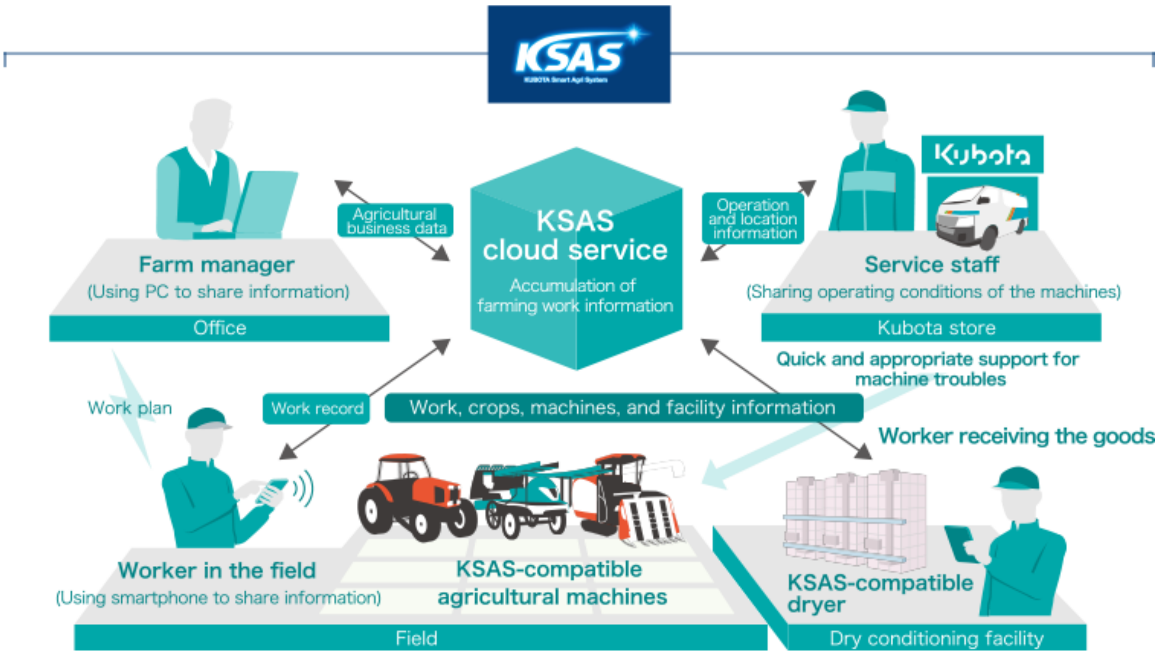


Figure 23: *KSAS existing workflow* *(Kubota, 2020b)*

Upcoming developments and concepts

Machine operation and path planning: *Agri-robo rice transplanter*

The next step for Kubota in tractor automation is to release an Agri-robo rice transplanter (Kubota 2020b). The current models such as the EP8D-GS are equipped with GPS but only have 'keep straight' steering as opposed to fully automatic steering. The Agri-robo rice transplanter due for release in 2020 steps up to fully automatic steering, removing the necessity of a human driver. Kubota envisions that this will allow the two-person operation to potentially be performed by one operator who walks beside the vehicle with a remote control and manually refills the seedlings.

Telematics and infield communications: *Whole of farming system approach*

Kubota is also currently expanding the capability of KSAS in the following areas:

- *Communication with machines*. Communication with post-harvest and intermediate management machine (e.g. drying systems) was launched in 2017, and Kubota are currently integrating communication with pesticide-spraying drones.

- *Integration of environmental data*. The addition of external weather information and other 'big data' sources would enable further optimisation of fertiliser and chemical applications and the prediction of growth and pest populations.

- *AI optimisation of planting patterns*. The addition of accounting and sales information from distributors and other sources will enable simulations-based optimisation of management decision from the start of the growing cycle.

Kubota's vision for the expanded role of KSAS is visualised in Figure 24 on the following page.

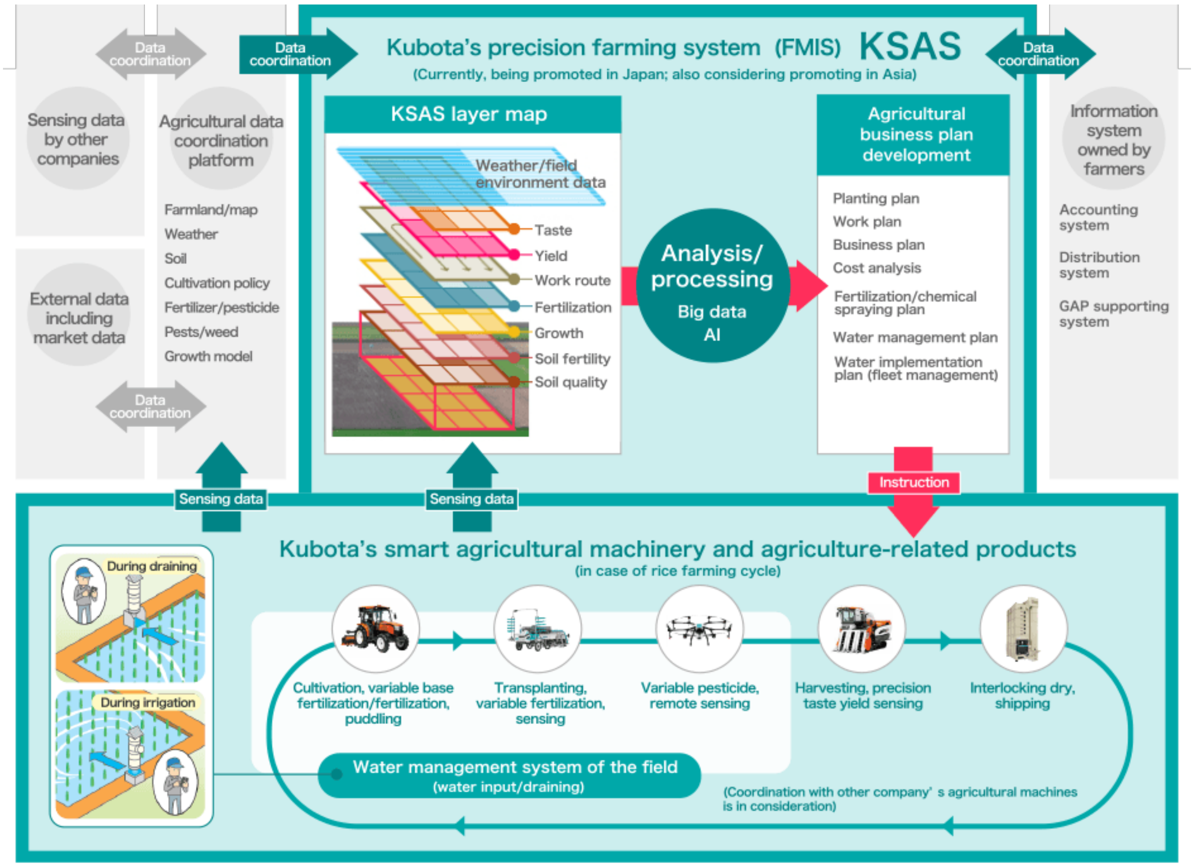


Figure 24: *KSAS concept for future workflow* *(Kubota, 2020b)*

4.1.7. Brand Cooperation

DataConnect

DataConnect is a manufacturer-independent software that allows operators to view and handle machine data from John Deere, Case IH, New Holland, CLAAS or Steyr brand farm equipment in a single interface. Operators that run fleets with multiple brands will be able to use any one portal from participating brands to view machine data for the entire fleet. DataConnect is a step forward in communication between brands and will welcome other manufacturers willing to join the initiative.

Agrirouter

Agrirouter is a data exchange platform run by DKE-Data that connects machine data and a variety of agricultural software venders. Users have full control over which machines share data with which software packages with 13 different telemetry modules currently compatible with the platform (Agrirouter, 2020). Case New Holland, AGCO and Same Deutz-Fahr are currently participating in the platform.

4.1.8. Discussion

There is an opportunity to look at current state of automation technologies by the six major tractor manufacturers compared to the review in Baillie et al. (2017) to see the current direction and priorities of the OEMs. In some cases, there are new product releases which enable an OEM to offer a similar level of functionality to competitors, increasing the standardisation of certain technologies. There has also been activity in new fields from multiple OEMs within a short time span.

Sensing – processing monitoring

In the field of sensing for process monitoring, there has been wider implementation of harvester optimisation. Optimisation systems for harvesters were previously reported for John Deere and Case IH and now there is also the Variable Rate Harvesting (VRH) system by CLAAS. In new developments, there is interest in improved implement sensing and control demonstrated by the Fendt OptiNozzle and the in-progress weed spot spraying technology by John Deere.

Machine to back office communications - telematics

Telematics is an area that now has more uniform offerings among the six manufacturers, similar to how GPS-guided steering is now considered standard. Recent software releases include AGCO Connect and SmartConnect, ClearVU for CNH, and CLAAS remote diagnostics (CDS).

Infield data

Additional data streams such as soil and weather data factor into farm management decisions. Users have had to access this data separate to machine data in the past, but CNH and Kubota are starting to integrate these ancillary data streams directly into their software. ClearVU integrates rainfall data and weather forecasts into a farm summary along with other data streams such as past harvest records and financial information so that users can get a ‘whole of system’ view from the software. Kubota plans to take this a step further and build in AI analysis of field data — including weather and soil data — to generate field management recommendations that span the entirety of the growing season.

4.2. Third-party providers

There are several companies outside of the tractor manufacturers that sell and fit automation technologies for tractors including Trimble, Raven, Ag Leader, Topcon and Precision Technologies. Some of these providers have agreements with OEMs to use their technologies, while others sell independently. The products cover a limited range of the automation technologies listed in Table 2, specifically:

- Automated tractor guidance
- Variable rate technologies
- Machine operation and path planning
- Sensing – process monitoring
- Machine to office communications

4.2.1. Trimble

As CNH integrates Trimble products into its offerings, the guidance products and variable rate technologies of Trimble have already been summarised in Section 4.1.2. Consequently, these products have been omitted from this subsection.

Sensing – process monitoring

The WeekSeeker 2 is a spot spray system that detects weeds when they pass underneath the sensor and signals a linked spray nozzle to deliver herbicide (Trimble, 2020c). The sensors come with a universal mounting bracket and is ISOBUS compatible for compatibility with many displays. Spot spraying is estimated to reduce herbicide use by up to 90% which translates to lower spraying costs and better environmental outcomes.

Trimble also supply an aftermarket yield monitor and moisture sensor for combines to map crop yield and moisture data in real-time. The sensor can generate yield maps which can be exported to farm management software to evaluate performance of a crop and plan for next season.

Telematics and infield communications

Trimble offers two tiers of farm management software in the Farm Works package which includes desktop and smart device apps (Trimble, 2020c). Farmer Core is the basic tier and includes all operational functionality and some of the farm records functionality. The Farmer Pro tier adds digital report generation for field/crop profitability as well as inventory tracking and in-season monitoring tools such as importing crop health imagery and UAV imagery.

Advisor Prime is a web-integrated tool targeted at agronomists and consultants for creating and sharing management zones and variable rate prescriptions. The app also simplifies the soil sampling process by enabling grids to be created on zone maps and giving GPS guidance to sampling locations.

4.2.2. Raven

Guidance and steering control

The Raven product range for guidance includes each individual component of the auto-steering system as well as more integrated solutions. The RS1 steering controller is the complete solution that integrates GPS and WI-FI/cellular connectivity for remote access and monitoring (Raven, 2020c).

For machines that already have a GPS receiver, the SC1 controller is available to provide similar functionality to the RC1 and is installed in the cab to connect to an external GPS receiver. Raven also offer two external GLONASS receivers that can offer corrections starting from sub-metre accuracy and upgradable to RTK. Additional RTK offering are available (RTK-L and RTK-PRO) which can maintain positioning accuracy through short connection outages (Raven, 2020b).

Raven also support visual guidance in places where vision is more effective than GNSS guidance with the VSN® sensor. VSN® uses stereovision to navigate straight and contoured crop rows at speeds up to 20 m/h and also includes radar sensors to guide the machine in full canopy crop. The system calculates a confidence in the row detection and the operator can set the system to switch back to GPS guidance when confidence is below a threshold.

Both mechanical and hydraulic drives are available to actuate the steering controller signal in the MD steering system and SDGuidance AUTO respectively. Both products can be installed on a range of tractor brands and include terrain compensation sensors. The SDGuidance brand also includes guidance solutions to fit an implement with a separate GPS receiver and steering system for tasks where implement precision is required.

SmartRemote allows some guidance functions to be activated remotely. The physical remote (see Figure 25) can be linked to a CANbus remote controller to control function such as activating/deactivate steering from the tractor or an implement, changing offsets to the left or right, manually steering the implement left or right, and activating/deactivating section control.

Figure 25: *Raven SmartRemote can be used to toggle guidance functions (Raven, 2020c)*

Variable rate technologies

The Raven rate control module allows for rate and section across a variety of implements including spreaders, sprayers, NH3 applicators, liquid fertiliser applicators and planters.

Raven also supplies the Hawkeye® 2 nozzle system for spraying which automatically regulates the system to achieve a target pressure and flow rate set by the operator. Individual nozzle control allows for the system to compensate for a turning tractor by varying the applications rates across the boom as well as reducing overlaps on previously sprayed or non-crop areas.

Sensing – process monitoring

The AutoBoom XRT is a pressure-based control system for spray booms that uses five radar sensors to detect the boom distance from the ground and from the top of the canopy. The system uses the sensor data to equalise the boom height to reduce spray drift and prevent accidental contact with the ground or canopy.

Telematics and infield communications

Raven's farm management software is called Slingshot® and is available on web and smart device apps. The features of Slingshot that assist with operations logistics include tracking of fleet vehicles, job creation tools that can be sent to the cab display, and an interface to assign personnel and equipment to jobs. Slingshot also includes a dedicated analytics section to track machine events and alerts, to set up custom alert groups for specific events that including phone text alerts and email alerts, to export live updates to email or text and to compile machine and field records.

Upcoming developments and concepts

Driverless tractor follower for harvesting

Raven are in the early stages of releasing the first driverless technology for harvesting operation in AutoCart®. AutoCart is an integrated aftermarket guidance system that allows a tractor with attached grain cart to be operating remotely by the driver of the nearby harvester. The system uses a perception system by Raven's subsidiary Smart Ag that uses camera and radar sensors to detect obstacles in the environment. Path planning enables the tractor to go to the harvester when called and travel back to the staging location when full for unloading. The system is currently only compatible with the John Deere 8RX tractors but will be expanded overtime. The full release of this technology is scheduled for 2021 (Raven, 2020a).

4.2.3. Ag Leader

Guidance and steering control

The SteerCommand Z2 is Ag Leader's hydraulic steering solution which can fit to the vehicle CAN bus or hydraulic valve in many tractor brands compatible with automated steering systems (Ag Leader, 2019a). The module contains a nine-axis terrain compensation for holding lines in a range of conditions. Ag Leader supplies two tiers of GPS receivers that feed into the SteerCommand Z2 which provide a range of corrections from WAAS/EGNOS to TerraStar-X or RTK. Two GPS receivers can be paired on a machine in a configuration labelled as DualTrac to provide high accuracy at speeds as low as 0.08 km/h.

SteadySteer is the electric wheel attachment variant for machines that aren't compatible with SteerCommand. SteadySteer achieves the same accuracies as SteerCommand depending on the GPS signal supplied but lacks some of the additional controls and features such as harvest controls.

Machine operation and path planning

Ag Leader also focus on aftermarket planting solutions with a range of product under the 'Sure' branding. SureSpeed is the seed distributor and combines with SureForce which provides hydraulic downforce to achieve uniform seed distribution at a consistent planting depth. SureDrive provides individual row section control and automatic turn compensation, while SureStop electric row clutches effectively shut off rows and remove the need to raise and lower the planter at the end of rows.

Telematics and infield communications

The SMS Software package is Ag Leader's farm management software. The base subscription level (SMS Basic) allows users to work with guidance lines, download soil survey maps, manage soil samples, and track financial information of fields. SMS Advanced is the second subscription tier which additionally allows users to use digital reporting, create prescription maps, calculate management zones, and load in NIR imagery of fields. Further additional modules are available for separate purpose which cover water management, designing field trials (see example in Figure 25), and research plot prescriptions.

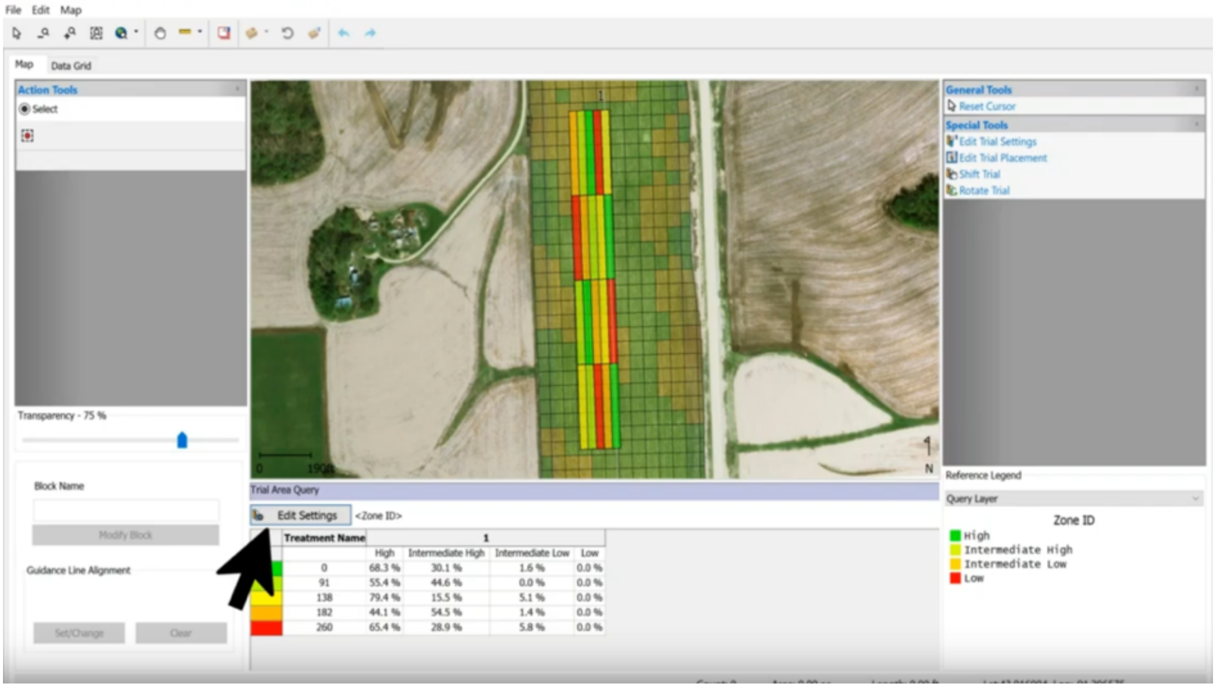


Figure 26: *SMS trial plot generation* *(Ag Leader, 2019b)*

Ag Leader have also released AgFiniti, a smart device app that integrates with SMS Software and carries other functionality such as fleet management and connection to Ag Leader displays for troubleshooting and other tasks.

4.2.4. Topcon

Guidance and steering control

Topcon has two guidance solutions for tractors – a manual guidance and an autosteering solution. The manual guidance solution consists of an SGR-1 GNSS receiver (or alternatively, the AGM-1 receiver) paired with a Topcon console in the cab (Topcon, 2020). The 32-channel GPS + GLONASS signal tracking generates a guidance signal which is presented to the diver by a lightbar on the console.

The AGI-4 GNSS receiver also incorporates a steering controller with inertial sensors for terrain compensation. The AGI-4 uses WAAS and EGNOS as standard and is upgradeable to 2 cm accuracy with RTK. The system can be fitted to steer-ready tractors, and the AES-35 electric steering system is available from Topcon for non-steer-ready machines.

Variable rate technologies

The Topcon range of displays have auto-section control for up to 200 sections via ISOBUS on the top model (X35 display) and variable rate control on up to 8 products. Interfacing an existing controller to the Topcon consoles can be done through the Topcon XLinks control interface, which can also interface with Topcon canopy sensors to inform the variable rate control.

Sensing – process monitoring

Topcon supply the CropSpec canopy sensor (see Figure 27) to be an input for variable rate applications. The sensor can generate a prescription on-the-go for a sprayer/spreader or record prescription maps for later use. The sensor is mounted on the cabin roof to be out of the way and also to generate a large sensing footprint.

Figure 27: *Topcon CropSpec sensor (Topcon, 2020)*

YieldTrakk is an aftermarket yield sensor for combines that uses optical technology to map yield in real-time. The system also includes terrain compensation and a moisture sensor which sends moisture readings to the display beside yield. Automatic header width control tracks and controls the width and area cut, improving accuracy of yield calculations. YieldTrakk supports industry standard data formats for exporting such as ISOXML and shape file format to maximise compatibility with data management solutions on the market.

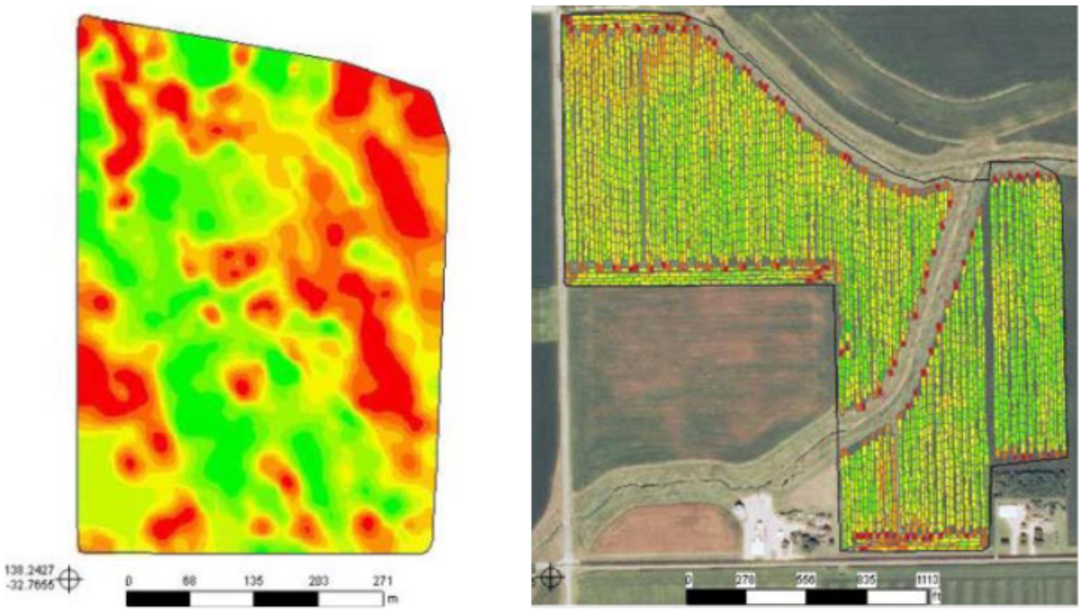


Figure 28: *Topcon YieldTrakk yield mapping (Topcon, 2015)*

4.2.5. Precision Technologies/Farmscan Ag

Guidance and steering control

AgGuide is a software package designed for Windows tablets and PCs that is the centre of Precision Technologies' automation offering. AgGuide supports connection with a range of GPS receivers to enable visual guidance or automatic guidance via hydraulic integration or a steering wheel attachment (Farmscan Ag, 2019). Supported GPS accuracies range from multi-metre (uncorrected), sub-metre (free-to-air correction), decimetre (Terrastar) and centimetre (RTK). The software also has an implement control system.

Figure 29: *AgGuide software designed for Windows x86* *(Farmscan Ag, 2019)*

Variable rate technologies

The AgGuide software has the capability for automatic boom section control (ABS) allowing for fingertip control of application rates. The software also reduces overlap by shutting sections off that travel of previously applied areas (Farmscan Ag, 2015). Variable rate control (VRC) is also available through AgGuide with on-screen control of up to 4 products.

4.2.6. Discussion

The review of automation technologies for tractors from outside the OEMs revealed several new products representing small (Raven SmartRemote) and major (Raven AutoCart®) steps towards tractor automation that are noteworthy when considering automation standards. Some of the products fill niches that don't make sense for the OEMs to cover, such as Ag Leader's dedicated software tools for consultants and agronomists, while other technologies such as Topcon YieldTrakk are universal versions of products which OEMs have made proprietary.

The most important development is Raven's AutoCart® which is a step forward on the automation framework proposed by Case IH and is due to release in 2021. It would be useful to further review the path planning, safety, and sensing capabilities in this product when it is available with respect to developing automation standards.

5. Regulations and Standards

This section shall include a holistic exploration of standards in a number of sectors which may inform autonomous developments within agriculture. These sectors include the transport, mining and defence industries. New standards for autonomous machinery in agriculture are being informed by work undertaken by the European Agricultural Machinery Association (CEMA) under the auspices of 'Project 4'. Each sector will be reviewed in detail within the following sections.

5.1. Autonomy in Transport

Self-driving cars are becoming reality and could have significant impacts on the transportation sector (Koopman et al., 2019). The potential benefits of autonomous vehicles are well acknowledged, however, the risks often associated with technological disruptions and unintended consequences are a major concern. With a rapid increase in autonomous vehicle technologies, appropriate regulations and strategies to address these concerns help maximise the benefits associated with autonomous vehicles. So far, governments around the world have avoided stringent measures to promote autonomous vehicle developments - mainly focusing on the creation of councils or workgroups to explore autonomous vehicle implications (Taeihagh et al., 2018). Organisations across the world that are presently active in developing standards for connected and automated vehicles (CAVs) are listed in Table 3 below:

Table 3: Organisations actively involved in developing standards for CAVs

Country/Region	Acronym	Organisation
Australia	SA	Standards Australia
Canada	CSA	Canadian Standards Association
China	SAC	Standards Administration of China
Europe	CEN CENELEC ETSI	European Committee for Standardization European Committee for Electro-technical Standardization European Telecommunications Standards Institute
Finland	FSI	Finnish Standards Association
France	AFNOR	Association française de normalisation
Germany	DIN VDA	Deutsches Institute Fur Normung Verband der Automobilindustrie
International	IEC ISO ITU IEEE	International Electro-technical Commission International Organization for Standardization International Telecommunication Union Institute of Electrical and Electronics Engineers
Italy	UNI	Ente Nazionale Italiano di Unificazione
Israel	SII	The Standards Institution of Israel
Japan	JSA	Japanese Standards Association
Korea	KSA	Korea Standards Association
Netherlands	NEN	Netherlands Standardization Institute
New Zealand	NZSO	New Zealand Standards Organisation
Singapore	ES	Enterprise Singapore
Spain	UNE	Spanish Association for Standardization
Sweden	SIS	Swedish Institute for Standards
UK	BSI	British Standards Institution
USA	ANSI SAE	American National Standards Institute Society of Automotive Engineers

As automated vehicle (AV) technology continues to advance, there will be a constant need to adjust and expand current vehicle regulations to inform a set of standards for AVs. These standards will also need to apply to special use AVs, such as autonomous or semi-autonomous tractors (ASATs). Current standards and regulations for vehicles will need to be extended to include vehicle registration, licensing, importation, compulsory third-party (CTP) insurance and testing and trialling requirements. However, standards and regulations vary both interstate within Australia and Internationally. A standardised set of regulations should therefore be established to allow for harmonisation between International and Australian standards and to allow Australian consumers accessibility to the broader AV market. In the following sections, the current state of vehicle regulations and requirements will be discussed with a focus on Australian standards; a discussion of expected issues with the implementation of the current standards for use with AVs; and additional regulation requirements to address these issues.

Levels of Automation

SAE International defines six levels of driving automation from 'no automation' to 'full automation' in its standard, J3016, under 'Levels of automation' (SAE 2018). Level 0 - 2 is partial, or driver assist automation; Level 3 is fully automatic, but driver must drive when feature requests; Level 4 - 5 are highly automatic driving features and require no driver control. Figure 30 (next page) details each step of automation including the level of human interference with the automated vehicles along with the example features. At Level 0, automation is mainly assisting the driver by warnings (e.g. blind spot monitoring, lane departure warning) and emergency braking. Level 1 supports the driver in steering, braking or acceleration. Level 2 supports the steering, braking and acceleration. Level 3 automation include automated driving systems (ADS) and operate the vehicle in limited condition and driver must present to drive the vehicle when prompted. Level 4 automation can drive the vehicle without human interference but under limited conditions. At Level 5, the vehicle drives automatically under all circumstances. SAE J3016: '*Taxonomy and definitions for terms related to Driving Automation Systems for on-road motor vehicles*', was issued in 2014 and updated in 2016 and 2018. SAE J3114 provides human factor definitions for automated driving for the user's interaction with L2 to L4 level driving automation as per SAE J3016. This definition of levels of automation (SAE J3016) is adopted by several international regulatory bodies including National Transport Commission (NTC), Australia; Department for Transport (DfT), UK; National Highway Traffic Safety Administration (NHTSA), USA; Government of Ontario, Canada; and the European Road Transport Research Advisory Council (ERTRAC), Europe.

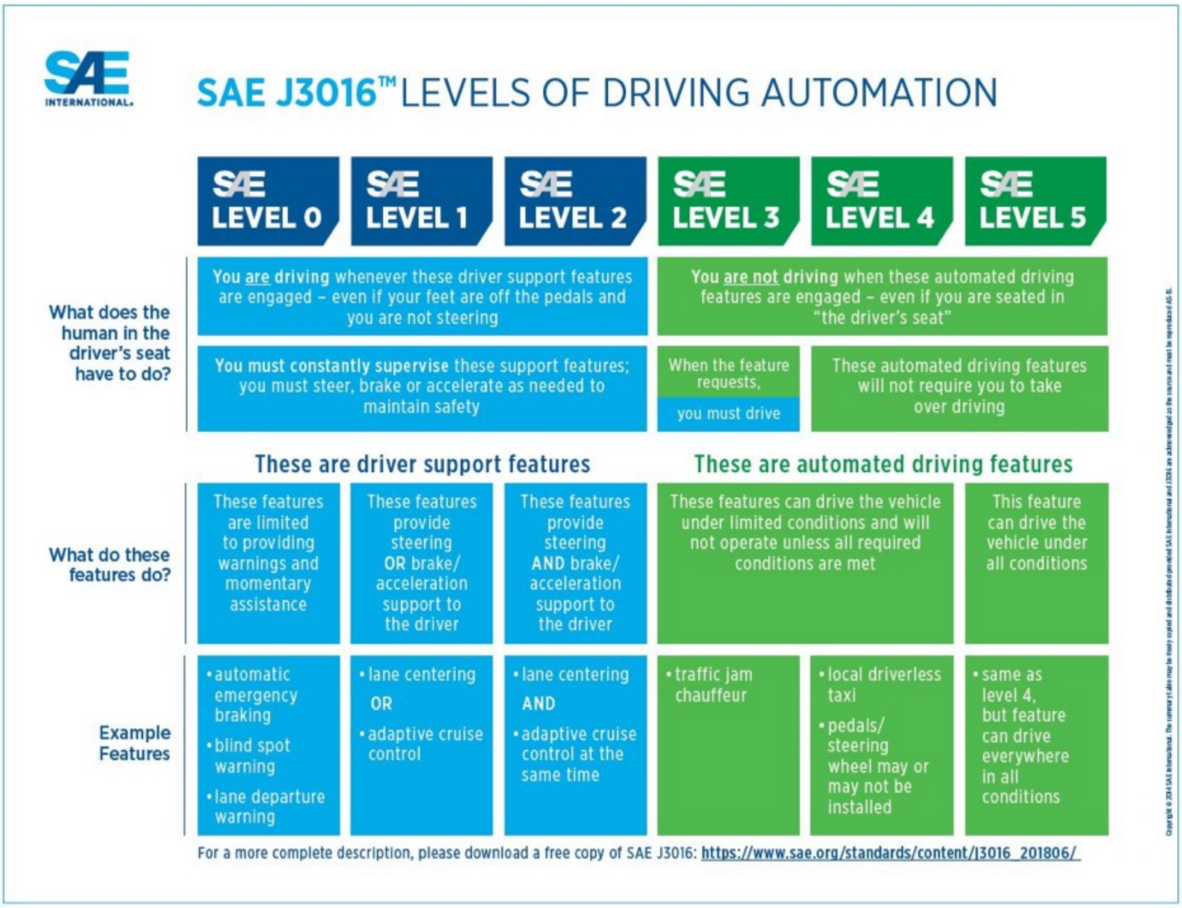


Figure 30: *SAE J3016 – Levels of driving automation* *(SAE International, 2018)*

Overall, J3016 provides a useful framework for ascertaining holistic 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 tractors equipped with AutoTrac Turn Automation (with the ability to steer, adjust throttle and control the implement, prior to performing an automated end-of-row turn), the current Level of driving automation for farming machinery may be deduced as SAE Level 3. To advance to higher levels, the tractor must be able to operate with no human intervention and/or possess some degree of intuition.

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.

Terminology

With large amounts of international research being conducted on CAV development, several workgroups and Standard Development Organisations (SDO) are working to formalise and maintain a consistent vocabulary. BSI (2020c) is one such organisation that has developed a set of terms and definitions for CAVs. Some of the terms defined in the vocabulary include: advanced driver assistance systems (ADAS), adaptive cruise control (ACC), automated driving system (ADS), automated vehicle (AV), and connected and automated vehicle (CAV). Use of the word "autonomous" is cautioned by SAE international, as it creates ambiguities when referring to the vehicle and traffic environment as compared to vehicle and driver interference. CAV and AV are widely used to remove this ambiguity.

Focus areas

BSI (2017) released a summary report on the analysis of 661 CAV-related standards published by various countries and SDOs. BSI's research identified a total of 15 priority areas for standards development, which would help accelerate CAV development in the UK. These 15 priority areas are further categorised into 6 focus areas (Table 4) (BSI, 2019). A total of 231 formal standards related to design, development, testing and operation of CAVs worldwide (by various international and national-standard bodies from USA, Australia, UK, Canada, Europe, Japan, Korea, Germany, China, Singapore, Israel and Netherlands). Some of these focus areas are divided into sub-segments as presented in the table below.

Table 4: Focus areas for standardisation along with sub segments (BSI 2019)

Sl. No	Focus area	Sub-segments
1	Communications and ITS	Vehicle to Vehicle (V2V) Vehicle to infrastructure (V2I) Vehicle to Everything (V2X)
2	Security	Cybersecurity System security
3	Autonomous driving and control systems	Control systems Safety Verification and validation
4	Human factors	No sub-segment
5	AI and Machine Learning	No sub-segment
6	Data management	Diagnostics and analytics Privacy

In addition to the above 231 standards, BSI Standards Watch reports that a total of 121 standards were published in 2019 (2020a). The below figure (Figure 31) represents the standardisation activity over the last 15 years, with 352 published standards relating to CAV development from 2005 to 2019. As evident in the figure, standardisation activity in 2019 is much higher compared to the previous 15 years.

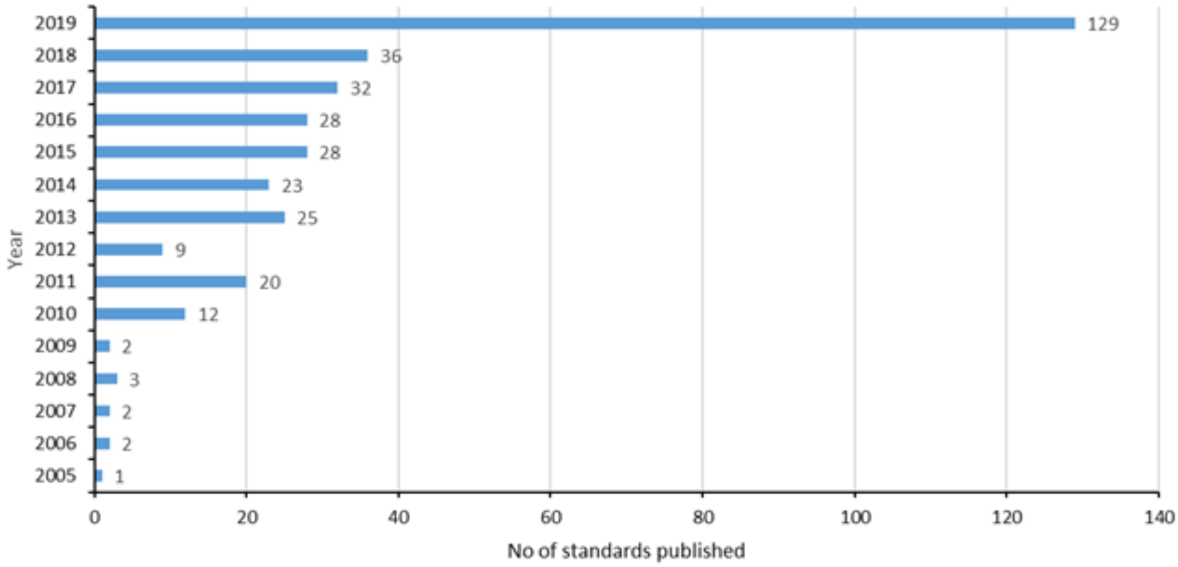


Figure 31: *Standardisation activity from 2005-2019 in CAVs* (BSI 2019, 2020a)

Category-wise, published and draft standards (2005-2009) for each focus area are presented in Figure 32. This analysis shows that the focus areas of 'Security' and 'Communication and Intelligent Transport Systems (ITS)', have high standardisation activity, with focus areas 'Autonomous driving and control systems', 'Data management' and 'Human factors' having medium standardisation activity, and 'AI and Machine Learning' having less standardisation activity.

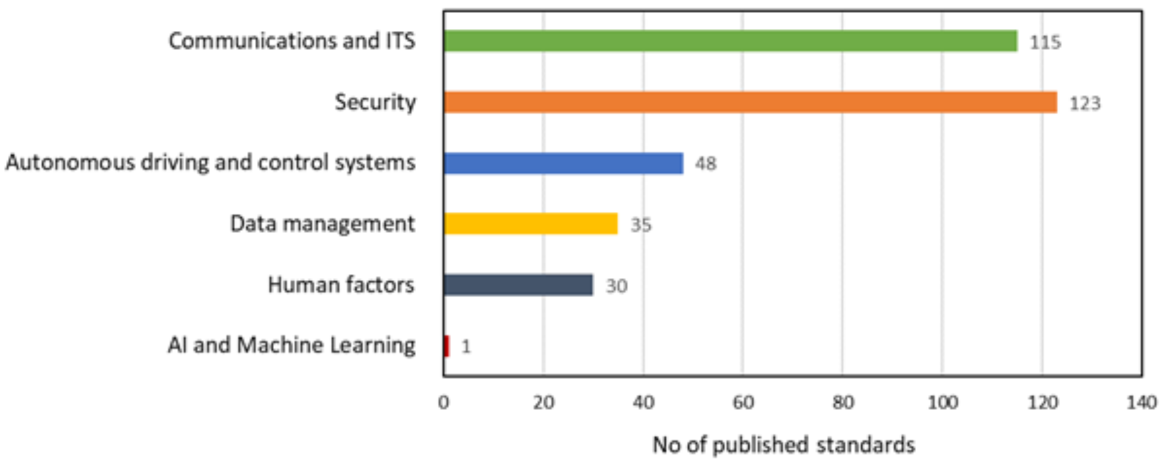


Figure 32: *Focus area standardisation activity from 2005 to 2019* (BSI 2019, 2020a)

To present the recent trends in standardisation activity, published and draft standards (62 and 86 respectively) of 2019 were considered, with sub-category standardisation activity presented below in Figure 33. V2X and cyber security are the more active areas, where present standardisation activity is focused.

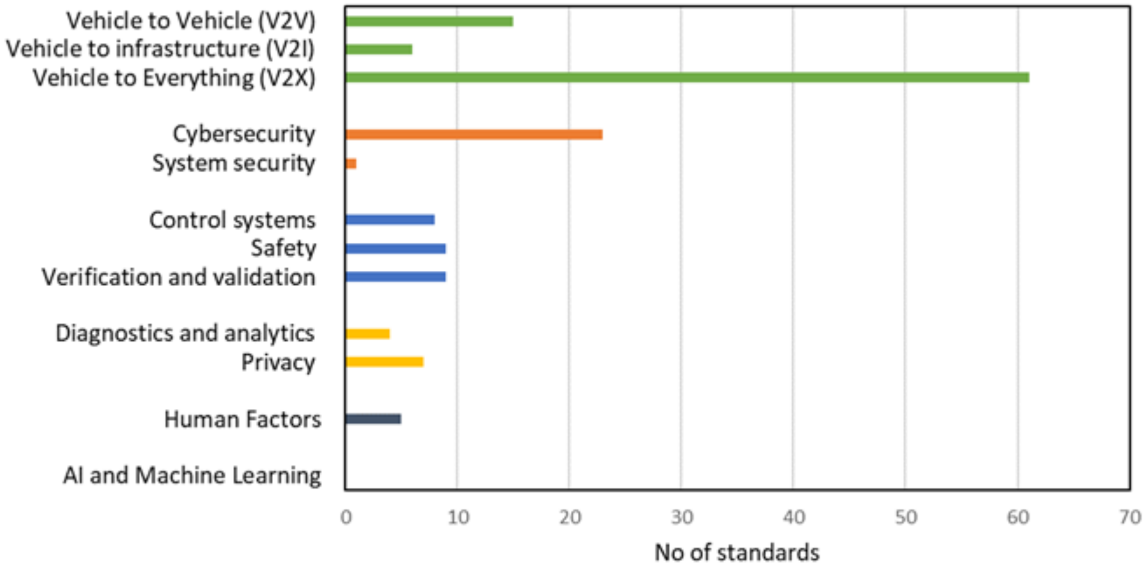


Figure 33: *Sub-category standardisation activity Q3 & Q4 of 2019* *(BIS 2020a)*

Communications and ITS

Vehicular communications and networks exchange information among modern connected vehicles and help improving road safety, optimising traffic flow and efficient use of fuel for ITS. Some of the examples of various safety related applications of V2X are forward collision warning, control loss warning, emergency vehicle warning, emergency stop, wrong way driving warning, pre-crash sensing warning etc. An example of increasing traffic efficiency is cooperative adaptive cruise control. Recent vehicle to everything (V2X) communications includes vehicle to vehicle (V2V), vehicle to infrastructure (V2I), and vehicle to pedestrian (V2P), and vehicle to network (V2N).

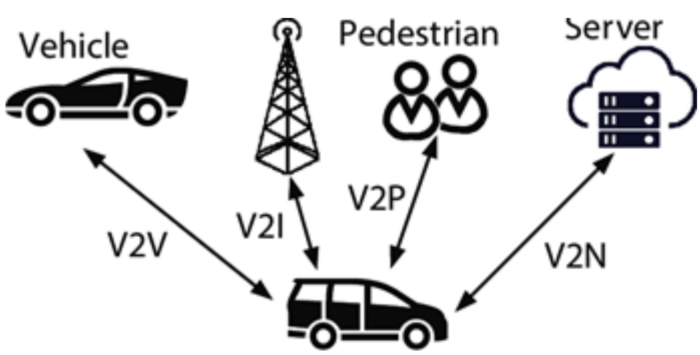


Figure 34: *V2X communications* *(Wang, 2017)*

WLAN and cellular based technologies are used for V2X communication. The standards relating to both technologies are listed in Table 5.

Table 5: V2X standards

Standards	Standards details
IEEE 802.11p: 2010	IEEE Standard for Information technology-- Local and metropolitan area networks-- Specific requirements-- Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications Amendment 6: Wireless Access in Vehicular Environments
ETSI ES 202 663 V1.1.0: 2010	Intelligent Transport Systems (ITS); European profile standard for the physical and medium access control layer of Intelligent Transport Systems operating in the 5 GHz frequency band
ITU-R M.1452-2 : 2012	Millimetre wave vehicular collision avoidance radars and radio communication systems for intelligent transport system applications
IEEE 1609.12:2019	IEEE Standard for Wireless Access in Vehicular Environments (WAVE)—Identifiers
SAE J2735: 2020	V2X communications message set dictionary
3GPP 36 series	LTE (Evolved UTRA), LTE-Advanced, LTE-Advanced Pro-technology
3GPP 38 series	Radio technology beyond LTE
ETSI TS 103 613 V1.1.1: 2018	Intelligent Transport Systems (ITS); Access layer specification for ITS using LTE Vehicle to everything communication in the 5,9 GHz frequency band

Dedicated short range communication (DSRC) uses the short-range wireless radio wave bands for communication and data exchange between V2V and V2I. IEEE 802.11p describe the physical and medium access control layers for DSRC messaging in a dedicated bandwidth in the range 5.850 to 5.925GHz and is based on the wireless access in vehicular environment (WAVE) technology defined by IEEE 1609.0-12 family of standards. IEEE ITU-R M.1452 is used in applications for collision avoidance radars. Standard ETSI ES 202 663 specifies the frequency bands in Europe and classifies as ITS-G5A (Safety related applications), ITS-G5B (non-safety applications), ITS-G5C (radio local area networks) and ITS-G5D (ITS standard expansion). In Japan these radio frequency bands for vehicle communication are defined by ARIB STD-T55, ARIB STD-T75 and ARIB STD-T109 (Kiela et al. 2020). SAE J2735 series of standards from 2006 -2020 specifies the data exchange message set used in DSRC communications. Example applications based on DSRC communications are front collision warning, electronic toll collection, passenger information, traffic light management, traffic congestion detection etc.

With commercial availability of Long-Term Evolution (LTE or 4G LTE), a wireless broadband communication standard for mobile devices, cellular based V2X (C-V2X) communications can provide better quality of support, higher data rate and larger coverage for moving vehicles compared to IEEE 802.11p (Wang, 2017). C-V2X standards are developed by 3rd generation Partnership project (3GPP) international organisation. 3GPP developed about 400 standards related to 5G, LTE and C-V2X through series 33, 36 and 38 (BSI, 2019).

Truck platooning is a semi-autonomous (Level 2 of SAE) concept in transport autonomy, where two or more trucks in convoy are linked continuously using wireless connectivity technology and automated driving support systems. The vehicles in platoon automatically maintain a pre-set, close distance between each other, with less or no intervention from drivers following the head truck by adapting to the changes in the movements. This technology can be likened to the 'leader-follower' systems present in agriculture, whereby a tractor can autonomously match the speed and direction of a harvester while being filled. Enabling Safe Multi-Brand Platooning for Europe (ENSEMBLE) consortium is the European Commission project to realise pre-standards for interoperability between "multi-band" trucks platooning on European roads (Boris Atanassow, 2019).

There is a risk and inconvenience to other road users when platooning in single carriageways. Bridge loading and road wear may also be issues when platooning AHVs (Kutadinata et al. 2018). However, minimum platooning following distances (stacking distance) may be able to be shortened, allowing more traffic on the road network. As AV systems can react faster than human drivers, they do not need as long to adjust speed in a platoon (Kutadinata et al. 2018). These are considerations that will need to be addressed in AV specific legislation and regulations. It is also likely that current road requirements, road-work requirements and signage requirements will need adjusting for use by AVs, particularly in remote areas (Cunningham et al. 2017, Kutadinata et al. 2018).

Security

The concept of an 'extended vehicle' (ExVe) explains vehicle data sharing through third party service providers at off-board locations (such as remote secure servers) rather than directly from the moving vehicle. For worldwide interoperability, standardisation of ExVe off-board data access is dictated by ISO 20077-1 (2017) and ISO 20077-2 (2018). Concepts relating to ExVe web services are defined in ISO 20078-1(2019), 20078-2 (2019). Sharing of vehicle data can have a wide range of uses (Figure 35). As per European Union's Regulation (EU) 2018/858, OEMs must be ready to share connected car data with third parties by September 1, 2020. However, using third party hardware and software for sharing vehicle data may include certain security and safety risks (Figure 36). Table 6 highlights those standards that address these security risks.

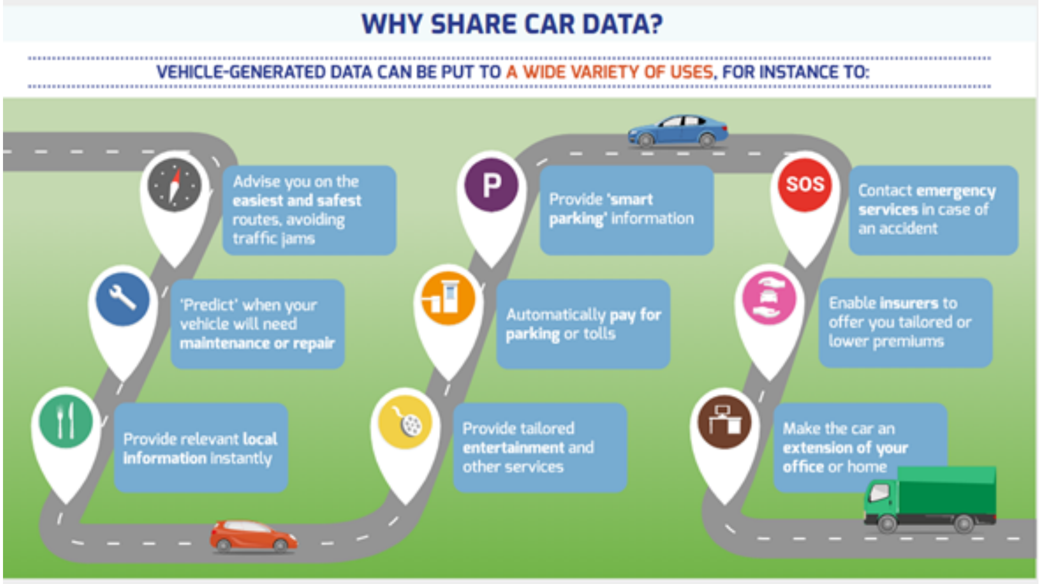


Figure 35: *ExVe data sharing advantages* *(Car Data Facts, 2020)*

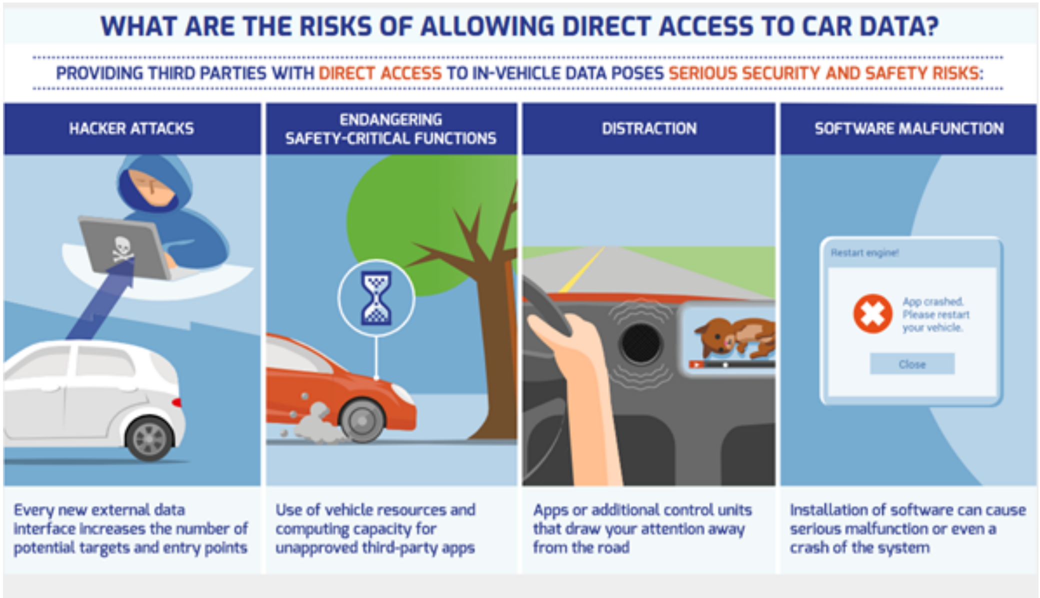


Figure 36*: Risks associated with ExVe data sharing* *(Car Data Facts, 2020)*

Table 6: Cybersecurity standards

Standards	Standard details
PAS 1885:2018	Fundamental principles of cyber security
ISO 26262-2: 2018	Road vehicles — Functional safety — Part 2: Management of functional safety
ISO/SAE 21434	Road vehicles — Cybersecurity engineering (Under development)
ISO IEC AWI 27030	Information technology — Security techniques — Guidelines for security and privacy in Internet of Things (IoT) –(Under development)
ISO IEC DTS 27110	Information technology, cybersecurity and privacy protection — Cybersecurity framework development guidelines (Under development)
ISO IEC NP 27014	Information security, cybersecurity and privacy protection — Governance of information security (Under development)

Automated driving and control systems

Highly automated vehicles mostly depend on sensor data, complex algorithms based on artificial intelligence techniques (randomised algorithms, which tend to behave unpredictably) and machine learning methods, and actuation implemented by electrical and electronic systems. Depending on the intervention of these automatic controls and advance driver assistance systems, safety systems can be categorised as active safety systems and passive safety systems. Passive safety systems (seatbelts, airbags etc.) protect the occupants of a vehicle and other road users if a crash occurs.

Table 7: Automated driving and control

Standards	Standard details
ISO 11270: 2014	ITS - Lane keeping assistance systems (LKAS) — Performance requirements and test procedures
ISO 16787: 2017	ITS - Assisted parking system (APS) — Performance requirements and test procedures
ISO 21717: 2018	Intelligent transport systems — Partially Automated In-Lane Driving Systems (PADS) — Performance requirements and test procedures
ISO 19638: 2018	ITS - Road boundary departure prevention systems (RBDPS) — Performance requirements and test procedures
ISO 26262: 2018	Road vehicles – Functional safety
ISO PAS 21448:2019	Road vehicles –Safety of intended functionality (SOTIF)
PAS 1880: 2020	Connected automotive ecosystems. Impact of security on safety. Code of practice
PAS 11281-2018	Guidelines for Developing and Assessing Control Systems for Automated Vehicles
PAS 1881: 2020	Assuring the safety of automated vehicle trials and testing. Specification
ISO 22737	ITS - LSAD systems for predefined routes — Performance requirements, system requirements and performance test procedures (under development)
ISO/SAE PAS 22736	ITS - Taxonomy and definitions for terms related to driving automation systems for on-road motor vehicles (under development)

Active safety systems (Figure 37) connects sensors, radar, cameras, GPS and lasers and continuously monitors surrounds, and actively assists driver to prevent accidents such as Autonomous emergency braking (AEB), Lane departure warning (LDW), lane keeping assistance (LKA), drowsiness and attention detection systems, speed limit information (SLI), tyre pressure monitoring systems (TPMS), intelligent speed assistance (ISA) etc. These active safety systems can take over control from the driver in case of an emergency – such as autonomous emergency braking (AEB). ISO standards 11270 (2014), 16787 (2017), 21717 (2018) 19638 (2018) explain some these safety issues.

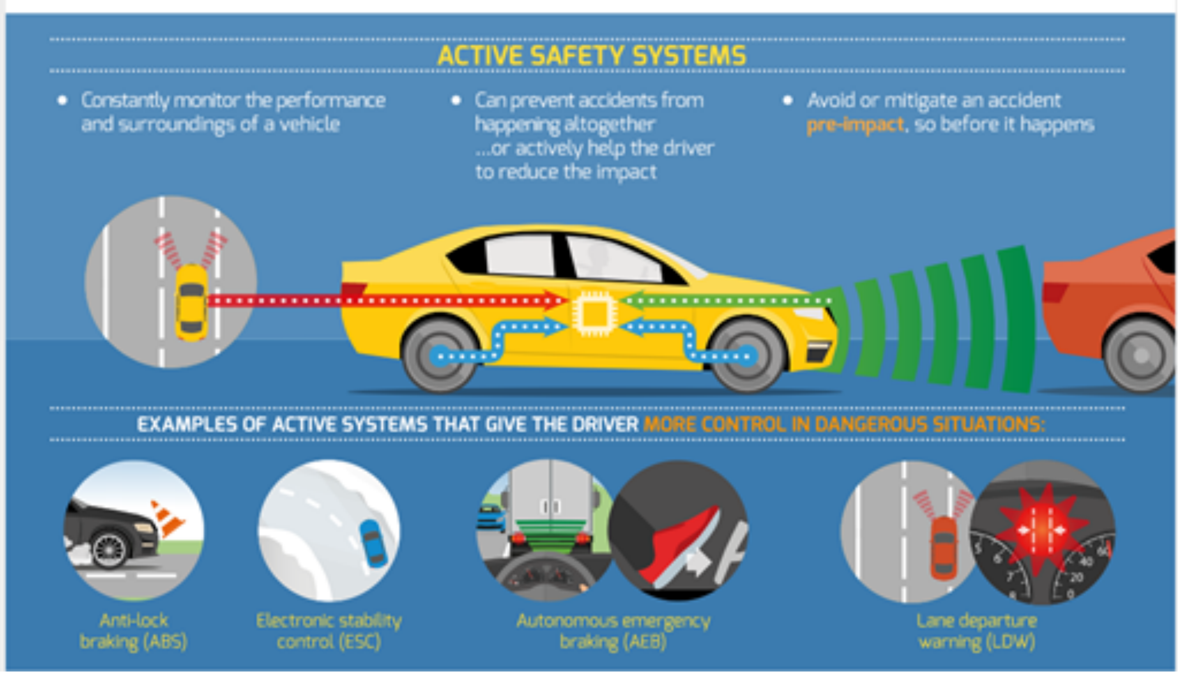


Figure 37: *Active Safety Systems (Car Data Facts, 2020)*

ISO 26262:2018 (ISO, 2018) appears to be the most pertinent safety-related document, describing the functional safety of electrical and electronic systems in road vehicles. This standard is consistent with international standard IEC61508 published by International Electrotechnical commission (IEC). ISO 26262 includes:

i. Tailoring Safety lifecycle (management, development, production, operation, service, decommissioning) for integrating existing systems and newly developed systems.
ii. Product development at various levels (system, hardware and software level).
iii. Specific risk-based approach for incorporating hazards, safety goals and Automotive Safety Integrity Level (ASIL)s
iv. Specifies analysis based on ASILs for achieving acceptable residual risk

ISO/PAS 21448 standard (ISO, 2019) describes the safety of the intended functionality (SOTIF) and covers guidance for design, verification and validation to achieve SOTIF. This standard applies where situational awareness is derived from complex sensor and processing algorithm, such as emergency intervention systems and advance driver assistance systems (ADAS) with Level 1 and Level 2 of automation standard SAE J3016.

ISO 26262 covers functional safety in the event of system failure, whereas ISO 21448 covers safety hazards that caused without system failure. PAS 1881 (BSI, 2020b) is the standard published by British Standards Institution (BSI) for the safe testing of automated vehicle trails in the UK to demonstrate the safety of activities. Underwriters Laboratories (UL) recently published (April 2020) its first standard for safety (ANSI/UL 4600) for evaluation of fully autonomous vehicles and other products (UL4600). The list of fully-autonomous systems encompasses self-driving cars, together with applications within mining, agriculture and lightweight unmanned aerial vehicles (UAVs).

Data Management

Data management describes vehicle diagnostics and analytics, personal data and privacy. ISO 11898-1 specifies the general architecture of communication protocols for classical Control Area Network (CAN) data-rate and CAN flexible data-rate format. Classical CAN allows bitrates of 1 Mbps of data, whereas flexible data-rate allows higher than 1 Mbps bit rates. ISO 11898-2 defines the high-speed physical media attachment to the CAN. ISO 15765 deal with the diagnostic communication over CAN. Privacy rules for the vehicle service providers in probe vehicle services (PVS) are specified by ISO 24100 and ISO 16461.

Table 8: Data management standards

Standards	Standard details
ISO 11898-1: 2015	Road vehicles - Controller area network (CAN) - Part 1: Data link layer and physical signalling
ISO 11898-2:2016	Road vehicles — Controller area network (CAN) — Part 2: High-speed medium access unit
ISO 15765-2:2016	Road vehicles — Diagnostic communication over Controller Area Network (DoCAN) — Part 2: Transport protocol and network layer services
ISO 15765-4:2016	Road vehicles — Diagnostic communication over Controller Area Network (DoCAN) — Part 4: Requirements for emissions-related systems
ISO 24100:2010	Intelligent transport systems — Basic principles for personal data protection in probe vehicle information services
ISO/TR 12859:2009	Intelligent transport systems — System architecture — Privacy aspects in ITS standards and systems
ISO 16461:2018	Intelligent transport systems — Criteria for privacy and integrity protection in probe vehicle information systems
ISO/TR 17427-7:2015	Intelligent transport systems — Cooperative ITS — Part 7: Privacy aspects

Human Factors

Human-machine interface requirements and test procedures for the onboard systems – especially in case of emergency such as forward collision warning (SAE J2400) and lane departure warning (ISO 17361) – are included within this focus area.

Table 9: Human factors standards

Standards	Standard details
SAE J 2400: 2014	Human Factors in Forward Collision Warning Systems: Operating Characteristics and User Interface Requirements
ISO 17361: 2017	Human machine interface for lane departure

AI and Machine Learning

Although technologically-advanced, standardisation in this area is substantially less when compared to other areas, with only one standard being published in 2019.

Relevancy of Standards

Upon analysing the relevance of the aforementioned standards, only 8 out of the 62 published standards were found to be relevant for CAV research (listed within Table 10), with 22 out of the 86 draft standards being deemed pertinent to such research (Table 11).

Table 10: Published standards relevant to CAV research (Courtesy: BSI 2020a)

Standards	Standard details
IEC 63005-2	Event video data recorder for road vehicle accidents - Part 2: Test methods for evaluating the performance of basic functions
ISO 16505	Road vehicles — Ergonomic and performance aspects of Camera Monitor Systems — Requirements and test procedures
ISO/DIS 15765-5	Road vehicles — Diagnostic communication over Controller Area Network (DoCAN) — Part 5: Specification for an in-vehicle network connected to the diagnostic link connector
ISO 23132	Road vehicles — Extended Vehicle (ExVe) time critical applications — General requirements, definitions and classification methodology of time-constrained situations related to Road and ExVe Safety (RExVeS)
SAE J1746	ISP-Vehicle Location Referencing Standard
SAE J 1760	Data Security Services
SAE J2186	E/E Data Link Security
SAE J 3018	Safety-Relevant Guidance for On-Road Testing of SAE Level 3, 4, and 5 Prototype Automated Driving System (ADS)-Operated Vehicles

Table 11: Draft standards relevant to CAV research (Courtesy: BSI 2020a)

Standards	Standard details
ISO/WD 24650	Road Vehicles — Sensors for automated driving under adverse weather conditions — Assessment of the cleaning system
ISO/WD 34503	Road vehicles — Taxonomy for operational design domain for automated driving systems
SAE J3224	V2X Sensor-Sharing for Cooperative & Automated Driving
ISO/AWI 39003	Road Traffic Safety (RTS) — Guidance on safety ethical considerations for autonomous vehicles
ISO/WD 34502	Road vehicles — Engineering framework and process of scenario-based safety evaluation
ISO/AWI TS 22133	Road vehicles — Test object monitoring and control for active safety and automated/autonomous vehicle testing — Functional requirements, specifications and communication protocol
SO/AWI 23374	Intelligent transport systems — Automated valet parking systems (AVPS) — System framework, communication interface, and vehicle operation
ISO/AWI TS 22726-2	Intelligent transport systems — Dynamic data and map database specification for connected and automated driving system applications — Part 2: Logical data model of dynamic data
ISO/WD 34501	Road vehicles — Terms and definitions of test scenarios for automated driving systems
ISO/WD 34504	Road vehicles — Scenario attributes and categorization
PAS 1883	Operational design domain (ODD) taxonomy for an automated driving system (ADS). Specification

Australian Regulations

Regulations for autonomous vehicles within Australia relate heavily to those developed by the National Transport Commission (2020) – an independent body responsible for developing regulations for Australia's roads and other transport systems. The Commission is currently in the process of reforming several regulatory documents to reflect the recent advances in autonomous car technology. The reforms focus on the following policies and/or decisions:

- Who is legally in control
- Development of a purpose-built national driving law
- Operational safety during 'entry-to-market'

From the initial stages of reforms, Australian Transport Ministers have already agreed upon the following points:

- The control system is legally 'in control' of the car while ADS is operating
- Driver will remain vigilant and resume control when requested/required
- New laws will be developed for autonomous car operation
- Existing insurance schemes expanded to cover damages caused by autonomous vehicles

A further Australian regulation currently in practice, relates to *NSW Transport Legislation Amendment (Automated Vehicle Trials and Innovation) Act 2017 No 41*. This regulation outlines the processes required for approving vehicular trials where a human may not be in control of the vehicle. Although designed for experimental trials, the legislation presents a range of pertinent points for the development and eventual commercial release of CAVs.
The regulation outlines:

- Requirements for approved vehicle, approved operator, trial area/location (including State roads) and trial period.
- Registration process of the vehicle (and whether registration is required to complete the trials)
- Relevant motor vehicle insurance - third-party insurance must be acquired prior to trials and indemnification of the 'Nominal Defendant' outlined
- Requirements of a 'trial supervisor' to be inside the vehicle at all times (albeit not in direct control), who holds a current Australian driver license
- Provision of pertinent information to legislative bodies, where required (e.g. if the trial vehicle collides with a person, vehicle or property - including near misses/possible accidents)
- Obstruction of trials – whereby an individual should not hinder/obstruct the trial without reasonable excuse
- Waiving of fines and/or demerit points incurred by trial operators

The above legislation represents one of many standards that have either been updated, or need to be updated, to reflect the developments of the autonomous car industry – specifically to reflect who is in control of the vehicle. Consequently, NRMA Insurance (2018) presented a report, identifying more than 50 federal and state laws requiring amendment, due to the assumption that the driver of a vehicle is human. Furthermore, the report outlines additional amendments to allow cars to be driven (legally) by computers.

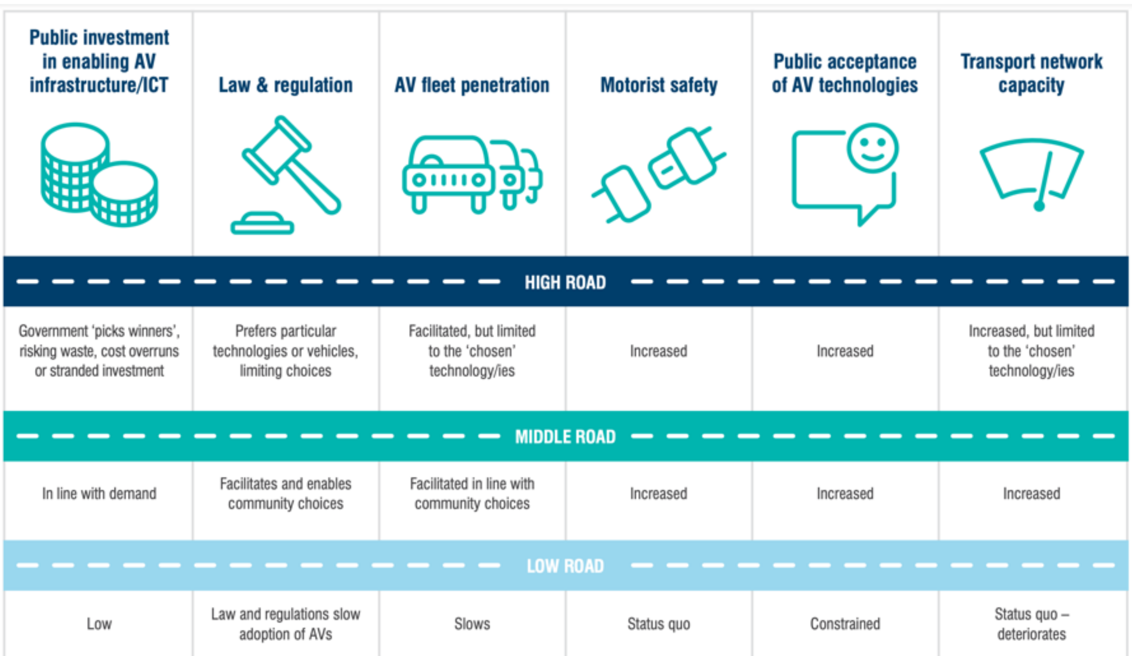
Infrastructures Partnerships Australia (2017) also presented a report, outlining the three possible approaches/outcomes for development of autonomous vehicle regulations. The three options, *High*, *Middle* and *Low Road*, are as follows:

High Road *(Option 1)* Community-centred
Regulation and investment severely lag AV adoption

Middle Road *(Option 2)* Government-community facilitated
Regulation is responsive, but follows observed community choices

Low Road *(Option 3)* Government-focused
The government sector 'picks winners' in advance of community adoption

The implementation of each option carries certain limitations. Option 1 may restrict important benefits to the development of 'the bigger picture' (such as improved safety and standardised/expected abilities); Option 3 may see investments in the incorrect sector, infrastructure or enabling technologies; Option 2 provides minimised limitations by drawing on the benefits of Option 1 and 3, yet may cause a slower uptake of CAVs due to the input of both government and community. Further outcomes of each scenario can be viewed in Figure 38 below.



	Public investment in enabling AV infrastructure/ICT	Law & regulation	AV fleet penetration	Motorist safety	Public acceptance of AV technologies	Transport network capacity
HIGH ROAD	Government 'picks winners', risking waste, cost overruns or stranded investment	Prefers particular technologies or vehicles, limiting choices	Facilitated, but limited to the 'chosen' technology/ies	Increased	Increased	Increased, but limited to the 'chosen' technology/ies
MIDDLE ROAD	In line with demand	Facilitates and enables community choices	Facilitated in line with community choices	Increased	Increased	Increased
LOW ROAD	Low	Law and regulations slow adoption of AVs	Slows	Status quo	Constrained	Status quo – deteriorates

***Figure 38**: Potential outcomes for development of autonomous vehicle regulations*
(Infrastructures Partnerships Australia, 2017)

Current Regulations

Specific standards around AVs need to be in place before an AV registration scheme can be implemented. Currently no standards exist in the Australian Design Rules (ADRs) that specifically relate to AV technology and current vehicle standards are not applied by default to all AVs (Cunningham et al., 2017). However, several standards have been published by the International Organization for Standardization (ISO) Technical Subcommittee Road Vehicles (ISO/TC22/SC31). Further, WP 29 of the World Forum for the Harmonization of Vehicle Regulations has developed guidelines for developing vehicle standards for AVs and has published design principles for control systems for advanced driver assistance systems, operational elements to allow manual control of AV functions and information to support the design of the human-machine interface (Cunningham et al. 2017). It has been predicted that the development of AV specific standards could take years or decades and that the most that could be accomplished before this regarding regulations is the identification of a minimum set of manoeuvres for AVs for manufacturer testing (Nowakosi et al., 2015). While these would be necessary, this set of guidelines is unlikely to be sufficient for public operation. However, they may be sufficient for on farm use with manual driving capability for use on public road networks. Full AV standards would need to address:

- The capability for the AV to perform specified tasks in automated mode
- The ability of the AV to deal with catastrophic events (connectivity failure, natural disaster, cyberattack)
- Standards governing human-machine interface for ease of use and safety
- Standards for software updates
- Standards for event data recorders (EDRs)
- Standards relating to connectivity with helper systems (e.g. inter-vehicle communication)

(Cunningham et al., 2017)

Vehicle Registration

Motor vehicles must be registered to be operated on part of the public road network in both Australia and New Zealand. In Australia the Department of Infrastructure and Regional Development (DIRD) is responsible for the regulation of vehicles until the point of first supply. Once in service, the state or territory governments take over the regulation of the registered vehicles (Cunningham et al., 2017). The National Heavy Vehicle Regulator (NHVR) is taking on an increasing role in heavy vehicle regulations (Cunningham et al., 2017 & Kutadinata et al., 2018), which could extend to ATs. NHVR administers the Heavy Vehicle National Law (HVNL) and provides permit applications, fatigue and driving hour diaries and sets vehicle standards. It is possible that SAE level 3 and 4 operations could allow exemptions from fatigue management laws (Kutadinata et al., 2018). HVNL is applicable to vehicles over 4.5 tonnes gross vehicle mass (GVM). All Australian states and territories, excluding Western Australia and the Northern Territory have adopted

HVNL (Kutadinata et al., 2018). Although many tractors are over 4.5 tonnes, they are currently exempted from HVNL and are registered for use on public motorways in Australia under a restricted/conditional/special registration which is handled by the state or territory government.

The current vehicle registration system is based on the ADRs and is administered under the Motor Vehicle Standards Act 1989 (Cunningham et al., 2017). Vehicle manufacturers are responsible for compliance with ADRs. Under this system, it is a condition of the registration that the vehicle continues compliance with roadworthy regulations set by the Australian Vehicle Standards Rules (AVSRs) and HVNL. However, different jurisdictions use different schemes to enforce this roadworthy compliance. Schemes include compliance at first registration, when a vehicle reaches a certain age (e.g. 5 years), at the transfer of ownership, at the transfer of registration between territories, at random, etc. (Cunningham et al., 2017). These differences in compliance enforcement underline the need for harmonisation between territories and states in regulation development for AVs. Further, ADRs apply before or at the point of vehicle supply to the market. This means that they would not be applicable for use in controlling how an AV behaves in traffic throughout its service life as the AV is operating as a driver (Cunningham et al. 2017). As ADR development must adhere to an Australian Government regulatory impact statement (RIS) process which incorporates a benefit-cost analysis on known statistical data, alternative regulatory frameworks to new ADRs may provide greater benefit (Cunningham et al., 2017). However, ADRs do not currently apply to non-road vehicles.

A safety assurance framework has been proposed by the National Transport Commission (NTC) (2016) which shouldn't overlap the current ADRs. Safety certification standards have also been put forward by Shladover and Nowakowski (2015), outlining four criteria for AV manufacturers including the developmental process, functional safety of the design, performance testing and behavioural competency simulation. An option to increase AV safety is to follow standards outlined in Europe by the Vienna convention where AV technology must be able to be switched completely on and completely off (Cunningham et al. 2017). This is the current practice enabling registration of AVs in Sweden (Cunningham et al. 2017).

Harmonisation aims to ensure that both vehicle safety and environmental protections can be provided to Australia at the lowest possible cost as any major variation from international AV regulations could be seen as a Technical Barrier to Trade under the World Trade Organization General Agreement on Tariffs and Trade (GATT) (Cunningham et al. 2017). The commonwealth currently has a policy to increase the agreement between ADRs and the United Nations Economic Commission for Europe (UNECE) vehicle regulations. Australia is also part of the 1958 and 1998 UNECE agreements around harmonised vehicle regulations and involved in the World Forum for Harmonization of Vehicle Regulations (WP 29) (Cunningham et al., 2017). WP 29 oversees development and approval of UNECE vehicle regulations, incorporating 'technical regulations' for improved vehicle safety and reduced environmental impact. The UN international convention was updated in 2016 to incorporate automated driving (Cunningham et al., 2017).

There is an ongoing discussion around how AVs should be classified for registration purposes. Options include classification according to the highest level of automation they support (SAE level), classification by operational design domain (ODD) and by behavioural competency of the AV (Cunningham et al., 2017). Further, there may be a need for new vehicle classes to be registered, as vehicles produced for the international market might not be eligible for registration otherwise. These classes may be aligned to international standards and may also require different obligations of the driver.

Concerns surround maintenance of the compliance of AVs once they are registered and in-service. Consultations with industry experts identified the need to ensure ongoing safety of AVs in the face of software upgrades and modifications (Cunningham et al., 2017). Suggestions included vehicle recalls to update and verify software and to assign the responsibility of alerting customers to updates and disabling vehicles with outdated software to the AV manufacturer. Additional options include running periodic physical diagnostics and if an update altered the AVs ADR compliance, the upgrade would be classified as an in-service modification. This would require the approval of the registering authority of the state or territory. An option is to classify AVs according to their ODD to help mitigate issues of recertification after upgrades/modifications. The International Technical Committee on Vehicle Inspections (CITA) is developing inspection tests for all vehicle types and recommend that in-service compliance checks be included in an annual registration safety check (Cunningham et al., 2017). It is predicted by experts that their will need to be a consistent national approach to roadworthiness checks for AVs (Cunningham et al., 2017).

Additional issues around registration include the predicted trend from one-to-one private ownership schemes to car sharing and car-pooling (Wallace & Silberg, 2012; Fagnant & Kockelman, 2014; Sivak & Schoettle, 2015). However, there is no suggestion that vehicles should be registered differently at this stage. The NSW Road Transport currently provides regulation for vehicle fleet owners with annual inspections required after 5 years (Cunningham et al., 2017). Further, there is no indication of a trend to fleet sharing of agricultural vehicles. Although this may be a consideration in the future.

Vehicle Licensing

In addition to changing registration requirements, there is a discussion around the impact of AVs on driver licensing schemes. Current car licensing schemes in Australia and New Zealand employ graduated licensing (GLS). GLS puts restrictions on the least experienced drivers in the form of learner permits, provisional/probationary licenses and zero blood alcohol limits. Progress between the GLS phases is based on age and/or time spent in previous licensing phases. All jurisdictions require an applicant to pass an age threshold and a written or computer exam for the issue of a permit or license. Further, additional restrictions can be put in place dependent on driver health conditions or impairments. Currently there are no license conditions based on vehicle automation other than transmission in either Australia or New Zealand (Cunningham et al., 2017).

In terms of additional training required for driving AVs, experts only expect additional training to be needed for SAE level 3 and SAE level 4 AVs (operating at level 4 some of the time) (Cunningham et al., 2017). Most training would likely revolve around operation of the AV functions and the maintenance of manual driving skills for the times when the operator is asked to take over control from the machine. Most experts suggest that the responsibility for AV training should fall with the OEM, but the government should provide some definition of training requirements (Cunningham et al., 2017). Initial focus of AV programs is likely to be on older and more experienced drivers with disposable income (Cunningham et al., 2017). These programs should be submitted to state licensing agencies for approval with a mutual recognition of approvals between Australia and New Zealand (Cunningham et al., 2017). This will regulate the training of instructors rather than individual drivers.

Most experts agree that no additional testing will immediately be required to obtain licenses for AVs, except in highly automated cases (SAE 5) where the manufacturer has given the option for manual control (Cunningham et al., 2017). Australian requirements for vehicle compliance for testing will need to be reviewed with vehicles used in licensing testing to be similar in level of assistance to those that the license holder would be permitted to drive (Cunningham et al., 2017). This would likely lead to a need to classify all road vehicles by level of automation. Further, enforcing a system of driving privileges would require the policing authorities to be able to quickly determine the level of automation of a given vehicle. Current driving laws assume a human driver and an AV cannot be held legally responsible for its action. Current law does not provide for a legal entity to be held responsible for the actions of an AV (NTC, 2017b). Legislation will need to clarify who has safety of duty in these cases.

Compulsory Third Party (CTP) Insurance

CTP insurance schemes cover vehicle owners and drivers who are legally liable for personal injury to any person in the event of a motor vehicle crash on a public road network. CTP insurance is compulsory for the registration of a motor vehicle for use on public roads in Australia. For more serious injury, no-fault coverage covers treatment and care costs for life through the National Injury Insurance Scheme (NIIS).

Considerations for CTP insurance in relation to AVs include the tying of CTP insurance to registration and not licensing, it does not cover all road users and should be harmonised if road rules are harmonised (Cunningham et al., 2017). CTP insurance schemes differ across Australia with most sold as part of the vehicle registration, they include both fault-based (Western Australia, New South Wales, Queensland, Australian Capital Territory, South Australia) and no-fault-based (Victoria, Northern Territory, Tasmania) schemes.

The primary issue around AVs on CTP insurance schemes is that CTP insurance may need to evolve to determine if the person or the machine is legally at fault. This will require a review of CTP insurance legislation. However, if fault or liability can be determined, there should be cover. The government may consider alignment of AV CTP insurance schemes to create no-fault cover across states and territories. This would be in line with the UK's announced plans to extend compulsory product liability insurance (Tovey, 2016).

It is predicted that changing control of the vehicle from the driver to the AV may result in a shift in liability (Cunningham et al., 2017). This may drive improvements in OEM safety but could also suppress innovation. Event data recorders (EDRs) may be needed to preserve data to determine liability in cases of accidents involving AVs. However, EDRs also raise issues around data security. Regulations and legislation will need to be reviewed and put in place to preserve data security while evolving CTP insurance legislation to handle AVs (Cunningham et al., 2017).

Autonomy Testing Regulations and Standards

Regulatory requirements in Australia may be ready for trials but not for commercial deployments (Kutadinata et al., 2018). OEMs have a responsibility for ensuring the AVs they bring to market are thoroughly tested and evaluated. To ensure technology can safely handle the variation in real driving environments, 'real-world' testing is necessary. This testing requires review of legislation to establish a regulatory framework for testing (UK Department for Transport, 2015). Approximately 15 AV trials have taken place in Australia (NTC, 2020).

Cunningham et al. (2017) reviewed five documents around testing criteria for 'real-world' AV testing:

- Document: (UK) Departments for Transport (2015) The Pathway to Driverless Cars: A Code of Practice for Testing
- Document: SAE International Standard J3018 (2015) Guidelines for Safe On-road testing of SAE Level 3, 4 and 5 Prototype Automated Driving Systems
- Document: Australian Driverless Vehicle Initiative (ADVI) (2015) Requirements for Demonstration of Volvo XC 90 Vehicle in Autonomous Mode
- Document: (New Zealand) Ministry of Transport (2016) Testing Autonomous Vehicles in New Zealand
- Document: California Department of Motor Vehicles (DMV) (2015) Article 3.7 - Autonomous Vehicles

All documents incorporated some sort of safety plan requirement with the Ministry of Transport (2016) specifying what a safety management plan should contain. The California Department of Motor Vehicles (2015) is the only document specifying a requirement for a testing permit. Most documents required appropriate insurance. Most documents also required testing organisations to engage with stakeholders in the planning of trials. All documents required some sort of training, specifically around the test driver or operator with training levels ranging from novice (not informed about ADS) to expert (usually an engineer or designer of the ADS system). All documents further specify that the operators must be fit for duty with the SAE (2015) also requiring the presence of a test manager. Further, most documents specify some minimum vehicle requirements around data recording and the functionality of software. Only the California Department of Motor Vehicles (2015) provides guidance on accident reporting. Recent regulatory requirements and legislative measure developments appear in a timeline in Appendix A (Regulatory Developments Timeline).

Importation

The importation of vehicles is administered by the Department of Infrastructure, Transport, Regional Development and Communications under the Motor Vehicle Standards Act 1989 (MVSA) and the Motor Vehicle Standards Regulations 1989. AVs don't all currently comply with ADRs or have their own import option under MVSA (e.g. automated shuttle buses) (NTC, 2020). However, they can be imported for trials through a discretionary approval or test and evaluation option. There are three import approval pathways for the import of vehicles for the Australian market under the Commonwealth's existing legislative framework:

- Approval for supply in unlimited numbers of 'standard' vehicles that fully meet all ADS
- Approval for supply in unlimited numbers of 'non-standard' vehicles that meet a sufficient number of ADS that apply for the vehicle to be considered suitable for use on public rules
- Concessional approvals

The 'standard' vehicle pathway would best support the entry of automated vehicles on a commercial scale (NTC, 2020). The 'non-standard' pathway would likely suit large-scale trials for commercial viability, but states and territories may need to make concessions for registration to mitigate non-compliance with ADS. Concessional approvals are currently being used.

The lack of a specific import pathway for AVs result in a lack of consistency in the evaluation of applications for AV imports. This also makes it legally possible to import a large number of automated vehicles into Australia, although this is not intended for commercial deployments (NTC, 2020). The expected number of vehicles approved are restricted to the minimum number required for the trial and a new importation framework will likely be needed to support the importation of larger numbers of AVs (NTC, 2020). Further, under the test and evaluate option imported vehicles must be returned within four years or destroyed which is regarded as a poor outcome by trialling organisations and OEMs (NTC, 2020).

Overall, organisations have found the importation process for AVs lengthy, costly, confusing and not repeatable (NTC, 2020). As such many organisations are paying other organisations to help navigate the process (NTC, 2020).

5.2. Autonomy in Mining

Given the scale and longevity of mining operations, autonomy lends itself appropriately 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 a recent report, 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 common 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 manage various automated operations across the Pilbara region from one, centralised location (Rio Tinto, 2020) (Figure 39). Additionally, a more individual example of hybrid systems within mining may include the interaction of human excavator drivers with autonomous haul trucks.

Figure 39: *Rio Tinto's Operations Centre (ABC News, 2019)*

Operating environments present 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 deal with continually changing landscapes, with the main sources of navigation being provided by pre-defined digital terrain maps (DTM). An example of a DTM can be viewed below in Figure 40:

***Figure 40**: Example of a mining environment DTM* (Wenco, 2018)

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/beings 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 heavily to ISO 5010:2019 (*Earth-Moving Machinery – Steering Requirements*). However, attention is raised to the periodic checking of steering capabilities, performed either autonomously or by the operator. These checks are to be carried out 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. As long as 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 emphasised 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 is meeting the specified requirements and accuracy of the task (in other words, have a closed-loop feedback system). If the accuracy is out-with the acceptable threshold, the ASAM should halt and enter a safe/idle state.

- 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 provide insufficient precision or accuracy. Current practices within agriculture tend to disable the ATG system and sound an alarm, but not halt the tractor and/or enter a safe idle state.

5.3. Autonomy in Defence

Autonomy in defence can be categorised as unmanned ground, underwater or aerial vehicles, corresponding to each of the major defence branches of army, navy and air force. The present work is more focused on ground vehicle automation, therefore is mainly focused on systems strategies and automation around army. When compared to tractor automation army robotic and autonomous systems strategies are much different as the automated vehicles or automated machines need to be operated in close collaboration with army personal and other machinery in adverse and heterogeneous environments with limited or no network availability. Adoption and incorporation of fully autonomous or semi-autonomous systems depend on reliability (robustness and endurance), user's trust on intended use capabilities of the systems, adaptability to changing communication environment, ability to work and operate or shutdown with no network and no human back up controls, power capabilities such as endurance of batteries, alternative fuel sources, etc.

Robotics and Autonomous systems Strategy (RAS) of the Australian Army (2018) suggests understanding the various levels of autonomy to describe the system to understand the human input from remote control to full autonomy (Figure 41).

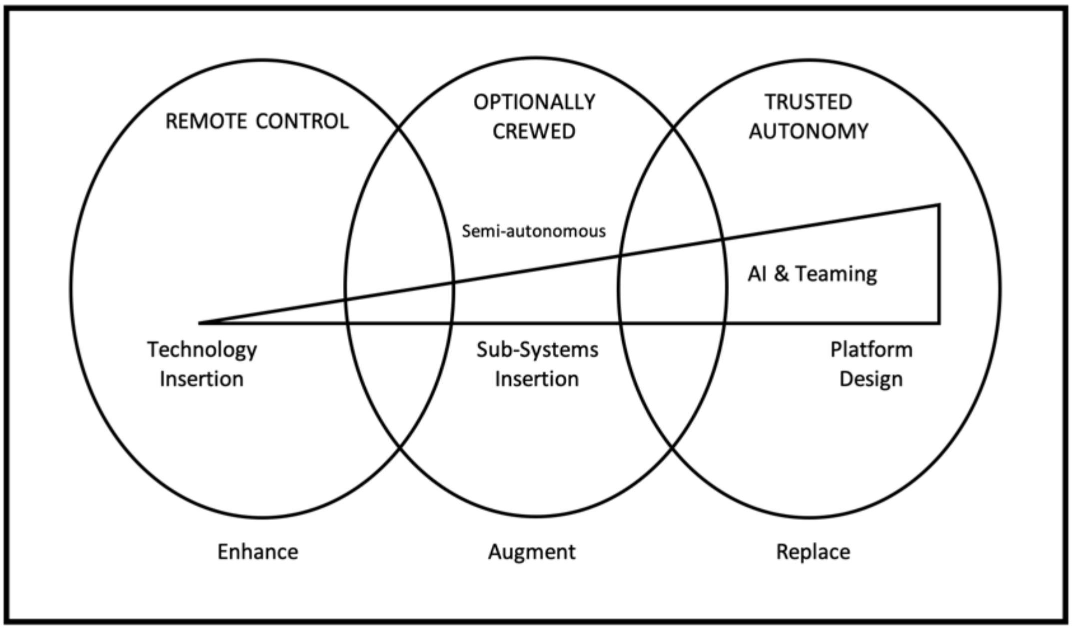


Figure 41: *Australian Army RAS realisation* *(Army 2018)*

Australian army's potential focus areas for realisation of RAS and various stake holders' activity is given in the following table (next page).

Table 12: Focus areas for realisation of RAS

Research	Research into autonomy, network resilience, IIP Program S&T plans, common architecture, Academia, Master Question List, ARDR
Experiment & Prototype	AID propositions, Future Soldier Lab, Autonomous Warrior 18, Land Autonomous Warrior, FLW Experimentation campaign
Collaboration	Coalition Assured Autonomous resupply, collaborative programs (Such as TORVICE), Allied Programs (such as Last Mile Delivery)
Influence	TAS-DCRC, AID Process, Defence Innovation Hub, DSTG, JOAD, Joint Force Design, Force Structure Reviews, Defence White Papers
Force Design	Force Design Experimentation, Prototype Force structures, Modelling & Simulation, Land Warfare Lab, Joint Land Force CONOP, CONEMP, Workforce Plans
Education	Tech Podcast, AARC, COMADC, trade schools, Army Knowledge Group, Social Media
Policy/Law	Strategic Policy Branch, WHS, CDLE, DFAT

One of the available governing standards for military systems is MIL-STD-882E (US DoD, 2012). This safety standard explains the approach of Department of Defence (DoD) systems, products, and equipment's to eliminate possible hazards and minimising the risks through all stages of design, development, testing, production, use and disposal including hardware and software. Key definitions and requirements are listed in Section 3.2 and risk acceptance requirements in 5000.02 of DoD instruction.

Apart from unmanned vehicles, Lethal Autonomous Weapon Systems (LAWS) are special category autonomous weapon systems in military for identifying and destroying the targets without manual interference. US Department of Defence (DODD) 3000.09 explains different categories of autonomy for US autonomous weapon systems. The categories include full autonomy or 'human out of loop'; human supervised or 'human on the loop'; and semi-autonomous or 'human in the loop'.

Machine vision plays an important role in automation, especially local situational analysis (LSA) applications in military. Vetronics Infrastructure for Video over Ethernet (VIVOE) Defence standard (Def-stan 00-82) published by British Ministry of defence (MOD) defines the architecture video distribution network and outlines the requirement for distributing the digital video within an Ethernet based system. US Department of defence, Vehicular Integration for C4ISR/EW Interoperability (VICTORY) is a similar standard for LSA. GigE Vision standard, an open standard developed by machine vision industry, meets most of military important requirements and is now being adapted by several countries in military LSA applications.

Automated combat trucks, consists of one manned vehicle followed by unmanned vehicles, are currently being tested for army requirements including cyber security by Tank Automotive Research, Development and Engineering Centre (TARDEC).

5.4. Autonomy in Agriculture

One of the most applicable documents currently available to automated and autonomous agricultural machines, relates to ISO Standard 18497:2018 (International Organization for Standardization, 2018). The purpose of this document is to specify safety parameters and outline verification and validation processes associated with the relevant HAAM safety systems, while also providing valuable information pertaining to specific safety protocols (for example, 'loss of communication' and 'engine fault' procedures). ISO 18497 also highlights the identification of failure modes and possible risks to the system (for example, occluded obstacles and difficult environmental/weather conditions).

Operational safety requirements of HAAM are also addressed in detail – 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 automated controls. Within the document, the means for enabling and disabling highly automated operations are outlined to be:

- Easily identifiable
- Readily accessible (incl. 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).

However, through current research activities, the existing ISO18497:2018 standard is being broken into four separate standards. The new standards have moved away from the definition of autonomy levels (similar to the transport sector) and are more focused on the function or mode of operation. The new standard is defined as a *B-Level Standard* – focused at a particular industry/sector, rather than specific machinery (i.e. *C-Level Standard*). The current revisions are being driven by manufacturers and feedback has been provided on draft versions of the new standards ISO18497/1 and 2 being developed. Internationally, there are various other groups and bodies with interests in agricultural autonomy including:

- OECD subgroup on agricultural robotics in Europe
- Japanese Ministry of Agriculture, Forestry and Fisheries
    - AGI-Robotics Safety Guidelines
    - National Agriculture and Food Research Organisation (Tractor Testing) - Institute of Agricultural Machinery
- ANSI Automated / Autonomous Standards Coordination Forum
- AEM Autonomous Machine Group
- ASABE Autonomous Field Equipment Group

Recent research completed by Torrance (2020), presents recommendations for the assessment of (semi-)autonomous tractor performance, abilities and field-readiness (PAFR) with respect to standardised test procedures. The independent research outlined in the paper also allowed the machine's PAFR to be presented as four marks out of ten – with an individual mark awarded for awareness and perception; automated tractor guidance; headland management systems and operational safety. The paper also outlines technical aspects that contribute to 'enabling' elements of fully autonomous tractor technology, such as emphasis on 'fail-safe'/'dead-man' protocols, awareness of machine operating limits and understanding the quality of work being performed.

Australian Regulations

The primary source of regulation for agricultural applications within Australia pertains to State/Territory Workplace Health and Safety. For Queensland, safe farming operations are governed by WorkSafe Queensland's *Code of Practice for Safe Design and Operation of Tractors* (WorkSafe Queensland, 2005). Although not explicitly designed for autonomous tractors, this document outlines the necessary design and safety protocols for a tractor operating in a typical farming environment. The Code emphasises the importance of consultation and briefing of workers/employees to ensure potential WH&S risks are identified and understood.

The Code of Practice requires the person managing or controlling a tractor to ensure the following items (WorkSafe Queensland, 2005):

- *No person other than the operator rides on the plant unless the person is provided with a level of protection that is equivalent to that provided to the operator*
- *That the plant does not collide with pedestrians or other powered mobile plant*
- *If there is a possibility of the plant colliding with pedestrians or other mobile plant, the person must ensure that the machine has a warning device that will warn persons who may be at risk from the movement of the plant.*

As previously discussed within '*Autonomy in Transport – Australian Regulations*', regulations that assume a human being is in control at all times (such as this Code of Practice), must be amended to suit the current applications and maturity of autonomous technology. Regardless, the aforementioned aspects may be applicable in relation to hybrid, remote-control, or fully-autonomous tractors.

For autonomous machinery that may be conducting chemical-spraying operations, regulation exists for the ground-distribution of agricultural chemicals. The *Agricultural Chemicals Distribution Control Act* (ACDC) of 1966 states:

"If you intend to use ground equipment to distribute herbicides on land that you or a close relative do not own or occupy, a commercial operator's licence is required" (ACDC, 1966)

Therefore, for applying chemical on owned property (by oneself, a relative, or an employer engaged primarily in pastoral or agricultural pursuits), no license is required. A licence is required if the services being rendered to the employer/client are explicitly for ground distribution of chemical.

However, regulation for 'Supervising Unlicensed Operators' reads:

"A licensed commercial operator is permitted to supervise an unlicensed operator or a group of unlicensed operators to use ground equipment to carry out ground distribution" (ACDC, 1966)

In which case:

- the supervisor must always be present while ground distribution is being completed
    - supervisor cannot issue instructions and leave the worker(s) to carry out the work on their own
- the supervisor must check calibration of spray equipment and be present during mixing/handling of chemicals
- the supervisor must check correct equipment/spray nozzle is selected

These regulations may present an issue when dealing with autonomous tractor legislation. Chemicals can be broadcast over one's own property (by either a licenced or unlicensed operator), yet, given the age of the Act, no mention is made to the autonomous distribution of chemical. For example, during autonomous spraying, it is likely that the tractor will be operating on its own accord, once instructions are issued, while also being responsible for the automated handling, mixing and application of chemical. As before, this highlights the need for revised regulations, given the advances in automated and autonomous technologies.

Code of Practice for Autonomous Agricultural Machinery

To aid regulation of autonomous machinery within agricultural environments, an industry Code of Practice (CoP) is to be developed to ensure field machinery with autonomous functions are operated both safely and in compliance with State and Federal legislation/regulations.

A CoP is currently being drafted through Grain Producers Australia (GPA), in conjunction with the Society of Precision Agriculture Australia (SPAA) and Tractor and Machinery Association (TMA). Intended for 'Agricultural Mobile Field Machinery with Autonomous Functions in Australia' (GPA, 2020), the aims of this document include:

- Outlining the desired safety outcomes when using ASATs in relation to satisfying WH&S Laws
- Highlighting safety and performance variables that may affect the operation of ASATs
- Defining the role of the operator in relation to hazard management of ASAT operations
- Outlining requirements for complying with both State and National Safe Work legislation (including regulations relating to the distribution of agricultural chemicals)

(GPA, 2020)

To concisely address the aforementioned aims, the CoP is sub-divided into three sections, relating to:

1. Risk management approach;
2. General hazard controls and emergency preparedness; and
3. Operational management.

(GPA, 2020)

The table on the following page (Table 13) both summarises the Code of Practice, and outlines the relevance of each section against current developments within the agricultural sector (including existing technologies, regulations and standards).

Table 13: Relevance of Code of Practice against current developments

Code of Practice	Current technology, standards and regulations
Safety and Risk Management Process	
Farming operation safety management plan to outline and mitigate hazards associated with ASATS • Identification of risks • Analysis of risks (probability and severity) • Evaluation and management of risks (mitigative strategies) • Monitoring and review of risk and mitigation strategy • Outlining of formal documentation to formally capture risk management	Most workplaces may have pre-existing Risk Management Plans and Processes, relevant to operations occurring on-site. *Safe Work Australia* presents example Risk Assessments and RMPs. Furthermore, WH&S risk assessments at the state/territory-level are also available online. AS/NZS 4360 and ISO 31000 provide standardised principles for both identifying and managing risk.
Roll-out of ASAT technologies	

Information, instruction, training and supervision discussed - imperative for safe farming operations that implement ASATs
• *Information*: manuals, legislation, CoP, operational practices (SOP) etc
• *Instruction* including:
  ○ System functionality
  ○ Tasks to be undertaken
  ○ Controls to actuate
  ○ Steps necessary to complete tasks
• *Training* (including assessment of competency)
• *Supervision* (including methods to ensure WH&S objectives are satisfied)
	No standardised testing protocols are currently implemented to assess the safety, performance and/or field-readiness of ASAT technologies. Research (by Torrance, 2020) is available that presents various testing protocols.
	
	Most commercial machinery is provided with user/operator manuals, albeit it with no standardised layout.
	
	No universally accepted training and/or competency assessments are currently deployed - it is left to the operators and supervisors to undertake accordingly.

Limitations of ASATs	
ASAT limitations briefly discussed: • Suitability for operational environment • Functionality • Multiple ASATs in close proximity • Use of fully-autonomous, semi-autonomous, hybrid and after-market systems • Competency of operator and/or support personnel	ASATs are limited by the designation of their 'Operational Design Domain' (ODD). Research involving the development of (semi-)autonomous systems is conducted within prespecified limits to ensure the product can be marketable, without designing a system for all possible scenarios. Direct limitations may relate to the ASAT's lack of 'intuition' when presented with an unfamiliar obstacle and/or scenario.
Farm Design and Planning	
Farming operation design and planning principles outlined for successful and safe integration of ASATs: • Designing and/or modifying existing infrastructure for ASAT operation • Managing interactions (including access control, traffic, input resource locations) • Operating environment to be suitable for ASAT operation (including work areas, traffic management and area segregation).	Little information is currently available for the planning, design and layout of farming environments for the successful and safe adoption of ASAT technologies. The report by Torrance (2020) briefly highlights methods to minimise foot traffic into areas in which an ASAT may be operating (including signage and use of a designated testing area)
ASAT Usage/Transport on Public Roads	
Transporting ASAT between fields and/or road travel is also discussed: • CoP only for in-field, on-farm operation • Transport between work areas is outside of ODD • ASAT to be in full view and control of manual operator when on public land/roads	ASAT research is typically conducted within pre-specified ODD, with most design domains excluding operations outside of the field. Most OEMs include a disclaimer within the user manual, to disable all automated functions (such as Automated Tractor Guidance) before travelling on public roads.

Commissioning of Hazard Controls	
Issues pertaining to the commissioning of hazard controls include: • Roles and responsibilities of operators, OEMs and distributors • Risk management processes • Planning (including checklists for installation, assembly and commissioning) • Testing (based on recommended commissioning procedures from the manufacturer) • Training and induction of operators • System acceptance	Vasic and Billard (2013) identify a range of incidents deemed harmful to the operator within the industrial workplace - including crushing, impact and entanglement hazards. Human-machine interactions are summarised by Heinzmann and Zelinsky (2003), whereby various requirements are recommended to avoid injury to both personnel and the machine itself. ISO 18497 details required safety measures to be implemented by ASATs within typical operations, together with outlining verification and validation processes associated with the relevant safety systems. ISO 17757 outlines the various systems and performance metrics required by a (semi-) autonomous machine for safe operation within a mining environment, including: braking and steering performance, protocols when dealing with environmental adaptations and navigational risks. Testing protocols produced by Torrance (2020) appear to be the only procedures developed for the assessment of autonomous tractor performance, safety and field-readiness (albeit not universally-accepted as of yet).

<table>
<tr><th colspan="2">Operational Hazard Controls</th></tr>
<tr><td>Discussion of hazard controls relating to safe operation of ASATs

management and supervision of ASAT operations
roles and responsibilities of ASAT, operators and support personnel
competency validation (e.g. operators, supervisors, technical and service support)
change management including

system updates and upgrades
changes to operational practices, documentation and training requirements

interaction rules
changing between semi, fully, hybrid and manual operating modes are managed, documented and communicated
performance monitoring and continuous improvement on ASAT performance
access control for semi-autonomous, autonomous, manned and mixed equipment operational
tools and processes

risk management (SWPs, JSAs, risk assessments, risk register)
communication protocols and considerations (e.g. radio network)
performance monitoring
incident reporting and emergency response

</td>
<td>Appendices within ISO 18497 outline potential obstacles that an ASAT may face during typical field operations (and also details the design of an obstacle to simulate a humanoid figure).

ISO 17757 highlights safety issues that a (semi-)autonomous mining vehicle may be presented with – primarily involving hazards relating to positioning, navigation and changes to the operating environment (including disabling certain operations under specific conditions).

Torrance (2020) put forth a list of potential obstacles and hazards that an ASAT may face (including subjecting the ASAT to various environmental conditions), yet did not test these procedures within a practical setting.</td></tr>
</table>

5.5. Summary of Autonomy within Various Sectors

The Venn Diagram (shown below in Figure 42) summarises the development of autonomy throughout the aforementioned sectors, while also highlighting areas where similar technologies/attributes are shared between industries.

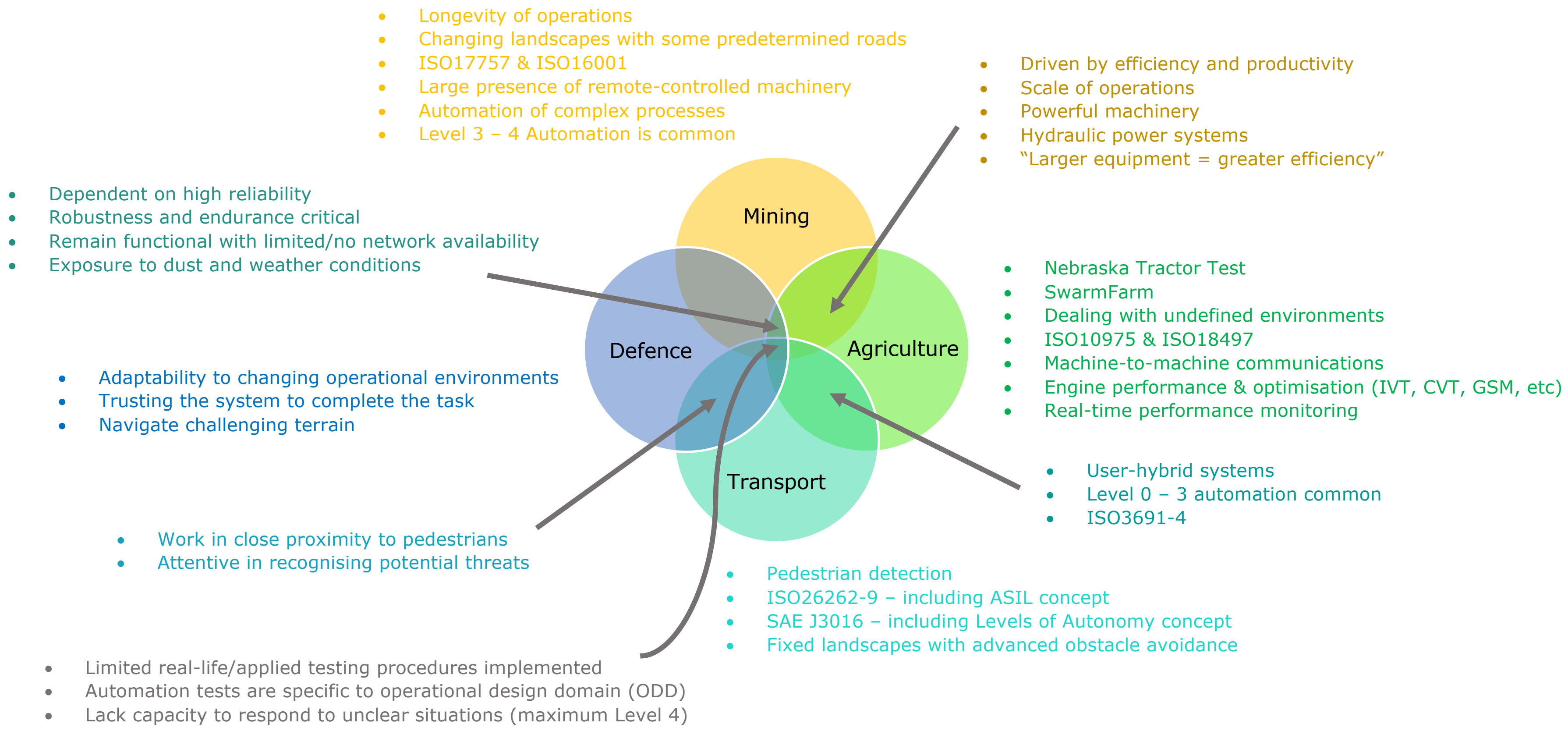


Figure 42: *Summary of autonomy within various sector*

6. Operational Requirements

6.1. Operational Design Domain (ODD) for Agriculture

Environments where a highly automated agricultural machine (HAAM) 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 maturity of autonomous technology required by the vehicle – the greater the freedom, the less defined the environment is and therefore, the more advanced the technology must be. To avoid autonomous machinery manufacturers investing considerable 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 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. The machine is further challenged by a low operating structure within the working environment - exacerbated by the intermittent, critical presence of people, animals, other vehicles and the effect of natural events (such as severe weather) that can produce unexpected consequences. 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 the field; initialising, undertaking and completing field work and returning to a 'home station' for refuelling or maintenance.

Structured environments, however, 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 may comprise 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.

6.2. Existing / Future Platforms and Standards Gaps

Autonomous vehicles will increasingly offer advances in agriculture workplace practices in terms of greater efficiency and exploitation of resources. This report has identified the prominent standards and has mapped the wider scope of standards for different application sectors where contrasts and similarities can be identified. With the benefit of this information and the experience in building and operating the early machines to date it is informative to consider the responding development of standards and to project a robust framework that will adapt to an advancing future by maintaining relevance and avoiding gaps.

From one aspect, the significant hurdles for autonomous agriculture vehicles stem from the wide range of use conditions and multi-function requirements. It is only within the last five years that activity has increased significantly with the realisation of opportunity for greater autonomy. This has been informed by key advances in fundamental enabling technologies such as materials, micro-technologies, electronics, micro-processing, communications producing new sensing techniques, approaches to machine perception and learning, and remote guidance.

Inevitably, there are further developments on the horizon. Future autonomous agriculture land vehicles as formidable sensor platforms is an expectation. The advance in automated perception is key to an increasing operating range of variable conditions supported by machine autonomy. In previous sections current advances in autonomous agriculture machines are shown with significant strides to prepare product readiness in the range of autonomous capability, performance, communications and safety. Technologies that will have greater impact than witnessed so far are machine learning, the role of 'Big data', the means to enable deeper interactive functions with operators, other machines, trailed agriculture tools, and the physical environment.

As is the case with products, consideration of consumer needs is an integral part. Increased complexity is expected in autonomous agriculture land vehicles. The consumer/ user is unlikely to be an expert with knowledge of the methods and capability of the machine, and thus is further removed. It could be argued that standards have a responsibility to protect and formulate schemes to communicate on machine suitability for task expectations, performance and safety criteria.

While most often robust and safe operation is the normal expectation of automation technology in domestic and business products, the nature of autonomous agriculture land vehicles and operating conditions pose some risks that are difficult to mitigate completely. This raises a question for manufacturers on how to both excite and manage customer expectations in the interest of building a stronger business.

7. Operational Risks

7.1. Safety Requirements and Risks

Although published statistics are not widely available for autonomous tractor accidents and/or associated safety issues, a correlation may be established with respect to industrial robot accidents. By identify a range of incidents deemed harmful to the operator, Vasic and Billard's research (2013) broadly corresponds to the risks identified within ISO 18497 (including crushing, impact and entanglement hazards). Personnel injuries when working with robots are also outlined within the paper, with 72% of injuries affecting the operator, while programming and maintenance workers account for the remainder. Figure 43 summarises the taxonomy of failures regarding robots in the industrial workplace:

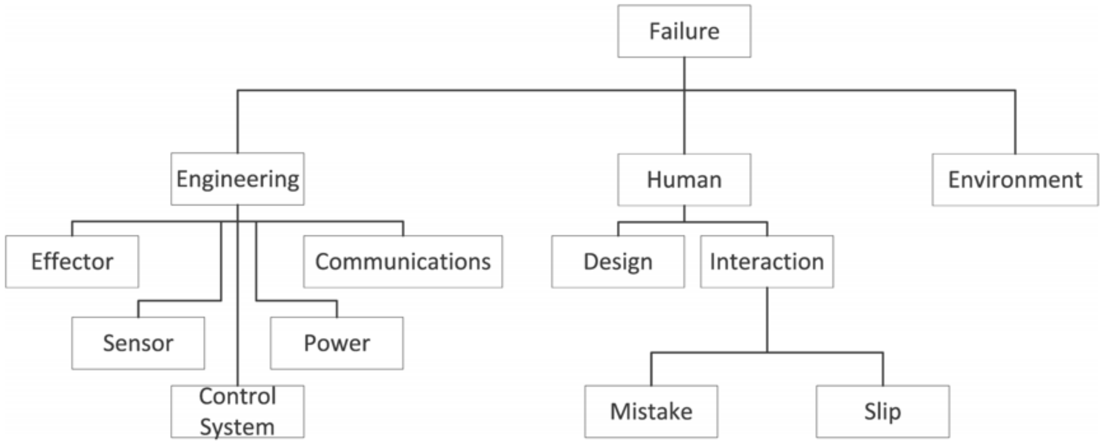


Figure 43: *Taxonomy of failure mechanisms with respect to human-robot interactions*
(Vasic and Billard 2013)

Heinzmann and Zelinsky (2003) further highlight the importance of safety between humans, developing the following safety guidelines regarding human-robot interactions:

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 by Heinzmann and Zelinsky 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.

8. Operational Performance & Testing

8.1. Performance Standards for Agriculture

Developed in 1920, the Nebraska Tractor Test remains 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).

To ensure continued viability of farming operations, Grisso et al (2009) emphasise the importance of correct selection and specification of tractors. Although the Nebraska Test does not assess the performance of autonomous tractor functions, Torrance (2020) puts forth recommended test protocols for the assessment of semi/fully-autonomous tractor performance, ability and field-readiness. The purpose of both tests allows the comparison of functions between different makes and models of tractors – with the Nebraska Test assessing mechanical performance, and Torrance presenting tests for ASAT operational performance.

Torrance (2020) also confirmed the lack of existing research and literature available for the standardised testing of ASATs (including documentation for expected abilities and performance metrics). Furthermore, Torrance (2020) also highlighted the pertinence of refining the operation design domain when both assessing and implementing ASATs within a practical farming environment. By restricting the operating domain, the requirements/abilities of a tractor can be classified into four distinct categories – awareness and perception; automated tractor guidance; headland management; and operational safety. The testing procedures developed by Torrance (2020) employ these categories, prior to implementing various tests determine the respective performance, ability and field-readiness of each element. Results from these tests are then processed using the recommended grading system, before each mark is presented, individually, out of ten. Consequently, unlike the higher-order, systems-based research conducted by Blackmore (2002 & 2004), the testing procedures developed by Torrance (2020) may afford more realistic benefits through the development of practical, potentially standardised, testing procedures for the assessment of ASAT operational performance. Although acknowledging potential limitations to the uptake of such procedures, Torrance's research provides a suitable foundation to base future work, relating to the development of universally-accepted performance testing for autonomous tractors.

8.2. Key Performance Indicators

Early use cases for autonomous machinery on farm will most likely be informed by an operating design domain (ODD) that includes a highly structured operating environment. Within a structured operating environment, autonomous operations are somewhat limited - significantly reducing the technology requirements, machine performance, associated testing and implementation. An ODD that is reflective of a highly structured environment would include (as a minimum) the following attributes:

- The path of the ASAT is pre-programmed (i.e. either linear from weigh points, multiple location points - curves or recorded manually) to create fixed trafficked areas.
- The ASAT follows a series of pre-programmed procedure when approaching a headland.
- An operator is responsible for moving equipment to the field and initialises the field procedure prior to activation of autonomous functionality
- The ASAT is in contact with the operator and messages when a task is complete or something unexpected occurs (machinery alerts, environmental issues such as obstacles or changes to the known terrain).

Tasks relating to these attributes must include scenarios that an ASAT would need to perform during typical field operations. Under the categories defined by Torrance (2020) such as i) perception, ii) tractor guidance iii) headland management and iv) operational safety, the following key performance indicators are suggested.

Perception

Perception relates to the ability of the machine to understand its own operational status as well as the environment that it is working within. Apart from self-monitoring, this includes the ability of the ASAT to sense and adjust to its environment in real time which includes interaction with the terrain, soil and crops. Specific measures of performance suggested by Torrance (2020) include the following:

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 and avoidance

- 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
- 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

Automated Guidance

Automated guidance relates specifically to the infield operations as the ASAT traverses the field. Auto steer technologies although advanced must be capable of controlling the ASAT in more complex conditions and challenging environments. Specific measures of performance suggested by Torrance (2020) include the following:

Path Following

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

Performance of Auto Guidance under various conditions, including:

- Implement loading
- Unbalanced load
- Undulating terrain
- Independent braking

Headland Management

Headland management is implemented to turn the ASAT around at the headland as it works across the field. This implies the ability to reduce speed, raise and lower the implement, cycle through various procedures (i.e. turn off hydraulic motors, spray pumps) and align the ASAT with the next pass. Performance indicators also include mechanical turning constraints and headland allowances. Specific measures of performance suggested by Torrance (2020) include the following:

- 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
- Required headland width
- Turning circle
- Maximum steering angle

Operational Safety

The interface between the operator and the ASAT when assuming control is critical to the operation of an ASAT. Occasionally there will be the requirement for the operator to take control of the machine to avoid collisions, harm to machinery or harm to something or someone else. On other occasions there might be a requirement to override autonomous operations for circumstances outside of the ODD. In addition to operator intervention, the ASAT must also be able to alert the operator to engine / machinery faults or machine performance. Specific measures of performance suggested by Torrance (2020) include the following:

Disabling of automated systems:

- 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

Criteria for Successful Test Protocols

Torrance (2020) also suggested the following criteria for establishing test protocols subscribing to these 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.

Torrance (2020) subsequently developed and piloted a series of tests (A-E) and grading system on a John Deere 6120R for A) Perception; B) Auto Guidance; C) Headland Management and D) Operational Safety. A test procedure was canvased for E) Obstacle Avoidance but not undertaken.

9. Discussion

Highly automated agricultural machinery is becoming more prevalent as manufacturers progressively move towards full autonomy. These developments include features on commercially available machinery to optimise performance and inform a pathway to autonomy where value can be exploited now. Labour savings, productivity improvements and the precision of machinery operations are key drivers for this technology. Examples include GPS auto steer guidance, automated turn / headland management systems, variable rate technologies and machine performance optimisation (i.e. Infinitely/Continuously Variable Transmissions).

In terms of current developments, full autonomy is primarily limited by machine perception which includes the ability of the machine to sense its surrounds, its operation within those surrounds and the ability to monitor and adjust performance without operator intervention. To a large extend these aspects are reflected in the current development of standards for autonomy in agricultural machinery in which machine perception in a focus. This includes the development of four new standards based on ISO18497:2018 Agricultural Machinery and Tractors – Safety of Highly Automated Agricultural Machines. These Standards are in the relatively early stages of development and apart from the inclusion of perception, they canvas an array of specific safety protocols (loss of communication, engine fault procedures), identification of failure modes including risks to the system and protocols for human intervention. Importantly the new standards in agriculture depart from the SAE levels of autonomy used in the transport sector and focus on the function or mode of operation given agricultural use cases vary significantly.

A key consideration for agriculture and the introduction of autonomous machinery is the definition of the operating environment or specifically the Operating Design Domain (ODD). The ODD defines particular machinery requirements and these can be separated into structured and unstructured environments. While farming may appear to be an unstructured environment there are operating parameters which can be defined to provide particular structure such as defined pathways (tramlines), field based activities and pre-programmed tasks. Conversely an unstructured operating design domain has a multitude of scenarios, technologies need to deal with the unexpected, are not constrained to defined paths, subject to a variety of different operations with unique requirements and other complicating factors such as travelling between fields (transport mode), refuelling and refilling. A structured ODD considerably reduces the expectations and requirements of the technology as well as non-technical factors and provides an earlier entry point to autonomy on farm. Currently the standards and the discussion around autonomy on farm is relatively silent on the ODD.

An understanding of standards and regulations in other sectors provides some insights that might inform agriculture where there are overlap on issues. In particular standards were reviewed in the transport, mining and defence sectors to provide this perspective. Most work has been undertaken in the transport sector and informed by the introduction of driverless cars. The level of automation required to operate road vehicles has been simplified through the refinement of the ODD. While the vehicle must be attentive to recognising potential threats (perception), the operating environment as a whole is expected to remain fixed and predictable. This allows the technology requirements to follow a fixed path and focus on obstacle avoidance. Notably this eliminates to some extent technologies which are required to adapt to changing landscapes and terrains and controlling the vehicle under challenging conditions. The recent development of standards in the transport sector have particularly focused on communications and cybersecurity. This includes the ability of the vehicle to communicate with other vehicles, infrastructure and "everything". In comparison the mining and defence sectors are relatively less advanced in terms of standards but more closely aligned with the considerations in agriculture which include safe operating environments, navigational systems in difficult working environments, obstacle avoidance, reliability and robustness.

Notwithstanding the current development of standards that focus on safety, specific experience and statistics surrounding operational risks and accidents are limited given the recent emergence of autonomous machinery in agriculture. Observations from industrial robotics provide some insights including general design principles which apply to field robotics and include: i) allowance for coexistence of humans and robots, ii) predictability of motion to avoid collisions and iii) collisions (human and robot) should not result in series harm. A key mechanism for mitigating the potential risk of accidents includes the implementation of "motion bandwidth limits" which is similar to defining a structured ODD i.e. predefined pathways of operation to increase predictability and to reduce operational risks.

Beyond safety considerations in standards and from other domains, an area requiring additional work is the development of test protocols for assessing the field readiness of autonomous machinery. Considering the testing requirements as technology is released, a lack of information on performance expectations and the assessment criteria for autonomous agricultural machinery was found. Independent research undertaken by Torrance (2020) developed and recommended a testing and grading system for evaluating field readiness. This included a series of tests (A-E) including perception, guidance, headland management, operational safety and obstacle avoidance. Torrance (2020) applied the proposed testing procedure to a recent model tractor equipped with best in class technology and assessed the level of field readiness to be 8.3 out of 10. Further work is required to more broadly develop the test procedures as commercial technologies are released.

Notably approved testing procedures are a required component of public testing for driverless cars in the transport sector and inform a controlled release of driverless technology informing commercial release. This is likely to be a key consideration in the agricultural sector as well, where technology will need to be evaluated in a commercial format before wide spread availability.

Looking ahead current technology limitations are likely to diminish with rapid developments in sensors, machine perception, machine learning, artificial intelligence, big data and connectivity. Apart from machine perception, a suite of other enabling technologies which are commercially available, provide some clues as to the maturity of autonomous machinery developments and the relatively close proximity to commercial reality. This in turn suggests the timing is critical to consider non-technology impediments that provide clarity for manufacturers to proceed with commercial release or indeed to accelerate commercial release of this equipment. The development of new Standards, Test Protocols and a Code of Practice for Autonomous Agricultural Machinery provides the basis for these considerations.

10. Conclusions & Recommendations

A review of technologies, standards and regulations was undertaken to inform the development of a Code of Practice (CoP) for autonomous machinery in agriculture. This work identified: i) state of the art autonomous tractor technology developments; ii) current standards and regulations informing the development and use of this technology; iii) insights from other sectors such as transport, mining and defence and iv) future considerations and requirements for agriculture. From the work undertaken a number of key conclusions and recommendation can be made:

- Tractor technologies are mature and inform the need for new standards, testing protocols and a Code of Practice for Autonomous Machinery in Agriculture. The emergence of autonomous machinery in agriculture is within reach of commercial reality.
- Good insights can be gained from the development of standards in various sectors relating to autonomy in transport, mining and defence and informs future considerations in agriculture.
- Notably the experience in the transport sector suggests communication between vehicles, infrastructure and the internet (including cybersecurity) is a future consideration for agriculture.

- Developments in agricultural autonomous machinery has lacked an agreed definition for the Operating Design Domain (ODD) which provides specifics on the operating environment and machinery requirements.
- Clarity on the ODD will help define technology requirements, the development of standards, expected performance and protocols for testing and assessment.
- Restricting the ODD to a structured operating environment will provide a progressive implementation of autonomy in agriculture.
- There is currently an absence of existing standards (currently in development), performance expectations, testing protocols and assessment criteria for the infield application of autonomous machinery which requires further development.
- Performance expectations need to include various aspects of machinery operation with suggested areas for consideration including perception, guidance, headland management, operational safety and obstacle avoidance.

Overall the development of a Code of Practice for Agriculture (CoP) is timely however key areas which are subordinate to the CoP and support the commercial release of autonomous agricultural machinery such as standards and test protocols are still developing. It is apparent from the transport sector and the roll out of driverless cars that a controlled release of this technology on farm and under commercial use cases will greatly assist more broad scale / wider release. A Code of Practice will help facilitate this process by engaging with manufacturers and providing the supporting structure to progress this work.

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