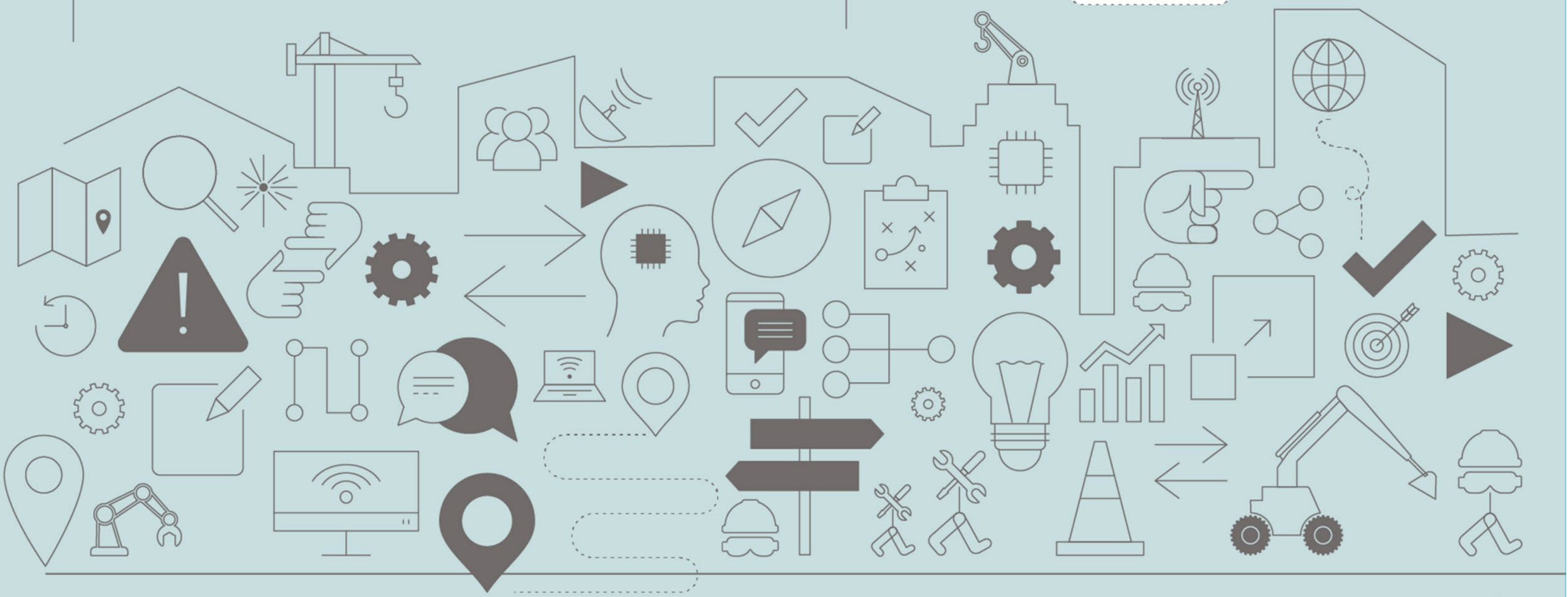
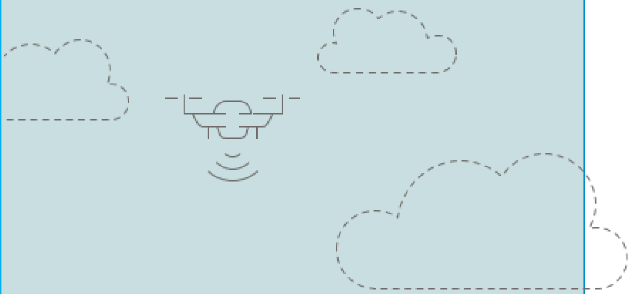
Connected and Autonomous Plant

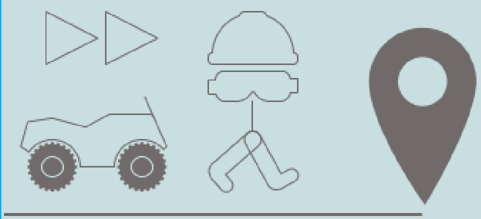
Autonomous Capability Framework





Connected and Autonomous Plant (CAP) are becoming increasingly utilised on construction sites as technology advances and more roles can be supported through automation.

The CAP Autonomous Capability Framework provides a common language to understand the different abilities of automated plant to perform tasks without human intervention.



Executive Summary

The UK construction industry is facing a number of challenges, including the climate crisis, an aging workface, and rising material and production costs. This has driven a rising interest in the use of digital and automated technologies, and in particular Connected and Autonomous Plant (CAP) to replace traditional human operated machinery. A reduction in human involvement in plant operation could improve productivity, efficiency, and quality of construction, whilst improving the safety and welfare of construction workers.

In response to this increasing interest, National Highways commissioned the development of an industry–wide Roadmap for the Adoption of Connected and Autonomous Plant as Business as Usual by 2035. The Roadmap was jointly launched by National Highways and the Innovation in Infrastructure Partnership (i3P) in June 2020. The Roadmap identified potential barriers to the adoption of CAP and proposed nine parallel workstreams to achieve the vision of CAP as standard business practice. An early milestone identified within the Roadmap was the development of a set of capability levels to understand the performance of Connected Autonomous Plant, and its capacity to perform tasks without human intervention. The Roadmap suggested that a **capability levels framework** could provide a common language for the industry to understand how autonomous plant could be used to achieve tasks with reduced human intervention, and hence give unified direction to the industry. The development of this framework has been the focus of the work described in this document.

A cross–industry literature review was carried out to understand how other sectors classify automation and to identify the aspects most suitable for the construction sector. The taxonomies of all of the reviewed industries define a range of levels – from those that require human participation to no need for human involvement once full automation is achieved. The levels are broadly based on information acquisition and processing, making a decision, and then acting on these decisions. However, the approach varies across industries. Some, such as the automotive sector, wrap the levels into a combined taxonomy whilst others, such as aviation, separate the information processing streams into each logical stage. This separation adopts the principle that "if developing machines to replace human capability, understand their capabilities in the same way that we understand human capability". This approach has been deemed appropriate for CAP, due to the higher level of complexity required to define the wide range of activities undertaken by plant, the flexibility of the approach, and its amenity to re–classifying plant after retrofitting (e.g., to accommodate upgraded capability in existing systems, something that is not common in the automotive industry). This had led to the development of a 4 stage process, forming a loop. The loop starts with the **Observe** stage to acquire information, which is then **Understood** in the context of the desired task, before a **Decide** stage decides on the next step, followed by the **Act** of executing this decision. This loop can be applied to understand the level of automation of high level strategic activities, tactical activities, and the second–by–second activities that make up the fine detail of carrying out a construction task. A set of levels is defined for each stage in the loop.

Whilst some industries are able to apply automated systems in very controlled environments, such as manufacturing where all aspects of the factory can be specified, this is not the case within construction (or with automotive). Therefore, the concept of the Operational Design Domain (ODD) is included in the framework. This acts as a limiter on where, when, and in what conditions a system can operate automatically. However, the definition of different ODDs is not explicit within all industries. As this could lead to confusion across stakeholders regarding the capability of a machine within different environments, the CAP levels framework recommends that an explicit understanding of the ODD of plant within should be included when classifying its level of capability. Finally, and also reflecting practice in other industries, the levels framework includes a Responsibility and Fallback stage. This reflects the need for clearly defined expectations about the role of plant and people when a machine begins to operate outside of its capability, or ODD.

Peer review and stakeholder engagement sought to validate the levels and understand if they were fit for use within the industry, culminating in a series of workshops attending by 35 different organisations to capture their views and opinions. During the workshops, participants were asked to rate how easy the levels were to understand and how useful they were perceived to be. The scores were respectively 4/5 for ease of understanding and 3.9/5 for usefulness.

To visualise the application of the levels framework, examples are given of its application to a compactor and an excavator. These represent two extremes of plant operation – a compactor has a tightly defined role and can be automated relatively easily. In contrast, an excavator is a versatile piece of equipment for which automation is likely to be introduced in a piecewise manner, as different functions are automated. Finally, this document provides examples of how different end users within the construction sector could utilise the levels, from its use as a universal language to understand the capabilities of plant offered by different manufacturers, through the creation of research and development programmes, to understanding the different expectations and requirements of operators and sites to adopt higher levels of automated plant.

Table 1: List of acronyms used within this document

Acronym	Definition
ACL	Autonomous Classification Level
ADS	Automated Driving System
AFS	Automated Flight System
ATC	Automatic Train Control
ATM	Air Traffic Management
ATO	Automatic Train Operation
ATP	Automatic Train Protection
AV	Autonomous Vehicle
CAP	Connected Autonomous Plant
CAV	Connected Autonomous Vehicle
DDT	Dedicated Driving Task
ECA	European Cockpit Association
GNSS	Global Navigation Sat
LOA	Level of Automation

Acronym	Definition
LOAT	Level of Automation Taxonomy
ODD	Operational Design Domain
OEDR	Object and Event Detection and Response
OODA	Observe, Orient, Decide, Act
OUDA	Observe, Understand, Decide, Act
RTK	Real–time Kinetic
SAE	Society of Automotive Engineers
UAS	Unmanned Aerial System
UAV	Unmanned Aerial Vehicle
UGV	Unmanned Ground Vehicle
USV	Unmanned Surface Vehicle
UTO	Unattended Train Operation
UUV	Unmanned Underwater Vehicle
VMS	Variable Message Sign

Content

Introduction

The UK construction sector is experiencing a period of transformational change as new technologies and ways of working are being developed to respond to the challenges and evolving priorities experienced by the industry. One key component of this transformational change is the development and adoption of Connected and Autonomous Plant (CAP) which aims to reduce the human input needed to complete construction task through the use of increasingly automated processes, delivering improvements in safety, efficiency, and quality across the sector.

In 2019, National Highways recognised that although CAP technologies were gaining presence in the UK construction sector, there was a need for a unified approach to facilitate adoption, mitigate the risks associated with the new technologies, and bring forward the realisation of benefits. This led to the collaborative development of an industry wide Roadmap for CAP as Business as Usual within the UK construction sector by 2035, (TRL, i3P, Highways England, 2020). The Roadmap drew on contributions from over 75 organisations, identifying 9 workstreams which would be delivered in parallel to achieve this vision. It was jointly launched by National Highways and i3P in June 2020.

The Roadmap identified priority tasks which would accelerate the CAP journey, including an activity to "define CAP levels". These levels are a shorthand convention, used to describe the relative capabilities of different plant for operating without human input. This draws a strong parallel with the journey that the Connected Autonomous (road) Vehicle industry has taken, where the development of the (Society of Automotive Engineers, 2014) levels of autonomy provided a unified language for discussing automation, setting clear targets for development, and providing context to decision makers.

This document proposes a taxonomy for levels to characterize the ability of Connected and Autonomous Plant to operate without human input.

- The methodology applied in the development of the levels is presented, including a review of how other industries have approached this problem.
- The core framework used to define CAP capability levels is discussed, with illustrative examples around the parking of a car providing a simplified understanding of what each level means.
- As autonomous capability is partially dependant on the environment in which the plant is operating, a summary is presented of the important aspects of the environment that should be considered when describing a potential automated system.
- To demonstrate how the levels apply to the construction environment, examples are presented based on the tasks of compaction and excavation.
- Finally, we highlight a number of areas in which end users could apply the levels across the UK construction sector, exploring how to maximise the value they could bring.

Background

Objectives of this Work

The objective of this work has been to establish a set of levels which characterize the ability of Connected and Autonomous Plant to operate without human input. These levels will serve two functions within the industry. Firstly, they will provide an understanding and description of the current level of automation, which can be applied by the industry. Secondly, they act as a reference for the journey towards automation through the provision of targets for developers of CAP technology.

The work has defined a taxonomy for automated capability by providing detailed definitions to augment simple descriptors such as "semi–autonomous". These definitions take the form of short, narrative descriptions that focus on how outcomes are achieved through varying levels of automation. Care has been taken to avoid developing the levels through a hierarchy of technological implementations or ranking specific solutions that can be used to achieve automation.

The levels have been developed in a task–agnostic manner so that they are consistent in terms of operator/system control across different construction activities. As they are task–agnostic this creates a set of levels that enables the comparison of different pieces of plant in terms of their relative level of automation (i.e., this compactor is more capable of automatic compaction than that dozer is of automatic earthmoving). This supports the aim to develop a set of levels which can be used across the CAP ecosystem of manufacturers, developers, end users and clients.

Automation and Autonomy

When discussing the classification of Connected Autonomous Plant it is important to understand what is meant by autonomous, and how this differs from automation. In general, the following definitions are used by the literature for these terms:

- **Automation**: the conversion of a task that was carried out by a human to one which is carried out by a machine or computer.
- **Autonomy**: the capacity of a system to operate as an independent unit to complete a task – i.e., can collect its own information, make its own decisions, and carry these decisions out.

Despite being commonly referred to as autonomous, in many cases the objective is to establish an automated system to complete the task – there is no requirement that the task is carried out by a single machine operating independently, or outside of defined and well understood operational constraints. Indeed, for many instances in construction the task requires the co–operation of multiple pieces of plant, each of which may be operating to some degree of automation. As such, we can see that the term Connected Autonomous Plant is often a misnomer, and more accurately such plant could be referred to as Connected Automated Plant.

Levels of Automation

The simplest implementation of the concept of levels of automation is the binary of split of completely human controlled or completely automated. However, this split does not apply to a wide range of scenarios. Consider the gearbox. With no automation the human uses the gearstick to manually move between gears. This might progress to an electronic gear box – the human still moves the gearstick to change gears but, this is connected to a set of switches which instruct an electronic system to change the gears. The automatic gearbox chooses the appropriate gear for the vehicle, with no direct human instruction.

Thus, we can see that the implementation of automation is not a discrete process, there is a continuum of automation where increasing amounts of the process require less direct involvement of a human. The concept of levels of automation is to divide this continuous process into discrete steps. Introducing levels of automation allows for an easier comparison between different systems, understanding the expectation placed on the human operator and the capability of the system in a simplified manner.

Peer Review

Peer review and stakeholder engagement have been held to discuss, review, and refine the levels developed in this work.

The proposed taxonomy underwent continuous review by Zenzic[1] as it was developed. Following the production of the complete draft version, it was reviewed through a series of workshops held with 31 industry stakeholders between the 30th of November and 2nd of December 2021. These stakeholders were drawn from all parties who interact with plant throughout the construction process, from OEMs who design and develop plant, designers who create the designs that plant implement, procurement and contract writers who determine what plant is used on site, site managers who control the deployment of plant within a construction site, and plant operators who physically use the plant.

During the workshops the taxonomy was presented to the stakeholders, alongside construction specific examples on how the taxonomy applied to both a compactor and an excavator. Finally, potential use cases for different end users within the construction industry were presented. Between each session feedback from the attendees was sought and discussions on each aspect of the taxonomy held. The feedback from these workshops was collated and used to refine the taxonomy presented herein.

[1] https://zenzic.io/

Literature Review

Literature Review

The concept of developing levels of automation has been applied in a wide range of industries, including on–road vehicles, aviation, metros, and manufacturing. The taxonomies developed in each of these industries have employed different methodologies and produced different classifications depending on the particular requirements of that industry. A literature review of the existing taxonomies helps to identify the practices and aspects of the other taxonomies that are most useful to the development of a classification of automatic capability for plant in construction.

Hence, a systematic literature review of how autonomy is classified in other areas was carried out to help identify a suitable approach for the development of the Capability Framework for CAP. The review was carried out in both standard and academic literature search engines, using the terms listed in

Table **2**. Where any other useful references were found from the reviewed literature, these were also reviewed.

Table 2: Search terms used to carry out the systematic literature review (1 from each column)

Synonym for Autonomy	Synonym for Classification	Industry/Area
Automation	Categorisation	Agriculture
Autonomous	Classification	AV
Autonomy	Hierarchy	Aviation
Unmanned	Levels	CAV
UAV (aerial)	Taxonomy	Driving
UGV (ground)		Infrastructure
USV (surface)		Manufacturing
UUV (underwater)		Metro
		Military
		Mining
		Ports
		Rail
		Space

General Framework for Automation

Sheridan (Sheridan & Verplank, 1978) has proposed a ten-point scale to represent the continuity of possible automation from none to all (Table **3**). This model attempts to provide a more objective basis for automation design than approaches based purely on technological capability or economic considerations. However, more recent work (Parasuraman, Wickens, & Sheridan, 2000) noted that the above only applies to the act of decision and action selection. Parasuraman hence proposed to extend the levels to cover the complete set of human information processing, divided into four classes/functions, which could each be automated to a different degree:

1. Information acquisition.
2. Information analysis
3. Decision and action selection.
4. Action implementation.

Unfortunately, while this work recognised that a parallel scale could be developed for these additional classes, it did not propose one. It is also worth noting that although the scale presented in Table **3** was developed for the *decision and action selection* functions, it includes aspects which belong to *action implementation* from level 5 onwards. This demonstrates, that although it is possible to divide human information processing into multiple classes, when replicating higher levels of human capability by machine it is necessary to consider a holistic view of the process.

Table 3 Levels of automation of decision and action selection. Reproduced from (Sheridan & Verplank, 1978).

Level	Description
10	The computer decides everything, acts autonomously, ignoring the human.
9	Informs the human only if it, the computer, decides to
8	Informs the human only if asked, or
7	Executes automatically, then informs the human, and
6	Allows the human a restricted time to veto before automatic execution, or
5	Executes the suggestion if the human approves, or
4	Suggests one alternative
3	Narrows the selection down to a few, or
2	Offers a complete set of decision/action alternatives, or
1	Offers no assistance: human must take all decisions and actions.

Automation in Specific Industries

Automation/autonomy in Autonomous Driving

In recent years, the most widely known definitions for classifying autonomous capability have been produced by the SAE (Society of Automotive Engineers, 2014). This has been revised several times for clarity (Society of Automotive Engineers, 2021), and is referred to as the SAE taxonomy. The SAE taxonomy is broadly based on the levels for autonomy produced by an expert group of the German Federal Highway Research Institute (BASt) in (Federal Highway Research Institute, 2013).

The SAE taxonomy is shown in Figure 1. The SAE divided the act of driving a vehicle into several components, comprising a feedback loop. The loop is broadly based on how a human would go about the driving task – starting with the decision of where to go and how to get there, followed by the actual task of driving the vehicle. This has been termed the "Dedicated Driving Task" (DDT) and is split into two broad components – "Object and Event Detection and Response" (OEDR) (not crashing or running in to people) and "lateral and longitudinal vehicle motion control" (speed and steering). The SAE levels increasingly assign components of the DDT to the "system" from the driver as the level increases.

The SAE taxonomy establishes two other factors. Firstly, who is responsible for the "DDT fallback" – that is, if a subsystem of the Automated Vehicle (AV) fails or experiences something out of its design domain, who is responsible for either taking over the driving task or ensuring that the vehicle enters a safe environment or operation. Secondly, whether the AV has a specific Operational Design Domain (ODD) or not. The ODD refers to the physical (weather, terrain, etc.) and digital (5G network, GPS satellite available, etc.) environment, which can change through time, in which the AV can operate automatically.

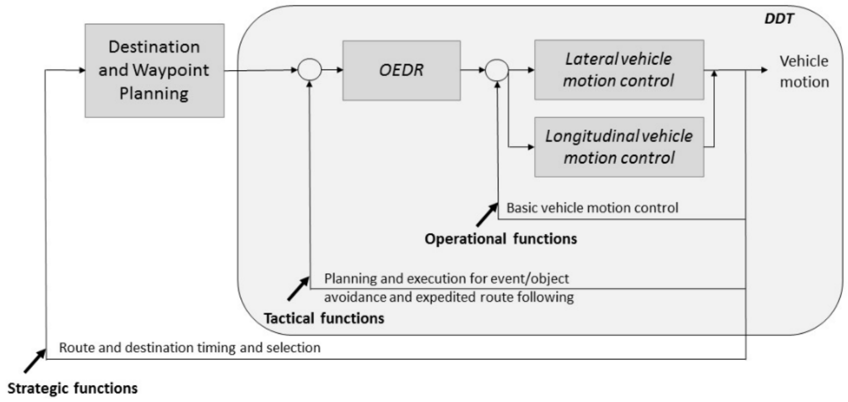


Figure 1: Schematic view of driving task showing the dedicated driving task (DDT) portion. OEDR stands for Object and Event Detection and Response. Reproduced from (Society of Automotive Engineers, 2021).

If the AV can only safely drive in a particular set of conditions it is operating in a more limited manner than a human driver, and thus is considered to be at a lower level of automation than one which can replicate (or exceed) the full range of human driving capability. This coarse classification of ODD (limited or unlimited) can lead to some confusion over how the levels are applied, as similar level systems can be completely different in terms of the complexity of their operating conditions or technological capability. For example, it is possible to have a level 4 system which is only capable of driving on a specific route between two points autonomously (an airport shuttle bus for example) and an equally valid level 4 system which can drive on any route, to any location within a confined geographic area (an autonomous taxi service operating within a city centre for example). Both systems are considered to be level 4 despite the complexity and technological requirements of the latter being significantly larger than the former. The final set of levels defined by the SAE are presented in Table 4.

Table 4: Summary of levels of driving automation proposed by the SAE, (Society of Automotive Engineers, 2021)

<table>
<tr><th rowspan="2"></th><th rowspan="2">Level</th><th rowspan="2">Name</th><th rowspan="2">Narrative Definition</th><th colspan="2">DDT</th><th rowspan="2">DDT Fallback</th><th rowspan="2">Operational Design Domain (ODD)</th></tr>
<tr><th>Vehicle Motion Control</th><th>Object Event Detection Response (OEDR)</th></tr>
<tr><td colspan="8">Driver Performs Part or All of the Designated Driving Task (DDT)</td></tr>
<tr><td rowspan="3">Driver Support</td><td>0</td><td>No Driving Automation</td><td>The performance by the driver of the entire DDT, even when enhanced by active safety systems</td><td>Driver</td><td>Driver</td><td>Driver</td><td>Limited</td></tr>
<tr><td>1</td><td>Driver Assistance</td><td>The sustained and ODD–specific execution by a driving automation system of either the lateral or the longitudinal vehicle motion control subtask of the DDT (but not both simultaneously) with the expectation that the driver performs the remainder of the DDT.</td><td>Driver and System</td><td>Driver</td><td>Driver</td><td>Limited</td></tr>
<tr><td>2</td><td>Partial Driving Automation</td><td>The sustained and ODD–specific execution by a driving automation system of both the lateral and longitudinal vehicle motion control subtasks of the DDT with the expectation that the driver completes the OEDR subtask and supervises the driving automation system.</td><td>System</td><td>Driver</td><td>Driver</td><td>Limited</td></tr>
<tr><td colspan="8">Automated Driving System (ADS, "System") Performs the Entire DDT (While Engaged)</td></tr>
<tr><td rowspan="3">Automated Driving</td><td>3</td><td>Conditional Driving Automation</td><td>The sustained and ODD–specific performance by an ADS of the entire DDT with the expectation that the DDT fallback–ready user is receptive to ADS–issued requests to intervene, as well as to DDT performance–relevant system failures in other vehicle systems and will respond appropriately.</td><td>System</td><td>System</td><td>Fallback–ready user (becomes driver during fallback)</td><td>Limited</td></tr>
<tr><td>4</td><td>High Driving Automation</td><td>The sustained and ODD–specific performance by an ADS of the entire DDT and DDT fallback without any expectation that a user will need to intervene.</td><td>System</td><td>System</td><td>System</td><td>Limited</td></tr>
<tr><td>5</td><td>Full Driving Automation</td><td>The sustained and unconditional (i.e., not ODD–specific) performance by an ADS of the entire DDT and DDT fallback without any expectation that a user will need to intervene.</td><td>System</td><td>System</td><td>System</td><td>Unlimited</td></tr>
</table>

The influence of infrastructure

Road infrastructure is likely to influence the ability of an AV to operate autonomously. This is relevant because there is potential to increase the level of automation of a system by operating it within a suitable environment. In the context of the SAE levels this could be thought of as modifying/controlling the Operational Design Domain. No general classification for the relationship between the infrastructure and autonomous capability was found in the review. However, the INFRAMIX project developed a set of levels of support for autonomous driving (Anna Carreras, 2018). The goal of this work was to define a harmonised classification framework to identify the ability of road infrastructure to support autonomous driving. The basis of the classification is to make gradual steps towards full digitalisation of the infrastructure and hence the information that can be delivered to AVs. These infrastructure support levels are independent of the AV levels (that is, an SAE Level 3 AV does not need Infrastructure Level B to operate) – see Table 5.

Table 5: Infrastructure support levels for autonomous driving proposed by INFRAMIX, (Anna Carreras, 2018).

				Digital Information provided to AVs			
	Level	**Name**	**Description**	**Digital map with static road signs**	**VMS, warnings, incidents, weather**	**Microscopic traffic situation**	**Guidance: speed, gap, lane advice**
Conventional Infrastructure	**E**	Conventional infrastructure / no AV support	Conventional infrastructure without digital information. AVs need to recognise road geometry and road signs.				
	D	Static digital information / Map Support	Digital map data is available with static road signs. Map data could be complemented by physical reference points (landmarks signs). Traffic lights, short term road works and VMS need to be recognised by AVs.	X			
Digital Infrastructure	**C**	Dynamic digital information	All dynamic and static infrastructure information is available in digital form and can be provided to AVs.	X	X		
	B	Cooperative perception	Infrastructure is capable of perceiving microscopic traffic situations and providing this data to AVs in real–time.	X	X	X	
	A	Cooperative driving	Based on the real–time information on vehicle movements, the infrastructure is able to guide AVs (groups of vehicles or single vehicles) in order to optimize the overall traffic flow.	X	X	X	X

Automation/autonomy in Agriculture

While no industry wide or manufacturer-independent classification of automation levels in agriculture was found in the literature, Case IH have published an infographic on the 5 levels of automation they use within their Research & Development programme (Case IH, 2018), Figure 2. This infographic does not include a level of automation associated with zero automated assistance. No information has been provided to explain how these automation levels were developed, but it can be seen that the levels take a slightly different approach than the SAE levels: they include cooperation between machines as an explicit level 2, and the relaxation of the requirements for a fallback or supervision system even at the level of full autonomy. These differences may reflect the expectation that the environment in which these systems operated is more tightly controlled (contained sites/locations) with a more limited range of equipment (making inter-vehicle cooperation achievable).

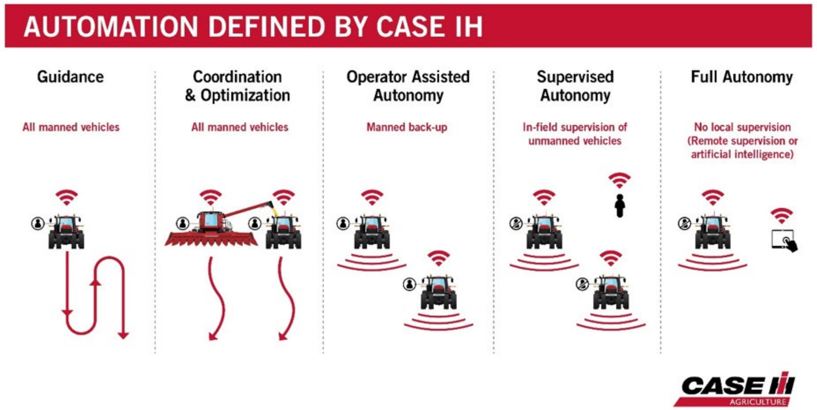


Figure 2 Infographic showing 5 levels of automation proposed by Case IH, (Case IH, 2018)(Case IH, 2018)

Automation/autonomy in Metro & Rail

Five grades of automation have been described for metro and rail systems (International Electrotechnical Commission, 2014), Table 6. The grades of automation have been developed by determining the specific tasks that a metro must undertake and the need for a fallback system. The tasks and the fallback system are then increasingly automated, instead of relying on a human driver or attendant. It is worth noting that the grades of automation developed for metro and rail make no mention of an Operational Design Domain. This is reasonable, as metro has a very well-defined ODD with little expectation/risk that the metro will transition out of its ODD due to its motion. In contrast an AV has more freedom to change domains – an AV may be able to operate autonomously in a city centre but could transition to other areas outside of this ODD. As a result of the (effective) ability to control the ODD, Metro & rail is an industry where all the defined grades of automation currently exist and are employed in different scenarios.

Automation/autonomy in Mining

No industry wide definitions were found for classifying autonomy levels in mining. However, (ABB, n.d.) and (Modular Mining, 2020) have defined levels of autonomy to support research & development in this sector. The levels are shown in Table 7 and Table 8. There is no information available describing how these levels were developed. However, in both cases the levels are similar to those of the SAE Taxonomy.

Table 6: Grades of automation for the control of metro and rail systems, (Observatory of Automated Metros, 2014).
(ATP – Automatic Train Protection, ATC – Automatic Train Control, ATO – Automatic Train Operation, and UTO – Unattended Train Operation)

Grade of Automation	Name	Type of train operation	Setting train in motion	Stopping train	Door closure	Operation in event of disruption
0	On Sight	Manual operation with no ATP	Driver	Driver	Driver	Driver
1	Non–Automated	Manual operation with ATP and ATC	Driver	Driver	Driver	Driver
2	Semi–Automated	ATP and ATO with driver	Automatic	Automatic	Driver	Driver
3	Driverless	Driverless	Automatic	Automatic	Train attendant	Train attendant
4	Unattended	UTO	Automatic	Automatic	Automatic	Automatic

Table 7: Levels of autonomy proposed by ABB for mining (ABB, n.d.).

Level	Description
1	Systems provide operational assistance by decision support or remote assistance
2	Occasional autonomy in certain situations. Here, the automation system takes control in specific circumstances when and as requested by a human operator, for limited periods of time. People are still heavily involved, monitoring the state of operation, and specifying the targets for limited control situations.
3	Automated systems take control in certain situations. This can also be called “limited autonomy.” People “sign off,” so to speak, confirming proposed solutions or acting as fallbacks. A prerequisite is a complete and automated monitoring of the environment. In such a setup, the (remote) operator can still be alerted in exceptional situations and can take over or confirm a suggested resolution strategy
4	The system is in full control in certain situations and learns from its past actions, for example, to be able to better predict and resolve issues by itself.
5	Full autonomous operation occurs in all situations. No user interaction is required, and humans may be completely absent. Today, this is aspirational, but for instance an electric self-driving mining vehicle for full autonomous loading of the ore would carry major advantages of safety and productivity.

Table 8: Levels of autonomy proposed by Modular Mining (and parent company Komatsu) for mining (Modular Mining, 2020).

Level	Name	Responsibility	Description
0	Manual	Operator	Operator is fully responsible for all functions
1	Operator Guidance	Operator	Provides feedback to improve task execution
2	Partial Automation	Operator	Limited functions are controlled by system with operator able to resume control
3	Conditional Automation	Operator	Core functions automated, operator required to intercede as needed or for complex functions
4	High Automation	Vehicle	System able to execute core functions; intervention only required for complex functions
5	Fully Autonomous	Vehicle	All functions automated, system able to manage significant environmental uncertainty or system failures without external intervention, performance exceeds manual in all scenarios

Automation/autonomy in Aviation

The SESAR research and innovation programme (Save & Feuerberg, 2012) developed a taxonomy for the level of automation in aviation (Table 9). The taxonomy draws on the work of Parasuraman (Parasuraman, Wickens, & Sheridan, 2000), discussed above. They create a scale for the 4 classes of human information processing discussed above. Although the levels were developed using examples from the aviation industry, the taxonomy itself is generic and could be applied to different fields in its current form.

It noted that each of the functions/classes can have a different level of autonomy, with few restrictions on the possible combinations being imposed by the taxonomy. Hence a design principle of the taxonomy is that an automated system does not have a single "overall" level of automation. The statements defining the levels of automation refer to the specific function (A, B, C, or D) being supported. The descriptions of each level consider how the automation impacts the human (the extent to which the human is supported in achieving their task).

A 6 level summarised model of the levels of automation was developed In the 2020 European Air Traffic Management Master Plan (SESAR Joint Undertaking, 2013), aimed at audiences who are not experts in automation. This model combined the work of Save & Feuerberg with the autonomous driving levels developed by the SAE, as shown in Figure 3.

Table 9: Levels of Automation Taxonomy proposed by Save & Feuerberg for Aviation, (Save & Feuerberg, 2012).

A INFORMATION ACQUISITION	B INFORMATION ANALYSIS	C DECISION & ACTION SELECTION	D ACTION IMPLEMENTATION
A0 Manual Info Acquisition	**B0 Working Memory Based Info Analysis**	**C0 Human Decision Making**	**D0 Manual Action and Control**
The human acquires relevant information on the process s/he is following without using any tool.	The human compares, combines and analyses different information items regarding the status of the process s/he is following by way of mental elaborations. S/he does not use any tool or support external to her/his working memory.	The human generates decision options, selects the appropriate ones, and decides all actions to be performed.	The human executes and controls all actions manually.
A1 Artefact-Supported Info Acquisition	**B1 Artefact-Supported Info Analysis**	**C1 Artefact-Supported Decision Making**	**D1 Artefact-Supported Action Implementation**
The human acquires relevant information on the process s/he is following with the support of low-tech non-digital artefacts.	The human compares, combines, and analyses different information items regarding the status of the process s/he is following utilising paper or other non-digital artefacts.	The human generates decision options, selects the appropriate ones, and decides all actions to be performed utilizing paper or other non-digital artefacts.	The human executes and controls actions with the help of mechanical non-software based tools.
A2 Low-Level Automation Support of Info Acquisition	**B2 Low-Level Automation Support of Info Analysis**	**C2 Automated Decision Support**	**D2 Step-by-step Action Support:**
The system supports the human in acquiring information on the process s/he is following. Filtering and/or highlighting of the most relevant information are up to the human.	Based on user's request, the system helps the human in comparing, combining, and analysing different information items regarding the status of the process being followed.	The system proposes one or more decision alternatives to the human, leaving freedom to the human to generate alternative options. The human can select one of the alternatives proposed by the system or her/his own one.	The system assists the operator in performing actions by executing part of the action and/or by providing guidance for its execution. Each action is executed based on human initiative and the human keeps full control of its execution.

A3 **Medium–Level Automation Support of Info Acquisition**	B3 **Medium–Level Automation Support of Info Analysis**	C3 **Rigid Automated Decision Support**	D3 **Low–Level Support of Action Sequence Execution**
The system supports the human in acquiring information on the process s/he is following. It helps the human in integrating data coming from different sources and in filtering and/or highlighting the most relevant information items, based on user's settings.	Based on user's request, the system helps the human in comparing, combining, and analysing different information items regarding the status of the process being followed. The system triggers visual and/or aural alerts if the analysis produces results requiring attention by the user.	The system proposes one or more decision alternatives to the human. The human can only select one of the alternatives or ask the system to generate new options.	The system automatically performs a sequence of actions after activation by the human. The human maintains full control of the sequence and can modify or interrupt the sequence during its execution.
A4 **High–Level Automation Support of Info Acquisition**	**B4** **High–Level Automation Support of Info Analysis**	**C4** **Low–Level Automatic Decision Making**	**D4** **High–Level Support of Action Sequence Execution**
The system supports the human in acquiring information on the process s/he is following. The system integrates data coming from different sources and filters and/or highlights the information items which are considered relevant for the user. The criteria for integrating, filtering, and highlighting the relevant information are predefined at design level but visible to the user.	The system helps the human in comparing, combining, and analysing different information items regarding the status of the process being followed, based on parameters pre-defined by the user. The system triggers visual and/or aural alerts if the analysis produces results requiring attention by the user.	The system generates options and decides autonomously on the actions to be performed. The human is informed of its decision.	The system automatically performs a sequence of actions after activation by the human. The human can monitor all the sequence and can interrupt it during its execution.
A5 **Full Automation Support of Info Acquisition**	**B5** **Full Automation Support of Info Analysis**	**C5** **High–Level Automatic Decision Making**	**D5** **Low–Level Automation of Action Sequence Execution**
The system supports the human in acquiring info on the process s/he is following. The system integrates data coming from different sources and	The system performs comparisons and analyses of data available on the status of the process being followed based on parameters defined at design level. The	The system generates options and decides autonomously on the action to be performed. The human is informed of its decision	The system initiates and automatically executes a sequence of actions. The human can monitor all the sequence

filters and/or highlights the information items considered relevant for the user. The criteria for integrating, filtering, and highlighting are predefined at design level and not visible to the user	system triggers visual and/or aural alerts if the analysis produces results requiring attention by the user.	only on request. (Always connected to an Action Implementation level not lower than D5.)	and can modify or interrupt it during its execution.
		C6 **Fully Automatic Decision Making**	**D6** **Medium–Level Automation of Action Sequence Execution**
		The system generates options and decides autonomously on the action to be performed without informing the human. (Always connected to an Action Implementation level not lower than D5.)	The system initiates and automatically executes a sequence of actions. The human can monitor all the sequence and can interrupt it during its execution.
			D7 **High–Level Automation of Action Sequence Execution**
			The system initiates and executes a sequence of actions. The human can only monitor part of it and has limited opportunities to interrupt it.
			D8 **Full Automation of Action Sequence Execution**
			The system initiates and executes a sequence of actions. The human cannot monitor nor interrupt it until the sequence is not terminated.

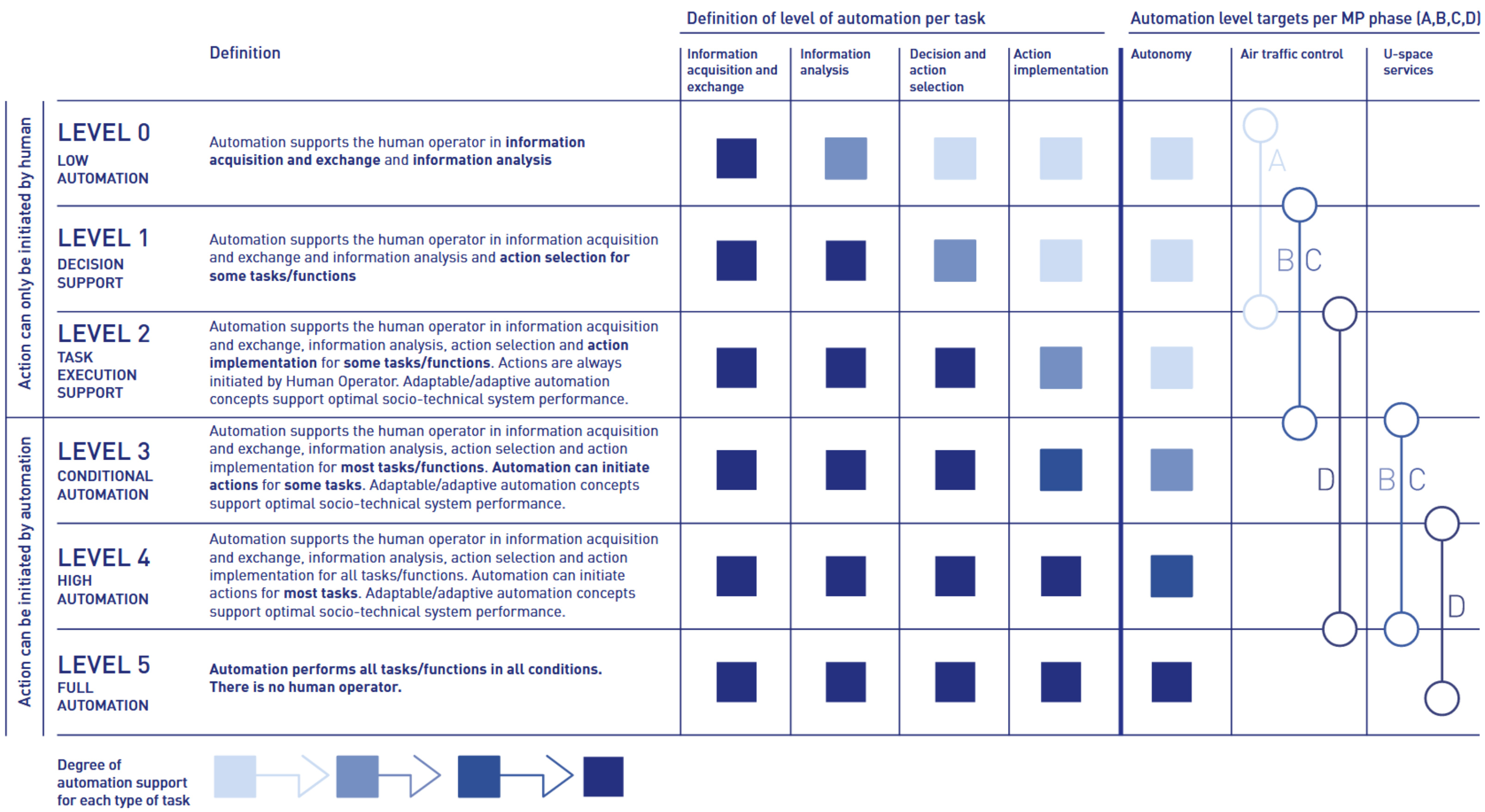


Figure 3 Summarized table of Levels of Automation Taxonomy proposed by SESAR for Air Traffic Management (ATM), (SESAR Joint Undertaking, 2020).

Automation/autonomy in Unmanned Aviation Vehicles

(Clough, 2002)(Clough, 2002) defined a set Autonomous Classification Levels (ACLs) to describe the autonomous capability of unmanned aerial vehicles (UAVs), Table 10. They are based on the Observe, Orient, Decide, Act (OODA) loop developed for combat operations by Boyd (Boyd, 1995)(Boyd, 1995), but since adapted to many other industries, including litigation, business management, and law enforcement. The underlying principle for applying the OODA loop to the question of autonomy levels for UAVs was "If you're replacing a human, why not measure like one?". That is, since the goal is to develop algorithms which replace human decisions and actions these algorithms should be judged in the same way as which human effectiveness can be judged. In addition, the taxonomy developed by Clough is explicit that higher levels of automation feature co-operation and planning across multiple vehicles where this is needed to achieve goals.

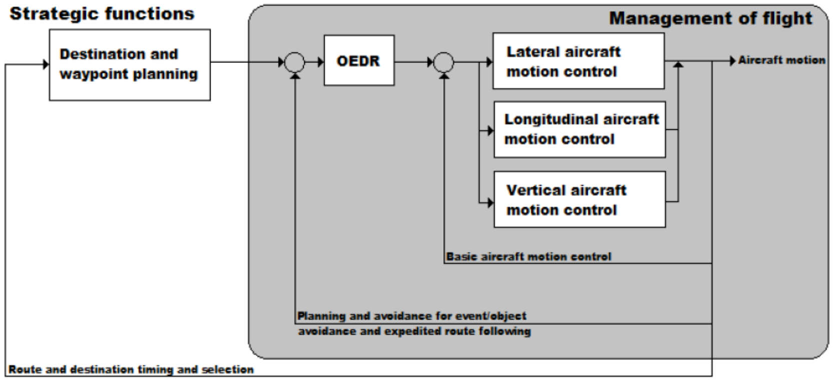


Figure 4 Schematic of UAV Operation – schematic based on SAEJ3016, JUN2018 (reproduced from (European Cockpit Association, 2020))

Taking a different approach, the (European Cockpit Association, 2020) took the SAE levels and redefined them so that they are applicable to the increased degrees of freedom that UAVs are capable of (that is UAVs can freely move in the vertical direction as well as laterally and longitudinally). This gave the taxonomy shown in Table 11, which, barring the necessary language changes, are identical to the SAE levels.

Table 10 Autonomous Classification Levels for UAVs, (Clough, 2002)

Level	Descriptor	**Observe** Perception / Situational Awareness	**Orient** Analysis / Coordination	**Decide** Decision Making	**Act** Capability
0	Remotely Piloted Vehicle	Flight control (attitude, rates) sensing Nose camera	Telemetered data Remote pilot commands	N/A	Control by remote pilot
1	Execute Pre-planned Mission	Preloaded mission data Flight control and Navigation Sensing	Pre/Post Flight Built in Test Report status	Preprogramed mission and abort plans	Wide airspace separation requirements (miles)
2	Changeable Mission	Health/status sensors	Real-time health diagnosis (Do I have problems?) Off-board replan (as required)	Execute preprogramed or uploaded plans in response to mission and health conditions	Self-accomplishment of tactical plan as externally assigned
3	Robust Response to Real-time Faults/Events	Health/status history & models	Tactical plan assigned Real-time health diagnosis (What is the extent of the problems?) Ability to compensate for most control failures and flight conditions (i.e., adaptive inner-loop control)	Evaluate status vs required mission capabilities Abort/Return-to-Base if insufficient	Self-accomplishment of tactical plan as externally assigned
4	Fault / Event Adaptive Vehicle	Deliberate awareness – allies communicate data	Tactical plan assigned Assigned Rules of Engagement Real-time health diagnosis Ability to compensate for most failures and flight conditions – inner loop changes reflected in outer loop performance	On-board trajectory replanning – event driven Self resource management Deconfliction	Self-accomplishment of tactical plan as externally assigned Medium vehicle airspace separation (100s of yds)
5	Real-Time Multi-Vehicle Coordination	Sensed awareness – Local sensors to detect others Fused with off-board data	Tactical plan assigned Real-time health diagnosis Ability to compensate for most failures and flight conditions Ability to predict onset of failures (e.g., prognostic health	On-board trajectory replanning – optimizes for current and predictive conditions Collision avoidance	Group accomplishment of tactical plan as externally assigned Air collision avoidance Possible close air space separation for Automated Aerial

			management) Group diagnosis and resource management		Refuelling (1–100yds) Formation in non–threat conditions
6	Real–Time Multi–Vehicle Cooperation	Ranged awareness – on–board sensing for long range, supplemented by off–board data	Tactical group goals assigned Enemy location sensed/estimated	Coordinated trajectory planning and execution to meet goals – group optimization	Group accomplishment of tactical plan with minimal supervisory assistance Possible close air separation (1–100yds)
7	Battlespace Knowledge	Short track awareness – History and predictive battlespace data in limited range, timeframe, and numbers Limited inference supplemented by off–board data	Tactical group goals assigned Enemy trajectory estimated	Individual task – planning/execution to meet goals	Group accomplishment of tactical plan with minimal supervisory assistance
8	Battlespace Cognisance	Proximity inference – Intent of self and others (allies and foes) Reduced dependence upon off–board data	Strategic group goals assigned Enemy tactics inferred Automatic Target Recognition	Coordinated tactical group planning Individual task planning / execution Choose targets of opportunity	Group accomplishment of strategic goal with minimal supervisory assistance (e.g., go SCUD hunting)
9	Battlespace Swarm Cognisance	Battlespace inference – Intent of self and others (allies and foes) Complex / intense environment – on–board tracking	Strategic group goals assigned Enemy strategy inferred	Distributed tactical group planning Individual determination of tactical goal when required. Individual task planning /execution Choose tactical targets	Group accomplishment of strategic goal with minimal supervisory assistance
10	Fully Autonomous	Cognisant of all within Battlespace	Coordinate as necessary	Capable of total independence	Requires little guidance to do job

Table 11 Taxonomy for automation levels of UAV, based on the SAE Taxonomy, (European Cockpit Association, 2020).

			Management of flight			
Level	**Name**	**Definition**	**Lateral, longitudinal, and vertical control**	**Object Event Detection Response (OEDR)**	**Management of flight fallback**	**Op. Design Domain (ODD)**
0	No automation	Controlled by the Pilot-in-Command during the entire operation, even when enhanced by active safety systems.	Pilot-in-Command	Pilot-in-Command	Pilot-in-Command	Limited
1	Pilot assistance	The sustained and ODD-specific execution by a flight automation system of either the lateral, the longitudinal or vertical vehicle motion control subtask, but not simultaneously, with the expectation that the Pilot-in-Command performs the remainder of the management of flight.	Pilot and system	Pilot-in-Command	Pilot-in-Command	Limited
2	Partial automation	The sustained and ODD-specific execution by a flight automation system of the lateral, longitudinal, and vertical vehicle motion control subtasks of the management of flight with the expectation that the pilot completes the OEDR subtask and supervises the flight automation system.	System	Pilot-in-Command	Pilot-in-Command	Limited
3	Conditional automation	The sustained and ODD- specific performance by an AFS of the entire management of flight with the expectation that the fallback-ready Pilot-in-Command is receptive to AFS-issued requests to intervene, as well as to management of flight performance-relevant system failures in other aircraft systems and will respond appropriately.	System	System	Pilot-in-Command	Limited
4	High automation	The sustained and ODD-specific performance by an AFS of the entire management of flight and management of flight fallback without any expectation that a mission commander will respond to a request to intervene.	System	System	System / Mission Commander with aviation knowledge/skills	Limited
5	Full automation	The sustained and unconditional (i.e., not ODD-specific) performance by an AFS of the entire management of flight and management of flight fallback without any expectation that a mission commander will respond to a request to intervene.	System	System	System / Mission Commander	Unlimited

Table 12: Levels of Automation for computerised and mechanised tasks within manufacturing, (Forhm, Lindström, Winroth, & Stahre, 2008)

Level of Automation	Mechanical and Equipment		Information and Control	
	Name	**Description**	**Name**	**Description**
1	**Totally manual**	Totally manual work, no tools are used, only the users own muscle power. e.g., The users own muscle power	**Totally manual**	The user creates his/her own understanding for the situation and develops his/her course of action based on his/her earlier experience and knowledge. e.g., The users earlier experience and knowledge
2	**Static hand tool**	Manual work with support of static tool. e.g., Screwdriver	**Decision giving**	The user gets information on what to do, or proposal on how the task can be achieved. e.g., Work order
3	**Flexible hand tool**	Manual work with support of flexible tool. e.g., Adjustable spanner	**Teaching**	The user gets instruction on how the task can be achieved. e.g., Checklists, manuals
4	**Automated hand tool**	Manual work with support of automated tool. e.g., Hydraulic bolt driver	**Questioning**	The technology questions the execution if the execution deviate from what the technology consider being suitable. e.g., Verification before action
5	**Static machine / workstation**	Automatic work by machine that is designed for a specific task. e.g., Lathe	**Supervision**	The technology calls for the users' attention and directs it to the present task. e.g., Alarms
6	**Flexible machine / workstation**	Automatic work by machine that can be reconfigured for different tasks. e.g., CNC-machine	**Intervene**	The technology takes over and corrects the action, if the executions deviate from what the technology consider being suitable. e.g., Thermostat
7	**Totally automatic**	Totally automatic work, the machine solve all deviations or problems that occur by itself. e.g., Autonomous systems	**Totally automatic**	All information and control is handled by the technology. The user is never involved. e.g., Autonomous systems

Automation/autonomy in Manufacturing

(Forhm, Lindström, Winroth, & Stahre, 2008) presented a comprehensive review of previous attempts at producing levels of automation (including some of the earlier works discussed here). This work notes that many of the existing taxonomies were developed for specific, predefined tasks, and thus have limited applicability to other systems (including manufacturing). As such the authors have proposed a new taxonomy for manufacturing based on the split in modern manufacturing between tasks and operations which can be mechanised (physical tasks) and those which can computerised (cognitive/control tasks). The resulting levels of automation are presented in Table 12. Note that the scales are independent, producing a 2 dimensional assessment of autonomy – it is not necessary for both the mechanical & equipment and information & control tasks to be at the same level of autonomy.

Automation/autonomy in other areas

The literature review did not locate a widely used or proposed classification system for understanding the autonomous capability of machines within:

- Infrastructure – except in relation to supporting autonomous driving
- Military – except with respect to UAV
- Ports
- Space

It is clear that these industries are pursuing automation and autonomous capability, but there appears to be no publicly available standardisation of autonomy levels within these areas.

Summary and Conclusions of the Review

Automation – summary

The general approach applied across different industries is that human *participation* is required where there is low level of automation. As the level of automation increases this advances to only requiring human *intervention*, with no need for human *involvement* at any point in the process once full automation is achieved. When considering the development of the levels, these are broadly based on:

- Information acquisition and processing
- Decisions on actions to be made
- Carrying out the decided actions

Table 13 compares the different functions that comprise the information processing "workflow". The taxonomies for agriculture, metro (rail), and mining are not included in this comparison as they are focused only on capabilities for specific tasks and each level features a combination of these different aspects of information processing. Manufacturing has also not been included as the Information and Control taxonomy starts from being a combination of information acquisition and analysis, through to levels which encompass the entirety of the information processing task.

Table 13 shows that information processing is broadly split into the same categories across each of the taxonomies, although the automotive taxonomy (and UAV, which was based on automotive) combines the acquisition, analysis, and selection tasks into one. This creates a simpler taxonomy, but this hides some of the detail and occludes the possibility of human-machine co-operation. The simpler taxonomy for automotive is similar to that developed in agriculture, mining, and metro, where the levels of automation are defined on the basis of when a human has to intervene.

Table 13: Comparison of terms/defined functions used within the reviewed taxonomies

<table>
<tr><th></th><th>Aviation</th><th>General</th><th>Military UAV</th><th>Automotive & UAV</th></tr>
<tr><td rowspan="4">Information Processing</td><td>Information Acquisition</td><td>Monitoring</td><td>Observe</td><td rowspan="3">Object Event Detection Response (OEDR)</td></tr>
<tr><td>Information Analysis</td><td>Generating</td><td>Orient</td></tr>
<tr><td>Decision and Action Selection</td><td>Selecting</td><td>Decide</td></tr>
<tr><td>Action Implementation</td><td>Implementing</td><td>Act</td><td>Vehicle Control</td></tr>
</table>

In contrast, the aviation and military UAV industries have developed a more comprehensive taxonomy, which considers the automation of each aspect of the information processing workflow, to create a "4-dimensional" taxonomy for automation. The increased detail these provide is beneficial when considering taxonomies for construction, because construction is more complex than automotive and features different aspects which can themselves be automated to various levels. In addition, the development of automated solutions for each aspect of the information processing workstream is more amenable to retrofitting – e.g., a retrofitted solution for information acquisition and processing that provides an updated topographic map that can be displayed to the operator. However, in addition to considering the taxonomies for automation of the overall task, we note that some of the taxonomies, automotive in particular, have considered the influence of the operational environment, or domain, on the level of automation, as discussed in the following section.

Operational Design Domain

The SAE taxonomy used in the automotive industry is the only taxonomy which makes it explicit that the system has an Operational Design Domain (ODD) to limit where, when, and in what conditions the system can operate automatically. A 5th level of automation is defined, Fully Automated, where the ODD becomes unlimited. This is not a truly unlimited ODD but means that the automated vehicle can operate automatically in any conditions in which a human driver would be able to drive. For Levels 4 and below, the ODD is described as "limited", but no further details are given by SAE. This lack of clarity on the ODD acts as a variable in the use of the SAE taxonomy – it is entirely possible (and has been demonstrated in reality) to have two systems which are both described as Level 4, but which require different capability, e.g., an autonomous bus which delivers passengers from an airport car park to the terminal along a fixed (closed) route, versus autonomous taxi trials on the public road network.

In other taxonomies the concept of ODD is implicit. For example, the taxonomy for metros assumes a rigidly defined ODD (because the metro is firmly constrained to a specific part of the rail network) to develop the levels which have been achieved. The implicit nature of the ODD in these taxonomies may be due to the fact that they are all "professional" fields, where humans operate within a well–defined set of rules and physical constraints – in contrast to the relative freedom to users driving on the road network.

Fallback

The concept of fallback is closely linked to that of ODD. Fallback refers to who or what is responsible for controlling the automated system should it leave its ODD, or a sub–system of the automated system fails. The automotive and metro taxonomies are explicit about this and have built fallback into the levels, with higher levels of automation requiring the automated system to be its own fallback. Other taxonomies do not explicitly mention fallback, but similar concepts of self–dependence are found in the higher levels of automation.

Implications for the development of levels for CAP

Drawing on the outcomes of the review, the methodology for the development of the CAP levels in this work has been to:

- Base the taxonomy on the 4–stage information processing split found in the aviation and UAV taxonomies. However, we incorporate the concept of fallback into the taxonomy more explicitly. *This is discussed in the **Taxonomy for Levels of Automation in CAP** section* .
- Include a detailed discussion of what aspects constitute the Operational Design Domain for CAP. This should overcome the lack of transparency in the SAE approach, by developing an explicit understanding of the Operational Design Domains of plant in the construction industry. *This is discussed in the **Classifying the Operational Design Domain** section.*
- Provide short, narrative examples of what each of the levels in the taxonomy looks like for plant in specific applications. *This discussed in the **Examples** section*.

Automated Capability Framework

Taxonomy for Levels of Automation in CAP

Introduction

It is proposed that the CAP Levels of Automation will be based on the 4-stage information processing employed in the aviation and UAV taxonomies, which classifies the automated capability of machines in a way that is comparable to how humans carry out information processing. Figure 5 shows the stages of information processing we define for CAP; it can be seen that there is a flow from one stage to the next.

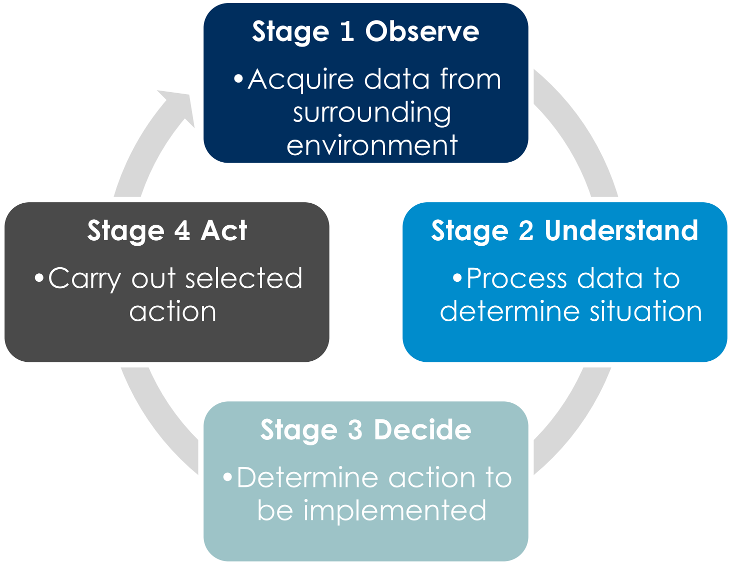


Figure 5 Stages in human information processing

The information processing is not a linear process, with a start and end, but a loop. It starts from a high, strategic viewpoint, where the overall goal is developed, and leads down to sets of individual actions that are required to achieve the strategic goal, forming a set of nested loops applying to each level. For the individual actions there is a continuous process of observing and understanding the surrounding environment, deciding the next step, and carrying out the action, which leads to further observation and understanding based on the outcomes of that action.

To develop the levels of automation *within* each stage we focus on creating levels which offer a meaningful difference in capability between each level. We have not required there to be the same number of levels within each stage. It is also worth noting that there is no requirement for a different person or system to carry out each stage of information processing – this is most obvious for a system with zero automation, where the human operator is likely to perform the entire process. Furthermore, it is not the case that any level of automation within a stage must be followed by the same level in the next stage, and it is also not the case that a specific level in a stage can be followed by any level within the next stage – only certain combinations can be realised. This is discussed further at the end of this section.

Finally, when classifying a particular level of automation for specific types of plant, it is necessary to consider the Operational Design Domain in which the automated system will operate. This is discussed further in the next section.

In the remainder of this section, we present the taxonomies for each stage of information processing:

- The general structure is to first define each taxonomy with a narrative description alongside an example. All of the examples are in the context of parking a car, which is an activity that can be easily conceptualised with less complexity or prior knowledge than would be required for a CAP example. However, examples of how the taxonomy applies to CAP will be presented in a separate section later in this document.

- Following the narrative description, a simplified breakdown of the levels is given, to demonstrate how different aspects of each information processing stage move from being human controlled, to being shared between human and system, and ultimately fully controlled by the automated system.

- In addition to the taxonomies for each stage of the information chain, this section provides a taxonomy for the levels of automation in Responsibility and Fallback.

The following terms are used in the following:

- *Human:* Any human operator of plant, or a team of humans that are necessary to ensure the safe and successful operation of a piece of plant (e.g., banksmen who are employed to prevent collisions during plant movement).

- *System:* Any single or collective computerised machine which is able to carry out actions automatically (without human intervention).

- *Task:* A piece of work or an objective that is to be undertaken by the plant.

- *Action:* An operation or movement of the plant or part of the plant required to conduct the task.

- *Task Completer:* Either the human or the system which initiates or implements the actions required to do the task.

Stage 1: Observe

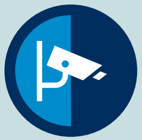
Observing is the act of acquiring information (Observations) on the current situation from the surrounding environment through various sensing organs / sensors and through any existing communications channels. The taxonomy for the levels of automation for observing is presented in Table 15.

To simplify the descriptions in the table on the right we can consider which parties are active *Sensors* at each level of automation – the parties actively acquiring information from the environment. This simplified description is presented in Table 14.

Table 14: Participation of human and system sensors for each aspect of Observe

Level	Name	Sensor
0	No automation	Human
1	Partial automation	Human and System
2	Full automation	System

Table 15: Levels of Automation for Stage 1: Observe

Level	Name	Icon	Description	Example (Reversing into a parking bay)
0	No Automation		The human observes all the necessary performance and environmental conditions for completing the task.	Observations provided via looking over your shoulder or using mirrors
1	Partial Automation		The human and system jointly observe the necessary performance and environmental conditions for completing the task.	Observations provided via looking over your shoulder or using mirrors AND using reversing sensors
2	Full Automation		The system observes all the necessary performance and environmental conditions for completing the task.	All observations provided by sensors to detect obstacles

Stage 2: Understand

After the observations on the surrounding environment and current situation are acquired through the Observe stage, this data must be processed to develop an understanding of the situation.

To accommodate the different aspects of the Understand stage we consider three components, *Compare, Predict,* and *Learn*, defined as:

- *Compare*: Understanding the current state by comparing the Observations to existing values and thresholds.
- *Predict*: Understanding the future state through a pre–defined model against which the Observations are applied.
- *Learn*: Understanding the future state by learning from the outcomes of past Decisions and Actions and applying this.

We include prediction and learning to provide the potential for operatives and systems to develop their skills. The relationship between the levels, the human/system, and these components of understanding are presented in Table 16. The resulting taxonomy for the levels of automation for the Understand stage is presented in Table 17.

Table 16: Participation of human and system for each aspect of Understand

Level	Name	Compare	Predict	Learn
0	No automation	Human	Human	Human
1	Automatic Comparison	Human and/or System	Human	Human
2	Automatic Prediction	Human and/or System	Human and/or System	Human
3	Full Automation	System	System	System

Table 17: Levels of Automation for Stage 2: Understand

Level	Name	Icon	Description	Example (Reversing into a parking bay)
0	No Automation		The human understands and analyses all information about the task throughout the entire process of completing the task.	No assistance required to understand situation
1	Automatic Comparison		The human understands all of the observations provided by the human. The system is capable of understanding the observations provided by the system through simple comparisons. When involved, the human is also responsible for predicting future outcomes and learning from the results of these predictions for all observations (both system and human).	Reversing sensors beep at different tones to indicate the distance to an obstacle, but the human understands where the vehicle is in relation to those obstacles.
2	Automatic Prediction		The human understands all of the observations provided by the human. The system is capable of understanding the observations provided by the system through comparisons and can predict future outcomes. When involved, the human is also responsible for learning from the results of these predictions for all observations (both system and human).	The system uses the observations to understand the current motion of the vehicle and to predict the trajectory of the vehicle.
3	Full Automation		The system processes all acquired information (local and external) to develop sufficient understanding to complete the task. The system can predict future outcomes and learning from the results of these predictions. The system provides that understanding to the task completer for decision selection.	The system uses the observations to understand the current motion of the vehicle and to predict the trajectory of the vehicle, and potential changes to this trajectory, using current and previous experience.

Stage 3: Decide

In the Decide Stage the outcomes of the Understanding stage are used to develop a set of possible actions that could be carried out, and a Decision made on which action to select. Hence Decide contains three components – *Generate, Select,* and *Inform* – defined as:

- *Generate:* The creation of a set or list of possible actions based on the understanding of the situation (from the Understand stage).
- *Select:* The choice of one of the actions. This can be an unrestricted selection (pick any option, or even an option not presented as part of the Generation step, i.e., can go off–list) or a restricted selection (choose an option that was presented as part of the Generation step, i.e., cannot go off–list).
- *Inform:* Provide awareness to the party responsible for approving and/or implementing the selected action.

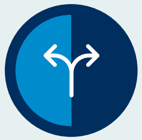
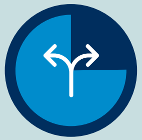
The breakdown of these components between the human and the system within the Decide stage is summarised in Table 18.

From this set of possibilities, a specific action is selected through the Decision–making process, which is passed on to the party responsible for approving and implementing the Decision. The taxonomy of levels of automation for the Decision process is presented in Table 19.

Table 18: Participation of human and system for each aspect of Decide

Level	Name	Generate	Select	Inform
0	No Automation	Human	Human	Human
1	Open List	System	Human (can go off–list)	Human
2	Closed List	System	Human (can't go off–list)	Human
3	Informed Selection	System	System	Human
4	Full Automation	System	System	System

Table 19: Levels of Automation for Stage 3: Decide

Level	Name	Icon	Description	Example (Reversing into a parking bay)
0	No Automation		The human generates all possible actions based on the understanding of the observations and selecting the course of action from them.	Human decides on all options
1	Open List		The system generates a list of possible actions based on the understanding of the observations. The human can select the action from this list or choose an action from outside this list.	System provides options for where to park and how. The human can choose an unlisted option.
2	Closed List		The system generates a list of possible actions based on the understanding of the observations. The human is required to select the action from this list.	The system provides options for where to park and how. The human can only select from list.
3	Informed Selection		The system generates a list of possible actions based on the understanding of the observations and selects the action from this list. The human is informed of the choice and has the option to override.	The system chooses where to park and how. The human can override this selection.
4	Full Automation		The system generates a list of possible actions based on the understanding of the observations and selects the action from the list.	The system chooses where to park and how. The human cannot change this.

Stage 4: Act

The selected Decision must be implemented through Action. To assist in understanding the roles of the human and the system at each level of automation within the Act stage, we consider two components:

- *Implementation:* The party which initiates and carries out the action selected at the Decide stage.
- *Monitoring:* The party which ensures that the action selected at the Decide stage is being carried out as intended.

The breakdown of these components between the human and the system within the Act stage is summarised in Table 20. The taxonomy describing the levels of automation for this process is described in Table 21.

Table 20: Participation of human and system for each aspect of Act

Level	Name	Implement	Monitor
0	No Automation	Human	Human
1	Automated Guidance	Human	System guides human
2	Automated Intervention	Human	System restricts human
3	Supervised Automation	System	Human monitors system
4	Full Automation	System	System

Table 21: Levels of Automation for Stage 4: Act

Level	Name	Icon	Description	Example (Reversing into a parking bay)
0	No Automation		The human implements all actions necessary to carry out the decision.	Human operates steering and speed controls to park without assistance
1	Automated Guidance		The human executes the actions necessary to carry out the decision. The system provides guidance to the human in how to complete the task through informative displays and warnings of when the human is deviating from the intended actions.	Human operates steering and speed controls with guidelines projected onto a reversing camera screen
2	Automated Intervention		The human executes the actions necessary to carry out the decision. The system intervenes to prevent the human from deviating from the intended actions by restricting the range of actions or by automatically adjusting the performance of the plant to optimise outcomes.	Human operates steering and speed controls, but the system stops the vehicle if it is going to hit something
3	Supervised Automation		The system executes the actions necessary to carry out the decision. The human supervises the automated system and can intervene to modify or stop the actions of the system.	System steers and controls the vehicle, but the human can override these inputs
4	Full Automation		The system initiates and implements all actions necessary to carry out the decision.	System steers and controls the vehicle; the human cannot override these inputs

Responsibility and Fallback

The concept of responsibility and fallback underpins the entire information processing chain. In this document we have defined these terms as:

- *Responsibility:* Who or what ensures that the task is being carried out (either manually or automatically) in a safe and proficient manner to the desired quality.
- *Fallback:* Who or what ensures that, when the plant suffers from a component failure, encounters an unexpected situation, or leaves its Operational Design Domain, it either continues to operate or fails in a safe manner.

It is possible for each component of the information processing chain to feature different levels of automated responsibility and fallback, which would create a complex classification system. To simplify this, the lowest level of automation of responsibility and fallback can be used to indicate the level of human responsibility expected. The different levels of automation of Responsibility and Fallback are presented in Table 22.

We have considered there to be two aspects of responsibility and fallback which can be automated. These are *Judgement* and *Intervention*, presented in Table 23 and defined as:

- *Judgement:* Who or what decides when the plant has entered a situation which is not within the standard operation of the plant.
- *Intervention:* Who or what takes over the operation of the plant when it has a entered a situation which is not within the standard operation of the plant.

Table 22: Levels of Automation of Responsibility and Fallback

Level	Icon	Name	Description
0		Human Monitoring	The human is wholly responsible for monitoring the plant in all circumstances, including the performance of any automated systems. The human operates any non–automated systems and takes control of automated systems based on when the human *judges* it necessary.
1		Human on Request	The human is responsible for monitoring and operating the plant when the automated system requests the human to *intervene*.
2		System	The automated system is wholly responsible for the monitoring and operation of the plant in all circumstances.

Table 23: Participation of human and system for each aspect of Responsibility and Fallback

Level	Name	Judgement	Intervention
0	Human Monitoring	Human	Human
1	Human on Request	System	Human
2	System	System	System

How the levels combine

We have established a set of levels for each stage of the information processing loop and for responsibility/fallback. These have been presented as separate, standalone classifications such that each could be independently automated. However, when applying these to a particular piece of plant they would interact, with each stage having implications for the next.

A simple example is that of undertaking the Observe stage with a level 0 system. Here no observations are made by automatic components, and it is not possible for any meaningful level of autonomy to be applied to the Understand, Decide, and Act stages. This can be generalised to a useful principle for determining if a particular combination of levels is allowed – information collected and used at each stage must be passed to the relevant party for that party to remain involved in the processing loop at subsequent stages. In simpler terms, this means if a human or automated system is not involved at an earlier stage then this should not be involved in subsequent stages.

To better understand the potential combinations of levels that are likely to be realised (across stages) we have undertaken a study of the application of the levels to the relatively simple activity of automated compaction systems. This study involved considering all possible combinations and examining if any existing system would be classified with this combination. Where such a system did not exist in real life, we investigated what the required data and information flows were required to complete the task according to each combination to assess if there were any breaks in the chain, see Table 24 for examples.

This has resulted in the graphical representation of potential combinations in Figure 6. Clearly this does not form a definitive list of what permutations are allowed for all implementations – it is possible that for individual use cases, and with the use of different technologies, a different set of combinations could be derived.

One consequence of the highly granular levels is the complexity in assigning levels to a particular piece of plant and then reporting on it. This contrasts quite significantly with level systems such as the SAE taxonomy, which report a single number for all of the capabilities of the vehicle. However, much detail is lost within this simplification, and it is possible to have two machines which are widely different in their practical capabilities which are assigned the same levels, even within the simpler environments which CAVs operate. For example, one level 4 system might be an automated bus driving between an airport terminal and car park within an airport. This automated bus follows a set route, within a well–defined environment and with controlled access to the route. Another level 4 system may be an automated taxi that operates within a city centre, capable of driving to any location within this defined locale and operating on public roads alongside other vehicles. Clearly the requirements for these systems are widely different but they both meet the definition of a level 4 SAE system.

This problem is exacerbated when we move to construction sites, which are significantly more complex than the road network, and when we consider the operations that occur on a construction site involve modifying the environment in which the plant is operating. The distinction between different capabilities of plant becomes of critical importance when considering the safety implications of deploying plant on a construction site, where there is a clear need to understand how that plant will behave in a given environment and around human workers. As such, we have maintained the detailed specification of levels to provide an accurate assessment of the automated capabilities of plant.

Table 24 Example combinations of the levels and their validity

Observe	Understand	Decide	Act	Valid	Reason
0	0	0	0	✓	Purely human controlled so all information stays with the human
0	1	2	2	✗	All observations are performed by the human, but the machine assists with understanding and deciding and restricts the humans actions which cannot happen without awareness of the environment
1	1	2	2	✓	In contrast, the observations are shared between the human and machine in this situation so the machine can assist with understanding and deciding as well as restricting the humans actions.
1	0	2	2	✗	Although the observations are shared in this situation, the understanding is purely reliant on the human so the machine cannot assist with the decision making process or restrict the humans actions.
2	1	0	2	✗	The observations are collected only by the machine in this combination, but the human is required to make a decision without any observations, so this combination is invalid.

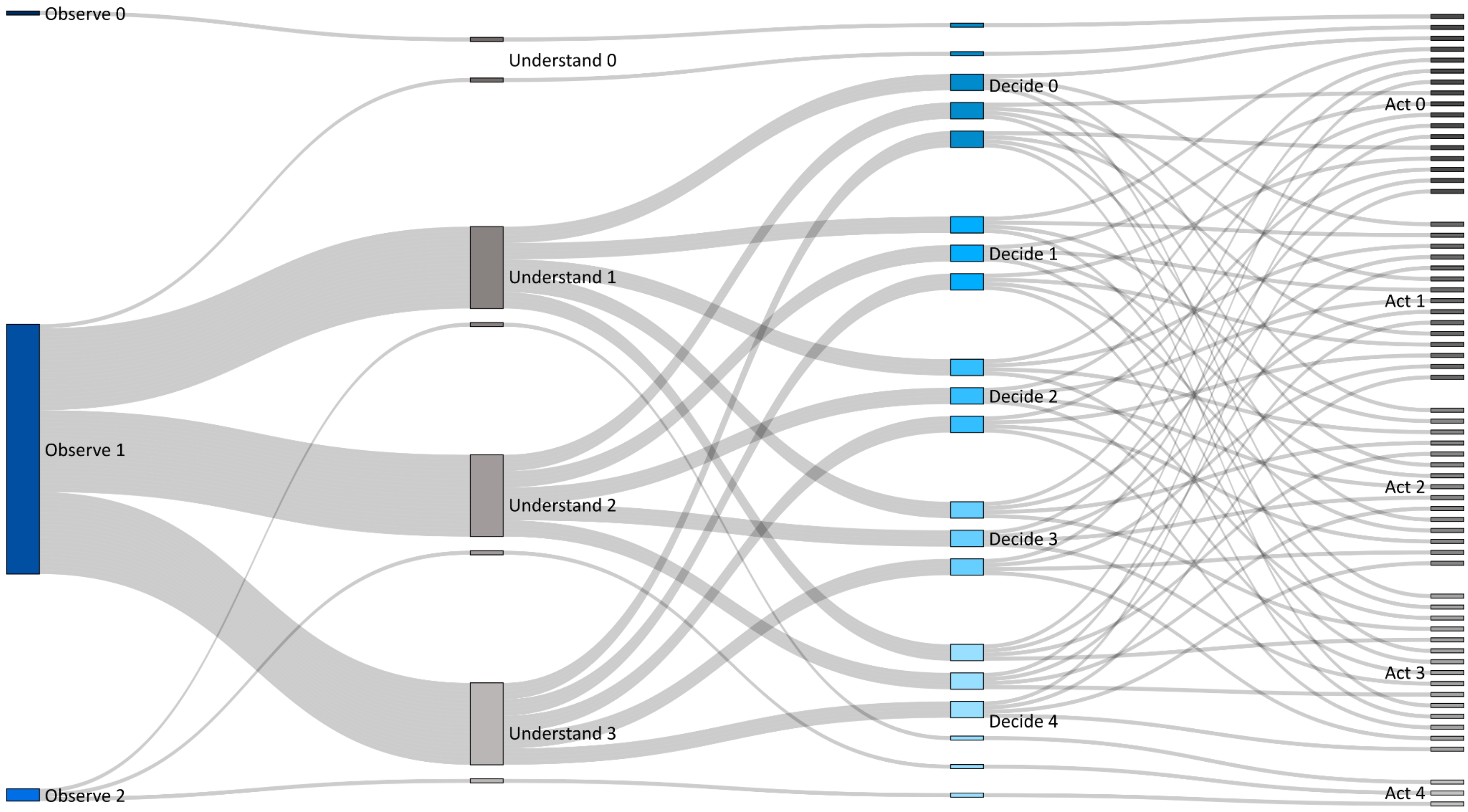


Figure 6 Possible combinations of levels of automation across stages

To provide further clarity on the use of the levels, we can work through each stage for an example compactor. At the outset, the compactor can have any level of Observation depending on how automated the system is. For the purposes of this example, we will assume that it is an Observe Level 1 – that is, the Observations are shared between human operator and machine.

As can be seen in Figure 7, an Observe Level 1 permits any of the possible Understand levels to be developed in the subsequent stages. This is because the information is shared by both the human and system such that each can develop whatever level of Understanding is required by the manufacturer. In this example we choose to implement an Understand Level 2 system, so the compactor is capable of understanding the observations and making predictions based on this understanding.

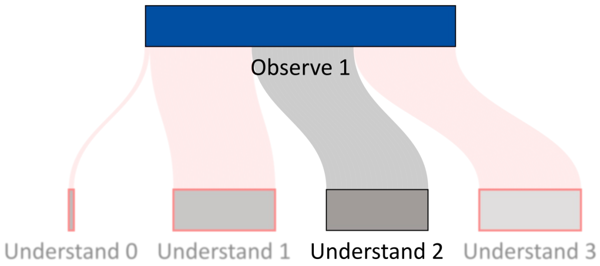


Figure 7 Observe Level 1 and the permitted Understand levels.

In Figure 8 we show the permitted options for the Decide stage following the selection of Understand Level 2. Once again, any Decision level can be allowed as an information flow to both human operator and machine is maintained.

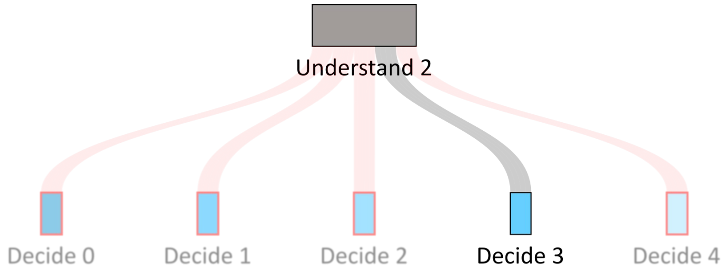


Figure 8 Understand Level 2 and the permitted Decide levels

In Figure 9 we can see that it is not possible for an Act Level 4 system to be chosen at this point. As an Act Level 4 systems operates entirely without human intervention this is incompatible with the Decide Level 3 which has the option for a human operator to modify the decision that the system has made. However, all of the other Act Levels can be chosen, and, in this case, we can select Act Level 3 to produce a compactor that is: Observe 1, Understand 2, Decide 3, Act 3.

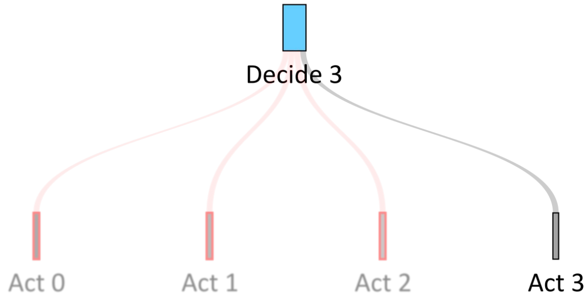


Figure 9 Decide Level 3 and the permitted Act levels

Operational Design Domain

Classifying the Operational Design Domain (ODD)

Background

The ODD specifies the operating conditions for a particular automated device and its control system. PAS 1883:2020 provides a specification for an ODD taxonomy for *on-highway* automated vehicles, separating ODD attributes into three groups:

- Scenery, composed primarily of different road attributes, e.g., road types, junction types, road signs, etc.
- Environmental conditions, including weather, illumination, and connectivity.
- Dynamic elements, including traffic and the subject vehicle.

The task of specifying the ODD for an on-highway vehicle is made somewhat simpler because highways are designed for vehicles. The paths that vehicles follow have, to a significant extent, been predefined (i.e., along the road not across it, and on the side appropriate to the country). For *off-highway* vehicles the operating environment is less well defined. The path taken may be at the discretion of the driver. There can be no assumption that a path is suitable – the terrain may be too steep, obstructed, or unable to bear the weight of the vehicle. It is therefore necessary to be more prescriptive when describing the ODD for an off-highway vehicle.

Off-highway, the ODD may broadly be divided into ***Physical*** parameters, many of which will match those used in PAS 1883 and ***Information*** parameters.

Physical parameters include:

- Scenery, composed of terrain and site attributes, e.g., site topography, soil conditions, site access arrangements etc.
- Environmental conditions, including visibility (potentially in different wavelengths of light), weather, soil moisture content, vegetation etc., but not including connectivity.
- Dynamic elements, including other vehicles and people entering the work area.

Information parameters include:

- Location data (available at the site).
- Communication infrastructure on site.
- Mapping/digital twin (including data on buried services, geology, etc.)

These groups of parameters can be further broken down into detailed sets of operating conditions under which an automated vehicle can complete some or all of its tasks.

In defining the ODD for a particular vehicle, consideration must be given to the mobility of the vehicle in mechanical terms and in terms of the capability of its control system. Like humans control systems must be 'trained' to operate on different types of terrain and will need to be equipped with sensors suitable for each type of terrain. For example, a skilled human operator could safely drive an articulated dump truck down a steep slope, but it may not be possible for an automated control system to drive the same vehicle on the same path because the required observation or decision-making capabilities are not present.

Specifying the ODD for a construction vehicle becomes even more complex when operations beyond driving tasks are required. For example, consider an excavator, which might safely be able to traverse a steep side slope, but would not be able to excavate on it because the forces would destabilise the machine. This vehicle thus requires separate attributes in its ODD – one for driving and another for excavating.

The complexity of the ODD will also be affected by external factors. For example, it may be appropriate to specify that a particular machine only operates in an area where there is no possibility that a person or other vehicle could enter its work zone. Such a machine would require little or no collision avoidance capability, significantly simplifying the design. However, this would require robust management of the site.

Specifying the ODD

The following sections provide illustrative examples of the parameters that may be included in an ODD specification for CAP. The examples are not exhaustive because of the diversity of plant and the tasks it carried out.

Scenery: Terrain

The capabilities of the perception and decision-making elements of the automated control system will have a significant effect on the ability of an automated vehicle to operate on terrains that have not been constructed for the carriage of vehicles. The ability to perceive the terrain conditions and understand their significance for safe operation is key to the ability of those vehicles to be able to operate on construction sites. This complex task is achieved by human operators routinely. Table 25 suggests the terrain parameters of importance to the specification of an ODD for CAP, and the likely effects of those parameters on the ability of the plant to complete its task, its design and operation.

Scenery: Site management

The ODD should specify the site management conditions required for the automated vehicle to operate safely. Some CAP may be able to share its worksite with human workers, visitors, intruders, and other vehicles (both automated and human driven). Sites may be designed to ensure that the area in which CAP is working is sterile and only accessible to CAP. The access arrangements for these areas are safety critical since the plant may not possess the ability to differentiate between safe and unsafe interaction partners. Table 26 suggests site management features that may be included in an ODD specification.

Environmental conditions

The ODD for a CAP should specify the limits of environmental conditions in which the vehicle is able to operate under automated control. Environmental conditions primarily affect the perception systems of CAP, although there may be interaction between environmental conditions and terrain features which may affect the mobility of the vehicle or its ability to carry out its task, e.g., the effect of heavy rain on soil conditions affecting the way in which an excavation is carried out. Table 27 suggests environmental conditions that may be included in an ODD specification.

Dynamic elements

Dynamic elements are any other actors that may be present in the area where CAP is working. The ODD should specify the dynamic elements within which the plant is able to safely share its worksite. Table 28 suggests dynamic elements that may be included in an ODD specification.

Table 25: Examples of terrain features that may be included in an ODD specification

Feature	Effect on plant	Effect on design	Effect on operation
Up/down/side slopes	Restrict access to terrain Cause a loss of stability	Slope perception system required (e.g., gyroscope) May require mitigations for mobility failures e.g., failed hill-climb Control system requires an understanding of the static and dynamic effects of slope (e.g., overturning when a load is lifted on a side-slope)	CAP is likely to take a more conservative approach to traversing slopes than human driven plant. This is likely to make CAP less incident prone, but also restrict the terrain on which they are able to operate.
Bearing strength	Restricts access to terrain Causes vehicles to get stuck Changes the approach required for earthmoving operations	Bearing strength perception system or information from site survey required Control system requires strategies for dealing with different bearing strength scenarios (e.g., different vehicle speeds when crossing the terrain) Control system requires safeguards to avoid a loss of stability on low bearing capacity terrains. Control system requires different strategies for earthmoving depending on bearing capacity (e.g., trench wall collapse)	CAP is likely to take a more conservative approach to crossing soft terrain. If properly designed, CAP will be better able to deal with variations in terrain conditions and will modify their strategies for driving or working to optimise their output in the same way that an experienced human operator might. In the absence of such strategies, human supervisors will have to compensate for terrain conditions in the tasks they choose for CAP.

Negative terrain features – trenches, cliff edges, holes etc.	Restrict access to terrain Cause a loss of stability	Negative terrain feature detection and assessment capability required (e.g., downward looking lidar) Control system requires safeguards to ensure that vehicles do not accidentally run over negative terrain features	Dealing with negative terrain features can be challenging as CAP will require not only the ability to detect the absence of solid ground, but also an understanding of how the ground around the negative feature will respond, (e.g., trench collapse). This may require tasks to be designed in such a way that plant does not encounter negative features that they unable to deal with.
Positive terrain features – rocks, berms, banks etc.	Restrict access to terrain Potential source of falling objects	Positive terrain feature detection and assessment capability required Control system requires safeguards to avoid destabilising positive terrain features, e.g., bank undermining	Positive terrain features may simply act as obstacles around which CAP must navigate. However, consideration must be given by the human supervisor to the ability of the plant to understand the consequences of undermining positive terrain features e.g., when an automated excavator is working at the bottom of a steep bank.
Services passing through the worksite	Restrict access to terrain Damage to the plant through explosion, fire, or electrification	The plant requires either access to up-to-date data on services in its work area, or the ability to detect them for itself. The automated control system requires knowledge of the critical dimensions of the plant to determine whether it can pass services (e.g., vehicle height for passing under suspended cables)	Appropriately specified surveys of any services on site are required before commencing work. This information should be available to the designers of any automated operation.

Table 26: Examples of site management features that may be included in an ODD specification

Feature	Effect on plant	Effect on design	Effect on operation
Uncontrolled access to worksite	Increased risk of collision	Collision avoidance system required that can differentiate between safe and unsafe interaction partners e.g., the soil in a trench vs. a worker in the trench	CAP may have to be deployed in a more conservative way to minimise risk. Special provisions e.g., fenced off work areas may have to be created for plant to work in.
Worksite shared between multiple sub-contractors with inadequate process sequence control	Site subject to changes that are unforeseen by the automated control system e.g., a new structure being erected		More human supervision required to mitigate the effect of unforeseen changes.

Table 27: Examples of environmental conditions that may be included in an ODD specification

Environmental conditions	Effect on plant	Effect on design	Effect on operation
Dust	Reduced the 'visibility' in some spectra	Sensors may require systems to clear dust and prevent dust ingress Some types of sensor are better suited than others to high dust environments e.g., radar. Sensors may have to be chosen for their tolerance to dust.	Site supervisors may need to take steps to supress excess dust. Operations may need to be separated either in time or space from dust generating operations. Suitably equipped plant may be able to operate in dust conditions that would be hazardous for human driven vehicles. Consideration must however be given to the risk associated with CAP operating in zero visibility situations.
High winds	Cause loss of stability Reduce precision of movement	Control system requires safeguard to avoid loss of stability due to wind Control system requires sensors and algorithms to compensate for external forces from wind	Site supervisors may need to restrict operations when winds are strong.
Heavy rain	Change soil conditions Reduces visibility Restricts operations e.g., concrete pour	Control system requires sensors or external information source to adapt processes to changing soil conditions e.g., trench wall collapse Sensors using spectra other than visible light may be required Autonomous control systems require access to weather data and procedures for dealing with heavy rain. Automated machines may rely on	Site supervisors may need to restrict operations during and after heavy rain.

		human input.	
Darkness	May prevent cameras or other visual sensors from working	CAP may require their own light sources	Sites may be able to operate with less lighting than would be required for human operations.
Bright lights	May blind cameras or other visual sensors	Cameras or other visual sensors require sufficient dynamic range to deal with bright lights in their visual field	Site supervisors may have to make special provision for plant working in low sunlight e.g., stopping operations while the sun sets. Site lighting may have to be specified to suit plant requirements.
Extreme cold	May prevent soil engaging implements from penetrating May lead to instability through skidding May restrict some operations e.g., concrete pour	Control systems may require access to temperature information Control systems may require alternative strategies for dealing with extremes of temperature	Site supervisors may have to make special provision for plant working in extreme temperatures.
Extreme heat	May restrict some operations or require alternative operating procedures to be adopted	Control systems may require access to temperature information Control systems may require alternative strategies for dealing with extremes of temperature	Site supervisors may have to make special provision for CAP working in extreme temperatures.

Table 28: Examples of dynamic elements that may be included in an ODD specification

Elements	Effect on plant	Effect on design	Effect on operation
Workers, visitors, or intruders on the site	Risk of deliberate or accidental interference with the plant	Collision avoidance system required that can differentiate between safe and unsafe interaction partners (e.g., the soil in a trench vs. a worker in the trench) Vulnerable systems (e.g., sensors, cameras etc. require protection against deliberate damage) Control systems require strategies for dealing with people in work area. These may include 'stop and wait', 'issue a warning', 'move away' etc.	CAP will usually be designed to be conservative in the way it interacts with humans i.e., will always give way to a human who enters the work zone. This important behaviour means it is very easy for humans to disrupt CAP operations accidentally or deliberately. This may require additional training for staff, briefings for visitors and additional security to prevent intruders from entering work zones.
Other vehicles on the site	Risk of collision between plant and other vehicles Risk of deliberate or accidental interference with the plant (e.g., vehicles being parked in the path of plant or in the operational safety zone)	Collision avoidance systems required that can identify other vehicles and track and predict their paths. Control systems require strategies for dealing with other vehicles in the work area. These may include plotting a path around the other vehicle or stopping and waiting for the other vehicle to proceed.	Sites may require segregated routes for automated and non-automated vehicles. Non-automated vehicle drivers may need instruction on how they should behave around CAP and any special considerations to prevent disruption to CAP operations, e.g., not parking on haul roads even when there may be enough space for another vehicle to pass.
Other CAP on the site	Risk of unintended behaviour when CAP encounters other CAP (e.g., converging vehicles both stop and wait.)	Control systems require strategies for dealing with other CAP CAP may need to be equipped with systems to allow them to recognise other CAP	Site operators need to consider the compatibility of multiple CAP running on the same site

Human driven vehicles collaborating with CAP (e.g., a human driven excavator loading an automated dumper)	The CAP needs to understand how it is allowed to collaborate with human driven vehicles The CAP may need to communicate with the human drivers of other vehicles (sending or receiving information)	The CAP may require a means of communication with the human driver of its collaborator (e.g., to signal when it is ready to load). In some instances, this may require relatively complex information to be passed (e.g., an automated compactor following a human driven bulldozer in which the human driver shares information about the area that is ready to be compacted with the CAP via a graphical interface)	The operation may need to be designed around the capability of the CAP (e.g., the automated dumper will always stop in the same loading position and drive away as soon as it reaches capacity, the human excavator driver must modify their routine to suit the CAP) Some combinations of collaborators may not be feasible or safe, e.g., an automated excavator loading a human driven dumper
Collaboration between CAP	The CAP needs to understand how it is allowed to collaborate with other CAP The CAP may need to communicate with other CAP or with a central computer	The control system requires strategies for the collaborations that it is permitted to join. This may require the collaborators to be designed as a single system rather than as entirely independent vehicles. The CAP requires a means of communication with other CAP or a central computer	Site operators must consider the compatibility of collaborating CAP.

Information parameters: Location services available at the site

Location services are the elements of infrastructure external to the plant that permit it to determine its position. Table 29 suggests location services parameters that may be included in an ODD specification.

Information parameters: Communication

Communication parameters are those infrastructure elements that permit CAP to exchange information and instructions with operators, other CAP, central data sources or other external actors. The ability for CAP to communicate may be a crucial factor in the level of capability of the vehicle. Table 30 suggests communication parameters that may be included in an ODD specification.

Information parameters: Site information

Site information includes maps of the existing topography, information about soil conditions, buried services avoidance areas and other key geographical information, and information about the current and intended state of the structure under construction. This information may be collected in real time by sensors, supplied from survey data or found from historical records. 4D site information includes information about the temporal as well as spatial condition of the site, e.g., information about the sequence of operations for a particular task. Table 31 suggests site information parameters that may be included in an ODD specification.

Table 29: Examples of location services parameters that may be included in an ODD specification

Location services	Effect on plant	Effect on design	Effect on operation
Access to GNSS	Real time access to low precision location information independent of any site infrastructure. Allows rapid calibration of approximate absolute position which may then be augmented by higher precision services. Allows CAP to be geofenced within specific work zones	The control system is able to obtain absolute position information	Shortens setup times
Access to high precision location services e.g., RTK	Allows precise (<50mm) absolute positioning	The control system is able to obtain absolute position information that is sufficiently precise for most construction tasks without other external sensors	CAP is able to work to absolute references and feedback absolute position information about their work e.g., utility locations Sites in regions not served by RTK will have to provide their own base station
Access to dedicated location assets e.g., laser datum lines	Allows highly precise (≈1mm) relative positioning	The control system is able to obtain highly precise relative positioning information	Dedicated infrastructure may be required on site

Table 30: Examples of communication parameters that may be included in an ODD specification

Communication parameters	Effect on plant	Effect on design	Effect on operation
Access to two-way communication	Allows CAP to receive commands and send responses	Allows remote interfaces to be used to start, stop, or modify operations. Removes the requirement for on-board operator controls.	May require dedicated communication infrastructure to be installed on site Permits operators/supervisors to be remote from the plant May mean that operators are now moving around site on foot rather than in vehicles
Access to low latency, high bandwidth, two-way communication	Allows CAP to be remotely controlled from a central computer or remote operator	Allows remote interfaces to be used to provide complex task information or control Allows the CAP to provide real-time information on work progress, site conditions or other information to central control systems or other CAP	May require dedicated communication infrastructure to be installed on site Allows real-time control of CAP from digital twin models Allows real-time updating of digital twin models

Table 31: Examples of site information parameters that may be included in an ODD specification

Site information	Effect on plant	Effect on design	Effect on operation
Information on buried and overhead services available	Improves CAP situational awareness and prevents service strikes	Allows CAP to be designed without the means to detect services Requires access to high precision location services	Requires accurate survey to be undertaken before commencing work Prevents service strikes
2D site plan available in a machine-readable format	Allows CAP to work from a central plan	Control systems require the ability to use CAD files as an input. Requires access to absolute positioning services	Allows operations to be co-ordinated from a central information source thus making outcomes more predictable and assists with the co-ordination of activities
3D site plan available in a machine-readable format	Improves situational awareness e.g., understanding vertical separation	Control systems require the ability to use CAD files as an input. Requires access to absolute positioning services in order to ensure work is done in the correct location	Improves site co-ordination by highlighting the stratigraphy of operations Allows for better estimates to be made of material movements required on site
Facility to update plan with progress information	Provides the CAP with up-to-date information e.g., progress on tasks, new hazards etc Allows CAP operations to be co-ordinated and correctly sequenced e.g., having a compactor move to an area once that area has been levelled by a bulldozer	Requires the facility to transmit information Requires absolute positioning information	Improves the co-ordination of activities on site. Provides a feedback loop for project plans to ensure that project plans are updated in light of progress and the proper sequencing of tasks is maintained Supports the active management of procurement and logistics
4D site plan available	Allows for central control of CAP Allows for process optimisation – delays are minimised, rework avoided, down-time reduced	May allow for CAP with less capable perception abilities to operate at a higher level of capability by collecting site information from other sources e.g., a central computer	Ensures that the sequencing of operations is done in the most efficient manner Allows for digital rehearsals of tasks Optimises the flow of materials and resources into and out of the site

Examples

Applying the Levels – Plant Examples

In the following sections, we demonstrate the application of the levels to two types of construction plant – a compactor and an excavator. It is notes that, although we have developed discrete levels for each part of the process and have proposed criteria for assessing at which level a particular system is operating, it is important to recognise that these levels are an abstraction of a continuous process and as such we expect there to be differences in assessment in the early stages of using the levels. We anticipate, that as the levels are used by more people and wider audiences, a consensus view of when a system transitions between levels will be developed and accepted by the industry which will provide increased clarity on how to use the levels.

Compaction

Compaction is perhaps one of the simplest operations with potential for full automation. We can divide the task of compaction into three components:

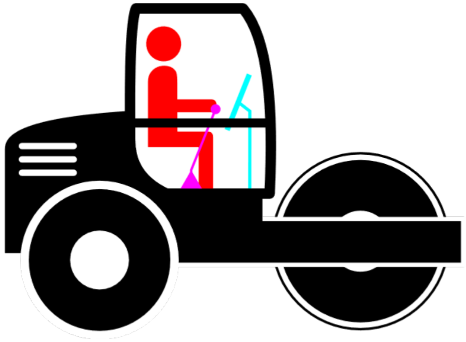
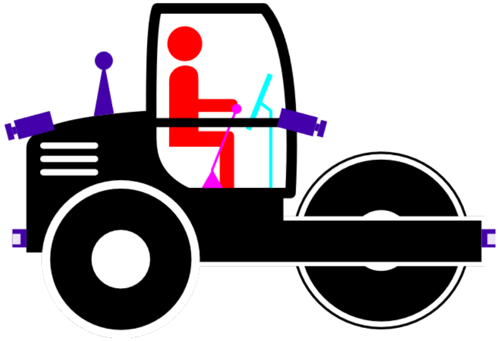
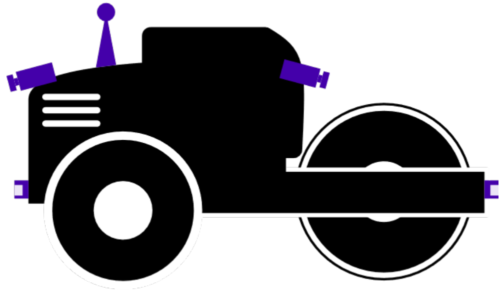
- Control of the locomotion of the compactor (i.e., speed and direction).
- Control of the settings associated with the compaction (e.g., the frequency and amplitude of oscillation in a vibratory compactor).
- Monitoring the completion of the task. This could be a simple pass count or more sophisticated monitoring of the stiffness achieved.

Each of these sub-tasks can be automated independently, with varying levels of automation. The following examples describe how each of the levels of automation within the 4-stages of information processing, and Fallback, apply to a compactor operating on a greenfield site, compacting soil for a base layer after it has been graded/spread by a dozer.

Stage 1: Observe

The following must be Observed (by either the human operator, the compactor, or both depending on the level of automation):

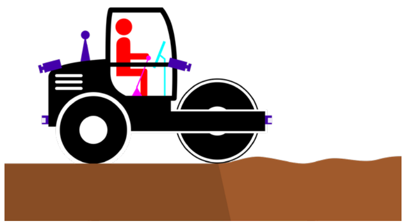
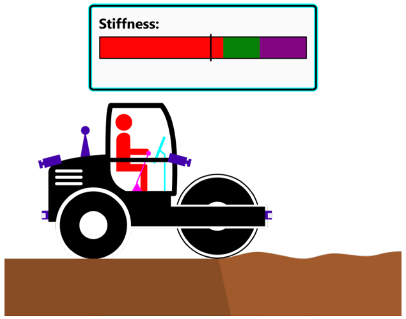
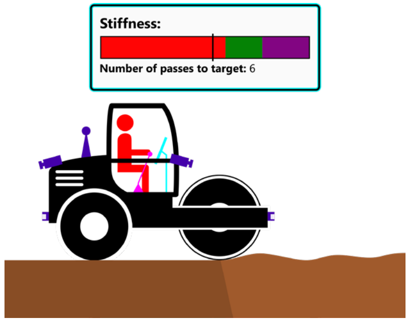
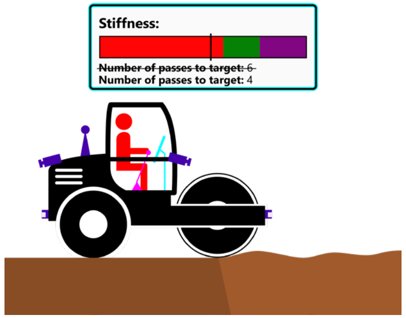
- The position of the compactor within the compaction area and the broader, surrounding environment.
- The presence of potential hazards which might interfere with the compaction task.
- The current state of the compaction task, including the type of material being compacted and how degree of compaction achieved.

No Automation	Partial Automation	Full Automation
		
A conventional compactor with a human operator. Compactor has no sensory capabilities, or if it does these are to inform the human only. Human operator (or supporting team) is responsible for observing the surrounding environment, including the position and trajectory of the compactor, the kind of material being compacted, and its current state of compaction.	Human and system share the observations Compactor has sensors which allow it to observe it's position, including GNSS and a radar/lidar system for surveying its local environment. This might be augmented with a RTK or local base-station for increased accuracy. It also includes a compaction monitoring system. Human operator is also observing the surrounding environment and the location of the compactor within the compaction area.	The system performs all observations through its sensors. Compactor has sensors which allow it to observe it's position, including GNSS and a radar/lidar system for surveying its local environment. This might be augmented with a RTK or local base-station for increased accuracy. It also includes a compaction monitoring system. The human is not required to make observations.

Stage 2: Understand

Understanding consists of:

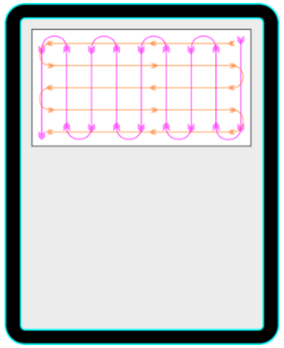
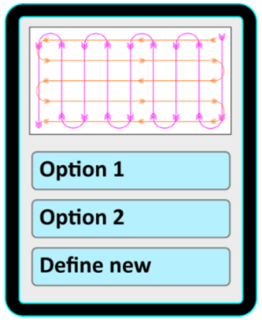
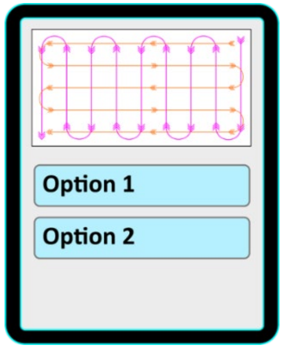
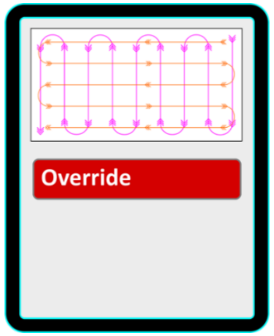
- Understanding the relative position of the compactor (i.e., where the compactor is located within the compaction area and what this implies for where the compactor needs to drive next).
- If any of the potential hazards that were observed will cause an issue and what the nature of that issue is.
- The current compaction state of the target area and hence the progress of the compaction task (e.g., if 4 passes have been completed but 6 are required then understanding that 2 further passes are required).

No Automation	Automatic Comparison	Automatic Prediction	Full Automation
			
Compactor is not capable of understanding. Human operator uses their observations to understand the current progress of the compaction task in terms of which locations have been compacted, how many passes out of the target have been completed, and how the stiffness metrics compare to the target value.	Compactor processes its sensor data through simple comparisons, comparing current and past positions to the defined compaction area to understand which locations have been compacted, and if so by how much. Human operator uses this information to augment their understanding, understanding what needs to be compacted, predicting the behaviour of the compactor, surrounding vehicles, and the material being compacted.	Compactor processes sensor data through comparisons, e.g., comparing current and past positions to the defined compaction area to understand which locations have been compacted, by how much, and where the compactor needs to drive next. The compactor can predict future outcomes (e.g., the extent of compaction that would be achieved in a further pass, or if the trajectory of another vehicle will result in a collision). Human maintains the requirement to fully understand the situation. Human uses the observations to augment their understanding and learn.	Compactor processes its sensor data through comparisons, comparing current and past positions to the defined compaction area to understand which locations have been compacted, and if so by how much. The compactor is capable of predicting the future outcomes (e.g., if the trajectory of another vehicle will result in a collision) and can learn from previous operations to improve its performance (e.g., learning how a material behaves under compaction).

Stage 3: Decide

Decide chooses the action to undertake to complete this information processing stage. Conceptually, Decide generates options and selects one of these options. Within the various information processing stages, decisions must be made regarding:

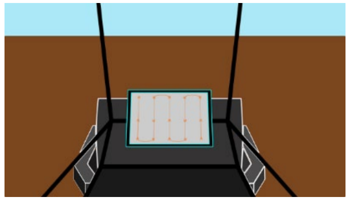
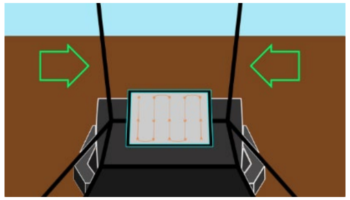
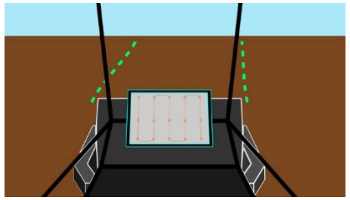
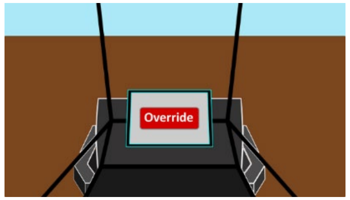
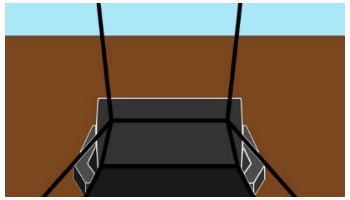
- The driving lines and speeds to be implemented.
- How identified hazards are to be mitigated and/or avoided.
- The compaction settings/activities required to complete the task.

No Automation	Open List	Closed List	Informed Selection	Full Automation
				
Human operator determines which options exist for completing the task, including driving lines and speeds, how to avoid potential collisions, and if the current target no. of passes is correct to achieve the target compaction and/or the machine settings appropriate to the task. Human operator selects one of these options for implementation.	Compactor determines the options for completing the task, including driving lines and speeds, how to avoid potential collisions, if the current target passes is the correct amount to achieve the target compaction and/or the machine settings appropriate to the task. Human operator selects one of these options for implementation or may choose to develop/select their own.	Compactor determines the options for completing the task, including driving lines and speeds, how to avoid potential collisions, if the current target passes is the correct amount to achieve the target compaction and/or the machine settings appropriate to the task. Human operator selects one of these options for implementation.	Compactor determines the options for completing the task, including driving lines and speeds, how to avoid potential collisions, if the current target passes is the correct amount to achieve the target compaction and/or the machine settings appropriate to the job. Compactor selects one of these options for implementation, but the human operator can override this with another choice from the list of options.	Compactor determines the options for completing the task, including driving lines and speeds, how to avoid potential collisions, if the current target passes is the correct amount to achieve the target compaction and/or the machine settings appropriate to the job. Compactor selects one of these options for implementation.

Stage 4: Act

Once a Decision has been made in the previous stage, it is implemented. Act consists of:

- Controlling the steering and speed of the compactor.
- Modifying any compaction machine settings as needed.

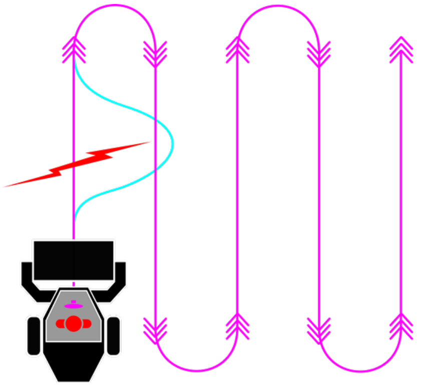
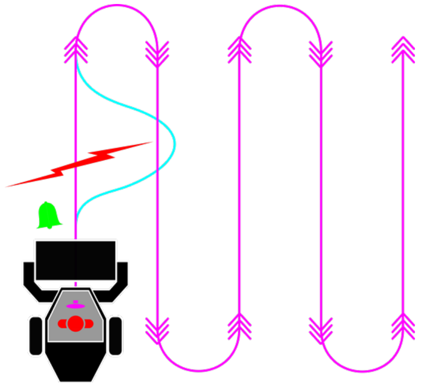
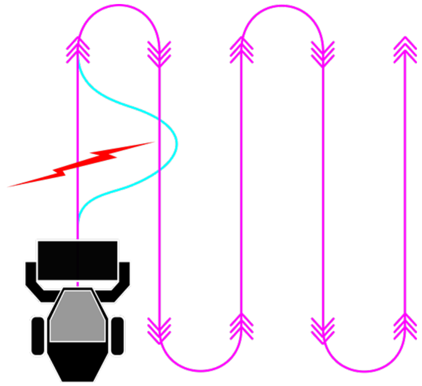
No Automation	Automated Guidance	Automated Intervention	Supervised Automation	Full Automation
				
Human operator initiates and implements the chosen decision, controlling the compactor steering and speed, as well as modifying the compactor settings as appropriate.	Human operator initiates and implements the chosen decision, controlling the compactor steering and speed, as well as modifying the compactor settings as appropriate. The compactor provides guidance to the operator, indicating the motion (driving line and speed) and settings to use that align with the chosen decision.	Human operator initiates and implements the chosen decision, controlling the compactor steering and speed, as well as modifying the compactor settings as appropriate. The compactor restricts the operator (but can be overridden), maintaining the speed of the compactor and preventing them from deviating beyond acceptable limits from the chosen driving line.	The compactor initiates and implements the chosen decision, controlling the compactor steering and speed, as well as modifying the compactor settings as appropriate. The human operator monitors the performance of the compactor and adapts/overrides the actions of the compactor as needed.	The compactor initiates and implements the chosen decision, controlling the compactor steering and speed, as well as modifying the compactor settings as appropriate.

Responsibility & Fallback

Responsibility & Fallback applies to every step of information processing and consists of:

- Recognising when an unplanned situation occurs
- Developing and implementing a response to the unplanned event that maintains safety, and if possible, continues the task.

In the following example, we consider a compactor which is compacting a target area by automatically following the magenta line, along a “digital track”. A hazard (represented by the red lightning bolt) occurs, and a solution (represented by the cyan line) must be developed and implemented. The three levels of Responsibility & Fallback are shown.

Human Monitoring	Human-on-Request	System
		
Human operator is responsible for ensuring the compaction task is completed to the specification and must actively monitor the performance of the compactor to ensure this is achieved. Human recognises that a hazard has occurred and acts to mitigate it.	The compactor monitors its own activity. When it encounters situations outside of its operational domain the human operator takes over. For example, the compactor following the "digital track" encounters an obstacle and requests the human operator to take over. The human operator either stops and removes the obstacle or drives around it, after which autonomous operation can resume, and the compactor continues along the digital track.	The compactor is responsible for ensuring the compaction task is completed to the specification in all circumstances. If this isn't possible the compactor maintains a safe state. For example, a compactor following the "digital track" encounters an obstacle. The system recognises the hazard and responds to it, either by deviating from the original route (blue line) or coming to a stop. If the compactor isn't able to complete the task it notifies the appropriate controller and maintains a safe state.

Excavation

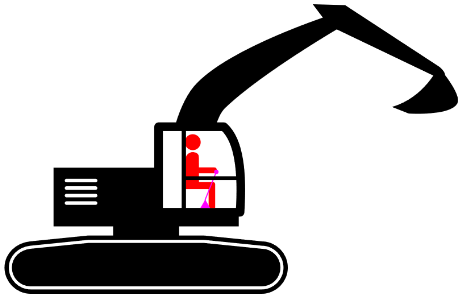
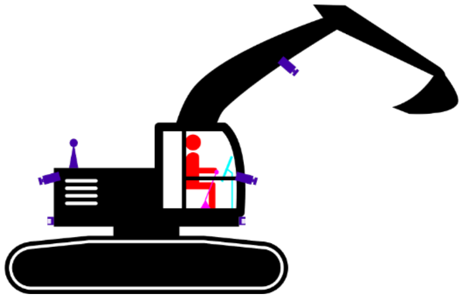
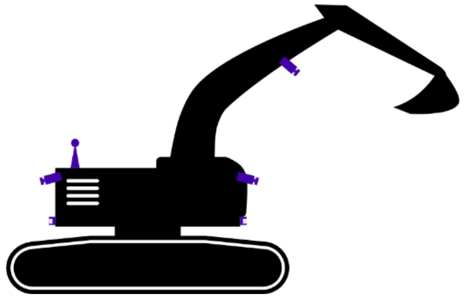
Excavators can conduct a wide variety of tasks, have different attachments, and traverse complex and varied terrain. The activities they undertake have different requirements in terms of sensing and capability. They are challenging to *fully* automate, but automated operator assistance functionality is common on new excavators (Bennink, 2021).

For the purpose of this example application of the levels we have considered a specific task – an excavator digging soil on a sloped surface. This is more challenging than an excavator digging on a flat surface because the excavator must remain stable and cope with the additional forces on the slew axis due to operating at an angle. To operate on a slope, the human operator and/or automated system must know, for example:

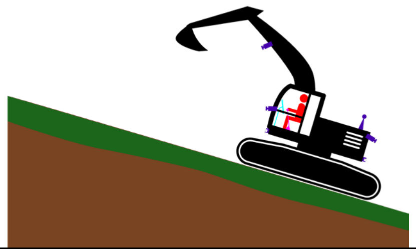
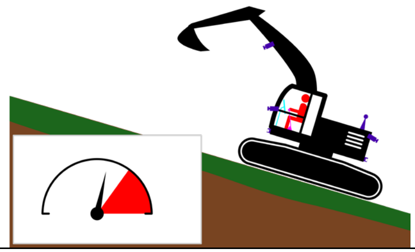
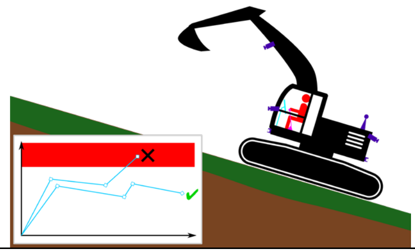
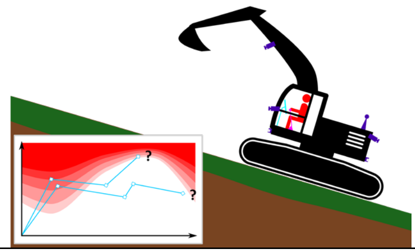
- The angle of the slope (and therefore excavator)
- The position of the boom, dipper, bucket, and cab
- The position of the crawler chassis
- The load in the bucket
- The properties of the material being dug
- The load bearing capacity of the ground
- The maximum force that can be generated by each actuator
- The surrounding objects (e.g., obstacles, people, other vehicles)
- Where the material should be moved from and to
- The characteristics of the location or container the material will be placed on or into (e.g., ground surface, container, another vehicle)

Each of these must be Observed and Understood in the first two decision steps. The implications of this will then inform the Decide and Act steps. All of these variables will also have to be within the ODD of the automation system of the excavator. This is so the automated functions of the excavator can operate successfully and safely. For example, the automated system may have limits on the types of materials it understands and can therefore dig, a minimum ground bearing capacity, or limited object detection capability, so requires other safety protections.

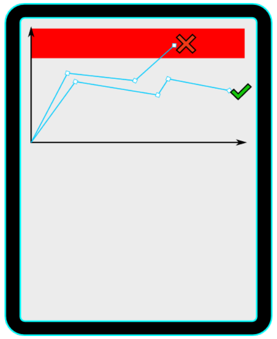
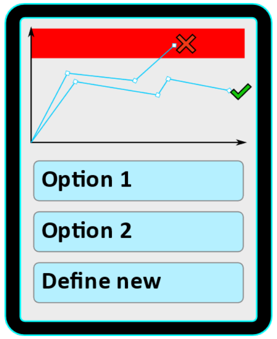
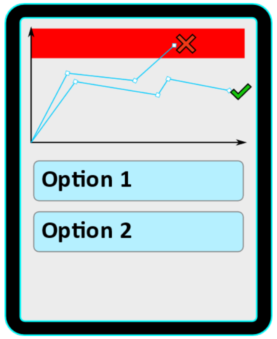
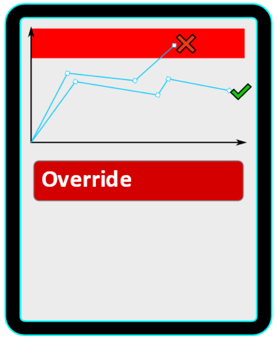
Stage 1: Observe

No Automation	Partial Automation	Full Automation
		
The human observes the necessary information about the excavator itself, its surroundings, and the progress on the task. They use human senses and observe instruments that are not automated (the excavator may have sensory capability, but these are to inform the human only).	The excavator has sensors which allow the system to Observe its position (e.g., GNSS, radar/lidar for surveying the local environment) and itself/on-board systems (e.g., location of components of the excavator). The human makes their own observations and may also observe the sensor outputs, to provide the necessary observations to perform the task. For example, the load in the bucket is observed through force transducers and the relative position of arm and bucket are instrumented. Simultaneously the human either duplicates these observations or observes feedback systems/screens, and also makes the other observations necessary for the task.	The automated system performs all observations required for the task through its sensors. Everything that needs to be observed is achieved through one or more sensing methods. The human is not required to make observations.

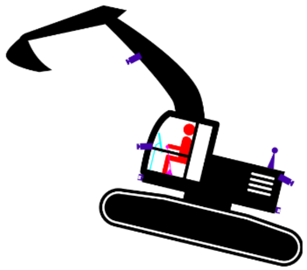
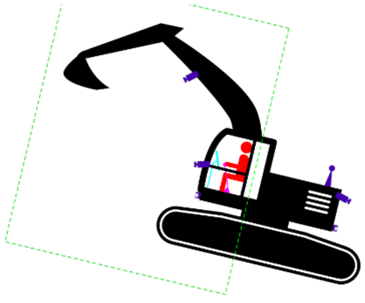
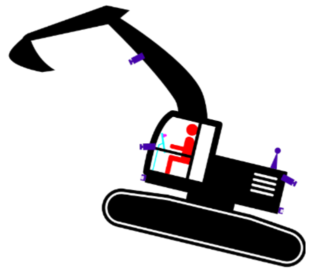
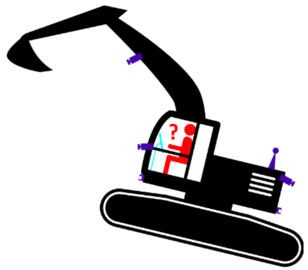
Stage 2: Understand

No Automation	Automatic Comparison	Automatic Prediction	Full Automation
			
The human understands both their own observations and, if relevant, those of the automated system. For example, they may use a view from a remote camera or the output of a load cell on the bucket. They use these observations to understand the status of the task. For this task, they would understand if the excavator is stable for the current course of action. This understanding is based on interpreting the immediate situation, predicting the outcome of future actions and lessons learnt from past experience. The automated system has no understanding.	The automated system makes simple comparisons using its current observations. In this example, this could include calculating a stability value from the current loading and arm position and comparing this to a threshold to understand if the excavator is stable for the current course of action. It cannot predict what future actions may do to the stability of the excavator. It does not learn from past performance. If involved, the human uses their own observations and, potentially, the comparisons performed by the automated system to predict how the excavator will behave and understand if the stability of the excavator is at risk, taking in to account their past experience.	The system can understand the observations and predict the consequences of future actions. In this example that might be predicting how different future courses of action would impact the stability of the excavator. The automated system does not learn from past performance. If involved, the human maintains the requirement to fully understand the situation. Humans uses the observations to learn.	The automated system can understand current observations, predict the consequences of future actions, and learn from past performance. For example, it could use these capabilities to predict stability based on experience gained in this task or tasks it has previously operated upon. There is no requirement for the human to understand the situation.

Stage 3: Decide

No Automation	Open List	Closed List	Informed Selection	Full Automation
				
The human decides what the next course of action will be. They utilise both their own understanding and, optionally, the understanding gained by the automated system.	The system generates possible options for the next actions based on its understanding. These could be, for example, the options for the next arm and bucket movements to continue the task, whilst maintaining stability. The human makes the decision on what actions to take based on their own understanding and may pick one of these options or define their own.	The system generates possible options for the next actions based on its understanding. These could be, for example, the next arm and bucket movements to continue the task, whilst maintaining stability. The human must pick one of these options based on their own understanding.	The system generates possible options for the next actions based on its understanding. These could be, for example, the next arm and bucket movements to continue the task, whilst maintaining stability. The human can override this decision and pick another option.	The automated system generates possible options for the next actions based on its understanding. These could be, for example, the next arm and bucket movements to continue the task, whilst maintaining stability. The human is not involved in deciding which course of action to take.

Stage 4: Act

No Automation	Automated Guidance	Automated Intervention	Supervised Automation	Full Automation
				
The human operates the excavator and follows the course of action chosen at the previous step.	The human operates the excavator, but the system will issue guidance/warnings if the human leaves boundaries set by the decision. For example, an alarm may go off if the human starts to move the arm past the stable operating zone, decided in the previous step.	The human operates the excavator, but the automated system limits the possible movements, based on the Decision made. For example, the automated system will actively prevent the operator moving the arm in a way that will destabilise the excavator.	The system operates the excavator according to the Decision. The human monitors what the automated system is doing and may intervene to modify or stop the actions of the excavator. For example, the human may intervene and stop the excavator if a fault occurs that has not been observed by the system, or if the human judges that the system is likely to commence an unsafe operation.	The automated system carries out all of the actions with no human intervention. Whether a human is required at all is determined by whether they are required for other stages in information processing.

Responsibility & Fallback

The Responsibility & Fallback example considers the specific scenario of an excavator is digging on the slope in heavy rain, which causes localised flooding and destabilises the slope.

Human Monitoring	Human-on-Request	System
		
The human is responsible for judging that an intervention is necessary and then performing the intervention. Therefore, the human needs to observe that heavy rain is occurring and that it is destabilising the slope. They must take control of the excavator to stop operation and/or to move it to a position of safety.	The automated system is responsible for noticing that an intervention is necessary and asking for human assistance. The human is responsible for responding to this request and performing the intervention. In this example, the automated system is capable of noticing the heavy rain and flooding and judging that it is no longer operating in conditions within its ODD. It alerts the human that this is the case. The human is responsible for intervening and stopping the excavator and/or moving it to a position of safety.	The automated system is capable of maintain a safe state in all conditions without support. It can Observe all condition changes, Understand that the change of conditions will be outside of its ODD, Decide whether to move to a position of safety or stop operating, and Act on that decision.

Applying the Levels – End User Examples

Within this section we explore how the capability levels could potentially be applied by different stakeholders within the industry. This is not an exhaustive list of potential applications. The aim is to help end users understand how they might benefit from them. In the following we have considered the activities undertaken in different roles could undertake which would increase the benefit of the CAP levels, both to themselves and to others, see Table 32. The roles have been selected from across the construction industry to cover the important stages that determine what plant is available, what it is intended to be used for, and how it is used in practice.

Table 32: Examples of end user application of the levels

End user	Application Example	Benefit
Manufacturer	Employed throughout development programmes to target the development of capability that delivers specific levels of autonomy. This could be supported with the inclusion of benchmarks to quantify the benefits associated with safety, productivity, efficiency, etc., as increased levels of automation become available.	Aligns internal product development roadmaps with the levels and establishes common understanding of the programmes against which manufacturers plan to achieve similar standards of autonomous capability.
Manufacturer	Create a "catalogue" of plant offerings, taking advantage of the common understanding of automated capability presented by the levels to rate plant.	Offers the ability for manufacturers to use a common language when interpreting and understanding the needs and desires of their potential customers for different levels of automation, and how this varies across the construction sector. Allows manufacturers to demonstrate where plant achieves minimum requirements and where these have been exceeded by specific types of plant.
Specification / Procurement / Policy	Adapt specifications, procurement strategies, and policies to account for the evolving market and demand.	Permits the deployment of readily available technologies which contractors are already bought in to for use on site so has the potential for greater uptake.
Specification / Procurement / Policy	Update specifications, procurement strategies, and policies with requirements for particular automated capability.	Proactively drives the industry to adopt the new technologies, advancing the delivery of benefits of these technologies and associated desirable outcomes (e.g., safety improvements). Creates a "CAP-friendly" future through a collaborative approach with industry.

Designers	Understand the current and expected automated capabilities of plant, using the manufacturers' catalogues and development programmes	Use this understanding of automated capability to refine the designs they produce to better operate with CAP, optimising their designs for efficient use of time, energy, and materials based on the plant being used. Supports the implementation of a "design for machines" paradigm, were designers produce detailed designs with the expectation that they are delivered directly to automated plant for implementation, with no (or minimal) requirement for human involvement to achieve the intended designs
Programme Managers	Understand the current and expected automated capabilities of plant, using the manufacturers' catalogues and development programmes	Understand how different CAP levels will affect performance and quality, allowing for more robust quality assurance, and potential refinements to the quality requirements. This will be accompanied by changes to operational procedures to facilitate the use of CAP, requiring changes to the build programme.
Construction Site Manager	Understand the practical implications of applying different levels of automation to a construction site. This includes, understanding what safety implications there are with operating automated plant, including mixed fleets of differing capabilities, and how this will need to be controlled based on the different levels and apportioning of responsibilities between plant and humans on site	Supports the management of site layouts, zoning of personnel to appropriate areas, updating procedures for operation of plant with suitable system checks before operation, etc.

Construction Site Manager	Understand what the requirements are for operators using plant at each level of automation	Ensure that the operators have the necessary training and experience to use the plant at a given level of automation Understand who is responsible for the operation of the plant in what circumstances
Industry Bodies	Used to understand the skill requirements for operators for each level of automation, and hence the training requirements	Develop training schemes which would address these differing needs, across different professions with industry: • For operators so they can operate the plant • For site managers so they can create sites which maximise the benefits of using CAP of different levels • For designers, procurement specifiers, managers so they can understand the implication of different levels of automation on their processes
Industry Bodies	Understand the current and expected automated capabilities of plant, using the manufacturers' catalogues and development programmes	Assess plant for their capabilities, acting as a manufacturer–independent judge of the plant being developed so that end users can be more certain of the expected performance of the plant they use.

Conclusions

This document presents a taxonomy for classifying the capability of construction plant for automated operation. This addresses a key activity identified in the CAP Roadmap (2019) for Connected and Autonomous Plant as Business as Usual by 2035, (TRL, i3P, Highways England, 2020). Following a review of the application of levels across several industries, we have proposed that the principle of *"when creating machines which are intended to replace human capability, they should be assessed using the same language we use to assess human capability"* should be applied to CAP. This approach is more complex than "wrapped–up" taxonomies applied in industries such as automotive, but it reflects the higher level of complexity required to define the wide range of activities undertaken by plant. It also provided for flexibility and is amenable to the re–classification of plant after retrofitting.

We have therefore proposed a set of levels that adopt the 4–stages of information processing that describe human and automated capability across the full process of executing a task. Discrete levels have been established to describe how any stage of processing becomes increasingly automated. The development of the levels has avoided prescribing different technological solutions to achieving a certain level of automation, with the importance being placed on the degree of human intervention required at any point.

Supporting the taxonomy, we have included an extensive discussion around Operational Design Domain. This is a key component that must be included when discussing the capabilities of plant, as the capability of technology may depend on the specific environment in which it is being applied. Also reflecting practice in other industries, the levels include a Fallback and Responsibility stage. This reflects the need for clearly defined expectations about the role of plant and people when a machine begins to operate outside of its capability, or ODD.

Following the development of the levels, we have attempted to provide clarity on how the levels could be used in the construction industry through specific examples of their application to the tasks of compaction and excavation. We have also highlighted how they levels could be applied by different stakeholders within this industry to support technical, strategic, legislative, and contractual development. Our use cases are illustrative and in no way exhaust the potential uses that will hopefully occur as the levels are adopted across the sector.

Although this document has provided a complete taxonomy, it is expected that, as the levels are applied within the industry and further developments are made, there will be a need to update and refine the levels to adapt to the evolving context of the industry. As such, this document effectively represents a "public beta version" of the levels. We encourage trials of the levels by the intended end users to understand their content, fitness of purpose, complexity, suitability etc., which will hopefully lead to refinement and wider application across the industry.

Appendices

Appendix A – Stakeholder Acknowledgements

This Capability Framework has been created drawing upon the expertise and knowledge of the following organisations.

Arcadis

Balfour Beaty

BOMAG

Bosch Rexroth

CAT

Centre for the Protection of National Infrastructure

Construction Equipment Association

Costain

DBD Communications

Epitomical

Finning

Flannery Plant Hire

Harper Adams University

Hexagon, part of Leica Geosystems

i3P

Komatsu

Marubeni-Komatsu

National Highways

National Physical Laboratory

Network Rail

Siemens

Skanska

SMT GB

Topcon

TRL

Volvo

WSP

Zenzic

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