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## Remote operation of Connected and Automated Vehicles

Project Endeavour - WP15B

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## Disclaimer



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# Executive summary

Connected and Automated Vehicles (CAVs) offer numerous societal benefits; however, there is still a long way to go before CAVs can be considered reliable and safe. Even when CAV technology has matured, and is more readily available, there will be scenarios that require human intervention such as system failures, situations outside of the AV's Operational Design Domain (ODD), or to support users. As part of project Endeavour, TRL conducted research on potential human intervention scenarios, which has been considered and referred to as a part of 'remote operation'.

This study sought to understand the current roles of the in-vehicle Safety Driver and Test Assistant during CAV trials and testing to recognise the technical challenges of removing the roles and enabling remote operation. This report includes findings from a literature review and stakeholder engagement and contains:

- Information on the roles and responsibilities of the in-vehicle Safety Driver and Test Assistant and their remote counterparts
- Current terminology used in the CAV space, and recommended terms for remote operation
- Use cases and recommendations to enable safe remote operation
- A high-level roadmap describing the milestones to enable remote operation in the UK

The Safety Driver and Test Assistant both perform key roles in ensuring the safety of an AV test or trial by continually monitoring and observing the AV's environment and digital feedback devices. To perform their roles, both the Safety Driver and Test Assistant are expected to meet certain key requirements through selection and training; these requirements were used to deduce the roles and responsibilities of a Remote Operator. The role of a Remote Operator can be split into two categories - remote vehicle assistance and remote control - based on the level of control the Remote Operator has over the AV.

The taxonomy and terminology used when referring to remote operation remains largely undefined with standards and stakeholders across industry applying terms inconsistently. Through the literature review and stakeholder engagement several definitions have been developed for consideration as part of this study. It is also recognised that the definitions will need to evolve as the industry matures and new technology and use cases are developed.

The use cases which are most suitable for remote operation are those which have fewer risks and constraints compared to their in-vehicle operational methodologies. Initial high-level use cases where remote operation would provide safety benefits and may be appropriate were identified through development of a framework. The framework can be further developed to include additional use cases and mitigations as per relevant industry standards.

Remotely operated CAVs are still in their infancy and this study has identified some of the factors affecting the safe removal of the Safety Driver and Test Assistant from an AV and proposes a set of recommendations to address them. The factors relate to several themes

including legal requirements, standards, technological, and safety assurance requirements. Various gaps and challenges were identified in this study which were combined with the recommendations to facilitate the creation of a high-level roadmap to provide a pathway to enable remote operation in the UK.

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## Glossary

| Term | Definition |
|---|---|
| **ADAS** | Advanced Driver Assistance System |
| **ADASIS** | Advanced Driver Assistance Systems Interface Specifications - interface for exchanging information between the in-vehicle map database, ADAS and automated driving applications |
| **AI** | Artificial Intelligence |
| **AV** | Automated Vehicle |
| **BSI** | British Standards Institution |
| **CAV** | Connected and Automated Vehicle |
| **DfT** | UK Department for Transport |
| **DDT** | Dynamic Driving Task |
| **DGNSS** | Differential GNSS - a kind of GNSS Augmentation system based on an enhancement to primary GNSS constellation(s) information using a network of ground-based reference stations |
| **DOT** | US Department of Transportation |
| **EU** | European Union |
| **GDPR** | General Data Protection Regulation |
| **GNSS** | Global Navigation Satellite System |
| **GPS** | Global Positioning System |
| **HMI** | Human Machine Interface |
| **IMU** | Inertial Measurement Unit |
| **INS** | Inertial Navigation System |
| **ISO** | International Organisation for Standardization |
| **LIDAR** | Light Detection and Ranging |
| **OEM** | Original Equipment Manufacturer |
| **OTA** | Over-The-Air |
| **PAS** | Publicly Available Specification |
| **RADAR** | Radio Detection and Ranging |
| **RO** | Remote Operation |
| **SAE** | Society of Automotive Engineers |
| **V2V** | Vehicle-to-Vehicle |
| **V2X** | Vehicle-to-Everything |

# 1 Introduction

Project Endeavour was designed to accelerate and scale the adoption of automated vehicle (AV) services across the UK. Currently during AV trials and testing there are two personnel within each AV: The Safety Driver and the Test Assistant. To progress to advanced trials (see Section 2.1) it is important to understand what is required to remove these personnel from the AV without compromising safety.

## 1.1 Aims

The primary aim of this research was to understand how to progress to advanced trials and safely perform the roles of the Safety Driver and Test Assistant remotely. The study analysed the role of the Safety Driver and Test Assistant including their requirements to safely monitor and control an AV. This included an analysis of the latest relevant standards and the key risks and enablers of removing the roles including its overall impact on AV operation.

The outputs from this research will help industry gain an understanding of the technical challenges involved in removing the Test Assistant from the AV, the requirements to enable progression to advanced trials, and create a foundation for future requirements needed to remove the Safety Driver from the AV to enable remote operation.

## 1.2 Research areas considered

To better understand the roles of the Test Assistant and Safety Driver a review of relevant standards and literature was undertaken as well as discussion on the current responsibilities and expectations of the Safety Driver and Test Assistant through stakeholder interviews. The stakeholder engagement included gaining an understanding of the training a Safety Driver and Test Assistant undergo, particularly the training involved in effective communication between the roles and looking at how communication might change if any of these roles were carried out remotely.

The following key research areas were considered in this study:

- Definitions related to remote operation
- The current guidance, standards and regulation related to remote operation
- Applications of remote operation
- The role of the Safety Driver
- The role of the Test Assistant
- Safety considerations for the removal of the Safety Driver and Test Assistant roles from an AV

## 1.3 Report structure

The report is split into ten sections, with the first eight containing the research and findings. Section 1 provides an overview of the study, Section 2 summarises the approach taken for the literature review, followed by a detailed review of the key research areas mentioned in

Section 1.2. Section 3 then summarises the approach used for the stakeholder engagement with an accompanying detailed thematic review of the findings. This is followed by five sections which detail the findings of the wider research.

Section 4 describes the terminologies that have been developed as part of this study, with Section 5 detailing the framework that has been developed to identify use cases for safe remote operation. The different roles, requirements, and responsibilities for remote operation are summarised in Section 6. The overall recommendations that have arisen from the study are summarised in Section 7 alongside the gaps, challenges, and safety assurance requirements. Finally, a high-level roadmap on milestones needed to enable the removal of the Test Assistant and Safety Driver roles from the AV to enable remote operation is shown in Section 8.

## 2 Review of literature

The literature review was conducted following the principles and methods laid out by (Seidl *et al.* 2017). The systematic approach included the four steps outlined in Figure 1.

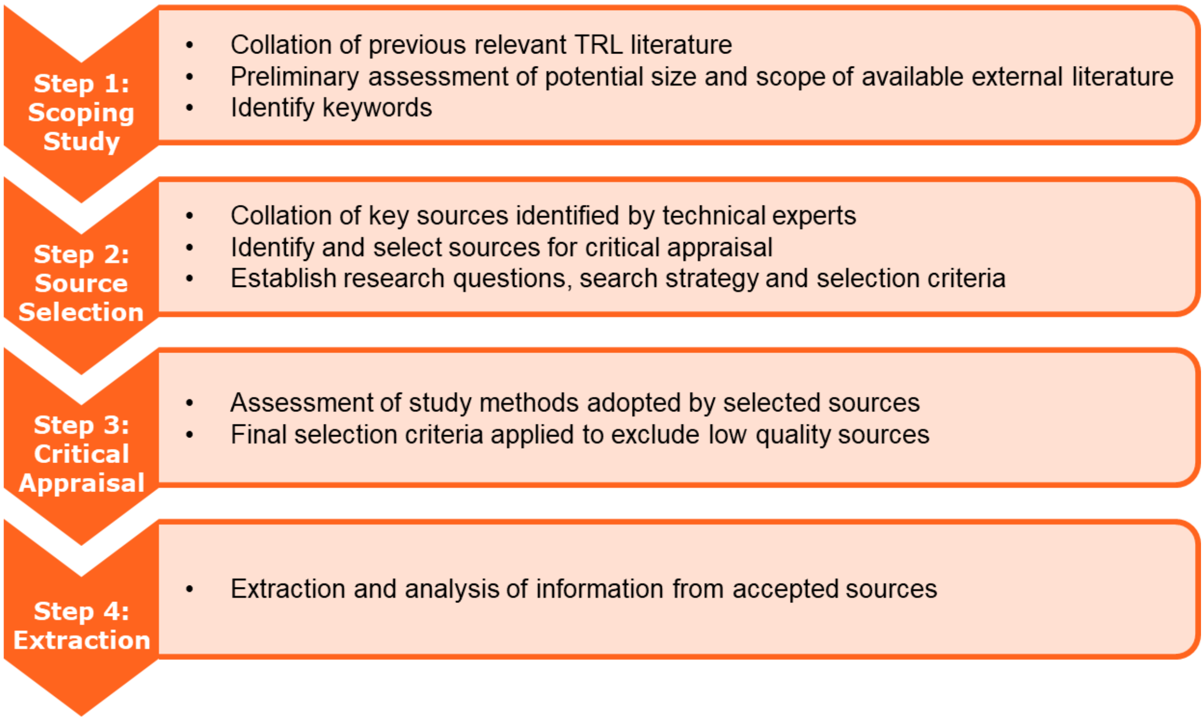


**Figure 1: High-level overview of systematic literature review process**

For each research area specified in Section 1.2 a research question was designed to query literature databases to support locating and identifying relevant sources, such as:

- What are the different terminologies and definitions used in remote operation?
- What is the current guidance, standards and regulation related to remote operation?
- What are the applications of remote operation?
- What is the role of the Safety Driver?
- What is the role of the Test Assistant?
- What are the safety considerations for the removal of the Safety Driver and Test Assistant roles from an AV?

A list of appropriate keywords, focused on the requirements of the research questions, was generated and grouped into four levels (see Table 1); Level 1, 2 and 3 applied to all research questions and Level 4 keywords were specific to individual research questions. All keywords were then transferred into a query with the following logical structure:

(“A” or “B” or “C” or…) AND (“D” or “E” or “F” or…) AND (“G” or “H” or “I” or…)

Where A, B and C are Level 1 keywords, D, E and F are Level 2 keywords and G, H and I are Level 3. Boolean logic operators (OR/AND) were also used to limit the scope of search.

**Table 1: Level 1, 2 & 3 keyword options for search strategy**

| Level 1 | Level 2 | Level 3 | Level 4 |
|---|---|---|---|
| **autonomous** | remote | operation | policy |
| **automated** | tele | operator | guideline |
| **driverless** | safety | control | guidance |
| **self-driving** | software | monitor | standard |
| **connected** | mobility | supervision | regulation |
| | advance | supervisor | safety |
| | | driver | risk |
| | | engineer | security |
| | | manager | assurance |
| | | assistance | trust |
| | | | technology |
| | | | interface |
| | | | data |
| | | | latency |
| | | | bandwidth |
| | | | delay |
| | | | trial |
| | | | test |
| | | | demo |
| | | | training |
| | | | situation |
| | | | human factors |
| | | | circumstance |
| | | | use |
| | | | use-case |
| | | | scenario |
| | | | role |

## 2.1 Defining 'advanced trial'

There have been many developments in the CAV field since the GATEway project brought CAV technology onto public roads, and into public awareness, in 2016 (Wakefield 2016; GATEway Project 2021). Now discussion in the CAV field is taking place about moving to 'advanced' trials and testing (Transport Scotland 2019b; BSI 2020b; CCAV and DIT 2020).

More recently the StreetWise project, which took to the roads of London in 2019, was referred to as an advanced trial of CAV technologies (Frost 2019c; Boland 2020) and reference to advanced CAV trials has been seen elsewhere in media articles (Frost 2019b; Paton 2019b; Road Safety GB 2019; Roberts 2019b). Yet, it remains unclear what led to the use of the term ‘advanced’ CAV trial. There does appear to be a consensus beginning to appear around one aspect of the use of the term: that ‘advanced’ trials take place on public, or at least publicly accessible, roads (Frost 2019a; GB 2019; GOV.UK 2019; Kennett 2019a; Lomas 2019; Paton 2019a; Roberts 2019a; Transport scotland 2019a).

Industry have suggested that an ‘advanced trial’ is one that comprises remote operation, without the presence of a Safety Driver in the AV (Kennett 2019b; Transport Scotland 2019b). Both the DfT’s Code of Practice for automated vehicle trialling (DfT 2019b) and Transport Scotland’s roadmap for CAVs (Transport Scotland 2019b) allow for trials of this type on UK roads as long as it can be demonstrated that a Remote Operator can have the same level of oversight of the AV as an in-vehicle Safety Driver. To-date, no known CAV trials without an in-vehicle Safety Driver have taken place on public roads in the UK.

It is unclear, based on the information in the Code of Practice or from the Centre for Connected and Autonomous Vehicles (CCAV) relating to their CAV programme for the assurance of safety and security (CAV PASS) (DfT and CCAV 2019), how a trialling organisation might demonstrate this equivalent level of safety and whether other aspects of safety, complexity, or environment will require additional consideration. Currently the Code of Practice requires trialling organisations to prepare a safety case to evidence and demonstrate that risk has been reduced to a tolerable level. In instances where a Safety Driver remains inside the AV these safety cases have focused on operational safety. If the Safety Driver is to be removed and replaced with a Remote Operator additional consideration of the related systems safety will be required.

The US DOT (2019) has created a conceptual framework consisting of three stages of testing:

1. Development and early-stage road testing
2. Expanded Automated Driving System (ADS) road testing
3. Limited to full ADS deployment

Although the term ‘advanced trials’ is not used here – stages 2 and 3 might be considered analogous to this. The second stage discussed the near completeness of the definitions of the Operational Design Domain (ODD), functional safety and aspects of the vehicle/trials, while stage 3 allows for remote operation and full specification of system requirements.

Elsewhere countries such as Estonia, Greece and Japan have included remote operation in their national policy/guidance documents (Arrúe and Heras 2018) but there is no mention of ‘advanced trials’ or equivalent terminology. To the best of our knowledge, and based on the literature and regulatory documents found and reviewed, the term ‘advanced trial’ is only used in the UK. What constitutes an advanced trial, and its definitions, are yet to be defined.

## 2.2 Remote operation terminology

Instances of the use of remote operation-related terminology have begun to appear in associated standards and regulation. In the UK DfT (2019b) the Code of Practice for automated vehicle trialling refers to ‘remote-controlled operation’, while the latest British Standards Institution (BSI) BSI (2020a) CAV vocabulary standard defines a Remote Operator as: “*an operator that oversees some or all of the operation of an automated vehicle from a* remote location"*. BS PAS 1881 also sets out guidance for the operational safety case involving Remote Operators (BSI 2020d).

The 2018 update to SAE J3016 (SAE 2018) includes definitions of three roles that can be performed remotely; it defines a remote driver as:

> *"A driver who is not seated in a position to manually exercise in-vehicle braking, accelerating, steering, and transmission gear selection input devices (if any) but is able to operate the vehicle";*

A dynamic driving task fallback-ready user as:

> *"The user of a vehicle equipped with an engaged level 3 ADS feature who is able to operate the vehicle and is receptive to ADS-issued requests to intervene and to evident DDT performance-relevant system failures in the vehicle compelling him or her to perform the DDT fallback";*

And a driverless operation dispatcher as:

> *"A user(s) who dispatches an ADS-equipped vehicle(s) in driverless operation".*

From the review of literature conducted at the time of this study it does not appear that these terms have been adopted widely among industry.

States across the United States (US) have begun to legislate to allow for remote operation in some form, while others have ruled out any form of remote operation stating that in order for a driver not to be required to be present the vehicle must be 'fully autonomous' (NCSCL 2021).[1] Terms such as 'teleoperation systems', 'remote operator', 'remote driver' and 'remotely-operated vehicle' are frequently used within these legislative documents, although they are often not explicitly defined.

Within literature from across industry, academia and the press terms such as remote (/tele-) operation (Ericsson 2017; Nuro 2018b; Buckland *et al.* 2020; Daw *et al.* 2020; Goodall 2020; Phantom Auto 2020a; Schwarz 2020; Designated Driver n.d.), remote monitoring (Man *et al.* 2015; Hampshire *et al.* 2020; T-Systems 2020), remote supervision (Costlow 2019; Lager and Topp 2019), remote control (Ericsson 2017; Hancock *et al.* 2019; T-Systems 2020; TÜV SÜD 2020) and remote driving (Liu *et al.* 2017; T-Systems 2020; Einride n.d.) have been applied, alongside discussions of emergency intervention and path planning tasks (Nissan n.d.). As yet, these terms do not appear to have an established common understanding or definition.

Currently, remote operation appears to be discussed within the CAV space with two purposes in mind:

1. **Proving system reliance by removing the in-vehicle Safety Driver:** It can be the case that during the trial and development of CAVs if a scenario is proving complicated to program into the system or the maturity of the system does not allow operation

[1] **IIHS HLDI (2021).** *Autonomous vehicle laws.* 8 January 2021. https://www.iihs.org/topics/advanced-driver-assistance/autonomous-vehicle-laws. regularly review and update their website in regard to whether each state allows for the case of an operator not in the vehicle: https://www.iihs.org/topics/advanced-driver-assistance/autonomous-vehicle-laws

under such a scenario, a Safety Driver is given the responsibility of taking back control of the vehicle. If advanced systems are to be developed that can deal with complex scenarios, removing the reliance on a Safety Driver as a fall-back is seen as a key step. Remote operation can maintain necessary oversight of the vehicle and fulfil the requirements of the Code of Practice (DfT 2019b).

2. **To support currently unforeseen scenarios:** Capturing all possible 'edge cases[2]' and unknown scenarios to program into the system with appropriate responses is a task that may never be complete, even after CAVs defined by SAE (2018) J3016 as Level 5[3] have gone into production. Remote operation can facilitate human oversight when these scenarios are encountered to plan an appropriate way forward.

In both cases, removing the Safety Driver from within the vehicle creates more space for occupants and/or goods storage and reduces the cost associated with having an in-vehicle driver. While there are clear benefits in remote operation, the high-level use cases and what a Remote Operator might be expected to do is less clear.

As part of this study TRL have consulted with relevant stakeholders to engage with them on this topic and start conversation on establishing and standardising these definitions. As an initial step, a blog post was published which sets out a preliminary argument for how these terms might be interpreted, how they are distinct, and where they overlap (Lawson 2021). This blog post was shared with stakeholders and included a survey which attempted to understand whether stakeholders saw what was set out as sensible and for them to make suggestions and comments as they saw fit. From this, an initial set of definitions was generated which was further consulted with a wider set of stakeholders as detailed in Section 3 and Section 4. A final blog post titled 'Remote Operation of CAVs: It's time to focus on terminology' is under development which will outline the challenges and the need for consistent terminology, and propose a set of definitions for the classification of remote operation activities that arise from this study.

## 2.3 The current guidance, standards and regulation landscape related to remote operation

This section considers the legislation, standards and guidelines in the UK relating to the governance of roads and the operation of vehicles on them which may prove a challenge to

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[2] The term edge case is defined by BSI as a:

> "*Rare but plausible independent parameter value within a scenario*".

Where a scenario is defined as a:

> *"Description of a driving situation that includes the pertinent actors, environment, objectives and sequences of events* ***BSI (2020a).*** *Connected and automated vehicles – Vocabulary v3.0. British Standards Institution."*

[3] Earlier editions of SAE J3016 could have been interpreted as seeing Level 5 as a level of automation that was able to appropriately navigate even unknown scenarios. The 2018 edition of the standard adds caveats to this that open up the possibility to remote operation being needed even at these high levels of automation.

the application of remotely-operated CAVs. Remote operation includes several use cases and the difficulty in satisfying the requirements is dependent upon the specific operational scenario. The following four attributes regarding the Remote Operator are considered in this section:

- The nature of the Remote Operator (human or machine).
- The actions of the Remote Operator (for example, execution of the dynamic driving task (DDT), nudges or path planning assistance).
- The location of the Remote Operator (within visual line of sight (VLOS) or distant).
- Whether or not the Remote Operator is continually supervising the AV.

An example scenario might comprise a human operator providing direct control of an AV from a remote location who was not providing prior vehicle supervision. This may occur when the AV is outside it's ODD and requests assistance.

### 2.3.1 *Definition of terms 'driver' and 'drive/driving'*

UK legislation, such as the Road Traffic Act 1988 and The Road Vehicles (Construction and Use) Regulations 1986, which govern the design, operation, and licencing of road vehicles, are based on the terms 'drive' and 'driver'. The legislation places a series of requirements on any person who is driving, or is responsible for, a vehicle on a UK road. Therefore, when reviewing the regulations, supporting guidelines and standards with respect to the application of remote operation these terms need careful consideration.

The term 'drive/driving' is rarely defined in these documents; generic definitions include:

> *"To move or travel on land in a motor vehicle. Especially as the person in control of the vehicle's movement" (Cambridge University Press 2021).*
>
> *"[to] Operate and control the direction and speed of a motor vehicle" (Oxford English Dictionary n.d.).*

Other definitions for 'drive' (usually used for non-vehicle use) include reference to providing power to propel or force someone or something to do something or go somewhere. Even when considering the definition for driving the AV the term can be used to refer to one activity or all of the tasks required to complete the DDT. The point at which the act of driving starts also requires clarity. For example, it is unclear if driving commences when the AV starts moving, when the AV's mode of propulsion is activated, or earlier.

In general, the entity responsible for driving is considered the 'driver' as defined in The Vienna Convention on Road Traffic, which came into force in 1977 and was ratified by the UK in 2018 as part of preparations for leaving the European Union and states:

> *Article 1 v: "any person who drives a motor vehicle or other vehicle (including a cycle) […] on a road".*

Interestingly, the Road Traffic Act 1988 specifically expands the term 'driver' to include the addition of persons who are involved in driving activities, such as a separate person who acts as a steersman of a motor vehicle and therefore is engaged in driving the vehicle. The Road Traffic Act 1988 provides the following interpretation of a driver as:

> *Part VII 192: ""driver", where a separate person acts as a steersman of a motor vehicle, includes (except for the purposes of section 1 of this Act) that person as well as any other person engaged in the driving of the vehicle, and "drive" is to be interpreted accordingly".*

Therefore, if an AV requests permission to proceed and a Remote Operator provides confirmation, are they considered to be 'driving' the AV and therefore the 'driver'? If a passenger uses an emergency stop, they are controlling the path of the AV and therefore should they be considered the driver? The latter question becomes further complicated when the passenger is situated in the AV and the 'driver' or Remote Operator is located elsewhere.

There have been various attempts to clarify the terms for 'driver' and 'driving' or provide additional terms to encompass CAVs. Below are some examples considered as part of this study.

#### *2.3.1.1 J3016 Taxonomy and definitions for terms related to driving automation systems for on-road motor vehicles*

As part of their work to clarify terms for CAVs, the SAE developed an associated standard (SAE 2021). This separates the terms for humans and the system, and defines the '(human) driver' as:

> *Section 3.29.1: "A user who performs in real-time part or all of the DDT and/or DDT fallback for a particular vehicle".*

And the '(human) user' as:

> *Section 3.29: "A general term referencing the human role in driving automation".*

Here, 'driver' is a generic term and is not dependent on their location whereas a remote driver is dependent on the position of the user and is defined as:

> *Section 3.29.1.2: "A driver who is not seated in a position to manually exercise in-vehicle braking, accelerating, steering, and transmission gear selection input devices (if any) but is able to operate the vehicle".*
>
> *Note 1: "A remote driver can include a user who is within the vehicle, within line of sight of the vehicle, or beyond line of sight of the vehicle".*

The standard provides specific terms for users that are not performing the DDT but have responsibilities related to the operation[4] of the AV; these are shown in Table 2. Definitions for 'DDT fallback user' and 'driverless operation dispatcher' can be found in Section 2.2. In the event the AV needs intervention, and the user performs some or all of the DDT, users become a driver.

[4] J3016 defines 'operate' as: *"collectively, the activities performed by a (human) driver (with or without support from one or more level 1 or 2 driving automation features) or by an ADS (level 3-5) to perform the entire DDT for a given vehicle during a trip".*

**Table 2: User roles while a driving automation system is engaged (SAE 2021)**

| | No driving automation | SAE level of driving automation | | | | |
|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 |
| **In-vehicle user** | Driver | | | DDT fallback-ready user | Passenger | |
| **Remote user** | Remote Driver | | | DDT fallback-ready user | Driverless operation dispatcher | |

The term 'system' is used to define the non-human entity which performs the driving tasks. What is out of scope of this standard, but needs clarification, is where the liability lies when the system is responsible for the driving task and therefore in accordance with these definitions there is no 'driver'.

#### *2.3.1.2 Other sources for definitions*

In the report by the Law Commission (Law Commission 2019b), the term 'user-in-charge' was used to refer to a driver in an AV however, to-date the term has not gained widespread use. The Law Commission has since decided (Law Commission 2019a) this would not be an appropriate term for a Remote Operator and they did not offer a new term for this role.

Several states in the US[5] have taken the approach to define the role of a 'remote driver' as a person who is positioned outside of the AV that can or does engage and/or supervise the AV. They all stipulate the requirement for the individual to be a natural person (human) that holds an appropriate licence with some states adding requirements concerning their physical location, responsibilities in the event of a collision, training, and the ability to communicate with the occupants (Goodall 2020).

A 2018 report from Sweden, presented to government proposing the regulatory changes necessary for the use of AVs, recommended that the definition of a driver be updated to allow for remote operation of AVs:

> *"A driver may drive a vehicle while inside or outside the vehicle, or control it remotely. A driver may drive multiple vehicles, and a vehicle may have multiple drivers. This means that a driver can drive multiple vehicles in platooning, for example, or when rearranging vehicles (Bjelfvenstam 2018)".*

When considering compliance with UK legislation in Sections 2.3.2 and 2.3.3, a conservative approach is taken; any of the possible actions of a Remote Operator described in Section 2.3

[5] At the time of writing these are: California, Florida, Alabama, Utah and Vermont **Goodall N (2020).** *Non-technological challenges for the remote operation of automated vehicles.* Transportation Research Part A: Policy and Practice 142. 14-26.

are considered an act of driving. Similarly, the Remote Operator is considered the driver when undertaking any of those actions.

### 2.3.2 *Are all vehicles required to have a human driver?*

Current UK law is based on the assumption that when a vehicle is used on the road there is a natural person present who is the driver of that vehicle (DfT 2015).

It is perceivable that this is because when the Road Traffic Act 1988 and The Road Vehicles (Construction and Use) Regulations 1986 were written there was no anticipation that the driving task could be conducted by anything other than a human, and that the person would be within the vehicle. Neither Act or Regulation explicitly states that a vehicle must have a driver which is human, however, The Vienna Convention on Road Traffic states that a driver is a person and that:

> *Article 8 (1): "Every moving vehicle or combination of vehicles should have a driver".*

When applying this alone, this precludes a Remote Operator from being any entity other than a person. This article does not prove to be a barrier for remote operation.

The Road Traffic Act 1988 requires a human driver to hold the appropriate licence for the vehicle they are driving:

> *Section 87: "It is an offence for a person to drive on a road a motor vehicle of any class otherwise than in accordance with a licence authorising him to drive a motor vehicle of that class".*

Additionally, the licensing requirements set out by the Road Traffic Act 1988 require a driver to be human in order to fulfil them. These include:

- Having passed a test (section 89);
- Completion of a declaration of physical fitness (section 92);
- Being a resident in the UK (section 97); and
- Being the correct age (section 101).

However, section 87 of the Road Traffic Act 1988 does not require a machine driver to hold an appropriate licence, so in isolation this does not prevent a machine from being a Remote Operator.

Another requirement that needs clarification with respect to the application of remote operation is section 107 of The Road Vehicles (Construction and Use) Regulations 1986 which states:

> *Section 107: "No person shall leave, or cause or permit to be left, on a road a motor vehicle which is not attended by a person licensed to drive it […]".*

This clause is ambiguous as it is not clear which person is being referred to, nor if any other requirements are placed on that person. It is sufficiently vague in that it may be satisfied if a human passenger, holding an appropriate licence, was present within the vehicle (and therefore attending it) for the entirety of the journey. However, the requirement for the vehicle to be attended by a person prevents a Remote Operator from being the sole driver of a vehicle in all other circumstances.

In response to a review of UK road traffic laws in 2015, the DfT published the Code of Practice: Automated Vehicle Trialling in 2015, updated again in 2019 (DfT 2019a). The Code of Practice provides guidance for trialling organisations when preparing for CAV trials; to-date, no such guidance has been written for CAV deployment. The majority of the guidance within this Code is non-statutory but trialling organisations are widely expected to comply with it. The Code allows for remote operation of AVs provided a series of conditions are met, one of which is that a Safety Driver or Safety Operator must be present at all times. The Code states that during AV trials in the public domain;

> *Section 2.5: […] "there must be a Safety Driver or operator who can use a remote-control function to be able to exercise proper control of the vehicles if necessary" […].*

The Code does not explicitly state that a Safety Driver or Safety Operator must be a person. However, it does state that:

> *Section 4.2: "A suitably licensed and trained Safety Driver or safety operator should supervise the vehicle at all times" […].*

The requirement for the Safety Driver or Safety Operator to be suitably licenced means that the Remote Operator must be a person; as previously stated, the requirements for obtaining a licence cannot be fulfilled by a machine.

PAS 1881:2020 (BSI 2020c) was created to expand on the recommendations made in the Code of Practice for a CAV trial safety case. The safety case framework details the contents expected to provide safety assurance for the operational safety of the trial. PAS 1881 expects that a Safety Operator will oversee any CAV trial and it defines a Safety Operator as a:

> *Section 3.20: "person who is trained and able to supervise the function of an automated vehicle and intervene at any time it is required".*

Therefore, PAS 1881 would also not permit remote operation where the sole operator is a machine.

The legislation, regulations, and standards considered above currently dictate that all vehicles must have a human driver. They do not prohibit more than one driver per vehicle splitting the DDT, or the use of an additional non-human driving system. However, this may introduce issues with the allocation of liability in the event of an incident. In addition, the documents do not specify where the driver in control of the vehicle must be located.

### 2.3.3 *Location, action, and monitoring requirements of the Remote Operator*

The previous section concluded that current UK legislation and standards dictate that all vehicles must have a human driver present. This section will examine the location, action, and monitoring requirements placed on the human driver.

UK legislation, specifically the Road Traffic Act 1988 and The Road Vehicles (Construction and Use) Regulations 1986, does not explicitly state that a person driving a vehicle must be within it. The requirements of the person driving the vehicle must be met, whether the person is in the vehicle or not. In accordance with the Road Traffic Act 1988 and The Road Vehicles (Construction and Use) Regulations 1986, a person driving a vehicle has ancillary responsibilities in addition to the safe completion of the DDT. These additional responsibilities complicate the task of human remote operation, especially in circumstances where the Remote Operator takes control of the AV having not have previously been monitoring it. For example, the Road Traffic Act 1988 states that a driver is responsible for the correct application of a seat belt for a child;

> *Section 15: "Except as provided by regulations, where a child under the age of fourteen years is in the front of a motor vehicle, a person must not without reasonable excuse drive the vehicle on a road unless the child is wearing a seat belt in conformity with regulations".*

The Road Traffic Act 1988 states that it is the responsibility of the user to ensure that the vehicle is not used in an unsafe manner. This includes ensuring that it is roadworthy, and it is safely loaded either with respect to the passengers or cargo.

> *Section 40A: "A person is guilty of an offence if he uses, or causes or permits another to use, a motor vehicle or trailer on a road when -*
>
> *(a) the condition of the motor vehicle or trailer, or of its accessories or equipment, or*
>
> *(b) the purpose for which it is used for, or*
>
> *(c) the number of passengers carried by it, or the manner in which they are carried or.*
>
> *(d) The weight, position or distribution of its load, or the manner in which it is secured,*
>
> *is such that the use of the motor vehicle or trailer involves a danger of injury to any person".*

This requirement to ensure the safe condition of the vehicle does not, in itself, provide a barrier to the use of remote operation however clarity is required around the term 'use' with respect to where the responsibility lies. If the vehicle is operating in automated mode it is not clear whether the responsibility to ensure that it is in a safe condition rests with the CAV operator (either the owner/service provider or Remote Operator) or a passenger who would be considered as the person using the vehicle. If the Remote Operator is considered the 'user' in this context this may influence the use of continuous monitoring or technology to ensure compliance throughout operation.

Other legislative challenges when a driver is located remotely include the obligations in the case of a road offence or collision. The Road Traffic Act 1988 states that:

> *Section 164: "Any of the following persons—*
>
> *(a) a person driving a motor vehicle on a road,*
>
> *[…]*

*must, on being so required by a constable, produce his licence for examination, so as to enable the constable to ascertain the name and address of the holder of the licence, the date of issue, and the authority by which it was issued".*

The driver has seven days to provide the information stated above so it does not prevent remote operation but needs consideration with respect to remote drive location.

As outlined in the previous section, The Road Vehicles (Construction and Use) Regulations 1986 states:

> *Section 107: "No person shall leave, or cause or permit to be left, on a road a motor vehicle which is not attended by a person licensed to drive it unless the engine is stopped and any parking brake with which the vehicle is required to be equipped is effectively set".*

Compliance with this requirement depends on the interpretations of the word's 'leave', 'left' and 'attended'. If this means a person has to be physically present, then it will prevent remote operation. It may allow for use cases whereby a Remote Operator is continuously monitoring and therefore 'attending' the AV. However, this would not cater for types of remote operation where a Remote Operator only attends to the AV in the case of a request for assistance from the AV (i.e. in an emergency). It is also unclear when applied in a scenario whereby a human user has left the AV in accordance with the requirement but then the CAV starts a mission entirely independently.

The Road Vehicles (Construction and Use) Regulations 1986 also states:

> *Section 104: "No person shall drive or cause or permit any other person to drive, a motor vehicle on a road if he is in such a position that he cannot have proper control of the vehicle or have a full view of the road and traffic ahead".*

In principle, this regulation can be fulfilled remotely. A 'full view of the road and traffic' is more feasible during VLOS operation and can be obtained from a distant location through the use of camera equipment and screens.

'Proper control' may be achievable through remote control but would require over-engineering for use cases where a Remote Operator solely provides path planning assistance as this regulation would require the Operator to have the capability to be able to take control of the AV through direct remote control.

Similar ambiguity is found in PAS 1881 regarding this topic. The PAS specifies that a safety case shall provide evidence to demonstrate that:

> *Section 5.8: "the remote operator has an appropriate level of control to ensure the minimal risk condition can always be achieved within appropriate timescales to avoid an incident*
>
> *[…]*
>
> *the system is able to deliver at least the same level of safety, situational awareness, control and response times as an alert and competent Safety Driver manually driving the same vehicle within the same ODD".*

It is again unclear as to whether a Remote Operator would need to be able to take direct control of the AV, or whether path planning assistance would be sufficient. The need to deliver the same response time as an in-vehicle Safety Driver would require a Remote Operator to be constantly supervising the AV and is a barrier to any remotely-operated system that is not constantly supervised.

The DfT's Code of Practice (DfT 2019a) also requires a trialling organisation to demonstrate that a remotely-operated system is at least as safe as having an in-vehicle Safety Driver. Additionally, it requires evidence of:

> *"A system which provides proper control of the vehicle and real-time supervision of the vehicle and its surroundings. This includes the ability to always be able to over-ride the automated system".*

As above, 'proper control' is open to interpretation and this requirement is a barrier to any remotely-operated AV that is not constantly supervised.

Another possible obstacle when applying remote operation can be found in The Road Vehicles (Construction and Use) Regulations 1986 which states that a person shall not drive a vehicle on a road while using a *"hand-held mobile telephone or other hand-held interactive communication device".* In 2018, this regulation was amended to the following to allow for remote control parking functions;

> *Section 110: (1) "No person shall drive a motor vehicle on a road if he is using—*
>
> *(a) a hand-held mobile telephone; or*
>
> *(b) a hand-held device of a kind specified in paragraph (4).*
>
> *[…]*
>
> *(5) A person does not contravene a provision of this regulation if, at the time of the alleged contravention—*
>
> *(a) that person is using the mobile telephone or other device only to perform a remote controlled parking function of the motor vehicle; and*
>
> *(b) that mobile telephone or other device only enables the motor vehicle to move where the following conditions are satisfied—*
>
> *(i) there is continuous activation of the remote control application of the telephone or device by the driver;*
>
> *(ii) the signal between the motor vehicle and the telephone or the motor vehicle and the device, as appropriate, is maintained; and*
>
> *(iii) the distance between the motor vehicle and the telephone or the motor vehicle and the device, as appropriate, is not more than 6 metres".*

The applicability of this section is dependent on the nature of the controls used by a human Remote Operator. If the controls are deemed to be a hand-held device, then this section precludes remote operation for all but close VLOS applications, as the distance between the AV and the device must not exceed 6 metres. Similarly, if a Remote Operator providing assistance does so through use of a hand-held device, and this is considered to be driving, then they would be in violation of this regulation.

The technological developments that have enabled remotely-operated CAVs has blurred the definitions of what it means to drive or the activity of driving. This has meant that the language used in legislation drafted decades ago has become ambiguous and open to interpretation when considering remote operation. It would be challenging to ensure that remote operation could be used lawfully without the clarification of definitions and potential amendment of current road traffic legislation.

Based on the review of legislation further interrogation of, and the possible need to update, legislation, standards and guidance is needed in order to apply the many possible use cases of remote operation. It is worth considering that, even with the changes that may enable these use cases, research is still needed to understand whether each use case can be applied safely. The work involved in this study will explore the gaps, enablers and research that is needed for the remote operation of CAVs on public roads in the UK. The Law Commission's 3rd consultation on AVs is aimed at addressing outstanding legal issues with remote operation and developing a legal and regulatory framework for AVs which includes remote operation. This work might address some of the possible issues highlighted in this section, however, a review of their recommendations and findings may need to be conducted to identify gaps that are not addressed.

## 2.4 The Safety Driver

### 2.4.1 *Who is a Safety Driver?*

According to (BSI 2020a) a Safety Driver has been described as a person who:

- Is situated within an AV with access to its controls.
- Paying attention to the vehicle's operating environment.
- Ensuring the rules of the testing area are followed.
- Identifying risks.
- Identifying deviations from expected behaviours and able to take full control of the DDT of the vehicle when necessary.

They perform the above tasks to ensure safety during development, testing or trial operations based on the safety case. This differs from a Remote Operator who is situated outside the AV performing similar tasks.

Similar to (BSI 2020a) definition of a Safety Driver, various countries have defined a Safety Driver in their AV trialling guides as a person situated within the vehicle who is always able to override the vehicle's automated systems whenever necessary and have a clear view of the road ahead (DGT 2017; DfT 2019a; National Transport Commission 2020). In addition, the person must be able to control the vehicle's speed and direction using manual controls at any time (Belguim FPS Mobility and Transport 2016).

In some countries such as Belgium, a Safety Driver is required to be present in the vehicle over a given speed threshold. In other cases, a Remote Operator may oversee its operation (Belguim FPS Mobility and Transport 2016).

### 2.4.2 *What are the responsibilities of a Safety Driver?*

Where vehicles are to be trialled in publicly accessible areas, countries often expect the trialling organisation to authorise the Safety Driver to oversee the safe operation of the vehicle during a trial (FPS Mobility and Transport 2016; DGT 2017; Risksdag 2017; DfT 2019a).

The Safety Driver must hold a valid licence for the vehicle category, regardless of if the vehicle's ability to operate entirely in automated mode is being tested (FPS Mobility and Transport 2016; DGT 2017; DfT 2019a). Some countries such as Spain require the Safety Driver to have held the required licence for a given minimum number of years. Belgian authority suggests drivers hold the nearest equivalent licence for prototype vehicles that are not easily categorised. Various countries recommend that individuals whose driving history indicate that they may pose an increased risk to the safety of the trial should not be used as a Safety Driver (FPS Mobility and Transport 2016; DGT 2017; Lovdata 2017; Risksdag 2017; Sano 2017; DfT 2019a; Lee and Hess 2020; National Transport Commission 2020).

During the testing process, the Safety Driver is expected to adhere to the trialling organisations robust risk management processes in place and use the knowledge and skill gathered during prior training – which should cover the type of test to be carried out – to mitigate safety issues and ensure the safe operation of the system (FPS Mobility and Transport 2016; DfT 2019a; Lee and Hess 2020).

Belgian authorities have provided a minimum set of training requirements for Safety Drivers undertaking trials in Belgium (Belguim FPS Mobility and Transport 2016). The training requires Safety Drivers to have skills over those of regular drivers of conventional vehicles. This includes having an excellent understanding of the capabilities and limitations of the technology being tested and being able to assess and control any associated risk. It also recommends that Safety Drivers get acquainted with the vehicle and system to be tested in controlled environments, such as testbeds, before trials in public areas. It also requires Safety Drivers to understand when to intervene through training covering potential hazardous situations and how to react to them. Additionally, training is expected to cover transition between manual mode and automated mode and vice versa.

A Safety Driver is the person responsible for driving and operating the vehicle at all times, hence they are expected to be able to drive, operate or control the vehicle safely and under any condition (FPS Mobility and Transport 2016; DfT 2019a; Lee and Hess 2020). Safety Drivers are obligated to take full control of the vehicle under circumstances that may be detrimental to the vehicle's occupants or other road users. In some countries such as the UK and Belgium, Safety Drivers are expected to maintain a conventional driving posture and remain alert during operation in all driving modes to avoid distracting other drivers. However, in Germany the law does not require the Safety Driver to constantly concentrate, but they are required to immediately take control of the vehicle when needed. The regulation in Japan requires the Safety Driver to be seated in the driver's seat, pay attention to the surrounding traffic and the condition of the vehicle as well as being capable of immediately taking control of the vehicle's DDT when necessary.

In Germany, the Safety Driver and trialling organisation are liable for incidents that may occur due to the Safety Driver's failure to regain control of the vehicle when prompted.

However, the liability for incidents that may occur due to the ADS failure does not lie with the Safety Driver (Lee and Hess 2020).

Based on various countries' guidelines for AV trialling, in cases where the testing area is publicly accessible the role of the Safety Driver during operation may be broken down into the following (FPS Mobility and Transport 2016; DGT 2017; Lovdata 2017; Risksdag 2017; Sano 2017; DfT 2019a; Lee and Hess 2020; National Transport Commission 2020):

- The Safety Driver is expected to always supervise the vehicle regardless of its mode of operation (i.e., manual, or automatic), ensuring its safe operation at all times. They must remain alert and ready to intervene if necessary, throughout the test operation.
- They are expected to pay attention to the vehicle's environment, observing the traffic laws, and the safety laws and laws restricting vehicle access.
- Safety Drivers should be sufficiently conversant with the system, including its capabilities, performance, and limitations, be able to detect deviations from expected behaviours and take full control of the vehicle's DDT if necessary.
- In the UK, if AV operation is on publicly accessible private roads, the Safety Driver is expected to, as a minimum, be able to apply an emergency stop control whenever necessary.
- In Belgium, if the vehicle carries passengers the Safety Driver or trialling organisation is obligated to inform the passengers about the test and the fact that the vehicle is a prototype prior to the test.

Across industry, the Safety Driver is viewed as integral to the safe operation of the vehicle. As a result, Safety Drivers are often carefully selected by the trialling organisation for the role (Aerotek n.d.; Startup.jobs n.d.). In accordance with most countries' guides, trialling organisations require eligible Safety Drivers to hold a driving licence; however, the minimum number of years that they are expected to have held the licence varies from 2-5 years. Trialling organisations also require that the maximum number of points on eligible drivers does not exceed a given threshold, which also varies among the organisations. They require the Safety Driver to be without convictions (including driving while intoxicated) in their driving history for a minimum number of years prior to the test commencement, which is sometimes based on the jurisdiction of the testing area. The trialling organisation also usually requires the Safety Driver to be conversant with the testing area for various reasons including providing effective feedback of the vehicle's behaviour, location and general performance.

In terms of their responsibility during trialling operations, according to trialling organisations' job descriptions for Safety Drivers in the US, a Safety Driver may be required to perform the following tasks as part of the testing operation (Aerotek n.d.; SimplyHired n.d.-a; SimplyHired n.d.-b; SimplyHired n.d.-c; Startup.jobs n.d.):

- Remain alert during the entire testing operation and comply with the set maximum working hours to avoid fatigue while in operation.
- Remain seated in the driver's seat of the vehicle and operate the vehicle in both automated and manual modes.

- Follow all policies and safety procedures and ensure the safety of both the vehicle and other road users through monitoring and intervention when required.
- Operate the vehicle on routes that may or may not be defined including various geographical and environmental conditions. They may be required to be able to read a map or use a Satnav application.
- Work in teams where they may alternate between:
    - Driving the vehicle in manual mode and monitoring the vehicle's behaviour in automated mode, taking control of the vehicle where necessary.
    - Monitoring the system's software, the cameras and error messaging, operating in-vehicle data recording computers (e.g., start/stop recording) and logging data.
    - Providing verbal feedback/directions about the vehicle's environment.
- Involved in the vehicle preparation which may include:
    - Inspection of the vehicle before and after trips, including external and internal visual inspection and testing all necessary equipment.
    - Assist in mounting of the ADS hardware, including sensors, computers, and general wiring.
    - Prepare the vehicle for testing and functional support as well as fuelling or charging the vehicle.
- Providing subjective feedback on the test, which may involve documenting test results.
- Involved in diagnosing and troubleshooting issues related to the hardware and software aspects of the system (such as GPS, actuators, network communication, radios).
- Involved in developing testing procedures.
- Potentially required to provide quality service for passengers when applicable, including chauffeuring guests in a responsible, safe, and friendly service-orientated manner.
- Engaging with public safety officers if necessary.
- Completing accident and incident reports as required.
- Controlling and managing emergency situations based on the trialling organisation's procedures.

## 2.5 The Test Assistant

### 2.5.1 *Who is a Test Assistant?*

Different terms have been used to refer to a Test Assistant including Autonomy Control System Operator (ACSO) and Software/Test Engineer. For the purposes of this report, the term 'Test Assistant' will be used.

The role of a Test Assistant is not widely defined. According to (Belguim FPS Mobility and Transport 2016) and (Isle of Man DoI 2017) a Test Assistant is a person who assists the Safety Driver when conducting trials. This could be done by, for example, monitoring the behaviour of the vehicle through digital information displays, or other information feedback devices, and by observing other road users.

Depending on the test being carried out, a Test Assistant could be deployed to assist a Safety Driver during the trialling operation (Belguim FPS Mobility and Transport 2016). This could be in a situation where a conventional vehicle being tested has been modified to include automated functionalities. In this instance, the Test Assistant could assist the Safety Driver by monitoring the information on the system's display, or other information feedback systems, and relaying relevant information to the Safety Driver when necessary.

### 2.5.2 *What are the responsibilities of a Test Assistant?*

According to the industry's job description for a Test Assistant, a Test Assistant is responsible for (Aerotek n.d.; SimplyHired n.d.-c):

- Monitoring the vehicle's behaviour through software.
- Logging data related to the trial, which may include starting and stopping recording of data by the sensors.
- Data marking and performing minor debugging operations when needed.
- Providing verbal feedback/directions to the Safety Driver concerning the AV's environment.
- Occasionally providing subjective feedback to the engineering teams on the vehicle's behaviour.
- Localising the vehicle and sometimes relaying this information to the Safety Driver when needed.

## 2.6 Safety considerations for the removal of the Safety Driver and Test Assistant roles from the vehicle

### 2.6.1 *Communications*

Remote operation methods, particularly those that require control of the vehicle or uninterrupted communication with it (such as remote supervision or remote control), require the transmission of large amounts of data over wireless networks with remote driving in particular having additional requirements on service reliability and availability. Other forms of remote operation that do not involve constant supervision or control of the vehicle still require wireless communication between the Operator and vehicle, although their requirements in data throughput are likely lower.

Transferred data include video streams or still images from camera sensors, Controller Area Network (CAN) data (such as vehicle speed and diagnostics), Global Positioning System (GPS) coordinates, and data from other sensors (such as LiDAR, Radar and ultrasound) from the AV to the Remote Operator. Remote Operators must also be able to send commands to the AV (e.g. waypoints) or take over driving (i.e. controlling vehicle actuators) (Goodall 2020).

Latency in the context of communications refers to the time required for a data packet to travel from one point to another (Techopedia 2020), with wireless connections having higher latencies due to the over-the-air transmission (instead of wired) and the distance between transmitter and receiver. CAVs can be very sensitive to high latency, with data collected from on-board systems and external sources that must be analysed and transmitted in real-time without fail. Even the slightest delay can significantly impact the driving experience and have a significant impact on safety. Remote operations introduce the possibility of additional delays that need to be considered, with the transmission of critical control and safety-related data across large distances – possibly many hundreds of miles.

Currently, there are no clearly defined latency requirements for remote operation, although existing wireless networks can support high bitrate video streams. 5G networks[6] will increase bandwidth and reduce latency significantly compared with current 4G/LTE (Long-Term Evolution, a wireless standard with higher specifications compared to 3G, but considered slightly inferior to a "true" 4G network) networks, with theoretical speed increasing by at least 10 times compared to 4G/LTE (depending on network frequency) and latency dropping potentially down to 1ms (Thales Group 2020). The table below presents a speed/latency comparison between different mobile network generations. It should be noted that the maximum speed values are theoretical (based on the specifications of each technology) and not representative of real-world performance, where lower speed should be expected.  They are indicative however of the differences between network generations.

**Table 3: Mobile network speed/latency comparison**

| Mobile network generation | Top speed (theoretical) | Latency (theoretical) | Average speed (approx.) |
|---|---|---|---|
| 3G | 42 Mbps (Mbits/s) | 100-500ms | 5 Mbps |
| 4G/LTE | 100 Mbps | 50-100ms | 10 Mbps |
| 4G/LTE Advanced | 1 Gbps | ~10ms | ~15-50 Mbps |
| 5G | 10 Gbps | 1-10ms | >50 Mbps |

[6] the UK aims for the majority of the population to have access to a 5G signal by 2027 **DCMS (2020).** *Factsheet 6: 5G.* https://www.gov.uk/government/publications/telecommunications-security-bill-factsheets/factsheet-6-5g.

The impact on network performance, quality of data transfer and performance of the remote driver is expected to be significant. The benefits of 5G for vehicles outside of urban areas will likely not be immediately apparent – a 2018 report by the RAC Foundation showed that even 4G coverage is not complete on Great Britain's roads (44% of roads in Britain only had partial network coverage and 6% no coverage at all) (RAC Foundation 2018).

Camera-based systems (remote operation being one such system) have 3 types of latency related to video transfer:

1. **Basic video latency:** delay between a real-time event and the display of the event through the control unit.
2. **End-to-end system latency:** delays between user input, system output and display of system execution (also known as System Response Time – SRT)(Ericsson 2017).
3. **Command to action latency:** delay between user input and observable system output (Zwiebel 2017).

Apart from video-based latency, other types of latency need to be considered for the remote operation of a vehicle. The key contributors for end-to-end latency for vehicles – System Response Time (SRT) are the following:

1. **Mechanical delays** (delays related to the physical actuators within the vehicle itself): This type of latency has been identified as the largest contributor to response time for vehicles. It is expected that the conversion of vehicle systems from manual (human) driving to automated operation will reduce this type of delay significantly.
2. **Video processing delay** (latency related to the processing of video frames, e.g., the time required to detect objects by a machine learning algorithm).
3. **Network delay** (also known as Round Trip Time - RTT): this is the delay due to the transmission of data over wireless networks (such as cellular and Wi-Fi) (Ericsson 2017).

Network latency depends on the type of network used and even in the case of the same network type, it can vary significantly. Various studies have shown that video latency over 3G is measured at over 120ms and 4G/LTE network two-way latency was measured at 75-100ms (Dano 2013; Chucholowski *et al.* 2014; Shen *et al.* 2015; Liu *et al.* 2017; Kang *et al.* 2018). That means that even sending a video file through wireless network introduces a delay that can impact remote operation performance. Any delay of this type can lead to delayed response (or loss of control) that can lead to safety-critical incidents, especially at high speeds. 5G radio networks are expected to lower network delay to under 4ms (theoretical latency as low as 1ms), a figure that is significantly improved compared with previous network generations. At this level, the physical distance between operator and vehicle under control is likely no longer a critical factor and the focus can shift to other delay types that affect driver performance.

In addition to reduced latency, 5G networks introduce other services that can benefit remote operation, such as beamforming and network slicing. Beamforming is the application of multiple radiating elements that transmit the same radio signal (identical wavelength and phase), which combine to create a single antenna with a longer, more targeted stream which is formed by reinforcing the waves in a specific direction (Veen and

Buckley 1988). Essentially, radio power can be focused on the remote vehicle, providing better communication between the vehicle and the station (Metaswitch 2020).

Network slicing allows independent logical networks that share the same physical infrastructure to be created on the same wireless network. Each slice is isolated from others (performance not affected) and consists of dedicated and/or shared resources (storage, processing power, bandwidth). This would mean that remote operation or CAVs could have dedicated resources and priority compared with other services/clients (RF Wireless World 2020).

Bandwidth requirements for remote operation are not clearly defined, with reported figures varying depending on the test setup. The quality of the video stream is a key parameter (compared to other sensors, cameras have much higher bandwidth requirements), with the number of cameras, video resolution and frame rate greatly affecting the bandwidth requirements. Upload requirements range from a high (and stringent) of 20Mbps (Saeed *et al.* 2019) down to 3Mbps (using 3 cameras at a low 640x480 resolution) (Neumeier *et al.* 2019). Remote operation of vehicles has also been tested with video upload requirements of 10Mbps (Inam *et al.* 2016). The upload requirement for a single 1080p60 video feed is calculated at 8Mbps, with Ericsson testing solutions using 3 such cameras (24Mbps bandwidth requirement) using current codecs (Ericsson 2017; Goodall 2020). High availability will also be necessary, especially for remote operation, where any network failure can have significant impact on safety.

At present, the effects of latency on driver performance during remote operation are tested in closed tracks or simulations. While the effects of different latency figures on driving performance and vehicle control have been evaluated, it is not yet known how this might translate in a dynamic driving environment. Driving under constant latency has been found to offer a better experience compared to driving with fluctuating latency even if latency in general is problematic when responding to emergencies (Goodall 2020).

### 2.6.2 *Data*

A CAV, with or without remote operation, is dependent on numerous data sources to operate. These data sources can be internal or external to the CAV and include sensor data, mapping and external operational data. These data sources determine what information the control systems in the CAV have about its surroundings and the task it is to complete. Where a CAV is remotely operated, some of this data needs to be communicated and presented to the human Remote Operator to enable them to understand the surroundings of the CAV; this enables them to complete their task. Due to humans and machines requiring different forms of information for decision-making, often only parts of the data available to the CAV are communicated to the Remote Operator.

An early example of successful operation of CAVs is the DARPA Urban Challenge in 2007. The aim of the challenge was for completely autonomous vehicles to complete 55 miles of urban driving tasks within a 6-hour time limit. Three vehicles completed the challenge within the time limit and others completed it outside the time limit (Voelcker 2007). **Error! Reference source not found.** compares the sensor types and data sources of two entrants to the challenge (a semi-finalist and finalist) with two recently developed CAVs. It can be seen that the types of data sources used have remained quite constant over this time period. All of the CAVs listed use cameras, LiDARs, Radars, an Inertial Measurement Unit (IMU), a Global Navigation Satellite System (GNSS) and a form of High Definition (HD) mapping as the major data sources. This is typical of other current CAVs which are under development (Ford 2018; General Motors 2018; Nvidia 2018; Wood *et al.* 2019; Hartwig 2020; Lyft 2020; StreetDrone 2020b; Uber ATG 2020). Other data sources, such as retroreflectivity and ultrasound, are now less widely used. Audio data sources have been gained by current CAVs to communicate with passengers and emergency services, and to detect emergency vehicles. These were not requirements in the DARPA Urban Challenge. Although data sources have stayed similar over time, each will likely have improved in quality and accuracy because of more mature technology and greater data processing and storage capability.

**Table 4: An overview of the main sensor systems and data sources used in two vehicles used in the DARPA Urban Challenge and two current CAVs**

| | DARPA Urban Challenge | | Current CAVs | |
|---|---|---|---|---|
| **Vehicle operator** | Team Berlin (2007) | Team MIT (2007) | AutoX (2018b) | Waymo (2020) (Jeyachandran 2020) |
| **Vehicle/version** | Spirit of Berlin | - | - | 5th-generation Waymo Driver |
| **Approximate year(s) of operation** | 2006 - 2007 | 2006 - 2007 | 2018 - current | 2020 - current |
| **Camera(s)** | ✓ | ✓ | ✓ | ✓ |
| **Audio** | | | ✓ | ✓ |
| **LiDAR** | ✓ | ✓ | ✓ | ✓ |
| **Retroreflectivity** | ✓ | | | |
| **Radar** | ✓ | ✓ | ✓ | ✓ |
| **Ultrasound** | ✓ | | | |
| **Inertial Measurement Unit (IMU)** | ✓ | ✓ | ✓ | ✓ |
| **Odometer** | ✓ | | | |
| **Global Navigation Satellite System (GNSS)** | ✓ | ✓ | ✓ | ✓ |
| **High Definition (HD) maps** | ✓ | ✓ | ✓ | ✓ |

Sections 2.6.2.1 to 2.6.2.10 discuss data sources relevant to remote operation in turn. For each section, there is a table which gives details about the technology. This includes a brief description, a list of potential users of the data and an estimate of data transfer requirements. The list of potential users is based on those discovered in the references in that section and across section 2.6.2. The estimate of the data transfer requirements is an engineering judgement based on the type of data, its sample rate and sample size. For some of these data sources advanced data compression techniques exist which will go some way to reduce the data transfer requirements. Following the table in each section there is a short discussion of example of the data source being used during remote operation.

#### *2.6.2.1 Cameras*

| | |
|---|---|
| **Brief description** | Cameras are used to collect visual information at a point in time. This is normally done repeatedly in a video. A CAV would typically have many cameras at different angles to give a comprehensive view of the CAV's surrounds (Jeyachandran 2020). The cameras could operate in the visible or infra-red spectrums and may be supported by lights to enable them to operate in poor lighting conditions. Image quality and therefore data quality can be degraded by bright lights or poor weather conditions. Interpreting visual data from cameras is an advanced and active research topic for both CAVs and other applications. Techniques exist to use data from single or multiple cameras to determine depth and positions of objects, recognise objects and infer movement from video feeds (Janai *et al.* 2020). |
| **Potential users** | CAV systems, remote driver, remote assistant |
| **Data transfer requirements** | High |

Visual data from cameras is the most common data type to be used for remote operations of any kind. The vast majority of examples of remote operation found in the literature used a video feed with or without other data sources to inform the Remote Operator (Huawei 2017b; AutoX 2018b; Harris 2018; Designated Driver 2019b; Ottopia Team 2019; Sauliala 2020; Voyage 2020; Webb 2020).

For remote control of vehicles, a common arrangement of cameras is one forward-facing camera, two side-facing cameras and a rear-facing camera (Huawei 2017a; AutoX 2018a; Harris 2018). This gives the Remote Operator a similar perspective as if they were sitting in the driver's seat of the vehicle. It has been shown to be challenging to transmit the required data for multiple simultaneous high-quality video feeds. This requires either extremely reliable mobile network connectivity or carefully designed adaptive video quality approaches to maximise the transfer of useful information when connectivity problems occur (Harris 2018).

Another use of remote visual data is for interventions which assist the automation system. Where a CAV reaches a novel situation and it is unsure how to proceed, some developers have enabled a Remote Operator to approve if an action is safe or to assist interpretation of a scene (AutoX 2018b; Ottopia Team 2019; Sauliala 2020; Voyage 2020; Webb 2020). A primary data source used by the Remote Operator, found in all of these implementations, is the external-facing view from the CAV from the camera video feeds.

#### 2.6.2.2 Audio

| | |
|---|---|
| **Brief description** | Microphones are used to record the sounds occurring either inside the CAV or its surroundings. This can be for the purposes of communicating with passengers and emergency services or detecting the presence of emergency vehicles with sirens. |
| **Potential users** | CAV systems, remote driver, remote assistant |
| **Data transfer requirements** | Medium |

Remote audio data has been used to enable communication between a Remote Operator and passengers (Harris 2018; Sauliala 2020; Waymo 2020) or between a Remote Operator and emergency services (AutoX 2018b; Waymo 2020). The audio connection is to enable quick human-to-human communication when there are incidents, vehicle problems or a customer service need. No examples have been found where these audio connections have been used to aid the Remote Operator when in remote control.

Audio feeds might be considered for remote operation to assist a Remote Operator in interpreting information, such as acceleration based on engine sound, although this type of auditory information could also be simulated using data relating to vehicle speed and revolutions per minute (Chen 2015).

#### 2.6.2.3 LiDAR

| | |
|---|---|
| **Brief description** | A LiDAR is an instrument which can measure distance to a point using reflected laser light. Typically, the direction the laser is pointing is rapidly changing which enables many point distance measurements to be taken to build shapes and maps of the CAV's surroundings. A CAV may use multiple LiDARs to ensure full coverage of its surroundings at the resolution required for different ranges. LiDARs which are used on CAVs have a range of up to 300 m (Jeyachandran 2020). Interpreting visual data from LiDARs is an active research topic for CAVs to enable object recognition (Yang *et al.* 2018). Rain can attenuate the laser light from a LiDAR, reducing the data quality in bad weather (Filgueira *et al.* 2017). |
| **Potential users** | CAV systems, remote driver, remote assistant |
| **Data transfer requirements** | Medium |

Compared with visual data, LiDAR data is less immediately interpretable by humans because of its low resolution. Designated Driver state they make visualised LiDAR data available to a Remote Operator performing remote control. This is alongside camera and other data sources to help the Remote Operator understand the vehicle's surroundings (Designated Driver 2019b). Hosseini and Lienkamp (2016) demonstrate a method of combining LiDAR data with visual data to enable remote control of a vehicle in simulation. The LiDAR data is used to augment the visual data at angles where there is not a camera feed and to provide more certainty about the distance to close objects. The LiDAR data has the advantage that it requires less bandwidth than additional video feeds.

LiDAR data is one of the primary sources of information used by CAVs. Therefore, when a Remote Operator is intervening in the decision-making of a CAV, this data can be made readily available to them and visualised (Ottopia 2019; Voyage 2020).

#### *2.6.2.4 Retroreflectivity*

| | |
|---|---|
| **Brief description** | Retroreflectivity is the strength of the light reflected on the coincident path to the illumination source. This can be measured either as an additional output of a LiDAR (Asvadi *et al.* 2017) or by a dedicated device (Team Berlin 2007). Because this measurement requires a light source, the outputs are consistent between day and night. However, the measurements can still be affected by wetness or dampness. |
| **Potential users** | CAV systems |
| **Data transfer requirements** | Medium |

There are limited references of CAVs which use retroreflectivity data in the literature although high resolution ground plane reflectivity obtained using a LiDAR is included in the open Ford Multi-AV Seasonal Dataset (Agarwal *et al.* 2020). No examples of its use in a remote setting have been found.

#### *2.6.2.5 Radar*

| | |
|---|---|
| **Brief description** | A Radar is an instrument which can measure the range and velocity of objects using reflected radio waves. The dimensions of the transmitted radio beam can be different for different radars which gives choice over the size of area scanned. Radars are often rotated or multiple radars are combined to allow them to scan larger areas and build a spatial map. Radio waves are less sensitive to weather conditions than cameras or LiDAR. Radars used in CAVs typically have a range of up to 200 m so are used to detect objects both close and faraway from the CAV (Murray 2019). |
| **Potential users** | CAV systems, remote assistant |
| **Data transfer requirements** | Medium |

As discussed at the beginning of Section 2.6.2, radar data is one of the most common sources of information used by CAVs. Designated Driver state they make visualised radar data available to a Remote Operator performing remote control. This is alongside camera and other data sources to help the Remote Operator understand the vehicle's surroundings. Where the Remote Operator is intervening in the operation of the automation system, no explicit mention of remote use of radar data has been found. However, it is likely to be included in the bundled sensor data communicated remotely for this purpose (AutoX 2018b; Sauliala 2020).

#### 2.6.2.6 *Ultrasound*

| | |
|---|---|
| **Brief description** | An ultrasonic rangefinder can measure the distance to an object using reflected ultrasonic waves. The dimensions of the transmitted ultrasonic beam can be different for different ultrasonic transducers which gives a choice over the size of area scanned. An array of ultrasonic transducers can be combined to enable larger areas to be scanned and a spatial depth map to be built (Bank 2002). Ultrasonic rangefinders used in CAVs typically have a range of up to 5 m (Bosch n.d.) so are used to detect objects very close to the CAV. |
| **Potential users** | CAV systems |
| **Data transfer requirements** | Medium |

Ultrasound data is used for detecting objects near CAVs, which overlaps with the capabilities of radar data. As discussed in section 2.6.2, it has been observed that the use of radars is much more common than the use of ultrasonic sensors. This is probably because of the shorter range of ultrasonic sensors (Babak *et al.* 2017). An exception to this is Designated Driver who visualise ultrasonic data remotely to assist a Remote Operator during remote control (Designated Driver 2019b).

#### 2.6.2.7 *Inertial measurement unit*

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|---|---|
| **Brief description** | The Inertial Measurement Unit (IMU) is a device consisting of accelerometers and gyroscopes which measures the accelerations the IMU is subjected to in three axes. When attached to a CAV, it enables the CAV to determine its velocity and acceleration and this can be used to infer the position of the CAV over time. IMUs tend to suffer from drift over long periods of time which is the summation of small systematic errors leading to an overall error. They therefore need to be corrected periodically by referencing to another source of position information (Borenstein and Ojeda 2009). |
| **Potential users** | CAV systems |
| **Data transfer requirements** | Low |

The IMU provides acceleration and velocity data to the CAV control systems. What, if any, part of this information is transferred to a Remote Operator is not regularly mentioned in the literature. Given that the vehicle CAN holds similar information, together with other possibly useful diagnostic information, this is the more likely source of information that would be communicated in most remote driving scenarios.

### 2.6.2.8 *Odometer*

| | |
|---|---|
| **Brief description** | A device which measures the distance travelled by the CAV. The odometer records the output of a rotation sensor on the axel of the vehicle and from this the distance can be calculated. The same sensor can also be used to find the speed and acceleration of the vehicle (Sobey 2009). |
| **Potential users** | CAV systems |
| **Data transfer requirements** | Low |

Discussions on the use of odometer data as an input to CAV systems is rare. The exception is Team Berlin (2007), as part of the DARPA Urban Challenge. However, no examples of the remote use of odometer data have been found. It may be that odometers are used to support the IMU or CAN data but are not used as the primary data source.

### 2.6.2.9 *Global navigation satellite system*

| | |
|---|---|
| **Brief description** | A Global Navigation Satellite System (GNSS) consists of a device which receives time signals transmitted via radio waves from satellites. Interpreting these signals enables the GNSS receiver to determine its location. Multiple GNSS systems exist including GPS, GLONASS, BeiDou and Galileo. The accuracy of these systems varies significantly between systems and location but is approximately to within 5 m (Van Diggelen and Enge 2015). GNSS systems perform less well in urban areas because buildings can interfere with the radio waves from satellites (Ji *et al.* 2010). Therefore in CAVs, GNSS systems are often used as a secondary location system that supports location obtained using HD maps (Waymo 2020). |
| **Potential users** | CAV systems, remote driver, remote assistant |
| **Data transfer requirements** | Low |

GNSSs report the approximate location of the CAV to the accuracy available from the system. No direct references to the use of GNSS data for remote use have been found but the position of the vehicle is shown on road maps in images in the literature (AutoX 2018b; Harris 2018; Ottopia 2019; Sauliala 2020) and these will now be described. It is likely these positions came from GNSS data. In both Harris (2018) and Ottopia (2019), figures show a map can be seen being used by a Remote Operator performing remote control. In both AutoX (2018b) and Sauliala (2020), a map can be seen as part of the data available to a Remote Operator who is intervening in the operation of the automation system. The data requirements of transferring GNSS position would be very small compared to the primary data sources used for remote operation.

#### 2.6.2.10 High definition maps

| Brief description | High definition (HD) maps are highly detailed 3D maps of the location the CAV can operate in. They typically contain centimetre-level resolutions and, when used with the CAVs camera and LiDAR data, enable precise positioning of the vehicle in an environment. The maps may also contain other information about the environment, such as permitted routes, which inform CAV decision-making (Vardhan 2017). Generating and updating HD maps is an active research topic for both CAVs and other mobile robotics (Bresson *et al.* 2017). |
|---|---|
| **Potential users** | CAV systems |
| **Data transfer requirements** | High |

HD maps are primarily used by a CAV to determine its precise position. HD maps are not typically optimised for interpretation by humans (Vardhan 2017), so it is unlikely that they would be communicated in real-time for remote operation. However, a remote copy may be used as a reference to assist a Remote Operator. An example of this is shown in Voyage (2020) where the outline of buildings is used to help with the interpretation of LiDAR data.

### 2.6.3 *Workload and situational awareness*

#### 2.6.3.1 Situational awareness when remotely operating CAVs

When humans conduct tasks, such as driving, we continuously sample information from the environment, react, perceive changes in the environment, react, and so on (Groeger 2000). Driving involves sampling and processing sensory information from multiple human senses, such as vision, hearing, and haptic (Molholm *et al.* 2002). Cues from each sense deliver valuable information for the driver to respond safely to the dynamics of the traffic scene and anticipate future events (Stahl *et al.* 2014). Assigning the driving task to Remote Operators creates challenges as the sensory information delivered through the interface presents a limited view of the entire traffic environment, for example limited depth cues (Fong *et al.* 2001), limited aural and haptic cues (Gnatzig *et al.* 2013; Chen 2015). Providing a Remote Operator with as much information as possible about the traffic environment will help them to operate the vehicle accurately and safely.

#### 2.6.3.2 The concept of situational awareness

Situational awareness or situation awareness (SA), both used synonymously, is a concept widely used in literature. Endsley (1995) defines SA as the following:

> *"Situation awareness is the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future."*

SA is a dynamic process in which elements of the environment are perceived, interpreted and implications of their future states are drawn. Endsley (1995) describes that information from the environment is continuously processed in three levels to create and maintain SA:

- Level 1: perception of the elements in the environment.
- Level 2: comprehension of the current situation.
- Level 3: prediction of future status.

All three levels are important for decision-making.

Furthermore, when a remote operation interface is evaluated, consideration of those levels helps to determine any error and improve the design (Krajewski 2014). For example, if the Remote Operator navigated the vehicle through a car park and had a minor collision with a parked vehicle because they incorrectly estimated the distance, cues concerning distance and depth of objects present in the environment might be missing.

SA is of key importance because it describes how humans perceive a situation and interpret it to form their response Endsley (1995). When information on an environment is not perceived, or information is interpreted incorrectly, it can lead to collisions or other incidents such as the example described above. Humans perceive information on an environment using different sensory channels. Schweigert (2003) provides an overview of the sensory channels human drivers use to perceive information about the driving environment (Table 5). These are important considerations in order to provide a Remote Operator with information about the traffic environment - SA level 1.

**Table 5: Human sensory channels used to interpret information about the driving task, Table on page 4 in Schweigert (2003)**

| Information | Visual | Vestibular | Haptic | Acoustic |
|---|---|---|---|---|
| **Lateral Velocity** | X | | | |
| **Driving Velocity** | X | | | X |
| **Longitudinal and Lateral Accelerations** | | X | X | |
| **Yaw Speed** | X | | | |
| **Yaw Acceleration** | | X | | |

Stanton *et al.* (2001) summarise the following recommendations to maintain high SA from Endsley (1995) when designing interfaces controlling any safety-critical system:

1. Reduce the requirement for people to make calculations.
2. Present data in a manner that makes level 2 SA (understanding) and level 3 SA (prediction) easier.
3. Organise information in a manner that is consistent with the persons' goals.

4. Indicators of the current mode or status of the system can help cue the appropriate SA.
5. Critical cues should be provided to capture attention during critical events.
6. Global SA[7] is supported by providing an overview of the situation across the goals of the operator.
7. System-generated support for projection of future events and states will support level 3 SA.
8. System design should be multi-modal and present data from different sources together, rather than sequentially. in order to support parallel processing of information.

Although not specific to remote operation, these recommendations provide a set of guidelines that can increase SA in any interface controlling safety-critical systems.

Sections 2.6.3.3 to 2.6.4.1 below discuss a wide range of human factors topics that have been identified to impact the safe and accurate remote operation of vehicles and highlights how technology has attempted to address them.

#### *2.6.3.3 Workload*

When considering SA in a remote operation context, its relationship with mental workload needs to be addressed (Young *et al.* 2015). Research has widely assessed the impact workload has on SA (Edwards *et al.* 2017; Noy *et al.* 2018), finding that automation generally decreases the workload perceived by the Remote Operators. In turn, this can potentially lead to boredom (Matthews *et al.* 2019) and therefore reduced SA (UNECE 2020). In particular, Cummings *et al.* (2013) found that reaction times and directed attention significantly decrease over time when operating remotely; specifically, the experimental task lasted 4 hours, and the results showed that the participants were distracted almost half of that time. However, it was suggested that the development of effective attention switching techniques could counteract the reduced directed attention, although more research is necessary to identify these compensatory strategies.

Inadequate workload to sustain attention could pose several challenges to Remote Operators, as it has been highlighted that low SA results in longer take-over times (Clark *et al.* 2017) and overreliance on the system (Cooke 2006). This is especially important when considering less experienced operators, who tend to perceive a reduction in the required workload while the objective workload remained the same (Stapel *et al.* 2019). Therefore, operators with less experience are likely to underestimate the cognitive resources required to complete the tasks due to the perceived benefits of automation.

However, Regan *et al.* (2013) argued that the cognitive task demand does not automatically decrease with automation, but that it varies depending on the familiarity with the task. Specifically, operators still need to utilise the same number of cognitive resources for the higher-level tasks (i.e. tasks that tend to vary consistently), especially when they are

[7] Global SA refers to situational awareness over every aspect of the task at hand and the environment.

experiencing increased workload, so that performance is not affected. On the contrary, well-practised tasks (meaning that the operator performed it before) would be unaffected by the experienced workload (Engström *et al.* 2017). This means that driving and operating experience play a key role in determining the operators' workload and consequently their SA in the context of remote operation.

A theorised solution to promote the sustainment of attention, even with reduced workload, is gamification, which has been hypothesised to contribute to maintaining attention over time by enhancing arousal (Steinberger *et al.* 2017). Through the use of positive and "gameful" experiences (Hamari *et al.* 2014), which draw their inspiration from videogames (Deterding *et al.* 2011), operators are more likely to feel motivated and remain engaged on the task at hand.

When White *et al.* (2019) investigated how to enhance the building and maintaining of SA during takeover in level 3 automated vehicles, it was found that a top down guidance approach, with drivers being instructed to search for hazards during the takeover period, significantly increased the number of safety checks made. In a remote operation context, operators could be instructed to look for hazards after a period of low workload in order to regain SA in line with the suggestion of using gamification to increase engagement and motivation.

Furthermore, perceived workload is affected by the degree of discrepancy between remote operation conditions and those that would be experienced when driving a vehicle (Mizukoshi *et al.* 2020). Specifically, by reducing such discrepancy, the operators' perceived workload would be reduced, even in complex situations.

Another vital element to consider in the relationship between SA and workload is motivation. De Winter *et al.* (2014) showed that highly automated driving can reduce workload and can potentially increase SA. However, this occurs only if operators are motivated or instructed to pay attention to the environment by focusing specifically on the driving task instead of engaging in other non-driving tasks (for example, reading a book, using a phone) or if no specific task instructions are provided to the drivers. Otherwise, the decreased workload was associated with a reduction in SA. This was supported by Neigel *et al.* (2019), who argued that it is intrinsic state motivation (as opposed to being incentivised from somebody else) that predicts the successful identification of stimuli during a vigilance task, both in an underload and overload context.

Lu *et al.* (2017) found that the process of gaining SA while driving depends on the availability of time. In their study, participants watched a series of videos representing some real-life traffic situations; they were then asked to reproduce some characteristics of the videos (i.e., location of the other cars in the environment). As expected, participants took longer to gain SA when they had limited time to do so, possibly because of the excessive workload. The current study did not directly investigate if the findings would be transferable to a remote operation context, but the experimental set-up (the environment being displayed through screens) seems to suggest that this could be the case.

#### 2.6.3.4 *Trust in the automation system*

Trust in the automation system is another important factor affecting workload in the context of remote operation. It has been found to increase after task completion, but only in the case of low to moderate workload (Ma-Wyatt *et al.* 2018). However, the relationship between system complexity and trust in the system seem to be moderated by latency (Khasawneh *et al.* 2019); specifically, a higher latency value resulted in a longer time to complete the task, a higher perceived workload, and reduced SA. In turn, this lowered the operators' trust in the system and caused feelings of frustration, resulting in higher error rates and harmful outcomes (Rogers *et al.* 2017).

However, trust in the technological system seemed to increase if feedback from the interface was consistently present, as it allowed the operators to adjust their controls, providing a sense of action (Gao *et al.* 2013).

#### 2.6.3.5 *Lack of embodiment*

As explained by UNECE (2020), another factor that could potentially reduce SA is lack of embodiment. When driving a vehicle, drivers are able to perceive the vehicles and the surroundings, benefitting from their sensory perceptions to gain a comprehensive understanding of what is happening. However, this cannot occur to the same extent during remote operation, as information about the environment is still mediated through screens and control panels; this could potentially lead to a partial understanding of the conditions of the remotely-operated vehicle (Nostadt *et al.* 2020). Furthermore, operators might experience a lack of urgency because the immediate consequences of their actions do not affect them directly (for example, in the event of a collision they would be unharmed).

Haans and Ijsselsteijn (2012) reasoned that embodiment allows humans to adjust to the environmental demands, making the necessary changes to prevent the occurrence of unwanted consequences.

Considering the key role played by embodiment in the context of remote operation, research has attempted to identify ways to replicate the perceptual characteristics of traditional driving, achieving "tele-embodiment" (Almeida *et al.* 2014), which refers to enabling embodiment even through interfaces. This is in line with Toet *et al.* (2020), who argued that if the three subcomponents of embodiment (agency, self-location and sense of ownership) (Kilteni *et al.* 2012) are fully replicated in remote operation, perception and task performance would significantly improve.

Rea (2020) noted the similarities between remote operation and videogames, namely controlling an entity remotely while receiving feedback from it. He argued that the interaction between vehicles and operators would be improved if interfaces were modelled on videogames, considering the extensive research already conducted in the field.

Moreover, Luz *et al.* (2019) stressed the difficulty of controlling a remote entity, especially when new and unfamiliar settings are considered. They proposed the use of haptic tables, which consist of glass surfaces capable of providing tactile feedback to the users' fingertip through vibration with low amplitude and ultrasonic frequency, as a way to assist the operator in navigating the environment (Koslover *et al.* 2011). Specifically, the haptic tables can produce a wide range of stimuli including grating (Biet *et al.* 2008) and friction

(Abdolvahab 2011; Giraud *et al.* 2014), and can be used to signal warning to drivers and operators (Ferris and Sarter 2008; Mohebbi *et al.* 2009). Overall, this is because the enhanced feeling of embodiment, shortened reaction times and increased SA were observed. Furthermore, (Hacinecipoglu *et al.* 2013) observed improved task performances by using haptic cues.

Aymerich-Franch *et al.* (2015) argued that first person video and audio feedback were helpful in increasing the operators' feeling of embodiment in the remotely controlled environment.

Similarly, Almeida *et al.* (2017) argued that immersive interfaces could be helpful in enhancing the feeling of embodiment by the operators. They reasoned that by replicating as many conditions as possible to match the original environment, operators will be less likely to be impacted by the inconsistencies between the two conditions. This was tested by controlling remote robots through head-mounted displays reflecting head movements, but also through deictic gestures and body intention. The results showed that operators experienced a reduction of the perceived workload and improvements in task performance. These outcomes were attributed to the sensory and cognitive system being deceived due to the immersive interface.

Kilteni *et al.* (2012) suggested the use of virtual reality (VR) to reproduce road conditions remotely by creating a "virtual replica" of the environment. Yuan and Steed (2010) argued that, when engaged with immersive VR, users perceive themselves to be in the recreated environment. However, Shin *et al.* (2020) found that VR results in increased risk perception when high risk tasks are considered, which in turn negatively impacts work performance and decrease the operators' willingness to utilise VR in future.

Interestingly, VR has been used for training purposes to enhance hazard perception, for instance to increase pedestrians'(Rosenbloom *et al.* 2015) and cyclists' (Zeuwts *et al.* 2017) safety, but it has not been applied to a remote driving context yet.

On the other hand, head mounted displays (HMD) are becoming increasingly popular when considering remote operation Shen *et al.* (2015), as they allow the operators to observe the environment by moving their heads. HMDs, as opposed to VR, do not recreate the environment artificially, but they display it through a headset that controls the movement of a stereoscopic camera.

#### *2.6.3.6 Motion sickness*

Motion sickness is a term used to describe a wide range of symptoms (such as nausea, vomiting, malaise and sweating) that usually arise in the presence of certain kinds of motion (Money 1970). Although the symptoms are subject to individual differences (Golding 2006), sensory conflict theory (Kohl 1983) is the most supported explanation when experiencing motion sickness. It proposes that the experienced symptoms are the result of the mismatch between the visual system and the vestibular system (located in the inner ear). Specifically, the vestibular system perceives changes in the angular and linear acceleration of the body, therefore sensing movement. On the other hand, the visual system provides a feedback of a stable and immobile environment (the inside of a vehicle). According to the sensory conflict theory, the discrepancy between these pieces of information results in the motion sickness symptoms.

While usually experienced within a car, aeroplane or boat, motion sickness can be triggered by the exposure to dynamic visual displays and simulated travel scenarios: in this case, it is known as visually-induced motion sickness (VIMS) (So and Ujike 2010).

Kennedy *et al.* (2010) described the most common symptoms related to VIMS; some of the most impactful symptoms of VIMS (nausea, vomiting and sweating) coincide with those typical of motion sickness. However, "sopite" syndrome was also described as one of the early symptoms to appear when experiencing VIMS, followed by all of the other symptoms associated with motion sickness (Lawson and Mead 1998). "Sopite" syndrome consists of sleepiness and drowsiness and it is not typically experienced with traditional motion sickness (carsickness, seasickness).

VIMS is a key factor to consider when discussing remote operation, given the potential effects on the operator's ability to perform the driving task. VIMS could lead to a reduction of attention due to sleepiness and nausea, in turn affecting safety and task execution (Garbarino *et al.* 2014; Fletcher *et al.* 2015). Furthermore, it could cause postural instability and therefore worsened task performance (Diels and Bos 2016). Consequently, research focussed on identifying ways to reduce the likelihood of VIMS occurring in the first place.

VR was described as a successful tool to address VIMS, as it was found to reduce the impact of latency on Remote Operators, drastically reducing the experienced motion sickness (Tikanmäki *et al.* 2017). This was explained by the provision of a wider range of information about the environment compared with those provided by 2D monitors, which tend to limit the operators' control of the field of view (Moss and Muth 2011), in turn increasing the experienced motion sickness Hosseini and Lienkamp (2016). Additionally, Jankowski and Grabowski (2015) argued that VR in a remote operation context improves distance evaluation, spatial presence and productivity. Furthermore, the time necessary to acclimatise to the control interface (intended as the overall system used to control the remote vehicle) is reduced with VR given the enhanced intuitive control and increased comfort compared with traditional non-VR control panels.

Young *et al.* (2007) observed that reports of motion sickness after a VR session were considerably worse if the participants had been asked to predict their motion sickness before the session itself. However, further research is necessary to determine if it is due to confirmation bias (Oswald and Grosjean 2004) or some other cognitive mechanisms.

On the contrary, when (Chen 2015) investigated if using 3D displays (and VR) would reduce VIMS, no significant improvements were observed compared with traditional 2D displays.

Mizukoshi *et al.* (2020) argued that VIMS could be significantly reduced by providing the freedom to adjust the image they are shown on the displays. Specifically, operators would have the opportunity to zoom in on specific areas in the environment, while controlling the zooming speed. This method aims to replicate the active conditions operators would experience if they were physically driving a vehicle, resulting in a reduction of the perceived workload and VIMS. By providing more control, it is argued that Remote Operators would feel less detached from the environment by being able to control how the information is presented.

Doisy *et al.* (2017) expanded on the “zooming technique” by arguing that utilising the operators’ head movements to control the camera would facilitate remote operations. They argued that less experienced operators would particularly benefit from this method as the interface would be more user-friendly. However, the benefits of this methodology did not seem to apply to experienced operators, which did not show any improvements in their performance. Moss and Muth (2011) also found that the benefits deriving from head movements control were nullified by latency over 200 ms, with the operators experiencing motion sickness once again. This complements that argued by Wilson (2016), who found that constant latency resulted in reduced VIMS rates as opposed to variable latency, as the operators take longer to acclimatise to each variation.

Further to this, Ha *et al.* (2015) suggested that it would be helpful to take advantage of the dexterity of the whole body. Motion capture would allow the operators to better control the vehicles remotely, as they would not be limited by the capabilities of the control interface. The information provided on the interface would update based on the operators’ head and torso movements, which would be detected with motion capture cameras placed in the control room. This would result in a more fluid control by the operators, who would not be constrained by the set-up of the control panel (for example, buttons, switches, sliders) to manoeuvre the cameras.

As argued by Ross *et al.* (2008), it is important to use fast connection and adequate monitors to guarantee positive performances and low rates of accidents. In their research, they utilised fibre links that allowed the data to travel at 8.5 gigabytes per second, which did not cause any additional latency. Similarly, Gnatzig *et al.* (2013) explained that the quality of information provided and number of cameras that can be shown to the operators depended on the available bandwidth. The authors found 500 ms delay in visual information unproblematic for a driving speed of 30 km/h, but they emphasise that highly dynamic manoeuvres might not be possible.

Finally, Salter *et al.* (2019) found that individuals seated in AVs experienced motion sickness to a greater extent when they were facing rearwards. The rates of motion sickness were, overall, worsened by driving in urban areas, as opposed to highways. Therefore, it is important to consider these elements when designing the remote operation systems, especially with regards to camera orientation.

### 2.6.4 *Workspace set-up*

Remote operation of CAVs is discussed as a back-up for failures or limitations of automated driving systems (Hancock *et al.* 2019). SA is therefore an important concept for the design of a remote-control interface and interfaces for remote operation are proposed in a great variety. Frequently used elements are head-mounted displays (HMD) linked to an actuated stereoscopic camera Shen *et al.* (2015) or to use multiple sensors to collect information about the driving environment and to combine that information in one interface for the Remote Operators (a sensor fusion display) Fong *et al.* (2001).

In particular, Fong *et al.* (2001) propose a sensor fusion display, called *PdaDriver*, for remote control of robots. Information from LiDAR, ultrasonic sonar, monochrome video, stereo vision and vehicle odometry is combined in one display, particularly to enhance the Remote Operator’s depth perception. All sensors are selected to complement each other to deliver detailed information in a changing environment, such as in darkness, for close or distant objects, smooth and rough surfaces, and small or large objects. The user is able to access all the information about the environment 'at a glance' and can control remotely with visual gesture (hand motion is detected by a colour and stereo system and then processed with a geometric model that classifies the movement into predefined gestures) and synthetic gestures (pen on a touchscreen). It is argued that this type of control would favour the exploration of unfamiliar environments and would require little training of the operators. Furthermore, it is reasoned that this sensor fusion display would require low bandwidth and would result in low latency; however, considering that the information was transmitted through an ethernet cable, it is unclear about its applicability wirelessly.

Additionally, Fong *et al.* (2001) proposes a collaborative control. The higher-level strategy is set by the human operator, but otherwise the robot can decide how to use the human advice. This kind of control is suggested to enable a vehicle to respond better in a complex and fast-changing traffic scenario.

Gnatzig *et al.* (2013) also propose a sensor fusion display. Sensors were selected to sample information from main sensor inputs used for driving: visual, auditory, haptic and vestibular. The displayed visual information follows the EU guidelines for physically driving a vehicle (EC 1977; EC 2003):

- Front view horizontal view angle of at least 180 degrees.
- Side mirror views of at least 12 degrees each.
- Rear mirror views of at least 20 degrees.

Gnatzig *et al.* (2013) used five front-facing, two side and one rear-view camera to present visual information on monitors, with a steering wheel, pedals and gear shift as remote-control interface. All front-facing cameras are shown on monitors and mirrors are overlaid in the corners 'when necessary' – it is not clear if the mirrors are automatically overlaid or by choice. The display also shows information about speed and turning signals. Information from LiDAR scanners were overlaid as an optical grid in slow parking movements to aid the perception of depth and velocity. During driving, LiDAR data is overlaid in the video image to highlight obstacles. However, they emphasise that high dynamic manoeuvres might not be possible due to bandwidth requirements.

Hosseini and Lienkamp (2016) propose a 360˚ HMD to increase SA. The HMD adapts the view based on the user's head position. Wheels pointing in the direction of the steering input and vehicle boundaries are shown in combination with camera data to enhance the precision of navigation. Additionally, information from a LiDAR sensor is combined with camera images to construct a mixed reality environment that aids the operator's depth perception and judgement of distances to objects. The operator controls the vehicle with steering wheel and pedals. A limitation of this interface is that operators were not able to see where they input their information – hands, steering wheel, and pedal positions were not shown. Furthermore, it was stressed that the characteristics of the HMD should be considered carefully, as they could impact head movement behaviour. Specifically, if HMDs are not designed ergonomically, and bearing in mind users' individual differences and anthropometric characteristics, their effectiveness could be impaired, as users could be less keen on adopting them and could develop musculoskeletal disorders (Luz *et al.* 2019).

Hoffman *et al.* (2008) discuss the use of 3D displays to facilitate the embodiment of the Remote Operators, with the environment recreated on screens in 3D rather than 2D. Although these displays are becoming increasingly popular in different contexts, including remote operations, the authors argue that they should be used cautiously. Specifically, it emerged that 3D displays yield distortions because operators observe the images on one screen, making them perceive the focus cues as if they were of the screen itself, rather than of the depicted scene (i.e. the street). In addition, 3D displays cause difficulty in combining binocular cues[8], which in turn leads to the operators developing visual fatigue and discomfort. In conclusion, 3D displays can be a powerful asset, but only if the cognitive and sensory implications deriving from their use are considered.

Chen (2015) discusses the difficulty in perceiving speed due to missing vestibular cues in the remote operation of vehicles. The perceived speed of the vehicle itself influences the prediction of the interaction between objects in a traffic environment and consequently the decision to adjust speed to drive safely. The author used blur as a visual cue for speed, an artificial motor sound as an acoustic cue, and seat vibration as a haptic cue. The cues were combined when presented to test participants and resulted in improved perception of speed. However, the author notes that other potential crucial environmental cues are missing that may influence a driver's decision about the vehicle speed, such as sound from other traffic participants and cues from centrifugal forces.

#### *2.6.4.1 Control input*

When considering remote operation, the way the information is inputted in the system plays a key role, as it has physical and cognitive implications. Different devices have been employed to control the remote vehicles, and contrasting results have been found.

Axe (2008) reasoned that gamepads (defined as controllers similar to those used for gaming purposes) have been acquiring more attention as they present several advantages compared with other devices; firstly, operators tend to be more familiar with them, especially for new operators, and secondly, they are easy to transport and manoeuvre. Furthermore, they can provide haptic feedback without requiring the operators to look away from the screen.

Rupp *et al.* (2013) compared the performance of an Xbox 360 gamepad to that of a joystick and keyboard to remotely control an unmanned vehicle. The results showed that the gamepad was easier to use, which was operationalised as lower error rates and lower workload, as well as higher usability scores. However, the participants in the study were all aged between 18 and 22, meaning that they were more likely to have been exposed to a gamepad, and therefore the generalisability of the findings for older operators cannot be assumed.

Overall, their results confirmed those of Neumann and Durlach (2006), Guo and Sharlin (2008) and Pettitt *et al.* (2010), who found gamepads to be preferable to mice and keyboards. On the contrary, some other studies have identified a negligible, or even

[8] Visual cues perceived by two eyes, useful for detecting depth in space.

negative (Isokoski and Martin 2007), change due to the use of gamepads. Finally, Bonaiuto *et al.* (2017) found that gamepads were not more efficient than other devices, but participants preferred them due to the perceived better usability, as also confirmed by Wagner *et al.* (2016). Therefore, further research is necessary to establish the feasibility of gamepads as control devices for remotely-controlled vehicles instead of joysticks, mice and keyboards.

Hosseini and Lienkamp (2016), Turnage *et al.* (2019) and Appelqvist *et al.* (2007) adopted a different approach by utilising a conventional set of pedals and a streering wheel to drive the vehicle remotely. These devices, compared with gamepads, are more likely to increase the operators' feeling of embodiment by replicating the real life driving interface. Schaefer and Straub (2016) investigated the impact of removing the steering wheel and pedals on drivers in autonomous vehicles; they found that trust and usability scores were not affected, but participants were less likely to intervene when required if the streering wheel and pedals were not present in the interface.

Despite the positive findings with regards to steering wheels and pedals in a remote operation context, the potential development of muscoloskeletal disorders needs to be considered. Extensive research identified the negative physical effects deriving from driving for long periods (Porter and Gyi 2002; Robb and Mansfield 2007), with Serrano-Fernández *et al.* (2019) finding that weekly hours of driving, as well as cognitive irritation, significantly predicted the presence of muscoloskeletal disorders in the trunk and the extremities (arms and legs). Consequently, the use of pedals and steering wheel as input devices to control remote vehicles needs to be treated carefully to prevent negative long-term physical consequences on the operators.

#### 2.6.5 *Training and experience*

Due to the embryonic nature of the remote operation field, limited jurisdictions in which remotely-operated vehicles are allowed to be deployed, and the limited number of companies testing or utilising remote operation in the public sphere, there is a deficit of accessible information around the training and experience required of Remote Operators.

It is reasonable, however, to assume that several of the fundamental requirements of Remote Operator training are likely to mirror the training conventional Safety Drivers receive and therefore establishing the scope of existing work and programmes in this field, and their appropriateness, should provide an adequate initial steer on how Remote Operator training is likely to evolve.

The absence of Remote Operator training materials is further highlighted (and perhaps explained) by the limited information available on the training and experience of in-vehicle Safety Drivers, although arguably this is likely to have improved considerably since the Uber Phoenix incident in 2018.

The general emerging state of the Safety Driver discipline is further exemplified by the limited formal guidance or legislation provided by national governments or supranational organisations such as the United Nations (UN).

In the UK, the COP (DfT 2019b) provides some guidance on expectations around Safety Driver training but ultimately largely places the onus on trialling organisations to define the training and experience required for their individual trials.

The British Standards Institution (BSI) are currently developing PAS 1884, sponsored by The Centre for Connected and Autonomous Vehicles (CCAV), which will provide more detailed guidance on requirements and recommendations for Safety Driver training and experience, however this is likely to focus on the in-vehicle Safety Driver, with only initial minor consideration given to remote line-of-sight operation (BSI and CCAV 2020).

As the initial excitement and technological novelty of AVs has subdued, the safety-related challenges of delivering reliable widespread automation have started coming to the fore. As a result, major actors in the AV trialling and operating field make a considerable amount of safety-related information publicly available through their websites or other sources. Within this, there is often mention of Safety Driver training and experience, albeit at a relatively high level.

Examples include Oxbotica (2021):

> *"Our Safety Drivers are given the best training, starting before they even get in the car. Each driver participates in AV classroom training as well as an external advanced driver training course. They are then trained to control the AVs on private roads. We use fault injection testing to simulate possible system failures so that they can practise their responses in a training environment".*

StreetDrone (2020a), a UK CAV start-up, also provide some general information around Safety Driver training:

> *"Safety Driver training is the next essential step to safe deployment of autonomous vehicles. When anything occurs (weather changes, dynamic objects etc.) outside your ODD and VDD conditions, the Safety Driver will take control of the vehicle".*
>
> *"Distinct from other companies, StreetDrone's Safety Drivers are all engineers".*
>
> *"Our Safety Drivers must undergo the full StreetDrone Safety Driver training programme. This is a two day comprehensive programme covering several elements including:*
>
> *Written training, system induction, track/closed road induction, and on-road induction.*
>
> *Upon the completion of the training programme the Safety Driver training checklist must be completed and signed-off by the Safety Driver instructor and trainee".*

Uber Advanced Technologies Group (ATG) issued a comprehensive safety report in 2020 (Uber ATG 2020), but provided no information on their Safety Driver training regime, other than acknowledging their Safety Drivers were trained:

> *"Our Mission Specialists help to enforce ODD constraints by monitoring road conditions while operating in the field. Mission Specialists are trained on the governing ODD, and are prepared to take manual control of the vehicle when presented with a scenario or conditions not included in the relevant ODD".*

However, a technology website feature (Kerr 2017), including a corporate Uber ATG video that predates their safety report by several years, provides some insight into elements of their Safety Driver training programmes at the time, including a bespoke test track allowing drivers to experience and respond to a variety of scenarios. Rather than subsequently moving closer to remote operation, Uber now require two 'mission specialists' to be present in their AVs, one being the Safety Driver (Uber ATG 2020).

One professional driver training provider in the UK, CAT Driver Training, has developed a course to train Safety Drivers and operators of CAVs. They highlight that not only should Safety Drivers undertake driver training, but also software developers, engineers and others involved in AV development, as it will help give them a better understanding of the requirements of the system they are designing. However, this driver training is necessarily generic in nature, so has limited focus on any organisation-specific systems or elements centred around vehicle behaviour, as it has evolved from conventional driver training.

Nuro, a US company that has developed fully automated delivery vehicles, utilises remote operation "*as a backup with the same functional responsiveness as an in-person driver would experience"*. In their report 'Delivering Safety', Nuro (2018a) they outline the training progression required to become one of their Remote Operators. This includes first being an experienced in-vehicle Safety Driver, and concludes with Remote Operators having to "*show they are able to monitor vehicles without distraction, promptly take control of the vehicle when needed, and operate safely in a variety of situations before they complete the training*".

However, companies like ASI and Phantom Auto, both active in remote operation in its purest sense, with Remote Operators undertaking the full dynamic driving task, highlight the fact that remote operation opens up the pool of potential operatives to more items than those specifically trained on use of the base vehicle that is being remotely operated. For example ASI, when discussing deployment in private, off-road construction and mining scenarios, highlight that remote operation could be carried out by individuals without the conventional licence required for that vehicle (ASI 2021). Phantom Auto, meanwhile, identify "*previously-inaccessible labor pools such as the physically disabled*" (Phantom Auto 2020b), who would not be able to operate, for example, a forklift in real life, as being potentially capable of operating it remotely. Although both are referring to very specific use cases in closed environments, they also both indicate how Remote Operator training has the scope to diverge from the training required for conventional vehicle operation.

The paucity of information from companies undertaking, or testing, remote operation activities is understandable given that remote operation technology in relative terms is still in its infancy, as are associated trials. It is also a competitive and commercially sensitive field. However, given the ultimate scope for remote operation is to become a method for the control of CAVs, not only during trials and testing, but during deployment, the present would be an opportune time for legislative, regulatory and guidance bodies at all levels to demonstrate initiative and leadership around Remote Operator-related training and provide universally clear and accessible guidance on how it can, and should, be undertaken within existing and evolving legislative frameworks. For example, bodies such as CCAV and BSI could leverage the momentum and knowledge gathered and exploited in the development of their current series of PASs to develop a Remote Operator training PAS. This would, with appropriate input, define and steer the direction Remote Operator training takes, extinguishing the risk of diverging approaches, and consequent potential impacts on safety, timescales and costs, developing under competing test programmes.

## 2.7 Applications of remote operation

### 2.7.1 *First generation remote assistance services*

The first generation of remote assistance services were introduced by OEMs such as Hyundai, BMW and GM. These services generally allow customers to contact a call center through a button on the vehicle dashboard (Hyundai 2017) or smartphone application (Hyundai 2019) and request assistance with items like directions, which could then be pushed to the vehicle, and roadside assistance. This type of system has also been applied in fleet management using information on vehicle locations to optimize operations and provide assistance to the drivers. In addition, smartphone applications have introduced functions such as remote lock/unlock, climate control, vehicle location and diagnostics (BMW n.d.; Hyundai n.d.; OnStar n.d.).

In 2018, the EU mandated the installation of e-call systems in all new passenger cars and light duty vehicles (EC 2021). The system will automatically contact the emergency services, sharing details related to the location and time of incident, when the in-vehicle sensors or processors are activated during a serious road accident.

### 2.7.2 *Remote operation services*

Despite the fast pace of CAV development there remains a recognition that the data is not available, or cannot be available, to train CAVs to negotiate complicated or currently unknown edge cases (Koopman *et al.* 2019). As such, we are seeing the growth of a second generation of remote assistance services that include the control of vehicles. How this control is administered, and the level of control that is being offered, varies; from giving a ‘nudge’ (permission to continue on a path after entering a MRC) to full completion of the DDT from a remote ‘call center’.

#### *2.7.2.1 Permissions and path planning*

OEMs and start-ups like Nissan (n.d.) (in collaboration with NASA), Zoox (n.d.), Waymo (2021), Ottopia (2020), Kiwibot (n.d.), Sensible 4 (2019) and AnyConnect (2020) have each developed systems that allow a Remote Operator to intervene following identification of an issue by the AV. This does not require the Remote Operator to complete the DDT, but to approve the ADS to continue on its path after encountering an issue – often referred to as a ‘nudge’ (Designated Driver 2019c). Other actions that the Remote Operator might be required to undertake include approving changes to the route suggested by the ADS (AnyConnect n.d.; Ottopia n.d.) or generating and sending new path plans to the AV by laying down way points on a map (Higgins 2018; Said 2019; Sensible 4 2019; Nissan Motor Co. n.d.; Ottopia n.d.). Nissan has said that this new information will then be shared with other vehicles in the system to ensure continued learning and improvement across their fleet (Nissan 2018; Nissan n.d.).

#### 2.7.2.2 *Remote driving*

A number of start-ups Designated Driver (2019a), Phantom Auto (2020b), Starsky Robotics (2019), Voyage (2020), Drive.ai, Einride (2019) and (Valeo 2019) have taken remote control further, having set up 'control center'-type environments equipped with dynamic driving controls together with screens with camera and other data feeds directly from the vehicles (Phantom Auto 2018; Designated Driver 2019c; Einride 2019; Voyage 2020). This technology has been demonstrated on the Texas A&M University automated shuttle by Designated Driver (Davies 2019; Designated Driver 2019c); by Phantom Auto at CES[9] in 2018 when a Remote Operator completed the DDT of the AV along the Las Vegas Strip from a 'call center' in California while a Safety Driver was in the av at the time of demonstration (Newcomb 2018; Phantom Auto 2018); by Einride at the Mobile World Congress 2019 (Einride 2019); and by Valeo at CES in 2019 (Miller 2019; Valeo 2019).

The Einride remote operation systems will be integrated with their AV offering – the Einride Pod, a freight pod - and they recently announced they will begin hiring Remote Operators in 2020 (Einride 2020). Starsky Robotics' website (Starsky Robotics 2019) suggested that while they were developing a remote driving capability they were concentrating on the first and last-mile of freight journeys, working to make the remainder of the journey possible in a fully automated manner. Since then, Starsky Robotics has ceased operations (Straight 2020).

Drive.ai., before its acquisition by Apple Inc. (Nellis 2019), appeared to have taken a more conservative approach allowing their Remote Operators to apply braking commands and other basic commands (although not defined) only, but not complete the full DDT (Korosec 2018b).

Both (Tesla n.d.) and (Jaguar Land Rover n.d.) have developed smartphone applications that offer customers remote control of their vehicles. Both OEMs state that these applications were developed to facilitate parking manoeuvres in difficult or tight spaces. Jaguar Land Rover restricts the top speed during remote control to 4 mph and requires the user to be within 10m of the vehicle (using the 'smart key' functionality to determine this). It is not clear whether this application has been made available to customers. Tesla's 'Summon' feature allows only forwards and backwards movements of the vehicle via a key fob, while 'Smart Summon' activates the vehicle ADS to navigate and manoeuvre up to 200ft to a location chosen by the user. It appears that Tesla restrict the speed at which these functions can be used to 6 mph (Lee 2019).

A number of other organizations have mentioned plans and/or developments in this space, although the details that have been made available do not clarify whether these systems will allow the completion of the full DDT by a Remote Operator, or will take a more conservative approach. Some of these plans and developments are outlined below:

- Uber has previously filed patents relating to remote operation (Newcomb 2018), although media in this space would suggest Uber are likely to acquire a business already working on remote operation (Korosec 2018a).

[9] Consumer Electronics Show: https://digital.ces.tech/home

- Toyota has also previously filed a patent relating to remote operations (Okumura and Prokhorov 2016).
- In China, Suning Logistics uses small robotic vehicles for local deliveries in the city of Nanjing (Xinhua 2019). Remote Operators can take control manually if there is any issue, but details of this system are not clear.
- (Nuro 2018b) provided a description on their remote operation training in its public safety report but details of the system were not mentioned.
- Cruise, a start-up backed by General Motors, also uses Remote Operators in their AVs but mentions that the Operator only has the ability to stop the vehicle and not the full DDT (Hawkins 2020).
- Hyundai demonstrated its remote operation of a wheel loader in CONEXPO 2020, where the Operator was able to operate the wheel loader from within the exhibition (HCEAMERICAS 2020).

### 2.7.3 *Remote operation in other fields*

Remote operation has been adopted in off-highway sectors (such as mining and agriculture) for decades. This section focuses on relevant applications and practices in off-highway sectors that might bring valuable experience for this study given that they share similar challenges, safety, and legal requirements.

#### *2.7.3.1 Difference between on-highway and off-highway*

On-highway and off-highway vehicles are used in different operational environments and therefore may pose different challenges for CAV operators and test or trial managers. The difference between on-highway and off-highway vehicles can be described as follows:

- **On-highway vehicles –** vehicles operating on “public highways” – the public highway is an area where the public may have access. This includes places such as municipal parks and supermarket car parks as well as typical highways. Vehicles on public highways must comply with public road legislation, rules and codes.
- **Off-highway vehicles -** there is no clear definition for off-highway vehicles. Typically off-highway vehicles are referred to as vehicles which primarily operate in any location that is not an open public highway (this can be both outdoors and indoors), and are self-propelled (has an onboard method of propulsion such as an engine or an electric motor). Many sectors contain large numbers of off-highway vehicles such as mining, construction, ports, airports, logistics depots, and military facilities.

Numerous off-highway vehicles are intended for use on challenging terrain which can be uneven or have varying gradients and therefore be dangerous for conventional vehicle operations. The vehicles are required to be designed for a specific purpose, for example large tyres with deep treads and flexible suspension for construction and mining vehicles. Their operating environments can also be enclosed or open air. On-highway vehicles are typically operated on well-paved roads and are frequently used in dense urban environments with mixed traffic. Although off-highway vehicles’ operating conditions are different, significant experience can be gained in terms of addressing key gaps, safety measures, and applying a common vision for the technical and legal challenges.

The following table provides a detailed summary of both on and off-highway sectors, allowing comparison between each sector's features.

**Table 6: Feature comparision of on-highway and off-highway sectors**

| Feature | On-highway | Off-highway |
|---|---|---|
| **Operational Environment** | On the road - focus is on the safety and risk posed from road environments. Constitutes a fixed road boundary but with mixed traffic, pedestrians and different operating speed environments. | Normally in closed/semi-closed environments with a smaller number of vehicles and humans involved and substantial variation in the operational constraints and hazards. Normally comprises more challenging environments (for example, underground and challenging terrain). |
| **Digital Connectivity** | Connectivity support via cellular tower. Connectivity may not be an issue in urban areas, but it may become problematic in areas where infrastructure is not well-established, for example rural roads. | Connectivity varies and is dependent on the areas and environment. It is challenging to cost-effectively connect commercial and off-highway vehicles that often operate in remote areas. |
| **Legal Compliance** | All vehicles used on the public highway must comply with the relevant laws and codes. Legal rules are more comprehensive, can be programmed into an AV and many well-established codes/standards have been developed. | Codes of Practice are dispersive in sectors and there are no pre-defined rules for off-highway vehicles. A less standardised highway code can be found for off-highway vehicle safety[10]. |
| **Automation and Safety Requirements** | High safety requirements for road safety in order to reduce the number of killed and seriously injured | Requirements to maintain both operational safety and efficiency. The adoption of automation has occurred much earlier than the |

[10] TRL has developed a draft Code of Practice for the Operation of Automated Off-highway Vehicles that will be relevant to all industries that operate AVs away from the public highway.

| Feature | On-highway | Off-highway |
|---|---|---|
| | road users. Represents the most important task for road authorities and road users. Improving safety and road efficiency are the main objectives of CAVs. | on-highway sector, particularly in mining and agriculture. Unmanned vehicles have been deployed in challenging environments to reduce safety risks and improve productivity. |
| **Safety Risks** | Risks from humans, vehicles, road infrastructure, and environmental conditions are considered major factors in the on-highway environment. | Various risks and hazards that are not present in on-road environments may need to be addressed in off-highway environments, such as use and exposure to chemicals/pesticides and hazardous environmental conditions. |

#### *2.7.3.2 Aspiration for remote operation in the off-highway sector*

In off-highway sectors, taking the mining industry as an example, there is an increasing trend to build AVs or to convert conventional vehicles for unmanned operation that might have hop-in/hop-out capability allowing conventional and automated driving when required. In fact, such functions of remote operation have been deployed since the 1980s to realise the vision of Remote Mining (McKinsey 2020). Until now, this has been deployed in many mining sites across Australia. For example, Newmont's Boddington gold mine in Western Australia moved towards becoming automated by 2021 with a fleet of autonomous vehicles (Hall 2020). BHP decided to develop 20 autonomous trucks for its Newman East iron ore mine in the Pilbara region of Western Australia, which will be deployed by 2021 (Zhou 2020).

There are significant aspirations to deploy remote operation in many engineering sites with different purposes (e.g., civil, mining, construction, port) to gain some of the benefits from full automation. For example, after deployment of remote operation nearly all engineering sites can potentially gain benefits in:

- Reducing risks to improve safety (for example by safeguarding drivers from hazardous areas such as underground, toxic chemicals, pandemic impacts).
- Improving efficiency (for example through greater accuracy, longer durations without breaks at off-site locations, better decision-making by integrating functions).
- Reducing costs (for example a mix of human and machine driving would help avoid expensive operational costs).

However, the maturity and sophistication of remote operation and automation varies based on the capabilities available within each organisation. Organisations are dependent on the associated support infrastructure, technology, and resource availability.

Remote operation has been observed at different levels, subject to the application of scenarios (McKinsey 2020):

- **Lower Level** – aggregate site data into a single data lake that can be accessed, analysed, and visualised for decision-support, creating a "room of screens" (used for observations in mining, airport and port environments).
- **Middle Level** – manage and actively control plant automation systems, fleet management systems, and remote-controlled machines from the Remote Operating Centre (ROC) (used for observation in mining, airport, and port environments).
- **Higher Level** – the most sophisticated companies manage all these functions on a larger geographic scale, covering the value chain from end-to-end, optimising post-processed ore logistics and port facilities used by multiple mine sites within a region, with regional parts and supply warehouses monitored across multiple assets for supply-chain optimization.

While safety is a clear driver, the increased flow of information also leads to better tactical and strategic decisions for remote operation. Based on the research from those sectors, companies in off-highways sectors focus on a combination of value levels for remote operation:

- **Data-driven decision-making –** at this level remote control is used for adopting basic data collection and skills for analytics and decision-making.
- **Employee productivity, knowledge sharing and cross-functional team –** at this level data can flow between different teams; knowledge and insights are shared to achieve a goal or set of goals.
- **Centralised planning and execution –** minimise interaction between equipment, machinery, and people – this is based on an integration of various resources and capacity into one business centre for better coordination, particularly on planning and execution.

#### *2.7.3.3 Applications of remote operation in mining*

Remote operation has been deployed in mining for large regions within several countries. This ranges from drill control to the dispatch of trucks in a pit, train control and port control. In large mines, people working in different departments had to stay connected when they make decisions. For example, the remote decision-making team needs to understand the latest situation in real-time via equipped sensors and communicate with the site teams all around the mine. Companies such as Rio Tinto and Fortescue Metals have implemented automated processes that are overseen by Remote Operators from centres in Perth, Australia, around 1,200 km away from the site (Hall 2020). Gold Fields has been in the process of implementing remote-control systems for its underground machinery across its operations operated at surface-level control centres (Hall 2020). Volvo is developing people-free underground mines that one day will run 24/7, 365 days a year although cost is a still an issue given the deployment requirements for a wider pool of environments (AB 2016).

Advanced technologies such as Artificial Intelligence (AI) and Machine Learning (ML) may also form part of this powerful arsenal of digital technologies aimed at enabling key decision makers to monitor, track, and respond to possible business disruption in real-time. Generally, the mining industry is trending towards mitigating risk by using remote operation.

In general, the remote system allows operators to carry out tasks previously impossible or inefficient. For example,

- Monitoring the systems (deploying necessary resources to resolve issues).
- Over-the-air updates (supports firmware updates, resolution of issues).
- Real-time data (continuous monitoring and logging).
- Data analytics (prognostics and predictive maintenance, diagnostic machinery).
- Plug and play (connect online to other services).
- Positioning and tracking (security).

However, there are many challenges in deploying remote mining:

- Depending on the region, it may be difficult to deploy autonomous machinery or digital infrastructure to implement remote operation.
- Difficulties around signal strength and connectivity at-depths/ underground.
- There is a challenge that higher levels of isolation are still required for many mining sites, which increase costs for deploying automation (Site isolation is a security feature in site that divides a safety zone for deploying automated vehicles. Safety zone setting can provide additional protection for workers, avoid injury risk, and improve safety, which is then essential for many off-highway deployments such as mining).

#### *2.7.3.4 Applications of remote operation in agriculture*

Automation in the agricultural industry has radically transformed over the past 50 years. Advances in machinery have expanded the scale, speed, and productivity of agricultural equipment, leading to more efficient cultivation of larger areas of land. Seed, irrigation, and fertilizers have also vastly improved, helping farmers increase yields and developing higher efficiency in harvesting, planting, etc.

Typically, the agricultural industry has favoured automated functions over remote operation; this is primarily driven by a shortage in the available workforce. The main developments have been in the use of automated steering (autosteer) as well as automated speed control within tractors. The driver is almost always still present in the vehicle, but automating these functions allows them to instead focus on the activity being performed (seed sewing, spraying, ploughing and others) resulting in improved yields. Under certain automation, a small family farm can manage tens of thousands of acres which increases the agricultural productivity known as Remote Farming. Remote Farming normally adopts three kinds of existing technologies, such as GPS, automation, and sensing, to create a system that is designed to reduce the need for skilled labour by taking the human element out of the tractor cab. The goal is also to help reduce fatigue and help producers make the most of their productivity. Generally the principle can be seen as a permanent push for increasing efficiency, starting with the transition from animal power to machine power, to larger and larger implements so that a single farmer can cover more territory with fewer people (Bedord 2012).

While the growing need for unmanned farms is the main driving force behind this technology, the liability and safety issues, as well as a reliable means of communication, are concerns that need long-term solutions.

#### *2.7.3.5 Applications of remote operation in airports*

Remote operation has attracted significant interest in airports, such as through remote landing and remote traffic control centres. Remote traffic control centres can significantly reduce costs for the maintenance of towers and staff at airports. For small airports, the service is reduced due to the lack of staff, and also operating a control tower with little traffic, such as 2 or 3 flights a day, may not be cost-effective. In such cases, remote operation becomes an attractive solution.

The Norwegian airport operator and air navigation services provider, Avinor, opened the world's largest Remote Towers Centre in Norway on 20$^{th}$ October 2020. The Remote Towers Centre can perform the necessary air traffic control from a remote location (Business 2020). The centre uses high-tech cameras and sensors to provide tower personnel with all of the important information at any time. Eleven fixed HD cameras, together with image-stitching software and high-speed resilient connectivity, provide a 240-degree panoramic view displayed over three screens. Eye-tracking equipment and cognitive task analysis determine the controllers' physical and mental workload in the remote tower. The same equipment is installed in the same layout as the conventional tower so that the only significant difference for the controllers is the presentation of the view on screens instead of out of windows. Aerodrome Air Traffic Service (ATS) from a remote position is facilitated by streaming real-time views from an assembly of fixed and moveable HD digital video cameras situated at the remotely-controlled aerodrome.

One of the challenges of Air Traffic Controller training when moving from the existing air traffic control tower to Remote Towers Centre is the difference in visualization and perception of the aircraft's actual speed and position. Locating cameras on the existing tower made training for the remote tower significantly easier (Business 2020).

#### *2.7.3.6 Applications of remote operation in construction*

Remote control of construction equipment continues to gain acceptance as the technology continues to advance. In addition, semi-autonomous features are emerging, and autonomous construction machines are just over the horizon. Remote operation is of interest to many contractors within the construction industry as there is a lack of available workforce. Many construction projects require operators to relocate around their country of work for weeks or months at a time, and some are unable to commit to such high travel requirements. Remote operation centres will remove this requirement, increasing the amount of people who are able to be operators.

The Doosan Group is a South Korean company who uses 5G for long-distance remote control of construction machinery and they also use the term 'teleoperation' to describe the operation of construction equipment from a remote station. Doosan has demonstrated the remote control of a DX380LC-5 40-tonne crawler excavator located over 310 miles away in Incheon, South Korea. It is essential for live video streaming to be reliably delivered to the operator's station with a minimal time lag. With its ultra-reliability and low latency (signal delay), the new 5G network overcomes time lag issues in the Doosan system, providing 10 times faster bandwidth and 10 times lower latency than a 4G network (Harry 2019).

Remote control technology allows operators to safely run machines from outside the cab, removing them from high-risk operations or providing them with unobstructed views of the work area. The Korean Bobcat Company offers remote control options for its loaders, which can benefit from the increased productivity. It is clearly stated that: "*Bobcat MaxControl Remote Operation provides customers with the option to take traditionally two-person jobs, or jobs requiring frequent entrance and exit of the machine, and make them more efficient through remote operation of the machine from outside the cab*" (Bennink 2020).

BOMAG is a German company that produce earth and asphalt compactors. They now offer some remote-controlled compactors to remove the operator from potentially hazardous situations, particularly potential rollovers (BOMAG ; BOMAG 2019). BOMAG also created a fully automated prototype compactor called ROBOMAG (BOMAG ; BOMAG 2019).

Existing challenges for deploying remote applications in wider construction sector include:

- Task complexity – the tasks performed by some construction vehicles are highly complex and not easily repeatable (for example, tasks carried out by telescopic handlers and some excavators).
- Environment complexity – the environment in which construction vehicles operate often features numerous other vehicles, as well as personnel and visitors.
- Communication dropouts can be a major issue in remote areas.
- 'Habitual clearance' by remote supervisors of AVs. If the vehicle keeps presenting too many false positives that the supervisor has to clear, they may lose confidence in their accuracy, stop paying attention and clear an actual dangerous situation.

#### *2.7.3.7 Applications of remote operation in ports/maritime*

Remote operation in the ports industry commenced two decades ago. It originally began with remotely-operated stacking cranes and now nearly all stacking cranes ordered are equipped with automation and remote operations (Johanson 2015; Henriksson 2019). The operation is achieved by allowing data exchange among Remote Operators, checkers and deckman. The current industry practice for remote crane operations sees Operators working in centralised control rooms within the port terminal premises (Johanson 2015; Henriksson 2019).

Existing challenges for deploying remote operation in ports/maritime include:

- The limiting factor preventing remote operations over large distances is the ability of Operators to act quickly enough in a safety-critical scenario. The move from an internal port network to a long-range internet solution results in huge reliability problems (Johanson 2015).

- Transmitting video from the crane to a control centre requires substantial network capacity to avoid any delays in transmission (Johanson 2015).

#### 2.7.3.8 *Applications of remote operation in military*

The last decade has seen significant developments in military automation technology and a rapid re-thinking of equipment suitable for future threats to enable autonomy in the next generation of combat vehicles. The first armed robots used in combat were on patrol in Iraq in August 2007. One dominant theme within military is to counter threat at a distance without the deployment of military forces. Around the world the US Army's Next Generation Combat Vehicle Programme will consist of both an optionally-manned fighting vehicle and a family of automated robotic combat vehicles (Freedberg 2020). Automated vehicles could reduce workforce downtime as they can be designed to function 24/7 and they would not be subject to distraction or fatigue or need to change shifts with other military personnel.

Lockheed Martin offers an Unmanned Ground Vehicle (UGV) for carrying the equipment, weapons, medical supplies, and rations of large platoons. A company called Northrop Grumman offers an autonomous vehicle for improving airbase operations and this can purportedly tune into the airbase's radio system to receive orders (Roth 2019). BAE Systems in the UK is working on a medivac vehicle for transporting wounded soldiers back to base as remote-controlled armoured vehicles that are completely unmanned could save lives on the frontline. The idea is that the vehicle could enter a hostile battlefield completely unmanned, drawing out the enemy fire and exposing their positions (BAE 2017).

#### 2.7.3.9 *Summary*

Automation has radically transformed many industries and remote operation will become a prevailing trend in the future. The key findings from this section can be summarised as follows:

- Remote operation and remotely-controlled vehicles have been observed in many industries and at different levels. Some industries have demonstrated good development of automation at a higher level, for example the mining industry.
- Digital technologies have a significant impact on achieving remote operation. However, there are still some barriers to achieving the highest level of remote operation due to some technological barriers, for example high-precision positioning, sensor capacity, and communication.
- Communication is key for remote operation, for example transmitting video from the crane to a control centre requires substantial network capacity to avoid any transmission delays. Similar demand exists for other industries.
- Safety cases are important for remote operation. The limiting factor preventing remote operation over large distances is the ability for Operators to act quickly enough in a safety-critical scenario.
- The operating environment is another important factor that affects the deployment of remotely-controlled vehicles, such as in the mining, airport, and military industries.

# 3 Stakeholder engagement

## 3.1 Introduction

To address the limitations and gaps that emerged from the literature review, TRL conducted interviews with stakeholders from different industries associated with CAV development and remote operation experience. By engaging with a wide variety of stakeholders, TRL aimed to gather an in-depth understanding of remote operation and how industry is implementing it, with a focus on the issues that emerged and the potential solutions. To collect a comprehensive set of information and to guarantee that several perspectives were considered, TRL approached stakeholders located and operating in different countries. This allowed a wide range of issues to be identified across a range of topics associated with remote operation, encompassing environmental, legislative, and technological matters.

## 3.2 Methodology

A wide range of stakeholders were approached to provide their insight on the feasibility and challenges related to the implementation of remote operation. Stakeholders were classified based on their expertise and sector of operation. The stakeholders involved were part of one of the following groups:

- **Group 1 –** this group comprised ADS developers, including those looking at remote operation, and trialling organisations.
- **Group 2 –** this group consisted of stakeholders involved in driver training and assessment, fleet management, OEM/ Tier 1 suppliers, and those conducting research either privately or in academia.
- **Group 3 –** this group included stakeholders employed by public bodies, regulating agencies, Standards Developing Organisations (SDO) and insurers.

Stakeholder consultations were conducted via teleconference due to the restrictions related to the Covid-19 pandemic. The duration of each interview was approximately 1 hour and each followed a topic guide (as detailed in Appendix A) which was adapted to the specific interviewee. Two researchers were present during each interview.

A total of 17 interviews were conducted with stakeholders being part of the abovementioned groups. To gather a comprehensive understanding of the approaches and perception of remote operation, stakeholders from different countries were recruited. Figure 2 depicts the percentage of interviewees from each group together with a breakdown of interviewees by country.

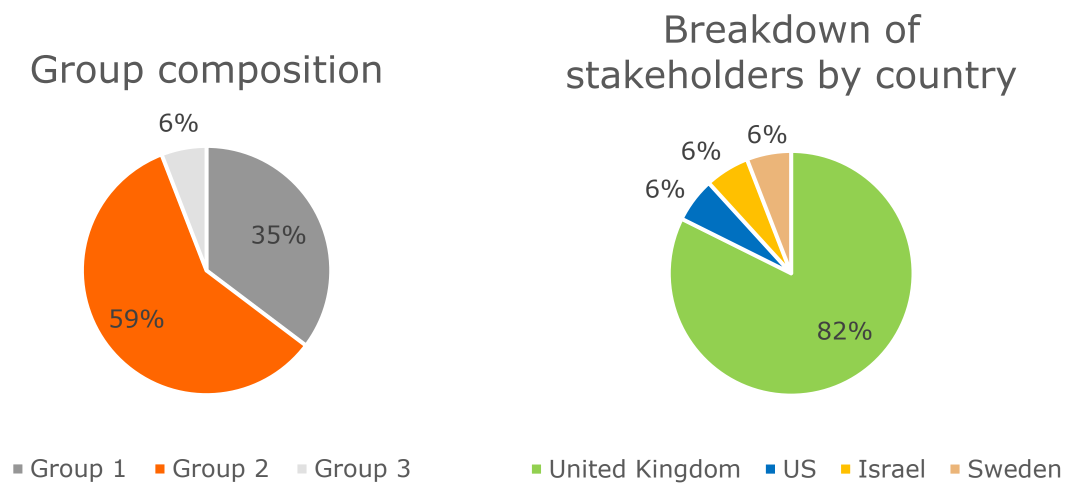


**Figure 2: Stakeholder group composition and breakdown by country**

Prior to the start of the interviews, stakeholders agreed to the following conditions:

- Direct quotes will not be utilised.
- Recordings were to be utilised only to facilitate the write-up of report.
- The information gathered was to be utilised to write-up a report that could potentially be published by Innovate UK.
- That they will not be identified personally in the report.

## 3.3 Thematic review of the findings from the stakeholder interviews

Interviews were analysed using thematic analysis (Braun and Clarke 2013). Thematic analysis is applied here as a systematic method of identifying and organising qualitative data to gain insight into patterns across the stakeholder responses. This involved familiarisation with the data, generation of initial codes relevant to the discussion topics, searches for themes and broader patterns of meaning, review and refinement of themes, and detailed analysis of each theme.

### 3.3.1 *The current guidance, standards, and regulation related to remote operation*

From the thematic analysis of the questions relating to “The current guidance, standards, and regulation related to remote operation” the following themes emerged: “Inconsistent terminology” and “Systematic testing”. Both themes are discussed in more detail below.

***Inconsistent terminology***

The stakeholders expressed their dissatisfaction with the current regulations, which they believe do not address specific roles and tasks that characterise remote operation. In addition, when terms are well-defined within standards and regulations (e.g., user-in-charge), their applicability in a remote operation context is not always guaranteed. On the contrary, it results in confusion and misunderstanding for the parties involved, with different industries utilising different terms to define homologous roles and tasks. This lack of shared understanding is likely to result in increased potential for hazards or incidents, as data and information might get misinterpreted across industries and decisions might be made under different assumptions and with inconsistent responsibilities in mind. Furthermore, the lack of shared definitions might present operating limitations as different roles and responsibilities are not defined and agreed upon among industry, which might mean that companies or sectors are adopting different approaches. This is particularly important considering the legal implications that inconsistent terminology can have, especially as remote operation is not limited to the transport domain and could have a wider range of applications, although not yet fully defined.

Furthermore, the stakeholder consultation suggested that the lack of a shared understanding and confusing terminology also has a negative impact on the uptake of such technologies. In particular, companies in different sectors and countries do not benefit from the research and development achieved elsewhere, meaning that the findings remain limited and do not extend to different use cases and industries. The stakeholder consultation highlighted an urgent need to focus on the taxonomy and definition of the terminology for remote operation to maximise the uptake of this technology. Also, clear definitions would help outline responsibilities for the parties involved, therefore facilitating the attribution of liability in the event of incidents or malfunction. Under the current legislation, it emerged that it would be challenging to understand where the responsibility lies given the confusion about the roles and the relative tasks to perform.

Although some attempts have been made to incorporate remote operation into existing legislation, there has not been a unified and coherent effort to define ‘remote operation’.

#### *Systematic testing*

When discussing remote operation and the regulations around it, a clear need emerged to test remotely operated vehicles extensively before their implementation on public roads. Specifically, stakeholders stressed the importance of a systematic and experimental approach that allows the companies involved to identify and address the weaknesses of the system. In turn, this was thought to lead to an in-depth understanding of the safety implications and requirements that remote operation entails, especially if the findings are made public and easily accessible.

In particular, the systematic testing of the technologies enabling remote operation should be mindful of the impact on the users involved, with special attention given to Remote Operators. The testing should not only focus on technical elements like latency and communication but should also incorporate human factors and cognitive load to guarantee that the operators involved are able to perform to the best of their abilities. One stakeholder stressed the importance of testing the control interfaces to maximise efficiency while guaranteeing a satisfactory level of situational awareness.

Additionally, it emerged that the need for systematic testing extends to cybersecurity. Contrasting opinions about the existing legislation arose, with some stakeholders deeming the current guidance satisfactory to guarantee safety from cyber-attacks, while others stressed the importance of redefining the requirements for cyber security, considering the catastrophic consequences in the event of malevolent interference. On the other hand, it emerged that there is a need to control for involuntary errors in the software (e.g., bugs) that could have an equally negative impact on system functionality and therefore extensive and systematic testing should be conducted.

### 3.3.2 *Definitions related to remote operation*

#### 3.3.2.1 *Definition of an advanced trial*

The consultation investigated the various definitions of an advanced trial being used by the industry. The themes that emerged were “Absence of the Safety Driver”, “Legality of the trial”, “Subjective definition” and “Public accessibility”. These themes are discussed in more detail below.

***Absence of the Safety Driver***

Most of the stakeholders agreed that an advanced trial involves excluding the Safety Driver from the vehicle, however there were variances to this definition. Some believed that a trial without a Safety Driver in the vehicle but someone – perhaps an ACSO – in the passenger seat who may intervene but is not required to be fully focused on the operation, also constitutes an advanced trial. Other stakeholders had more constrained definitions, such as that no human should be present in the loop for the trial to be regarded as advanced and this included the remote operator. The vehicle should be capable of performing an MRM to reach an MRC when needed. The CoP mentions that “*it is already possible to conduct trials without a human Safety Driver or operator in the vehicle, however, there must be a Safety Driver or operator who can use a remote-control function to be able to exercise proper control of the vehicles if necessary*” (DfT 2019a).

***Legality of the trial***

Another definition provided by stakeholders pertained to the legality of the trial. It suggested that a trial is advanced if the trial requires support from the authorities (e.g., legislative exemption, a special order or a permit). Although an advanced trial is not explicitly defined in the Code of Practice, it mentions that “*advanced trials may currently be outside of the law and may require support and facilitation from the Department for Transport to proceed. Those planning such trials should contact CCAV as far in advance as possible*” (DfT 2019a).

***Subjective definition***

Some stakeholders suggested that the definition is subjective. They indicated that it could be defined in terms of the current state of the trial with respect to the wider trial plan or testing more advanced technologies.

***Public accessibility***

There was also a suggestion that an advanced trial should be open to the public and offer a service to real users (e.g., rideshare).

#### 3.3.2.2 Definition of remote operation

The consultation investigated the various definitions of remote operation used by the industry. The themes that emerged were “Location of the operator”, “Proximity from the vehicle”, “Classification of remote operation”. These themes are discussed in more detail below.

***Location of the Operator***

The definition of a Remote Operator (which some stakeholders referred to as teleoperator) given by stakeholders generally included operating the vehicle from a position outside of the vehicle. Some stakeholders added that remote operation should not involve a physical link (e.g., a cable) to the vehicle.

***Proximity from the vehicle***

It was mentioned that the Remote Operators’ proximity from the vehicle may vary from having a direct line of sight of the vehicle to being miles apart. A stakeholder differentiated between an *External Operator* and a *Remote Operator* by suggesting that an external operator performs the same role as a Safety Driver from outside the vehicle but with less degree of control. They are able to make timely, safety-critical decisions although guaranteed latency level is key. Their view of the vehicle environment should be independent of the vehicle system. For a Remote Operator, they said that they cannot make timely, safety-critical decisions as latency level is not guaranteed. The data that they receive is only provided by the vehicle. They suggested that a remote operator may not be permitted to make commands due to latency issues and cybersecurity risks.

***Classification of remote operation***

The general classification of remote operation given by stakeholders were as follows:

***Remote assistance***: this involves assisting the vehicles’ operation remotely (e.g., advice on paths to take) and does not involve sending direct control information to the vehicle. The information passed to the vehicle by the Remote Operator are advisory only and the vehicle may not act on them for reasons such as potential safety implications. The level of dependencies and bandwidth required to safely achieve remote assistance was said to be considerably less than remote control and remote driving. Some of the use cases for remote assistance given by the stakeholders were:

- Manoeuvring the vehicle at the beginning and end of operations.
- Providing advice on alternative routes during a vehicle’s journey.
- Setting limitations for the AV (e.g., not expected to leave its lane even though there is nothing preventing it from doing so).
- To redress mission failures where an AV cannot complete its mission without intervention (e.g., to interfere with a set limitation, change destination, etc.).
- Navigating heavy automated machinery during off-highway operations (e.g., in mines and construction sites where the surrounding environment of an excavator may be constantly changing due to its excavating operation).

- Situations where the AV works alongside other systems (e.g., manually driven equipment) resulting in a dynamic path to their end goal.

***Remote supervision***: this involves monitoring the vehicles' operation which includes actively (i.e., without simultaneously performing other tasks) performing dynamic risk assessments of the ODD and the vehicle's behaviour and intervening where necessary. Remote supervisors can make safety-critical decisions. Some stakeholders mentioned that intervention should be limited to only bringing the vehicle to a safe stop. However, it was also mentioned that remote supervision is a subset of remote driving/control and that the supervisor takes full control of the vehicle during intervention without the vehicle safety system filtering their actions. Some stakeholders disagreed by indicating that as a safety precaution, the vehicle safety system may filter the remote supervisor's actions.

Remote assistance and remote supervision may be viewed as different levels of supervisory control. They could be utilised when the ADS system requires assistance, is performing an undesirable action or approaching the end of its ODD.

***Remote control and remote driving***: suggestions were made that both terms, which were also referred to as direct teleoperation and closed-loop control, were similar except in their use cases. Some stakeholders suggested that performing the vehicles' DDT in a conventional manner (i.e. use of steering wheels and pedals) is remote driving while using alternative forms of control (e.g., a lever or buttons) may be deemed remote control. A stakeholder suggested that remote control and remote driving are currently not considered safe due to the latency requirements. There is also significant dependency on network and communications infrastructure (e.g., multiple independent 4G masts).

***Remote management***: while some stakeholders did not believe that remote management was part of remote operation, one stakeholder suggested that remote management involves managing multiple vehicles. They also indicated that the remote manager does not constantly perform dynamic risk assessments during operation. Instead, the remote manager should attend to an ordered list of notifications flagged by vehicles (e.g., a nudge to carry on with the AV's generated decision). Remote managers are not required to perform any detailed task (e.g., draw a path) and do not make safety-critical decisions. The stakeholder suggested that remote assistance may be viewed as part of remote management.

### 3.3.3 *The role of the Safety Driver*

Multiple stakeholders were asked to provide their insights about the role of the Safety Driver; specifically, stakeholders were asked to define the tasks that the Safety Driver would undertake in an automated vehicle trial. Most of the stakeholders identified the following as the responsibilities of the Safety Driver:

- To monitor the functionality of the vehicle to guarantee its correct operation.
- To monitor that the decisions made by the AV are safe.
- To monitor the environment around the vehicle.
- To intervene in the event of a malfunction and bring the vehicle to a safe stop.

- To provide assistance if the vehicle is unsure on how to proceed.
- To manage participants/passengers and communicate with them where required.
- To ensure the safety of people outside and within the vehicle.

Additionally, one stakeholder highlighted that the role of the Safety Driver cannot be limited to monitoring the system to detect potential malfunctions and that they should be required to prevent the occurrence of such events. Unsafe events need to be anticipated whenever possible, however, the consultation suggested that the Safety Driver's role is dependent on the vehicle's level of maturity, with a high level of maturity requiring the Safety Driver to intervene only in limited circumstances.

The stakeholders were also asked to share their opinions about the challenges that the Safety Driver would face when interacting with a remotely-operated vehicle. The following themes emerged from the discussions: "Reliance on technology" and "Lack of a safety case". Both themes are discussed in more detail below.

***Reliance on technology***

A common theme that emerged from the stakeholder interviews is that in order for the Safety Driver to operate successfully from outside the vehicle they would need to heavily rely on technology (e.g., internal and external cameras, LiDAR, vehicle status log). This means that to effectively monitor the system and the environment, predict unsafe behaviours or interactions, and intervene whenever necessary to bring the vehicle to a safe stop, it would be necessary to have low latency, constant connection, and reliable controls. Contrasting opinions were captured about the feasibility of removing the Safety Driver from the vehicle; the most prominent belief was that the current technologies are not advanced enough to guarantee that reliance on the system can be maintained without malfunction. Therefore, work is needed to optimise the existing technologies to reach a point in which factors like latency and lack of communication are minimised and potential issues can be quickly solved remotely. On the contrary, some stakeholders believe that as long as the Safety Driver is aware of this significant reliance on the technology and the related limitations, this role can be performed effectively remotely. However, this would require the Safety Driver to be able to act remotely even in the event of unsafe behaviours or interactions and maintain constant oversight, not only of the vehicle and the environment, but also of the technologies used to monitor the system. In turn, this would have implications on the Safety Drivers' workload and their ability to continually maintain a sufficient level of situational awareness.

***Lack of a safety case***

As previously discussed, the Safety Drivers' reliance on the technology has some safety implications. From the consultation it emerged that the Safety Driver would not be able to monitor different vehicles simultaneously as they would be expected to detect any malfunctioning, as well as take over and bring the vehicle to a safe stop, if required. Therefore, the Safety Driver is expected to constantly monitor the vehicle, even though the current technologies cannot guarantee safety because of their intrinsic limitations (not advanced enough). This is especially important when utilising less mature systems (i.e., up to SAE Level 3), as the Safety Driver would be expected to maintain attention throughout while being subject to factors like high latency that would affect their ability to intervene where necessary.

### 3.3.4 *The role of the Test Assistant*

During the consultations stakeholders were encouraged to share their understanding of the role of the Test Assistant in trials. Most of the stakeholders identified the following responsibilities for this role:

- To support the Safety Driver by sharing some of the responsibilities (e.g., complex data gathering, monitoring of cybersecurity status).
- To monitor the system's performance to ensure it functions correctly.
- To relay information to the Safety Driver if necessary.
- To interact with users such as passengers.
- To carry out repairs to the vehicle in case of malfunctioning during the trials.
- To disengage autonomy in case of emergency (without taking over the driving task).

Overall, the Test Assistant carries out an assisting function to allow the Safety Driver to focus on the DDT and the vehicle's environment by overseeing more technical elements (e.g., successful data collection), as well as potentially distracting aspects (e.g., passenger management). Furthermore, stakeholders are of the opinion that the maintenance of the system is the responsibility of the Test Assistant. Additionally, some stakeholders explicitly stressed that it would be bad practice for the Test Assistant to take over the driving task instead of the Safety Driver.

Stakeholders were invited to consider the challenges in characterizing the role of the autonomy control system operator. The themes that emerged from the discussions are "Remote feasibility" and "Cyber risks". Both themes are discussed in more detail below.

***Remote feasibility***

When considering the challenges that remote operation would entail for the Test Assistant, it emerged that this role can be made remote more easily if the responsibilities allow it. Given that the Test Assistant is not expected to take over the driving task their responsibilities can be safely carried out remotely as they are less time-critical and therefore less sensitive to network and communication issues. Furthermore, one stakeholder believed that, if operating remotely, the Test Assistant would be subject to fewer distractions from within the vehicle (e.g., from passengers) and the environment. However, considering that one of the Test Assistants' responsibilities might involve passenger management, it is vitally important to define the tasks that are expected from the Test Assistant.

Additionally, it was noted that the value of the monitoring task is reduced when performed remotely; specifically, if the Test Assistant is not reliant on constant communication with the vehicle, they would not be able to intervene promptly should issues arise. On the other hand, if the Test Assistant is expected to be continuously aware of the real-time conditions of the system, the same problems faced with regards to the Safety Driver need to be considered.

*Cyber risks*

Cybersecurity emerged as one of the main concerns when addressing the role of a remote Test Assistant. Considering the absence of regulations specifically defining the cybersecurity requirements for remote operation, companies are dealing with cyber risks according to their internal procedures. However, in case of malevolent cyber-attacks, insufficient cyber safety could prevent the Test Assistant from noticing and addressing system issues in time to communicate them to the Safety Driver and bring the vehicle to a safe stop. Considering that the Test Assistant has no direct control over the driving task, they could potentially be unable to overcome system issues which therefore increases the risk of incidents. Consequently, the need to establish clear cybersecurity requirements is particularly important before the Test Assistant role can be safely performed remotely.

### 3.3.5 *Safety considerations for the removal of the Safety Driver and Test Assistant roles from the AV*

From discussing the research question above with stakeholders, the themes that emerged were “Detachment”, “Safe enough” and “Confidence”. These themes are discussed in more detail below.

*Detachment*

If the Safety Driver and the Test Assistant were to be removed from the vehicle, several safety considerations should be made. A common theme that emerged from the consultation is the detachment, which refers to the intrinsic risks that come with being in a different location from the vehicle. Specifically, it emerged that not being in the vehicle could lead the Safety Driver and Test Assistant to perceive a reduced sense of urgency and danger given the lack of direct and immediate consequences in the event of an incident. This would also apply to other road users as the remote operator and Test Assistant would not be able to interact with them in real-time, meaning that they could be unable to respond to signals that could alert them of imminent danger. The perceptual abilities of the Safety Driver and Test Assistant would be lessened by not being in the vehicle, as they would be dependent on systems’ technologies like LiDAR sensors and cameras that in turn have the potential to malfunction. This also applies to situational awareness, with the Safety Driver and the Test Assistant potentially not being as aware and cognisant of the surrounding environment as they would be if they were in the vehicle.

In light of these considerations, it emerged that it would be easier to make the Test Assistant remote first, given that this role does require less interaction with the surrounding environment compared to the Safety Driver. Furthermore, considering the Test Assistant is not expected to take over the driving task at any point, less situational awareness would be required and therefore the detachment would have a reduced impact. However, one stakeholder expressed their doubts about making the Test Assistant remote before the Safety Driver; specifically, it was argued that there is a greater business case for removing the Safety Driver as each vehicle currently requires one Safety Driver, whereas the Test Assistant can potentially manage several vehicles. This is in line with the opinions of other stakeholders, who pointed out that it is necessary to work towards a situation in which the Safety Driver can handle more than one vehicle remotely, therefore reducing costs.

However, this is not currently feasible considering the above-mentioned issues resulting from not being in the vehicle.

*Safe enough*

Discussions with stakeholders highlighted a recurring theme, the concept of “safe enough”. This theme refers to the idea that absolute safety when operating an vehicle remotely will be difficult, if not impossible, to achieve. This is because the technology, as well as the humans involved, are fallible and therefore it would not be possible to guarantee that safety will be absolute in any situation. However, from the consultation it emerged that the approach to follow should be to define some safety thresholds that need to be met for the vehicle to be allowed to be operate remotely. These thresholds should cover all of the technology involved (e.g., communication, visual perception, etc.), as well as identifying the conditions under which the remote operators can safely perform their tasks. Specifically, remote operators can only operate if the attributes of the Operational Design Domain (ODD) are met, meaning that if the ODD is not satisfied, the vehicle should not be operated.

Stakeholders agreed that conducting extensive trials is the best way to guarantee that as many situations are considered when defining the ODDs. It emerged that trials should be conducted to identify as many safety concerns as possible in order to be able to run remote operation with a satisfactory level of safety. By undertaking a large of numbers of trials over a period of time, safety technological thresholds can also be defined and utilised to determine the conditions that would allow remote operation to be implemented on a large and commercial scale and across different industries. In particular, one participant suggested the collection of objective surrogate endpoint measures, which would serve as surrogates for those end measures of adverse safety outcomes (e.g., a collision). Several measures were suggested, including assessing the degree of SA, near misses, closest time to contact; however, it was recognised that a caveat in their utilisation would be the lack of a comprehensive understanding of how they translate from a manual driving context to remote operation.

Nevertheless, it is likely that unexpected situations outside of defined ODDs will occur. In those cases, it was argued that the remote operator should bring the vehicle to a safe stop.

*Confidence*

A theme that emerged across the discussions is confidence in remotely operated vehicles. Specifically, given the novelty associated with such technology users utilising the remotely operated vehicle, and other road users, would struggle in having confidence in it. This is of key importance as it was argued that road users would behave differently if they were aware of the remote nature of the operation, even engaging with it in potentially dangerous ways. Therefore, once safety can be guaranteed, it will be vital to engage with local communities to build confidence, particularly amongst more sceptical, reluctant users. This theme is explored further in the section 3.3.9.

### 3.3.6 *The role of the Remote Operator*

The stakeholder consultation aimed to define the tasks that the Remote Operator would be expected to carry out. The following responsibilities were identified during the consultation with the stakeholders:

- To be able to take over the driving task if necessary (e.g., in the event a situation is outside of the vehicle's ODD).
- To monitor the correct functionality of the system.
- To potentially be in charge of several vehicles.
- To assist passengers.
- To liaise with the emergency services in the event of an incident.

However, it was stressed that these responsibilities may vary depending on several factors, including the presence of the Test Assistant in the vehicle and the maturity of the system.

The following themes were discussed in the interviews: "Awareness of limitations" and "Limited generalisability" and are discussed in more detail below.

### *Awareness of limitations*

Stakeholders considered the role of the Remote Operator to be a complex one, requiring them to coordinate multiple vehicles with different internal and external conditions. Therefore, a need emerged to extensively train Remote Operators on the capabilities and limitations of the system being used; this would enable Remote Operators to make appropriate and timely decisions. Remote Operators should also be aware of the functionalities of the system to take full advantage of what is available to them to enhance safety. However, it is equally important, if not more so, to understand the limits of the system and how to act in the event of a malfunction or unexpected behaviour. Stakeholders stressed the importance of exposing Remote Operators to all possible situations for the given test or trial and to train them on how to react appropriately. Trialling organisations should be aware of human limitations (e.g., fatigue), with support being provided to Remote Operators on the best way to handle those situations.

One stakeholder specified that apart from receiving technical training, Remote Operators should be exposed to the experience of travelling on a remotely-controlled vehicle from the perspective of a user or passenger. This would allow them to have a comprehensive understanding of the vehicle's behaviour and characteristics when under remote operation, highlighting the importance of smooth and considerate control and its impact on passengers.

### *Limited generalisability*

The consultation suggested that the training and tasks that a Remote Operator are exposed to are dependent on the use cases, which in turn inform the safety requirements. Even though some safety elements should be met regardless of the remote operation application, Remote Operators should receive adequate training based on what they are expected to perform as part of their daily role. As a baseline, the Remote Operator should have knowledge (and possibly qualifications) about the vehicle they are operating remotely. However, they are also expected to receive tailored training based on the exact tasks they will be performing. This is because some of the tasks can potentially be specific (e.g., fleet management) and therefore it would be beneficial to be exposed to it during training.

### 3.3.7 *Requirements and challenges for effective communication*

The interviews conducted with stakeholders aimed to identify the communication issues that could arise when controlling a vehicle remotely. The theme that emerged from this topic was "Reliability", which is discussed in more detail below.

***Reliability***

When discussing the potential communication problems that could impact system safety, it emerged that reliability of the transmission of information is of vital importance. Some stakeholders disagreed on the best technology to employ to guarantee a smooth and constant communication between the Remote Operator and the vehicle, however, they all agreed on the importance of a consistent connection. Stakeholders also suggested that variable and unstable communication is likely to be dangerous, as the Remote Operator cannot perform any action to reduce these changes. On the other hand, if the connection appears to be below the recommended level, the Remote Operator could perform some actions to address the problem (e.g., reduce the video quality). However, the instability of the connection is harder to address as any action could prove unhelpful or even detrimental in a matter of seconds.

Stakeholders also stated that in the event of high variability of the transmission, meaning that the quality of the transmission tends to fluctuate significantly, the system should bring the vehicle to a safe stop without waiting for the approval of the Remote Operator. This is because the subpar communication level would not allow the Remote Operator to have a comprehensive and satisfactory understanding of the conditions in which the vehicle is in, and they would be unable to have precise control of the vehicle. It was argued that this approach should apply also if the vehicle is in exceedance of the ODD.

A solution suggested by one of the stakeholders is to have dedicated channels as a back-up in case the main communication channels malfunction. However, it was recognised that the feasibility of this approach requires extensive investigation, as well as collaboration from networks providers.

### 3.3.8 *Data processing and transfer between the AV and the Remote Operator*

When discussing data processing and transfer between the vehicle and the Remote Operator the main theme that emerged was "As much data as possible". This is discussed in more detail below.

***As much data as possible***

Stakeholder interviews highlighted that a wide range of information should be provided to Remote Operators. This is thought to be key to realistically replicate the conditions of the vehicle and the environment. Several sources of information have been suggested to provide a detailed overview of the surroundings inside and outside the vehicle. When capturing the scene inside the vehicle the technologies that were suggested as being valuable were cameras (multiple and ideally to provide 360-degree views), temperature sensors, interphones, and a live vehicle status log. To capture the environment outside the vehicle stakeholders suggested the use of cameras (preferably with 360-degree views) and temperature sensors, as well as LiDAR, although it was noted that there is difficulty in utilising data derived from it without extensive training. Additionally, information should be gathered from the environment itself (e.g., data from infrastructure), but this poses some privacy and accessibility issues.

Furthermore, by providing a wide range of information to the Remote Operator, two main challenges need to be considered. Firstly, the provision of large amounts of data could overburden the system, meaning that the network connection would be expected to handle a significant amount of data simultaneously which could have an adverse impact on the connectivity speed. However, multiple pathways could be used to transmit the data, limiting the strain on individual channels, and therefore reducing the impact on the connectivity. Secondly, the Remote Operator would be presented with several sources of information and would be expected to analyse them all to maintain good situational awareness and be able to intervene if required. An approach to reduce the amount of information to process could be to operate with a software that notifies the Remote Operator if something is out of the ordinary and prioritises the most important information to share with Operator. This would make it possible for the Operator to oversee the safety and time critical tasks by being aware of the relevant information, with the less critical information accessible only if requested by the operator.

### 3.3.9 *Human factors considerations and limitations for remote operation*

The stakeholder consultation addressed the human factors considerations that need to be investigated for safe implementation of remote operation. The themes that emerged were “Human limitations”, “Pre-existing knowledge” and “Gaming”. All three themes are discussed in further detail below.

***Human limitations***

When discussing the human factors issues to consider in relation to remote operation, the predominant theme that emerged was human limitations. This theme was not intended to diminish the perceptual and attentional human capabilities; on the contrary, being aware of the best way to utilise what humans are capable of is the best way to enhance safety. Specifically, what emerged was that Remote Operators should not be exposed to an excessive number of screens or amount of information; if this was the case, they would be subject to excessive workload, which in turn would affect their situational awareness.

Situational awareness was a recurring theme on its own; stakeholders stressed the importance of assessing the Operators’ situational awareness to prevent them experiencing underload, which would lead to distraction, or excessive workload. Several strategies emerged from the conversations to address this; physiological measures (e.g., heart rate monitoring, eye tracking, skin responses) were suggested as potential solutions to monitor situational awareness, although their invasiveness should be considered. Furthermore, the use of methodologies already employed in safety-critical sectors (e.g., aviation, rail), such as fake stimuli appearing on screen, were recommended to be effective in assessing the operators’ alertness and fatigue. Overall, attention should be paid to all of these elements that could potentially impact the operators’ abilities, for example from the interface design through to the amount of information provided.

A need to consider human limitations in relation to acceptance of this new technology also emerged from the consultation. Once an acceptable level of safety for remote operation is achieved it would be important to expose the general public to this technology. It was stressed that trust and acceptance are hard to build, especially as the public would be naturally reluctant given the absence of a human visibly controlling the vehicle. For this reason, stakeholders stressed the importance of allowing users or passengers to communicate with the Remote Operators in case of a particular need or emergency. It was argued that this would increase the users' perception of safety, as well as slowly introducing this technology in simpler contexts (e.g., parking) before applying it to more complex and dynamic situations. Finally, to reduce the natural mistrust towards new technologies the consultation underlined the key role that needs to be played by media, as this could significantly accelerate the uptake of remote operation.

However, it emerged the need to enhance the trust that the Remote Operators have in the system. It was suggested that Remote Operators should be familiar with this technology and should receive extensive training covering all the possible events that could occur, ideally assisted by another RO with prior experience.

***Pre-existing knowledge***

Another theme that emerged from the stakeholder consultation was pre-existing knowledge. It was suggested that it could be helpful to utilise the expertise that Remote Operators already possess instead of having to retrain them completely. On a basic level, Remote Operators should have experience of manually driving the vehicle they would control remotely. However, this could be taken a step further. For instance, new control interfaces (e.g., joysticks, keyboards, 360-degree cameras on headsets) could be introduced if the operators would find them easier to operate. Overall, it emerged that there is a need to consider the capabilities and needs of users and passengers when designing interfaces and screens and to utilise any pre-existing knowledge in this area.

***Gaming***

Finally, gaming was a recurrent theme across the interviews. It was suggested that this industry could provide useful insights by addressing several issues that characterise remote operation. Given their conceptual similarity (controlling a remote object), investigating the gaming research could help resolve problems like motion sickness and reduced situational awareness. Furthermore, technologies such as Virtual Reality, and interfaces such as joysticks and keyboards, could be employed to facilitate embodiment and the control of the remote vehicle. However, it was noted that not all Remote Operators would be familiar with specific technologies, which also come with their own requirements for use. For instance, Virtual Reality (VR) requires a large and stable connection, and one stakeholder reported an increase of motion sickness feelings when VR was utilised. Therefore, it is critical to consider the transferability of the methods employed in the gaming industry to understand how they would impact remote operation.

### 3.3.10 *Roadmap for remote operation of CAVs*

The stakeholder consultation addressed the deliberations and limitations that should be considered when developing a roadmap for remote operation of CAVs. The themes that emerged were “Connectivity”, “Safety” and “Implementation”, which are discussed in further detail below.

### *Connectivity*

A recurring theme that arose during the stakeholder consultation was the connection between the operator and vehicle, which affects data transfer and the resulting latency. Several activities need to be conducted, including verifying the connectivity between Remote Operator and vehicle and sending different data to see how they are processed. Before full implementation many of these components can be tested through simulation and without utilising any vehicle. Several stakeholders also mentioned that the connectivity, latency thresholds and performance levels need to be determined and guaranteed before the Safety Driver could be removed. This theme further relates to the safety theme below, where the vehicle system will be required to operate safely in the event of a poor connection.

### *Safety*

Another theme that emerged during the stakeholder consultation was safety. A large proportion of activities that various stakeholders mentioned focused on how remote operation could be safely implemented. Both system and operational safety of remote operation technologies were highlighted as key considerations. Certain activities could be conducted to address this, such as agreeing on common terminologies that can be adopted and further developing the current standards to include remote operation. Active safety measures[11] for critical instances were also suggested; these situations include where there are failures in communications, detection of pedestrians, etc. Consideration of the control of the vehicle by the Remote Operator or the ADS will need to be developed for situations where either control fails to detect a hazard.

### *Implementation*

A staged development of the technology, its implementation and the need for necessary safety and regulatory frameworks were also a recurring theme. This would allow for different limitations to be solved before full implementation; sensor, processing and perception limitations were all suggested. Guidelines, the minimum thresholds, and the approval process for other aspects like cybersecurity, latency and situational awareness will need to be developed before implementation and commercialisation. Additionally, a stakeholder mentioned how the timeline for full remote operation implementation depends on the role of the Remote Operator and might take anywhere between 2-15 years. Further research on system design and situational awareness are also key aspects when controlling remotely operated vehicles and this process might take 5-10 years. However, while another stakeholder mentioned similar timelines, the complexity of dynamic public road environments was also suggested as a limitation for implementation of remote operation.

[11] Safety measures that constantly monitor the performance and surroundings of a vehicle to avoid or mitigate incidents.

# 4 Terminology

As identified in the stakeholder engagement the taxonomy and terminology used when referring to remote operation remains largely undefined with standards and industry applying terms inconsistently. This finding also corroborates with the response to a TRL blog by (Lawson 2021) which initiated discussion on the creation of common terminology that could be used and applied consistently across industry. Using the findings from the literature review and stakeholder engagement the study investigated the various definitions of remote operation used by the industry. The themes that emerged were "Location of the operator with respect to the proximity to the vehicle or the driving controls", "classification of activities", and "the authority or level of control of the activity". These themes were used to define some of the core activities described in Figure 3 below; the activities have been separated into driving or AV support activities as detailed in Sections 4.1 to 4.3 below. It is acknowledged that the definitions in this space will need to evolve as the industry matures, and new use cases and technology are developed.

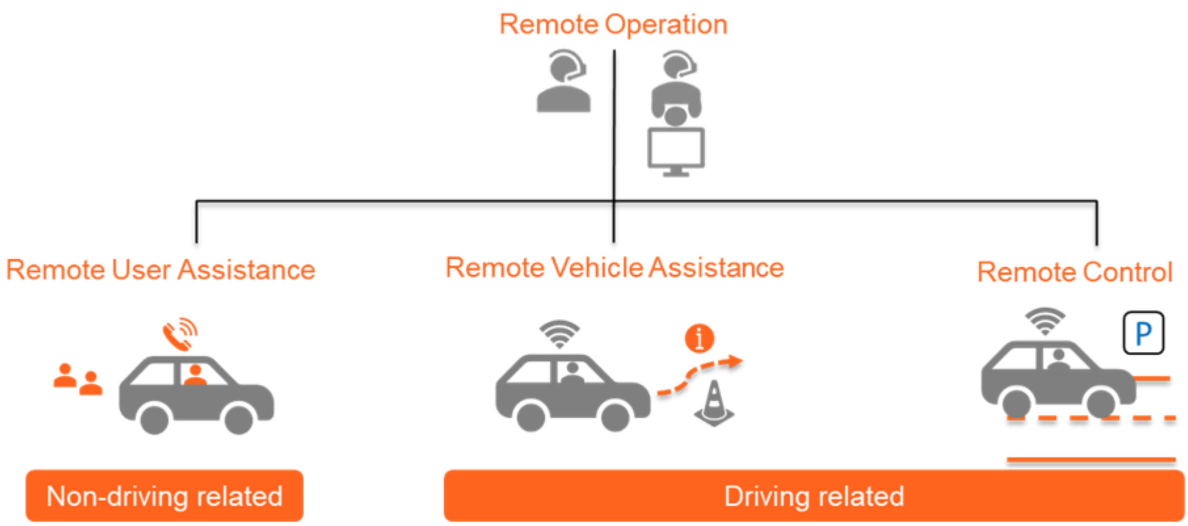


**Figure 3: Classification of remote operation activities**

## 4.1 Remote, remote operation and Remote Operator

### 4.1.1 *Remote*

The term 'remote' refers to operations such as supervising, assisting, controlling, and driving AVs from a location that can be within the AV (but not in the driver's seat), or outside of the AV from within visual line of sight (VLOS[12]) or beyond visual line of sight (BVLOS[13]) of the AV. The term does assume that hard-wired connection to the AV is not used.

[12] VLOS is an operating principle that involves a continuous maintenance of direct unaided visual contact of the subject AV during its operation.

[13] BVLOS is an operating principle where the Operator is unable to maintain direct unaided visual contact of the subject AV and relies on external aids (such as cameras) to maintain an oversight of the AV's operation.

### 4.1.2 *Remote operation*

Remote operation is an umbrella term that encompasses the functions needed to support the operation of an AV or a fleet of AVs by a Remote Operator (Figure 3). Remote operation includes both driving and non-driving related tasks. During remote operation, the Operator may have full authority for the AV's actions, the AV may retain final authority, or it may be split depending on the system design, maturity and safety assessments of the ADS developer and trialling organisation.

### 4.1.3 *Remote Operator*

A Remote Operator is a generic term for a human who supervises the operation of an AV from a remote location (see definition for 'remote' in 4.1.1 above). Supervision can comprise monitoring the AV, intervening in the AVs' operation, assisting passengers, or managing part of the AV service. The supervision of operations may need to be real-time, such as for remote driving (see 4.2.1.1), and the Remote Operator may or may not have final authority for control of the AV.  A Remote Operator may only be able to perform one or several of the remote operations defined in Section 4.2 and 4.3. All Remote Operators should be trained, however currently there is no recognised license or permit which defines a Remote Operator. Many organisations have developed their own terms for Remote Operators who perform specific activities.

## 4.2 Driving related remote operation activities

### 4.2.1 *Remote control*

Remote control comprises the continual oversight of an AV's operation by a Remote Operator who is performing a safety-critical role and has the ability to intervene in the AV's operations. This could range from pressing an emergency stop button (remote intervention 4.2.1.2) to performing the full DDT (remote driving 4.2.1.1).

#### *4.2.1.1 Remote driving*

Remote driving is a subset of remote control and is the activity of remotely conducting part or all of the DDT. This means conducting any combination of the following:

- Lateral motion control – steering.
- Longitudinal motion control - braking or accelerating.
- Environment and object monitoring and response.
- In-the-moment path planning (but not the strategic tasks of deciding the final destination).
- Changes to conspicuity – use of indicators, lights, horn.

Remote driving requires a significant level of situational awareness and therefore real-time monitoring of the operating environment. The control interface used for remote driving may resemble a conventional vehicle or may utilise devices such as tablets, joysticks, or Virtual Reality headsets.

#### *4.2.1.2 Remote emergency intervention*

Remote intervention is the act of intervening to change the movement, status or conspicuity of the AV in response to an event[14]. Remote emergency intervention differs from remote driving. Remote driving may be used to manoeuvre an AV from a safe location onto a recovery vehicle whereas remote emergency intervention may involve the use an emergency stop as a safety control. The requirements for remote emergency intervention may be significantly different (based on the trial, use case, ADS maturity, etc) so is considered a separate activity.

Note it is likely that remote passenger assistance will be needed in the case of an emergency and this may commence before, or end after, the remote emergency intervention activity.

### 4.2.2 *Remote vehicle assistance*

Remote vehicle assistance is the act of providing assistance to an AV or intervening in a way that changes the path or movement of the AV without directly conducting the driving tasks. It is likely to be intermittent and could be reactive in response to a request/demand from the AV or system, or proactive in response to monitoring and observations. 'Assistance' describes the high-level AV interventions to be able to continue or complete a trip such as permissions to proceed, instructions to change lane or take a path around an object, rather than low-level instructions for how to conduct a manoeuvre. It may be important to respond to these requests in a timely manner, however, remote vehicle assistance activities should not be time and safety-critical and therefore should not require instantaneous intervention. As a result, there are likely to be less demanding remote monitoring requirements, for example on latency, bandwidth or datasets which are needed as part of remote vehicle assistance.

### 4.2.3 *Remote monitoring*

Remote monitoring comprises observing the AV's operating environment (including the surroundings, other road users, weather) or data from the AV and supporting systems and can vary depending on the type of remote operation it is supporting. A single person may monitor one or more AVs, or multiple people may monitor the same AV. Monitoring may be intermittent to check correct operation or continuous with the possibility of intervening reactively if required. At the point of intervention, the remote monitoring activity changes to remote assistance or remote driving when response is required. Whilst it is likely that a large part of a Remote Operator time will be spent monitoring, it is expected they will also be available and capable to conduct one or more of the other types of remote operation listed above (4.2.1 and 4.2.2).

[14] An event is defined as a thing that happens or takes place, where the ADS is unable to resolve and is unable to take any further action without external assistance.

## 4.3 Non-driving related remote operation activities

### 4.3.1 *Remote passenger and road user assistance*

Remote passenger and road user assistance describes a range of services that can be provided by a Remote Operator to support the welfare of an AV user/passenger such as by answering queries and providing safety and security information. It also includes interactions with passengers or other road users as a result of an incident such as providing guidance in the event of an evacuation.

### 4.3.2 *Remote logistics management*

There are a number of other activities needed to manage the operation of a single AV or fleet of AVs from a remotely-located centre which is referred to as remote logistics management. As trials scale-up and services start to be deployed it is anticipated that this term and list of associated activities may need to evolve. Currently remote logistics management comprises similar activities that are carried out as part of conventional vehicle fleet management but with the information or instructions communicated to a computer (the AV) rather than a human, which may change or increase the safety implications.

## 4.4 Other terms used in the field of remote operation

### 4.4.1 *Approvals*

Approval may be provided by a Remote Operator following a request for assistance from the AV for permission to proceed on a planned path and carry out certain manoeuvres. It may be implemented as a safety measure to reduce risk, or because the Remote Operator has access to additional information that can assist in determining whether the planned path and manoeuvres are safe.

### 4.4.2 *Path planning*

Path planning is the act of planning the path an AV may take and may be defined by the AV's navigation or a Remote Operator. It may be in some cases, such as in response to an obstacle or request for assistance from the AV, that a Remote Operator sets the path. The control of the manoeuvre, for example the vehicle's speed or steering angle, is done by the AV.

### 4.4.3 *Path planning confirmation*

Path planning confirmation is provided by a Remote Operator when an AV, having reached an appropriate minimal risk condition (MRC), requests additional oversight for its planned path having encountered a scenario which required the calculation of an alternative path.

### 4.4.4 *Minimal Risk Manoeuvre (MRM)*

A MRM is defined by BSI as the:

*"tactical or operational manoeuvre triggered and executed by the automated driving system or the human driver to achieve the minimal risk condition* (BSI 2020a)*".*

### 4.4.5 *Minimal Risk Condition (MRC)*

A minimal risk condition (MRC) is defined by BSI as the:

*"stable, stopped condition to which a human driver or automated driving system brings a vehicle after performing the dynamic driving task fallback in order to reduce the risk of a crash when a given trip cannot be continued* (BSI 2020a)*".*

Note that for an SAE Level 3 vehicle the MRC may be to hand back control to a human driver.

### 4.4.6 *Dynamic Driving Task (DDT)*

The DDT is defined by BSI as the:

*"real-time operational and tactical functions required to operate a vehicle safely in on-road traffic* (BSI 2020a)*".*

### 4.4.7 *Fallback*

Fallback is defined by BSI as the:

*"process by which the full function of the dynamic driving task is delivered when a driving automation system or systems cease to operate* (BSI 2020a)*".*

### 4.4.8 *Handover*

A handover is defined by BSI as the:

*"process by which the sustained dynamic driving task (4.4.6) function transitions either from a human driver to an automated driving system or from an automated driving system to a human driver* (BSI 2020a)*" .*

Although in the context of remote operation, and for the purposes of this report, this should be updated to include a Remote Operator.

### 4.4.9 *Operational Design Domain (ODD)*

Operational Design Domain is defined by BSI as the:

*"operating conditions under which a given driving automation system (4.4.10) or feature thereof is specifically designed to function* (BSI 2020a)*".*

### 4.4.10 *Driving Automation System (DAS)*

Driving Automation System is defined by BSI as the:

*"hardware and software that are collectively capable of performing part or all of the dynamic driving task (4.4.6) on a sustained basis* (BSI 2020a)*".*

# 5 Use cases for safe remote operation

An important step to maximise the benefits of remotely-operated AVs is to determine when, and which type, of remote operation will have value and can be implemented safely. This section explores:

- A framework for classifying use cases, including initial criteria for assessing their suitability for remote operation;
- Initial high-level use cases where remote operation would have safety benefits and may be appropriate; and
- A risk rating for each of the initial use cases.

## 5.1 Framework for defining and developing use cases and scenarios

***There are three fundamental requirements for successful application of remote operation:***

***Operator's situational awareness of the environment***

The Operator must have sufficient situational awareness to understand the environment.

***Operator's level of control over the AV***

The Operator must have sufficient control to be able to influence the AV's actions.

***Connection between the Operator and AV***

The connection (a communications link or video feed) between the Operator and AV

An AV with remote operation capabilities must always be driven in a safe manner, whether this is by the ADS or the Remote Operator, including during any transitions of control. This is true in all situations, and these criteria are the foundations for determining the suitability of any particular use case or scenario. In the case of a partially or highly automated vehicle, intervention from a Remote Operator may be requested by the AV; in these applications the ADS must be able to operate itself in a safe manner when an Operator is not present. Remote operation can also include remote control of a vehicle which has no automated functionality (see Section 4.2).

Use cases can be generic or specific. Generic use cases are high-level and give a description of the type of activity and the broad environment in which it is being conducted, for example, providing remote vehicle assistance to an AV which is stuck along its route in a city. These use cases contain generic attributes which have inherent high-level risks and constraints that may apply differently in different circumstances. An example of a generic attribute is operating in a busy environment; this typically brings an increased risk of collision, but this generically labelled environment can present a broad range of challenges for individual instances of remote operation.

To implement remote operation for a particular instance, further consideration must be given to the risks present for the specific activity or environment. These must be taken on a case-by-case basis and would only be relevant for the situation in question. In the example above, this may include a specific type of assistance being provided (for example path planning instruction, classification of an object or obstruction), or the particular road layouts along the route in question.

This example, and the process for classifying use cases according to their attributes, is shown in Figure 4 below. The focus of this section is on generic use cases and attributes, although specific attributes have been included in Figure 4 for illustration.

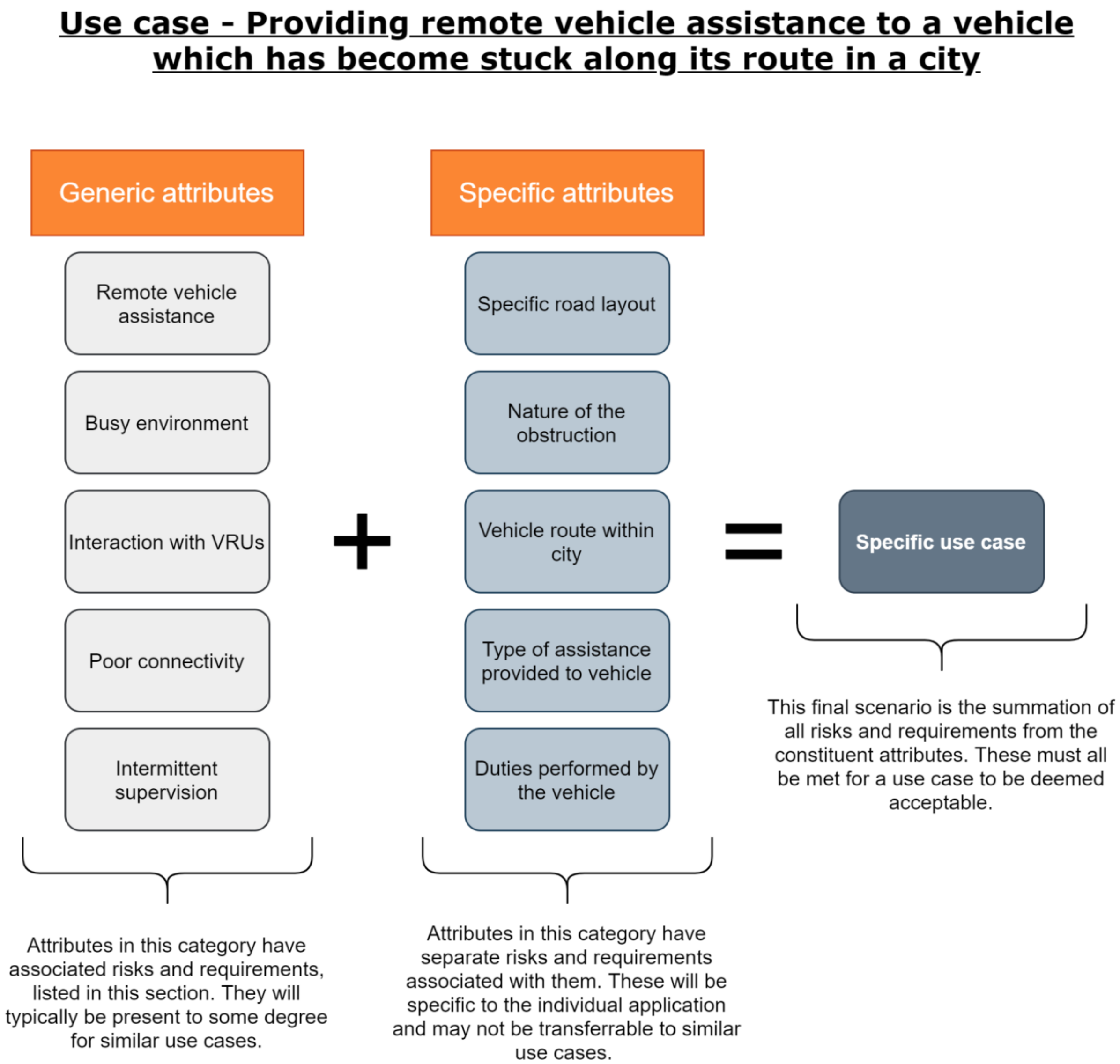


**Figure 4: Illustration of how use cases can be classified according to their constituent attributes**

What changes from use case to use case is the level of control and situational awareness required by the Remote Operator to conduct their role safely, and the time for which it is safe for an AV to be left unattended in an error state[15].

Four initial categories are proposed which significantly impact these variables:

- The type of remote operation in use,
- Environmental features,
- Activities being performed by the AV, and
- ADS capability and transition of control between the ADS and Operator.

The following sections outline these initial categories of generic attributes.

### 5.1.1 *Category 1: type of remote operation*

The Operator's required level of control and situational awareness, and by extension the quality of the connection between AV and Operator, are different for the different modes of operation. These are generally highest for remote driving and lowest for remote passenger assistance services. The requirements for each mode are summarised in Table 7. The quality of the connection is determined by the latency (both magnitude and fluctuation), the bandwidth, and the connection's stability.

**Table 7: Fundamental Remote Operator requirements for each mode of operation**

| Attribute | Situational awareness | Control | Connection |
|---|---|---|---|
| Remote driving | Understand and react to the environment in real-time. This includes seeing other vehicles and users, reading signs, and avoiding obstacles. | Maintain direct control of the vehicle in a safe manner. Haptic feedback would assist a Remote Operator in this respect.<br><br>If automated, the AV needs to be able to control itself safely until an Operator can take control. | Stable, low latency connection at all times. Higher vehicle speed requires lower latency. |
| Remote vehicle assistance | Understand the environment, including seeing other vehicles and users, reading | Provide the AV with instruction or additional | Stable enough to give the Remote Operator a clear understanding of the environment in |

[15] An error state is one where the ADS has detected an error which it is unable to resolve and is unable to take any further action without external assistance.

| Attribute | Situational awareness | Control | Connection |
|---|---|---|---|
| | signs, and avoiding obstacles. In some cases, it may be sufficient for the Operator to be able to accurately classify an object and the AV's response to it, rather than needing to assess the complete environment. | environmental information.<br>The AV needs to be able to control itself safely until an Operator is able to provide assistance. | approximately real-time - as the Operator is only providing instructions or information, a connection which occasionally lags can be managed. |
| Remote passenger assistance services | Basic vehicle information which may include location but does not require specific environmental data or information from the scene. | Remote Operator may need control of ancillary vehicle systems, such as door locks, but does not require control over vehicle kinematics. | Communicate with passengers in real-time through an audio or video link. |

### 5.1.2 *Category 2: environmental attributes*

Remote operation is likely to be conducted in a broad range of environments. Some of these environmental attributes make it more difficult to achieve the fundamental three requirements (see section 5.1), therefore making remote operation more challenging. For example, weather conditions which affect sensors may impact the level of situational awareness a Remote Operator has by partially obscuring their view and may also affect the level of control over the AV in remote driving situations. An initial set of these environmental attributes, and their associated risks and constraints, is contained in Table 8.

**Table 8: Risks and constraints associated with environmental attributes**

| Environmental attribute | Risks and constraints | Typical environment |
|---|---|---|
| Unstructured environments | • Difficult for an AV to navigate as it's difficult to gauge the intentions of other users. AV likely to become stuck/frozen more regularly.<br>• Clear path may not be available for remote vehicle assistance.<br>• Places increased requirements on Remote Operator's situational awareness, as they may need to react to other users coming from several directions. | • Pavements<br>• Shared spaces including off-road (warehouse, construction, mining)<br>• Car parks. |
| Busy environments | • Gaps in traffic may be too small for a cautious AV to proceed and it may become stuck/frozen.<br>• More actors to collide with.<br>• Clear path may not be available for remote vehicle assistance.<br>• Places increased requirements on Remote Operator's situational awareness, as they may need to react to other users coming from several directions. | • City roads<br>• Shared spaces<br>• Pavements<br>• Off-road (warehouse, construction, port)<br>• Motorways /dual carriageways<br>• Car parks. |
| Interaction with Vulnerable Road Users (VRUs) | • Severity of collision increases.<br>• Behaviour of pedestrians, motorcyclists, horse riders or cyclists tends to be less predictable, therefore more difficult to negotiate than behaviour of other vehicles. | • Pavements<br>• Shared spaces<br>• City roads<br>• Car parks. |
| High speed environments | • Severity of collision increases.<br>• Less time to react, which requires a lower latency connection between AV and Operator. | • Motorways / dual carriageways. |
| Poor connectivity | • Loss of connection or poor connection speed may lead to a loss of control during remote driving.<br>• May obstruct the Remote Operator from obtaining sufficient situational awareness. | • Rural roads,<br>• off-road (agriculture, mining, construction)<br>• Urban environments. |

| | | |
|---|---|---|
| Uneven terrain | • Remote Operator may not be able to judge conditions as well as an in-vehicle driver.<br>• Difficulty in producing appropriate haptic feedback. | • Off-road (military, mining, agriculture, construction). |

### 5.1.3 *Category 3: Activities conducted by the AV*

Similar to environmental attributes, there are certain activities which present an additional challenge to remote operation by making it more difficult to achieve the fundamental three requirements (see section 5.1). Initial attributes in this category are summarised in Table 9 below.

**Table 9: Risks and constraints associated with specific AV activities**

| Activity attribute | Risks and constraints | Typical environment |
|---|---|---|
| Vehicle carrying significant loads | • Difficulty in producing appropriate haptic feedback.<br>• Risk of Remote Operator being unaware of loads coming unsecure. Greater risk of load causing damage and/or injury. | • Off-road (military, warehouse, construction, mining, port, agriculture)<br>• HGV platooning. |
| Vehicle carrying passengers | • Risk of injury to passengers in the event of a collision.<br>• Require increased capability to deal with unexpected scenarios arising, such as a passenger emergency. | • City roads<br>• Rural roads<br>• Shared spaces<br>• Motorways / dual carriageways. |

### 5.1.4 *Category 4: ADS capability and transition considerations*

The capability of the ADS also has an impact on the environments, activities, and types of remote operation which can be conducted safely. For vehicles with no automated functionality, the connection between the vehicle and Operator is of paramount importance since the vehicle is entirely unable to operate itself in the absence of an Operator.

For AVs, where control of the AV transitions between the ADS and a Remote Operator, this transition must be controlled and must happen at an appropriate time. If supervision from the Operator is intermittent, the key capability is for the ADS to be able to reach an MRC in the event of an error. This is required for highly and fully automated vehicles (SAE Level 4 and 5 respectively) so intermittent supervision is only suitable for AVs which meet this standard. Initial attributes associated with a transition period are summarised in Table 10 below.

**Table 10: Risks associated with transition of control between ADS and Remote Operator**

| Transition attribute | Risk |
|---|---|
| Intermittent supervision | • Operator is required to intervene with little or no notice from the AV.<br>• A loss of connection may lead to a loss of control of the AV. |
| Operator unable to respond to intervention request | • AV left unattended in error state for a significant period of time.<br>• AV left in a dangerous position, which may be obstructing other actors. |
| Intervention request made while AV is travelling at high speed | • Operator unable to provide intervention during the required period.<br>• Operator unable to take smooth control of AV. |
| AV exit from specified ODD | • The ADS may not recognise an exit from the ODD which may lead to operating unsafely. |

## 5.2 Initial generic use cases

Use cases which are most suitable for remote operation are those which have fewer risks and constraints from their constituent attributes. Additionally, in the case of AVs, scenarios where a Remote Operator is required to intervene less frequently are well-suited to remote operation.

Based on the information in the sections above an initial list of generic use cases, which are believed to be achievable for remote operation and have value, has been generated. These, along with their main risks and a risk rating for each use case, are outlined in Table 11. This list is not intended to be exhaustive and is based on the initial research conducted; it will evolve alongside TRL's knowledge and understanding in this field. The stated risk ratings are an indication of the level of risk posed by each use case without specific mitigations strategies being employed.

**Table 11: Initial generic use cases**

| High-level use case | Typical operating environment | Type of remote operation | Potential risk attributes | Risk rating |
|---|---|---|---|---|
| Rerouting an AV when an obstruction is present. This may involve the AV committing a minor traffic violation which it is not able to do on its own | On-road AV. May or may not take passengers. AV with conventional controls and would travel on public roads with other vehicles. | Remote vehicle assistance | • Remote vehicle assistance<br>• Busy environments<br>• Interaction with VRUs<br>• Poor connectivity<br>• AV carrying passengers<br>• Intermittent supervision<br>• Operator unable to respond to intervention request | Amber |
| Navigating intermittent areas of high complexity which are outside the AV's ODD and/or which cause the AV to become stuck or unresponsive | On-road AV. May or may not take passengers. AV with conventional controls and would travel on public roads with other vehicles. | Remote driving | • Remote driving<br>• Busy environments<br>• Interaction with VRUs<br>• High speed environments<br>• Poor connectivity<br>• AV carrying passengers<br>• Intermittent supervision<br>• Operator unable to respond to intervention request<br>• AV exit from specified ODD | Red |
| Conducting the complete DDT for a vehicle in a dangerous environment or carrying hazardous substances. Vehicle may or may not have automated capabilities | Off-road machinery (mines, quarries, construction sites, road works, etc). Likely to be large, heavy duty machinery. May include workers on foot. | Remote driving | • Remote driving<br>• Unstructured environments<br>• Busy environments<br>• Interaction with VRUs<br>• Poor connectivity<br>• Uneven terrain<br>• AV carrying significant loads | Red |
| Shuttle services carrying passengers on short trips | Off-road shared spaces such as airports, railway stations, shopping centres, campuses. | Remote vehicle assistance, remote driving | • Remote vehicle assistance<br>• Remote driving<br>• Interaction with VRUs<br>• Poor connectivity | Amber |

| | | | | |
|---|---|---|---|---|
| | AV travelling at low speeds. | | • AV carrying passengers<br>• Intermittent supervision<br>• Operator unable to respond to intervention request | |
| Last-mile delivery services | Pavement, cycle lane, or any other low-speed environment which is likely to be shared by pedestrians, cyclists, and other VRUs, but not generally by other vehicles. | Remote vehicle assistance | • Remote vehicle assistance<br>• Interaction with VRUs<br>• Poor connectivity<br>• AV carrying passengers<br>• Intermittent supervision<br>• Operator unable to respond to intervention request | Green |
| Using an e-call system to call for roadside assistance or information from a call centre | Privately owned on-road vehicles. | Passenger assistance services | • Passenger assistance services<br>• Operator unable to respond to intervention request | Green |

## 5.3 Limitations and further work

There are some limitations to this study, the framework, and use cases developed within it which are summarised below:

- The framework has been developed by a very small team and has not been subject to extensive testing to ensure its robustness for classifying an appropriately wide range of use cases for remote operation.
- The risks included are not specifically aligned with industry standards and regulation, such as GG 104 Requirements for safety risk assessment.
- The proposed framework is a possible way of classifying use cases but should not be taken as prescriptive guidance.

Two ways in which further work can build on this study are summarised below:

- The framework should be further developed to:
  - Include further use cases where remote operation would be suitable.
  - Include criteria to classify specific use cases more completely.
  - Align the potential risks to relevant industry standards.
- Mitigation strategies should be developed for generic risks where possible. The aim of this is to bring the risk ratings to As Low As Reasonably Practicable (ALARP) and encapsulate a wider selection of use cases within a tolerable level of risk.

# 6 Summary of roles, requirements, and responsibilities

The Safety Driver and Test Assistant both perform key roles in ensuring the safety of an AV trial. While the Safety Driver performs their role by observing the AV's environment and behaviour in the real-world, and intervening when necessary, the Test Assistant performs their role using digital feedback devices and relays key information (including anomalies) to the Safety Driver. To perform their roles both the Safety Driver and the Test Assistant are expected to meet certain key requirements. Some of these requirements, as well as their responsibilities, are summarised in Table 12 and Table 13. The summaries are based on various countries' guidelines for AV trialling, various trialling organisations' job descriptions for Safety Drivers and stakeholder consultation (FPS Mobility and Transport 2016; DGT 2017; Lovdata 2017; Risksdag 2017; Sano 2017; DfT 2019a; Lee and Hess 2020; National Transport Commission 2020).

**Table 12: Summary of the current requirements and responsibilities of Safety Drivers during trials and testing of AVs**

| Category | Requirements and Responsibilities |
|---|---|
| **Licensing requirements** | • The Safety Driver must hold a valid licence for the vehicle category, regardless of whether the vehicle's ability to operate entirely in automated mode is being tested.<br>• The Safety Driver should have held the licence for a given minimum number of years prior to the trial or test.<br>• As good practice it was suggested that Safety Driver's hold the nearest equivalent licence for prototype AVs that are not easily categorised. |
| **Training requirements** | • Safety Driver training should include training on the trialling organisations' risk management processes and the type of test or trial to be carried out.<br>• Safety Drivers are expected to be conversant with the system, including its capabilities, performance and limitations.<br>• Safety Drivers are expected to understand when to intervene through training covering potential hazardous situations and how to react to them. This includes being able to detect deviations from expected behaviours and being able to take full control of the vehicle's DDT if necessary. |

| Category | Requirements and Responsibilities |
|---|---|
| | • Safety Drivers are expected to understand how to transition between manual and automated mode and vice versa.<br>• Safety Drivers are expected to have skills over and above those of regular drivers of conventional vehicles. |
| **Risk assessment and vehicle control** | • The Safety Driver is always responsible for driving and operating the AV; hence they are expected to be able to drive, operate or control the AV safely and under any operating condition.<br>• Safety Drivers are expected to always supervise the AV regardless of its mode of operation (i.e., manual, or automated), constantly ensuring its safe operation. They must remain alert and ready to intervene if necessary throughout the test or trial.<br>• Safety Drivers are expected to pay attention to the AV's environment, observing the traffic laws, and the safety laws and laws restricting vehicle access.<br>• Safety Drivers are obligated to take full control of the AV under circumstances that may be detrimental to the AV's occupants or other road users.<br>• Safety Drivers are expected to adhere to the trialling organisation's risk management processes in place and use the knowledge and skill gathered during prior training to mitigate safety issues and ensure the safe operation of the system. |
| **Liability** | • In Germany, the Safety Driver and trialling organisation are liable for incidents that occur due to the Safety Driver's failure to regain control of the AV when prompted. However, the liability for incidents occur due to ADS failure does not lie with the Safety Driver. |
| **Public engagement** | • The Safety Driver is expected to engage with the emergency services and the public when required. This may include discussing the design and build of the AV and informing members of the public that the AV is a prototype before they agree to take part in the trial. |

**Table 13: Summary of the current requirements and responsibilities of Test Assistants during trials and testing of AVs**

| Category | Requirements and Responsibilities |
|---|---|
| **Risk assessment, vehicle control and information relay** | • Monitoring the AV's behaviour/system performance through software.<br>• In the case of emergency where the Safety Driver is incapacitated, disengaging autonomy and bringing the AV to a stop using an emergency stop button (without taking over the driving task).<br>• Localising the AV and providing verbal feedback/directions to the Safety Driver concerning the AV's environment.<br>• Monitoring the cybersecurity status. |
| **Data handling, debugging and repairs** | • Logging data related to the trial, which may include starting and stopping data recording from the sensors.<br>• Data marking and performing minor debugging operations when needed.<br>• May carry out repairs to the AV in the event of malfunction during the trials. |
| **Training requirements** | • Basic training including how to turn on the system, location of the controls, etc.<br>• Training on how to monitor the AV/system in automated mode in a controlled environment.<br>• Training on how to debug the system.<br>• Training on how to stop the AV in case of an emergency.<br>• Data handling training, including data logging and data marking. |
| **Public engagement** | • Passenger management/interacting with users such as passengers. |

Some of the key requirements and responsibilities of a Remote Operator were deduced during the stakeholder consultation. Table 14 shows a comparison between the key requirements of a Safety Driver, Test Assistant, and a Remote Operator suggested by stakeholders with Table 15 showing a comparison between their responsibilities. The role of the Remote Operator was split into two based on the level of control the Remote Operator has over the AV.

Table 14 and Table 15 show the responsibilities and requirements when the remote vehicle assistance and remote user assistance activities are performed by the same person. However, when performed by separate people, the responsibilities and requirements of the role may differ. The best practice for Remote vehicle/user assistance is to hold a driving licence but it might not be necessary in every application especially in remote user assistance.  Remote user assistants may however need to be trained on how to interact with the users and monitor their welfare. They may also need to be trained on how to actuate aspects of the AV to support the users, such as the doors and the boot. Data handling or technical tasks such as debugging the software may not be required for remote user assistance.

Table 14 and Table 15 also show that the responsibilities and requirements for remote control are similar to those of the Safety Driver. However, since the role is performed remotely the training requirements may differ. The person performing a remote control is expected to be trained on how to perform the role of the Safety Driver using feedback systems including displays as well as other training requirements related to remote operation.

**Table 14: Comparison between the requirements of a Safety Driver, Test Assistant and the suggested requirements of a Remote Operator**

| Category | Requirements | Safety Driver | Test Assistant | Remote Operator | |
|---|---|---|---|---|---|
| | | | | Remote vehicle/user assistance | Remote control |
| **Licensing requirements** | Hold a driving licence for the vehicle category. | Yes | No | Yes | Yes |
| | Hold the nearest equivalent licence for prototype vehicles that are not easily categorised. | Yes | No | Yes | Yes |
| | Have held the driving licence for a given minimum number of years prior to trial commencement. | Yes | No | No | Yes |

| | | | | | |
|---|---|---|---|---|---|
| | Have skills over and above those of regular drivers of conventional vehicles. | Yes | No | No | Yes |
| **Training requirements** | Basic training including how to turn on the system, location of the controls, etc. | Yes | Yes | Yes | Yes |
| | Covers the trialling organisation's risk management processes and the type of test to be carried out. | Yes | Yes | Yes | Yes |
| | Covers understanding of the system, including its capabilities, performance, and limitations. | Yes | Yes | Yes | Yes |
| | Understanding when to intervene through training covering potential hazardous situations and how to react to them. This includes being able to detect deviations from expected behaviours and being able to take full control of the AV's DDT if necessary. | Yes | No | No | Yes |
| | Understanding how to transition between manual and automated mode and vice versa. | Yes | Yes | No | Yes |
| | Training on how to monitor the AV/system in automated mode in a controlled environment. | Yes | Yes | Yes | Yes |
| | Training on how to debug the system. | No | Yes | Yes | No |
| | Training on how to perform minor repairs of the AV. | Yes | Yes | No | No |

| | | | | | |
|---|---|---|---|---|---|
| | Training on how to stop the AV in case of an emergency. | Yes | Yes | Yes | Yes |
| | Data handling training, including data logging and data marking. | No | Yes | Yes | No |

**Table 15: Comparison between the responsibilities of a Safety Driver, Test Assistant and the suggested responsibilities of a Remote Operator**

| Category | Responsibilities | Safety Driver | Test Assistant | Remote Operator | |
|---|---|---|---|---|---|
| | | | | Remote vehicle/user assistance | Remote control |
| **Risk assessment and vehicle control** | Always responsible for driving and operating the AV. Expected to be able to drive, operate or control the AV safely and under any operating condition. | Yes | No | No | Yes |
| | Always monitor the AV regardless of its mode of operation (i.e., manual or automated), constantly ensuring its safe operation. | Yes | Yes | No | Yes |
| | Must remain alert and ready to intervene if necessary. | Yes | Yes | No | Yes |
| | Pay attention to the AV's environment, observing the traffic laws, the safety laws and laws restricting vehicle access. | Yes | No | Yes | Yes |

| | | | | | |
|---|---|---|---|---|---|
| | Must take full control of the AV under circumstances that may be detrimental to the AV's occupants or other road users. | Yes | No | No | Yes |
| | Comply with the trialling organisation's risk management processes in place and use the knowledge and skill gathered during prior training to mitigate safety issues and ensure the safe operation of the system. | Yes | Yes | Yes | Yes |
| | Monitor the AV's behaviour/system performance through software other than the display showing the AV's environment. | No | Yes | Yes | No |
| | In the case of an emergency, disengage autonomy and bring the AV to a stop using an emergency stop button. | Yes | Yes | No | Yes |
| | Localise the AV and provide verbal feedback/directions to the AV's operator concerning the AV's environment. | No | Yes | Yes | No |
| | Monitor the cybersecurity status. | No | Yes | Yes | No |
| **Liability** | Bears some liability for incidents that occur due to failure to regain control of the AV when prompted. | Yes | No | No | Yes |
| **Public engagement** | Engage with emergency services and the public when required. | Yes | Yes | Yes | Yes |
| | Passenger management/interact with users such as passengers. | Yes | Yes | Yes | No |

| | | | | | |
|---|---|---|---|---|---|
| **Data handling, debugging and repairs** | Log data related to the trial, which may include starting and stopping data recording from the sensors. | No | Yes | Yes | No |
| | Data mark and perform minor debugging operations when needed. | No | Yes | Yes | No |
| | May carry out repairs to the AV in case of malfunctioning during the trials. | Yes | Yes | No | No |

# 7 Recommendations to enable remote operation of CAVs in the UK

This section describes the key proposed recommendations to enable remote operation of CAVs in the UK based on findings from the overall study and particularly the outcomes from the literature review and analysis of the stakeholder consultation.

The field of remotely-operated CAVs is in its infancy hence various recommended actions have been identified in this study to aid the safe removal of the Safety Driver and Test Assistant from an AV. These factors relate to legal requirements, certificates and standards, and technological requirements, all of which are described in further detail below.

## 7.1 Legal

Currently there are legal documents that could inhibit the progress of remote operation, including The Road Traffic Act 1988 and The Road Vehicles (Construction and Use) Regulations 1986, that were written before remote operation was considered a possibility (see Section 2.3). The Law Commission's third Consultation on Automated Vehicles is aimed at addressing these issues (Law Commission 2019a).

***CCAV should conduct a review of the Law Commission's recommendations and findings to identify possible gaps related to remote operation of CAVs in the UK that have not been addressed.***

Identifying and addressing these gaps could help provide legal certainty within the remote operation field, potentially encouraging investment, research, and development.

In addition to legal documents some best practice documents, including PAS 1881 and the latest DfT Code of Practice for Automated Vehicle Trialling, contain unclear guidelines for remotely-operated AV trials including the requirement that a Remote Operator must be at least as safe as an in-vehicle driver (see Section 2.3) (DfT 2019b) (BSI 2020c). No measurement for safety is provided in the documents.

***Research could be commissioned and supported by CCAV to quantify appropriate levels of safety for remote operation. CCAV might also consider collaborating in the review and revision of current best practice documents to better clarify the guidelines provided for remote operation***.

This would help ensure that ADS developers and other stakeholders can develop their systems to be safe enough to avoid incidents during public trials.

PAS 1881 and the latest DfT Code of Practice for AV trials require Safety Drivers and Remote Operators to be conscious of their appearance to other road users, for example continuing to maintain gaze directions appropriate for normal driving, to prevent any distraction to other drivers (DfT 2019b) (BSI 2020c). This may not be achievable if the Safety Operator is located outside the AV or on the passenger's seat.

***Research could be commissioned and supported by CCAV on how to mitigate the risk of distracting other road users due to the absence of a driver in the driver's seat.***

This could help ensure that the absence of a driver in the driver's seat does not cause distraction that could lead to an incident.

Liability is an issue being faced by the entire CAV industry. Problems such as the lack of specific definitions for Remote Operators' roles and tasks could further exacerbate liability issues in the remote operation field (see Section 3.3.1). The consultation by the Law Commission on AVs also includes a section on civil liability and insurance (Law Commission 2019a).

***CCAV should review the recommendations and findings of the Law Commission's third Consultation on Automated Vehicles to identify further possible gaps on liability that need addressing.***

Again, clarifying issues related to liability could encourage investment, research, and development in the remote operation field.

Legal factors including liability and other legal requirements related to remote operation may differ across the UK's domestic borders (i.e., England, Scotland, Wales, and Northern Ireland) and international borders (e.g., borders with EU member states), and could potentially affect the ability to trial and the safety of remote operations.

***CCAV should liaise with relevant stakeholders to understand how the legal requirements across the devolved administrations within the UK could be aligned to facilitate remote operation.***

***CCAV could also coordinate with other countries' authorities (such as the European Commission) to understand how the policies and regulations related to remote operation could be aligned.***

This would help ensure that remote operation can be conducted around the UK and across international borders without significant conflicting legal requirements and complexities.

## 7.2 Standards and certifications

There are currently issues related to inconsistent use of terminology and a lack of definitive sources used in the remote operation field, including definitions of the requirements and responsibilities of Remote Operators. There are also issues related to inadequate coverage of remote operation in CAV standards and general established standards. This also includes the lack of certification for key elements of remote operation, such as the human machine interfaces (HMI), to provide assurance that the elements are compliant with established standards.

***To address the inconsistent use of terminology and lack of definitive sources across the remote operation field, CCAV should initiate dialogue with relevant stakeholders to ensure industry-wide adoption of consistent terminology.***

Consistent terminology within the remote operation field could provide benefits in meeting interoperability requirements and standards. It could also help in facilitating communication among organisations within the field and enable the collection of shared data to aid the development of the field.

There may be value in developing formal certification for remote operation systems including the HMIs used by remote operators. There are gaps in current CAV standards related to remote operation including minimum safety requirements for communication network, HMI, and workstation (see section 2.6). CCAV and the Department for Transport have already initiated the development of CAV PASS, an assurance system for CAVs (DfT and CCAV 2019). Its purpose is to ensure that CAVs are safe and secure by design and minimise any defects ahead of their testing, sale, and wider deployment on UK roads.

***To complement CAV PASS, CCAV should also initiate dialogue with relevant stakeholders to identify the gaps in current standards related to remote operation and potential requirements for remote operation system certification.***

Facilitating the development and adoption of standards and certification that include minimum safety requirements could help ensure consistency, security, compliance and data sharing.

Apart from the issues related to certification and standards there are also some enablers. The Teleoperation Consortium in the United States is in the process of developing a teleoperation professional credential course (Teleoperation 2020). Additionally, the scope of the draft BSI PAS 1884 includes a section on Remote Operator specific training (BSI 2021). Once completed, PAS 1884 will provide guidance for organizations engaged in AV trialling and developmental testing that utilizes safety operators to monitor the ADS. CCAV could promote these efforts and others by recommending them to trialling organisations as guidance for remote operation. This would help ensure that trialling organisations are informed of the latest best practice on how to train their remote operators.

## 7.3 Technology

Some of the technological factors that should be considered in the remote operation field pertain to communication latency, data sharing and situational awareness of the Remote Operator.

Latency has a huge impact on remote operation with the associated risk increasing as the operating speed of the AV increases (see section 2.6.1).

***To address latency issues, CCAV could support research aimed at investigating effective methods (such as network splicing and maintaining constant latency values) for dealing with latencies experienced during remote operation.***

Such research could provide information on best practice that could be included in guidance for remote operation.

As well as latency, data sharing is another factor that could be considered in the remote operation field. Organisations may be reluctant to share data (including near misses and lessons learnt) for commercial or other reasons.

***To support data sharing, CCAV could host workshops or establish a working group to promote data sharing of remote operation tests, trials, and research.***

This could be conducted in a way that does not compromise the intellectual property rights of organisations or negatively affect their reputation. Sharing data within the remote operation field could facilitate industry-wide learning and improve the efficiency and safety of remote operation system development.

Another key technological factor that could be considered is the Remote Operator's situational awareness of the AV under test or trial. Remote Operators require adequate situational awareness for monitoring purposes and in order to respond to certain situations. However, it may be affected by various factors including their alertness, their trust in the system, and the design of the human machine interface (HMI) (see Section 2.6.3).

***To help improve the Remote Operators' situational awareness of an AV, CCAV could commission and support further research on improving the Remote Operators' situational awareness.***

***Based on the research findings, CCAV could coordinate the development of guidance which include guidelines on how Remote Operators could avoid complacency and maintain focus on the AV's environment and driving task even when the Remote Operators seem idle.***

The guidance documents could also cover guidelines on how to provide accurate and consistent feedback from HMI systems. They could also cover how user-friendly HMI systems may be designed, including how they may present key feedback information (see Section 2.6.3). Gamification is known to improve the situational awareness of operators in other industries, further research may be needed to understand how this method could be employed in the remote operation field. Development of up-to-date guidance documents would help ensure that Remote Operators are well-trained and are equipped with appropriate HMIs to maintain an appropriate level of situational awareness during operation.

## 7.4 Safety assurance

There are various risks involved in the removal of a Safety Driver and Test Assistant from an AV. Before a remote operation system can be trialled in public various safety assurances may need to be evidenced, for example in the trial safety case, to demonstrate that the risks have been considered and mitigations are in place to manage them. This section highlights some of these risks and recommended actions for CCAV below.

### 7.4.1 *Redundancies to handle failures/disengagements*

Remotely-operated AVs undergoing trials may pose an increased safety risk to the public in the absence of either a Safety Driver or external operator within VLOS of the AV.

***A mandate could be made that during early trials, remote operation systems of any technological level can be tested if there is a Safety Driver or an external operator present (with a real-time view of the AV) overseeing operation who can at any point either take back full control of the AV or bring the AV to a stop.***

The system should include warning systems to the Safety Driver or external operator when safety issues are detected such as when the vehicle is approaching the end of its ODD and communication issues. The safety driver or external operator should promptly address such issues when they receive the signal by, for example, regaining control of the vehicle or bringing it to an emergency stop. The Safety Driver or external operator should understand any risks associated with remote access, this includes handling any communication or control latency and mitigating and responding to any network problems. The Safety Driver or external operator should comply with the guidelines provided for Safety Drivers in PAS 1881 and the latest DfT Code of Practice for AV trials (BSI 2020c) (DfT 2019b). This would help ensure that in the event that the remote operation system fails, risk mitigation strategies are in place to any avoid incident.

### 7.4.2 *Remote Operators' working hours*

Remote Operators' working for extended hours risk becoming fatigued which could result in reductions in situational awareness and potentially result in incidents (see Section 2.6.3). The recommended working hours for remote operation may differ from those of an in-vehicle Safety Driver. There may also be differences in recommended working hours for the different use cases of remote operation.

***Guidelines on appropriate working hours for each remote operation use case could be developed.***

These guidelines could be used to update the UK rules for drivers' hours (GOV.UK 2021). The guidelines would aid trialling organisations when setting daily, and whole lifecycle trial-related, working hours limits for Remote Operators.

### 7.4.3 *Licensing requirements*

Remote Operators may need to prove that they are qualified to safely perform their roles on publicly accessible roads by holding licences that reflect their competency to perform their responsibilities (see Section 6).

***Special licences (for example, for the use of specific equipment such as head-mounted devices and specific control interfaces) could be developed for each remote operation use case that reflects the responsibilities of the Remote Operator.***

Licence requirements for the remote control of an AV could include the requirements in the licence guidelines for Safety Drivers in the latest DfT Code of Practice for AV trials (DfT 2019b). Licencing Remote Operators would help ensure that they are fully qualified to perform their respective roles which could help improve the safety of remote operation.

#### 7.4.4 *Training requirements*

HMIs used in remote operation may differ from those used to manually drive conventional vehicles. Therefore, Remote Operators should be trained on how to appropriately use the interfaces including transitioning between the different modes of operation (e.g., remote, automated, and manual driving) and how to deal with the challenges that may occur when using interfaces, such as visually induced motion sickness (see Section 2.6.5).

***To ensure adequate safety when operating in publicly accessible areas, it could be mandated that Remote Operators are adequately trained on how to perform their roles.***

They should understand the capabilities and potential limitations of the technologies under trial as far as possible. This would help ensure that Remote Operators are fully prepared to deal with the safety challenges in publicly accessible areas.

#### 7.4.5 *Behaviour requirements*

Some laws regarding drivers' behaviour may not be easily met by Remote Operators hence special laws regarding Remote Operator's behaviour for each use case may need to be updated or developed for remote operation. Remote Operators would be expected to comply with applicable laws and the special laws for Remote Operators.

***A requirement may be made that for public trials, trialling organisations should demonstrate how their Remote Operators will comply with the special laws.***

This would help provide assurances that a remote operation trial is compliant with the law and will potentially improve the safety of the operation.

#### 7.4.6 *AV requirements*

AVs are expected to comply with the general road vehicle requirements which includes having appropriate rear-view mirrors.

***For remote operation, it could be mandated that the AV's sensors should provide at least the same level of depth and view of the AV's environment as an in-vehicle driver.***

This would help ensure that the Remote Operator can adequately view the AV's environment.

#### 7.4.7 *Mitigation strategies*

Remote operation might fail if there is a wider communication network failure, if access to the communication network is impeded, or if unmanageable latencies occur (see Section 2.6.1).

***To avoid risks associated with communication network failure, mitigation strategies may need to be in place, and it could also be mandated that trialling organisations are required to provide sufficient evidence that their AV can perform mitigation manoeuvres (e.g., an emergency stop) when such an event occurs.***

This would help ensure that risks associated with the network are appropriately managed to reduce the possibility of an incident occurring.

#### 7.4.8 *Transition between driving modes*

Similar to transitioning between automated and manual driving mode, transitioning between remote operation and automated or manual driving modes is an important safety issue.

***Recommendations such as ease of transition between driving modes, clear indication of the current driving mode and the use of audible, visible, or haptic signals to indicate take-over demands to the Remote Operator, should be made to trialling organisations for remote operation.***

Such recommendations should include monitoring Remote Operators' situational awareness ahead of and during transitions. In case the remote operator does not respond promptly, there should be safety measures in place to ensure that the vehicle can automatically reach a minimum risk condition, such as the vehicle coming to an emergency stop. The recommendations would provide key safety information on what trialling organisations should consider during transition to avoid an incident.

#### 7.4.9 *Minimum engagement guidelines and tools*

Some stakeholders that may have to review a trial's safety case might find it challenging. To address this issue TRL has recently developed guidance documents for trialling organisations, road and local authorities, and insurers to guide them through engagement with trialling organisations (TRL 2021b; TRL 2021c; TRL 2021d). TRL has also recently developed Connected and Automated Mobility – Safety Assurance Tool (CAM-SAT) aimed at facilitating a fast and efficient trial safety review process that allows safety to be assured to stakeholders, while addressing the outlined challenges (TRL 2021a). The tool is available for trialling organisations and reviewers such as local authorities, road authorities, landowners, and testbeds.

***CCAV could promote such guidance documents and tools by recommending them in guidance documents for remote operation.***

Promoting such tools would help ensure that stakeholders are aware of available support for remote operation engagements.

## 7.5 Summary of recommendations

Table 16 summarises the enablers and challenges in removing the Safety Driver and Test Assistant from an AV and the recommended actions for CCAV.

**Table 16: Summary of the enablers and challenges and recommended actions for CCAV**

| Category | Enablers/Challenges | Recommendations | Benefits |
|---|---|---|---|
| **Legal** | Legal documents written before remote operation was considered a possibility, such as the Road Traffic Act 1988 and The Road Vehicles (Construction and Use) Regulations 1986, could inhibit progress of remote operation. | Conduct a review of the Law Commission's recommendations and findings to identify possible gaps related to remote operation of CAVs in the UK that have not been addressed. | Identifying and addressing these gaps could help provide legal certainty for remote operation, encouraging investment, research and development. |
| | There are unclear guidelines in some best practice documents, such as PAS 1881 (BSI 2020c) and the DfT Code of Practice for AV trials (DfT 2019b), including the lack of safety measurements for remote operation systems. | Collaborate in the review of best practice documents and support research aimed at quantifying safety levels for remote operation. | This would help ensure that ADS developers can develop their systems to be safe enough to avoid incidents during public trials. |
| | The requirement for Safety Drivers and Operators to be conscious of their appearance to other road users to avoid distractions cannot be met by Remote Operators. | A study could be coordinated on how to mitigate the risk of distracting other road users due to the absence of a driver in the driver's seat. | This could help ensure that the absence of a driver in the driver's seat does not cause distractions that could lead to an incident. |
| | Liability is an issue being faced by the entire CAV industry, including for remote operation. | Conduct a review of the Law Commission's recommendations and findings aimed at addressing | Clarifying issues related to liability could encourage |

| Category | Enablers/Challenges | Recommendations | Benefits |
|---|---|---|---|
| | | legal issues related to AVs to identify possible gaps on liability. | investment, research and development. |
| | Legal factors related to remote operation may differ across the UK's domestic and international borders and could potentially affect the safety of remote operations. | Liaise with relevant stakeholders to understand how laws across the UK could be aligned and how these could be further aligned with those of other countries to facilitate remote operation. | This would help ensure that remote operation can be conducted across the UK and across international borders without legal uncertainty and complexity. |
| **Standards and certifications** | There are issues related to inconsistent use of terminology and lack of definitive sources for terminology in the remote operation field. | Initiate dialogue with relevant stakeholders to identify requirements and develop common terminology for use within the remote operation and wider CAV field. | This would help ensure industry-wide adoption of the terminology and potentially promote collaboration. |
| | There are also issues related to inadequate coverage of remote operation in CAV standards and general established standards. This also includes the lack of certification for key elements of remote operation, such as the human machine interfaces (HMI), to provide assurance that the elements are compliant with established standards. | Initiate dialogue with relevant stakeholders to identify the gaps in current standards related to remote operation and potential requirements for remote operation system certification. | Facilitating the development and adoption of standards and certification that includes minimum safety requirements could help ensure consistency, security, compliance, and data sharing. |
| | The Teleoperation Consortium is in the process of developing a teleoperation professional credential course, and BSI PAS 1884 (which is in | Promote these efforts and other similar efforts by recommending them to trialling organisations in | This would help ensure that trialling organisations are informed of best practice on |

| Category | Enablers/Challenges | Recommendations | Benefits |
|---|---|---|---|
| | preparation) includes a section on Remote Operator training. | guidance documents for remote operation. | how to train their Remote Operators. |
| **Technology** | Latency has a huge impact on remote operation with the associated risk increasing as the operational speed of the AV increases. | Support research aimed at investigating effective methods for dealing with latencies experienced during remote operation. | Supporting such research could provide information that could be included in industry guidance for remote operation. |
| | Organisations may feel reluctant to share data (including lessons learnt) for commercial reasons. | Host workshops aimed at promoting the sharing of remote operation system trial results and research findings. | Sharing data could facilitate learning from incidents and trials, which could aid in improved efficiency and safety of system development. |
| | The situational awareness of a Remote Operator may be affected by various factors including their activeness, their trust in the system and the design of the human machine interface (HMI). | Coordinate the development of guidance documents that cover how Remote Operators could stay active and how to design appropriate HMIs. | This would help to ensure that Remote Operators are well trained and equipped with appropriate HMIs to maintain acceptable levels of situational awareness during operation. |

Table 17 summarises the safety assurance recommendations for the removal of the Safety Driver and Test Assistant from an AV.

**Table 17: Safety assurance recommendations**

| Safety assurance issue | Details | Recommended action | Benefit |
|---|---|---|---|
| **Redundancies to handle failures/disengagements** | Remotely-operated AVs undergoing early trials may pose an increased safety risk to the public in the absence of either a Safety Driver or external operator within VLOS of the AV. | A mandate could be made that during early trials, remote operation systems of any technological level can be tested if there is a Safety Driver or an external operator present (with a real-time view of the AV) overseeing operation who can at any point either take back full control of the AV or bring the AV to a stop. | This would help ensure that in events where the remote operation system fails, risk mitigation strategies are in place to any avoid incident. |
| **Remote Operator working hours** | The recommended working hours for remote operation may differ from those of an in-vehicle safety driver. | Guidelines on appropriate working hours for each remote operation use case could be developed. | The guidelines would aid trialling organisations when setting limits for time that remote operators perform their role per day. |
| **Licensing requirements** | Remote Operators may need to prove that they are qualified to safely perform their roles on publicly accessible roads by holding special licences. | Special licences could be developed for each remote operation use case that reflects the responsibilities of the Remote Operator. | Licencing Remote Operators would help ensure that they are fully qualified to perform their respective roles safely. |

| Safety assurance issue | Details | Recommended action | Benefit |
|---|---|---|---|
| **Training requirements** | Remote operation HMIs may differ from those used for conventional driving. | It could be mandated that Remote Operators are adequately trained on how to perform their roles using the HMIs before undergoing a trial on publicly accessible areas. | This would help ensure that Remote Operators are fully prepared to deal with the safety challenges in publicly accessible areas. |
| **Behaviour requirements** | Special laws regarding a Remote Operators' behaviour for each use case may need to be developed (or updated) as some laws regarding driver's behaviour may not be easily met by Remote Operators. | A requirement could be made that for public trials, trialling organisations should demonstrate how their Remote Operators will comply with the special laws. | This would help provide assurances that a remote operation trial is compliant with the law and potentially improves the safety of the operation. |
| **AV requirements** | AVs are expected to comply with the general road vehicle requirements which includes having appropriate rear-view mirrors. | For remote operation, it could be mandated that the AV's sensors should provide at least the same level of depth and view of the AV's environment as an in-vehicle driver. | This would help ensure that the Remote Operator can adequately view the AV's environment. |
| **Mitigation strategies** | Remote operation might fail if there is a wider communication network failure, if access to the communication network is impeded, or if unmanageable latencies occur. | To avoid risks associated with communication network failure, mitigation strategies may need to be in place, and it could also be mandated that trialling organisations are required to provide sufficient evidence that their AV can perform mitigation manoeuvres (e.g., an emergency stop) when such an event occurs. | This would help ensure that risks associated with the network are appropriately managed to reduce the possibility of an incident occurring. |

| Safety assurance issue | Details | Recommended action | Benefit |
|---|---|---|---|
| **Transition between driving modes** | Transitioning between remote operation and automated or manual driving modes is an important safety issue. | Recommendations such as ease of transition between driving modes, clear indication of the current driving mode and the use of audible, visible, or haptic signals to indicate take-over demands to the remote operator, similar to those in the latest DfT Code of Practice for AV trials (DfT 2019b), should be made to trialling organisations for remote operation. | The recommendations would provide key safety information on what trialling organisations should consider during mode transition to avoid an incident. |
| **Minimum engagement** | Some stakeholders that may have to review a trial's safety case could find such safety cases challenging. There are tools designed to support stakeholders during such engagements. | CCAV could promote support tools for stakeholder engagements (such as TRL's guidance documents and CAM-SAT) (TRL 2021b; TRL 2021c; TRL 2021d) by recommending them in guidance documents for remote operation. | Promoting such tools would help ensure that stakeholders are aware of available support for remote operation engagements. |

## 8 Roadmap to enable remote operation of CAVs in the UK

The high-level roadmap (Figure 5) developed in this section aims to provide a pathway to enable the removal of the Safety Driver and Test Assistant roles from an AV for remotely-operated on-highway operation in the UK. It provides a high-level overview of the actions required to achieve this and can be used by organisations in industry or for research purposes.

The roadmap is developed based on an extensive literature review, industry stakeholder consultation, expert opinion from TRL, and reference to other CAV roadmaps (such as (Zenzic 2020), (TRL *et al.* 2020)). The contributors to this roadmap considered the gaps and challenges in the development and adoption of remote operation for CAVs and the recommendations (Section 7) that could address these gaps; these recommendations form the basis of the roadmap.

The roadmap brings together eleven thematic streams organised around three broader themes to be delivered through UK Government and industry-wide collaboration. The themes are subject areas for research and development, the streams are topics within each theme, and the milestones are individual elements (actions or outcomes) within a specific stream. The three themes (and associated streams) are:

**1. Industry, users and society**

- **Legislation and insurance** - revising legislation and regulations/standards to facilitate remote operation.
- **Licensing and use** - establishing licensing requirements for the Remote Operator and trialling organisations.
- **Public use and desirability** - improving public perception of CAVs and remote operation.
- **Training and skills development** - establishing the training and qualification requirements to deliver skilled Remote Operators.

**2. Vehicle and technology**

- **Cybersecurity** - Cybersecurity requirements to support remote operation.
- **Data** - Data gathering, governance and ownership.
- **Ergonomics and design** - HMI guidance for safe remote operation.
- **Network connectivity** - Establishing communication requirements to support remote operation.
- **Test and development** - Establishing safety requirements for testing remote operation.

**3. Infrastructure**

- **Data** - Establishing data sharing requirements to support remote operation.
- **Communications** - Identifying infrastructure requirements to support remote operation.

It should be noted that the milestones included in the roadmap offer a high-level overview of the steps required to enable remote driving-related remote operation activities (see Section 4.2). Essentially, it is possible to break down each milestone presented here into smaller steps, providing an additional level of detail. However, providing a list of shorter, more specific tasks at a granular level was out of scope of this study. Instead, the milestones included in this roadmap function as "umbrella" actions and have a minimum duration of one year. A comprehensive list of tasks providing additional detail on the actions needed to facilitate remote operation should be part of future work.

Another limitation to be considered is that the timeline provided in this roadmap is purely knowledge-based and should only be viewed as an estimate. The successful completion of each milestone is dependent on the progress made by industry and government bodies. Nevertheless, the fact that work for most of the milestones included in the roadmap is already underway has been considered in the development of the roadmap.

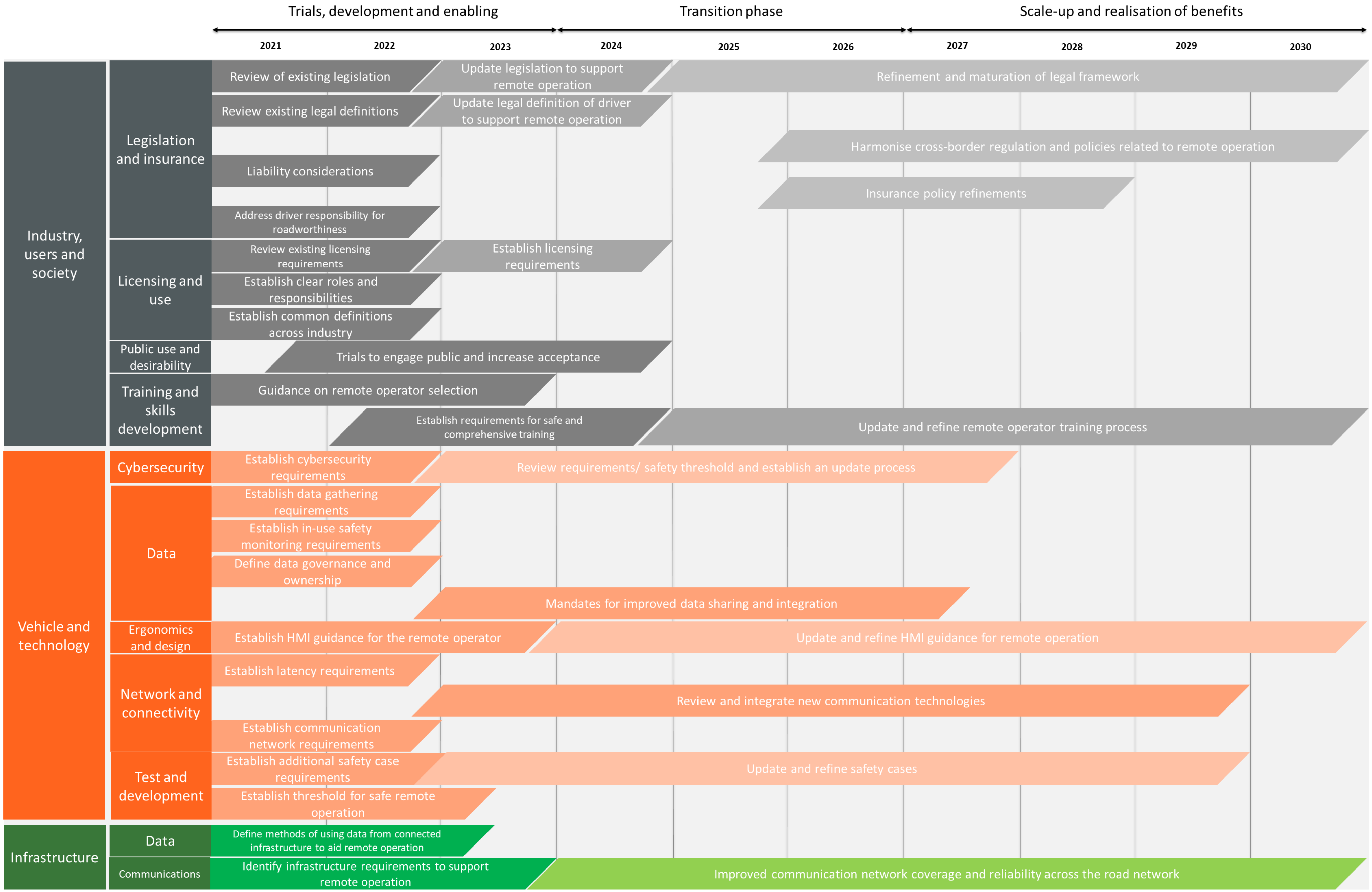


**Figure 5: Roadmap to enable remote operation of CAVs in the UK**

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# Appendix A Stakeholder consultation topic guide

Each stakeholder was asked several questions derived from the topic guide below based on individual competencies of the stakeholders and the activities performed by their company. The topic guide presented the following questions:

## Definitions related to remote operation

| Questions |
|---|
| How would you/your organisation define 'remote operation'? |
| What is your understanding of an 'advanced trial'? How would you differentiate advanced trials from other trials? |
| Have you been, or are you currently, involved in an advanced trial? |
| How could the proposed advanced trials that are not compliant with the law be supported to ensure compliance? |

## The current guidance, standards, and regulation related to remote operation

| Questions |
|---|
| The taxonomy and terminology used around remote operation (for example, operation, supervision, control) remains largely undefined by the current standards and regulation. Do you think the industry would benefit from having standard definitions for such terms included in documents such as BSI PAS 1890? |
| Do you think remote operation can be applied within the current law/regulations? |
| Are you aware of any proposals (and the timeline) to review and/or amend legislation to clarify the legality of remote operation? |
| In the event of an incident where should the liability lie if the vehicle is operating remotely?<br>(for example, the Remote Operator, the service provider/trial organisation, the software/ADS developer) |
| Besides contacting CCAV, what other approval processes need to be undertaken prior to remote operation and what do they encompass?<br>(For example, a type approval process, a licensing/permit process) |
| What steps are required for trials and full deployment of remote operation?<br>Do you think these steps will be common across software/ADS developers or do you expect developers to take different paths? |
| What additional training is required for remote operators compared with in-vehicle Safety Drivers? |
| Do you think the existing cyber security standards (the DfT's Principles of cybersecurity, PAS 11281 and PAS 1885) can sufficiently cover remote operation? |
| Are you planning to develop and use remote operation technology for AVs, if so when?<br>• What use cases are you developing solutions for (or planning to conduct trials for)? |

- What guidelines have you referred to/followed?
- What is the interest/drive behind those use cases?
- What challenges do you see in implementing them?

### Role of the Safety Driver

| Questions |
|---|
| What is your/your organisations' understanding of the role of the Safety Driver in automated vehicle (AV) trials? |
| What tasks are performed by you as a Safety Driver, or the Safety Drivers in your organisation, during AV operation? What information enables the Safety Driver to complete the tasks mentioned? |
| Does the ACSO assist the Safety Driver in completing the tasks mentioned in the above question? If so, how does the ACSO do this? |
| Is the Safety Driver required to complete any training? What does this cover? Is it conducted 'in-house'? |
| How does the Safety Driver respond to communication issues? |
| Do you think the Safety Driver role can be safely performed remotely?<br>What additional requirements do you/your organisation think should be in place to enable this? |

### Role of the Autonomy Control System Operator (ACSO)/Test Assistant/Test Engineer

| Questions |
|---|
| What is your/your organisations' understanding of the role of an ACSO in automated vehicle (AV) trials? |
| What tasks are performed by you as an ACSO, or the ACSOs in your organisation, during AV operation? What information enables the ACSO to complete the tasks mentioned? |
| Does the ACSO have controls to perform any elements of the dynamic driving task? |
| Does the ASCO need to perceive the movement of the AV and its surroundings? |
| Does the Safety Driver assist the ACSO in completing the tasks mentioned above? If so, how does the Safety Driver do this? |
| Is the ACSO required to complete any training? What does this cover? Is it conducted 'in-house'? |
| Do you think the ACSO role can be safely performed remotely? What additional requirements do you/your organisation think should be in place to enable this? |

## Safety considerations for the removal of the Safety Driver and ACSO/Test Assistant/Test Engineer roles from the AV

| Question |
|---|
| What do you think are the biggest risks and challenges in removing the Safety Driver and ACSO from the AV? |
| Whose role do you think will be made remote first (Safety Driver or ACSO) and why? What implementation stages should be required to make it happen? |
| How would you assess whether a remote operator provides as much safety as an onboard Safety Driver? And what evidence would you provide to demonstrate the safe removal of the Safety Driver and ACSO? |
| What other safety considerations should be taken into account when implementing remote operation? |

## Role of the Remote Operator

| Question |
|---|
| What are the responsibilities of a remote operator? Do you think they differ from those of an onboard Safety Driver? If so, how? |
| What qualifications/training are needed for a remote operator? What scenarios should be used to train a remote operator? |
| What level of control do you/your organisation see a remote operator having? |
| How do you think the remote operator will interact with other road users? |

## Requirements and challenges in data processing and transfer between the AV and the Remote Operator

| Question |
|---|
| What are the main sources of information that will be required for remote operation? (For example, HD maps, LiDAR, etc) |
| What information should be stored for investigative purposes in the event of an incident during remote operation? |
| What should be the communication requirements for safe and secure remote operation? |
| How can the remote operators safely respond to communication issues? |
| How should the system (ADS) respond to communication issues during remote operation? |
| What are the challenges with respect to communication requirements for remote operation? |

## Human factors considerations and limitations for remote operation

| Question |
|---|
| How do you ensure remote operators remain alert during operation? |
| How can the control of remotely operated vehicles be improved?<br>Is there any technology that could be beneficial? |
| How could public trust in remote operation be improved? |

## Roadmap for remote operation of CAVs in the UK

| Question |
|---|
| If you were to create a roadmap for remote operation,<br>• What activities does your organisation do in terms of remote operation?<br>• Where do you think you are with the status of these activities?<br>• When do you think these activities can be completed? |
| What milestones do you think are pending and what actions are required to complete the activities?<br>(For example, further research, funding) |
| Given the capability your organisation has, which remote operation activities could your organisation contribute to and would want to be recognised for delivering? |

## Remote operation of Connected and Automated Vehicles

Connected and Automated Vehicles (CAVs) offer numerous societal benefits; however, there is still a long way to go before CAVs can be considered reliable and safe. Even when CAV technology has matured, and is more readily available, there will be scenarios that require human intervention such as system failures, situations outside of the AV's Operational Design Domain (ODD), or to support users. As part of project Endeavour, TRL conducted research on potential human intervention scenarios, which has been considered and referred to as a part of 'remote operation'.

This study sought to understand the current roles of the in-vehicle Safety Driver and Test Assistant during CAV trials and testing to recognise the technical challenges of removing the roles and enabling remote operation. This report includes findings from a literature review and stakeholder engagement and contains:

- Information on the roles and responsibilities of the in-vehicle Safety Driver and Test Assistant and their remote counterparts
- Current terminology used in the CAV space, and recommended terms for remote operation
- Use cases and recommendations to enable safe remote operation
- A high-level roadmap describing the milestones to enable remote operation in the UK

**Other titles from this subject area**

**PPR1012** Remote operation of Connected and Automated Vehicles: Project Endeavour – WP15b - Summary report. A Kalaiyarasan, B Simpson, D Jenkins, F Mazzeo, H Ye, I Obazele, K Kourantidis, M Courtier, MCS Wong, P Ball, R Wilford. (2021)

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