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A Survey on Remote Operation of Road Vehicles

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ABSTRACT In recent years, the use of remote operation has been proposed as a bridge towards driverless mobility by providing human assistance remotely when an automated driving system finds a situation that is ambiguous and requires input from a remote operator. The remote operation of road vehicles has also been proposed as a way to enable drivers to operate vehicles from safer and more comfortable locations. While commercial solutions for remote operation exist, remaining challenges are being tackled by the research community, who is continuously testing and validating the feasibility of deploying remote operation of road vehicles on public roads. These tests range from the technological scope to social aspects such as acceptability and usability that affect human performance. This survey presents a compilation of works that approach the remote operation of road vehicles. We start by describing the basic architecture of remote operation systems and classify their modes of operation depending on the level of human intervention. We use this classification to organize and present recent and relevant work on the field from industry and academia. Finally, we identify the challenges in the deployment of remote operation systems in the technological, regulatory, and commercial scopes.

INDEX TERMS 5G, automated mobility, connected vehicle, remote driving, teleoperation.

I. INTRODUCTION

Remote operation or teleoperation of robots and vehicles has been widely studied in different contexts including air, ground, and underwater vehicles. Overview of vehicle teleoperation and different interfaces have been reviewed in [1]. Challenges and future directions with respect to teleoperation of robots are summarized in, e.g., [2] and [3].

In the context of road vehicles, the advent of new wireless communication technologies such as 4G or 5G cellular network and the developments in driving automation systems have enabled Remote Operation of Road Vehicles (RORV). Thus, this brings the need for an updated exploration of the current literature, as well as revisiting challenges and their respective solutions.

RORV is often considered in relation to automated driving systems (ADSs). For instance, in scenarios where

highly-automated vehicles could fail due to an ambiguous, unexpected or unidentified situation – e.g., unexpected roadworks – the ADS could either request authorization from a remote assistant to change routes, or yield full control of the vehicle to a remote driver in order to resolve the situation.

Applying remote operation to road vehicles, especially those equipped with ADS, comes with several benefits to safety and efficiency of road transport systems. RORV can enhance and support operations of automated vehicles as mentioned above, and thus enabling new mobility services such as *robotaxis*. This also improves operations of driverless vehicles that no longer have driver interfaces inside the vehicles (e.g., passenger shuttles from EasyMile¹ or Navya²) as the safety drivers can be located outside the vehicles. Furthermore, RORV could improve working conditions and

¹<https://easymile.com/vehicle-solutions/ez10-passenger-shuttle>

²<https://navya.tech/en/solutions/moving-people/self-driving-shuttle-for-passenger-transportation/>

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safety for drivers of commercial vehicles, e.g., long-haul and last-mile truckers. Last but not least, companies could potentially benefit from remote operation scenarios to avoid waiting long hours for loading and unloading operations in warehouses. For instance, a few remote operators could be assigned to handle loading and unloading of all vehicles on site, then the vehicles can be operated autonomously between sites.

Despite huge potential benefits and strong incentives from industry and academia, there are several challenges to be addressed before RORV can be realized on public roads. In this survey, we consider the challenges with respect to the following aspects:

- Technological feasibility (e.g., whether current technologies can support RORV)
- Human factors (e.g., what information do the human operator need for safe remote operation)
- Standards and regulations (e.g., whether RORV can be deployed in cross-border scenarios)
- Business models (e.g., potential of RORV to support large-scale commercial applications)

A. MODES OF REMOTE OPERATION

The bulk of the works in the literature often relate RORV to driving automation systems, proposing them as a complement across all levels of driving automation by keeping a human in the loop. In the context of RORV, the SAE J3016₂₀₂₁₀₄ standard [4] defines the terms related to *remote users* and their role with respect to each level of driving automation. These roles are: 1) remote driver [SAE's Level 0-2]; 2) remote fallback-ready user [SAE's Level 3]; and 3) remote assistant/driverless operation dispatcher [SAE's Level 4-5]

Apart from SAE's definition, we also consider the definition of Remote Human Input Systems (RHIS) in [5]. the work in [5] states that SAE's definition of "remote driving" is only available at the Level 1 and 2, while the most recent version of the SAE J3016₂₀₂₁₀₄ standard [4] considers the possibility of remote operation across all levels (Table 3 in [4]).

Therefore, we propose an updated set of operation modes of RORV as follows:

- 1) remote driving
- 2) remote assistance
- 3) remote monitoring

These four operation modes are described further in Section II.

B. CURRENT SURVEY

In this survey we review the research on RORV, covering the wide range of human intervention: from monitoring to fully controlling a vehicle through a communications network. We also explore relevant commercial approaches to RORV, and finally, we identify and summarize the challenges for research and deployment of RORV, ranging from feasibility to regulatory and business challenges.

The contribution of this survey focuses on analyzing and classifying the literature within the context of RORV.

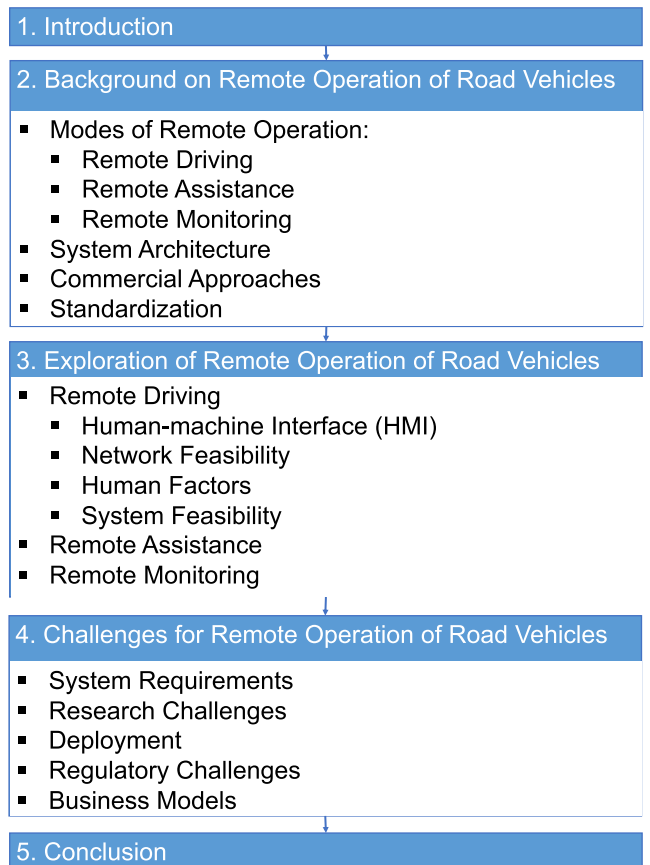


FIGURE 1. Structure of this survey.

We classify them by *mode* of operation that was considered, the type of study they perform (e.g., network measurements, trials on test tracks, simulations), and the type of road vehicles in their experiments or trials (e.g., heavy trucks, passenger vehicles).

Therefore, this work presents the following contributions that have not been fully addressed by other work:

- 1) We explore the recent literature on RORV and its relation to driving automation systems.
- 2) We categorize the literature by the experimentation methodology they use, e.g., driving simulations, network simulations, field tests, tests on confined and open spaces and demonstrations.
- 3) We identify and present remaining gaps and challenges for research and deployment of RORV.

The rest of the article is organized as follows: Section II briefly describes different modes of RORV and its relation to driving automation systems: this includes their requirements and the efforts by standardizing bodies to define technical specifications for RORV; Section III organizes and summarizes existing classification scheme of RORV in the literature; Section IV identifies the main future challenges for the research and development for different modes of RORV; and finally, Section V concludes this survey. The organization of this work is summarized in a flowchart depicted in Fig. 1,

which helps readers navigate the covered topics and the general structure of this survey.

II. REMOTE OPERATION OF ROAD VEHICLES

This section provides an in-depth background and introduction into the research field of RORV. A RORV system is one where a Remote Operator (ROp) performs the entirety or part of the Dynamic Driving Task (DDT), sometimes in conjunction with a driving automation system (SAE International (SAE) refers driving automation systems as ADS starting from Driving Automation (DA) Level 3, and discourages the abbreviation of driving automation systems). The DDT consists of operational and tactical functions. Operational functions refer to the lateral and longitudinal motion control (e.g., steering and brake/throttle control, respectively). Tactical functions include sub-tasks related to Object and Event Detection and Response (OEDR), e.g., planning and execution for object avoidance, and expedite route following. In a RORV system, the responsibility over the DDT is shared between a ROp and a driving automation system depending on: 1) the automation's Operational Design Domain (ODD) (i.e., when, where, and under what conditions an automated vehicle is designed to operate, or those conditions in which it can't operate); and 2) if the automation finds a situation that it cannot solve by itself and requires input or authorization from a ROp.

The implementation of a RORV depends on the supported mode(s) of operation(s); it is also typically related to the available technology and driving automation systems available in the *remotely-operated vehicles*. There are several requirements defined both by research and by standardizing bodies and the variable nature of these factors prompts the existence of a myriad of different implementations ranging from academic implementations to commercially-available services.

In this section, we describe different operation modes for RORV as defined in the literature and by standardized bodies, focusing on the existing system architectures and requirements for each operation mode. We also describe current commercial applications, that are being offered by manufacturers and other service providers, ranging from those directed to passenger vehicles to heavy trucks.

Fig. 2 summarizes roles and tasks for the ROp and the driving automation system for all the *remote operation* modes. For all modes of remote operation, a ROp remotely monitors the ADS according to the SAE's definition, which means that the ROp has full responsibility to actively monitor the environment (i.e., OEDR in SAE's terminology) when ADS level 0 to 3 is activated. For the level 4 and 5, the OEDR task is performed by ADS, and thus the ROp would mainly supervise the trip and assist the ADS when needed or requested by the ADS.

Remote Driving: This mode refers to situations when the ROp manually controls a vehicle by means of throttling, braking, and steering the vehicle. This mode is common within the scope of SAE's Levels 0 to 2 of driving automation.

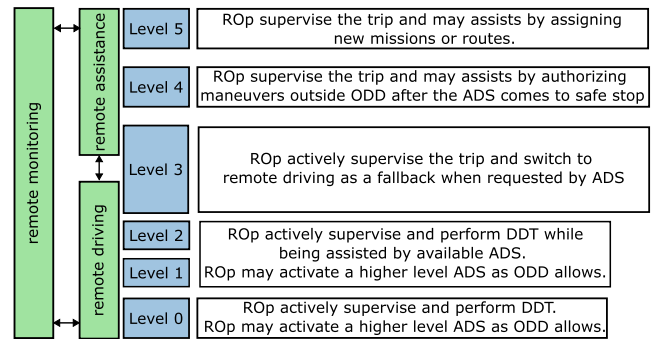


FIGURE 2. Modes of RORV (green boxes) in relation with SAE's levels of driving automation (blue boxes). Example scenarios for each combination are described in white boxes. Black arrows indicate transitions between different modes.

At these levels, the SAE specification gives the main responsibility for the DDT to the remote user (remote driver), since the driver is expected to perform part or all of the DDT (with assistance from the driving automation system starting from the Level 1). It is important to highlight that SAE does not consider remote driving as Driving Automation.

In our analysis, *remote driving* covers SAE's driving automation Levels 0 to 2. Hence, a ROp has to be present and active at all times during this operation mode. The ROp is fully responsible for monitoring the environment (i.e., OEDR in SAE's terminology), while the control of vehicles can be done through support of driving automation functions at Level 1 and/or 2.

Starting from SAE's Level 3 driving automation, the responsibility for the entire DDT is passed to the ADS while it is engaged. However, a fall-back ready user, who becomes a driver during fallback, is specified as the DDT fallback. Hence, the ROp will be in the remote driving mode during the fallback. Finally, for the higher levels of DA (i.e., 4 and 5), remote driving is not common, but may be performed when the ADS is operating outside its ODD and requires human intervention.

Remote Assistance: SAE defines *remote assistance* as the provision of advice from a remotely located human to an ADS-equipped vehicle when it is within its ODD but encounters a situation it cannot manage. An example mentioned in [4] is when a driverless vehicle encounters an unannounced area of road construction and communicates to a remotely located human that it cannot drive around the construction, and the remote assistant provides a new pathway to follow (which the ADS then executes accordingly). Another example cited in [4] is where the remote assistant performs a OEDR action: the driverless vehicle detects an object in its lane that appears to be too large to drive over and stops, then a remote assistance identifies it as an empty bag that can be safely driven through and instructs the ADS to proceed (even when [4] considers OEDR a DDT sub-task).

Our definition of remote assistance mode follows examples and definition by SAE mentioned above. This operation mode covers SAE's Level 4 and 5 of driving automation. This is an operation mode where the ROp only provides input and

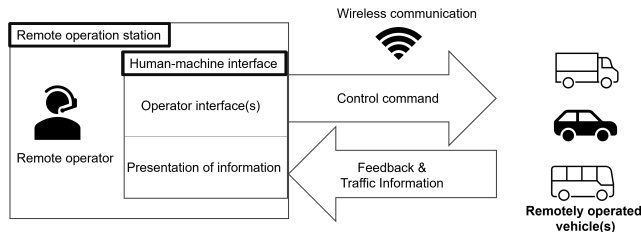


FIGURE 3. System architecture for RORV systems.

authorization to the ADS-equipped vehicle without directly performing any part of the DDT. The expected responses would be less time-critical than the *remote driving* mode, since the driving automation system shall handle the entire DDT and fallback within its ODD.

This mode also applies to Level 3 driving automation if the ROP intervenes and assists the ADS (without taking over control of the vehicle) within its ODD. Finally, if a situation outside ODD occurs, the ROP may need to switch from this mode to *remote driving* in order to resolve the it.

Remote Monitoring: We suggest *remote monitoring* as a part of RORV, although there is no respective definition by SAE. *Remote monitoring* is considered separately since a ROP can only act as an observer. It is an operation mode where there is no direct influence from the ROP on the performance of the DDT besides, e.g., performing system diagnostics or monitoring the task status from a screen.

Nevertheless, a ROP could possibly intervene and switch to either *remote assistance* or *remote driving* from this mode if needed. For instance, the ROP could re-route the vehicle (remote assistance) if an accident is reported ahead on the route, or intervene and divert the vehicle onto another path (remote driving) if the operator detects a potential situation outside the ODD ahead.

A. SYSTEM ARCHITECTURE

A simplified version of a system architecture for RORV is depicted in Fig. 3. The major elements in the system architecture are 1) remote operation station; 2) human-machine interface (HMI); 3) wireless communication; and 4) vehicle(s) that is being remotely operated.

Remotely operated vehicles inform about the status of the ongoing DDT to a Remote Operator through a network connection. This information is presented to the ROP through the Human-machine Interface (HMI), that can range from simple tables on a screen reporting sensor status (e.g., in a mobile phone or in a computer) to the display of audiovisual feeds and even haptic transducers (e.g., head-mounted devices, speakers, vibration, torque simulation).

Wireless communication network acts as a bridge between the remote operator and the remotely operated vehicle(s). The vehicle sends their status to inform the remote operator through this channel as described above. Furthermore, the control or assistance commands from the remote operator are then sent back to the vehicle through the network. Network technologies used in Intelligent Transport Systems

(ITS) range from those who require previously existing infrastructure to ad-hoc networks. Access technologies that are used in vehicular networking can be divided in two: 1) Dedicated Short Range Communication (DSRC) technologies [6], [7], which are based on IEEE 802.11p (IEEE 802.11 OCB — Outside the Context of a Basic service set), and 2) Cellular technologies, which range from currently-existing, commercial-grade cellular networks such as 4G and 5G to C-V2X (Cellular Vehicle-to-Everything), which has been developed by the 3rd Generation Partnership Project (3GPP) [8].

For the remotely operated vehicle, the complexity of the systems depend on the existing DA level available in the vehicle. For DA Level 0, where all the DDT is performed by a driver, all the tactical tasks are performed by the ROP and it is only required for the vehicle to act upon direct commands that affect lateral and longitudinal vehicle motion (i.e., only sensors and actuators are required). When the higher levels of automation are considered (e.g., where remote assistance is applied), more complex systems are required in the vehicle in order to perform tactical and operational functions. Therefore, possible remote operation modes also depend on existing functionalities in the vehicle and the degrees of DA that are available.

B. COMMERCIAL APPROACHES

In this subsection, we explore commercial approaches to RORV. We categorized them in three main categories, covering elements in the system architecture of RORV:

- 1) **Remote Operation Support:** companies that develop dedicated software stack for remote operation and design remote operation stations. These companies typically also develop their own human-machine interface for ROP.
- 2) **Network Providers:** companies that provide or support wireless communication network; they are typically telecommunication operators.
- 3) **Vehicle and Service Providers:** Original Equipment Manufacturers (OEMs), and providers of mobility and transportation services.

1) REMOTE OPERATION SUPPORT

In this category, we list companies that develop software stack for remote operation, which often include designs for remote operation stations and HMI to support the remote operation of vehicles and offer it to vehicle and service providers (e.g., those in section II-B3). The difference between these companies and the ones in II-B3 is that their main business model is focused on developing interfaces for remote operation, and not the mobility or logistic services themselves. Companies in this category usually follow a business-to-business model.

Designated Driver [9] is a company based in Portland, Oregon. It offers RORV-as-a-Service for vehicles with and without DA capabilities, as long as the vehicle has drive-by-wire capabilities [28]. Designated Driver ranges in all modes of RORV, from remote monitoring to remote driving. The

TABLE 1. Commercial approaches to RORV.

	Company	Remote Driving	Remote Assistance	Remote Monitoring
Remote Operation Support	Designated Driver [9]	✓	✓	✓
	Ottopia [10]	✓	✓	✓
	Fernride [11]	✓		
	Phantom Auto [12]	✓	✓	✓
	Voysys [13]	✓	✓	✓
	Imperium Drive [14]	✓	✓	✓
Network Providers	T-Systems [15]	✓		
	Telefonica [16]	✓		
	Ericsson [17]	✓		
Vehicle and Service Providers	Nissan [18]		✓	
	Cruise [19]		✓	✓
	Aptiv/Motional [20, 21]	✓	✓	
	Waymo [22]		✓	✓
	Uber [23]		✓	✓
	Zoox [24]		✓	✓
	Drive.ai [25]	✓	✓	
	Vay [26]	✓		
	Einride [27]	✓		

system operates over commercial cellular networks, with a module that can connect to up to eight different operators in order to ensure a stable connection, which enables a trained (and company-certified [29]) ROp to control the vehicle from a remote station equipped with six screens and video game controllers. As reported in a 2019 press release, it has achieved latencies below 100 ms over 4G connections provided by Verizon and AT&T networks [30].

Ottopia [10] is a software company that offers RORV-enabled mobility in an as-a-Service business model. It is in the Round A funding stage (i.e., a startup that is past the seed stage and is looking to reach the product-market fit previous to escalation), and it is currently partnering with vehicle manufacturers and OEMs such as BMW and Hyundai, as well as with companies that provide transportation services (e.g., robotaxis) [31]. Ottopia's services cover all RORV modes, from remote monitoring to remote driving, and according to a press release, its solution had been tested on public roads using public LTE networks in BMW's driving campus in Germany [32].

Fernride [11] is a spin-off company from a teleoperation research lab at the Technical University of Munich. It offers intelligent mobility in an as-a-Service business model for logistics companies, by providing them with RORV systems in the remote driving mode. Fernride tends to four use cases: yard trucks, forklifts, long haul freight, and last mile deliveries for companies (i.e., in a business-to-business model).

Phantom Auto [12] offers three main services for logistics companies: 1) remote forklift operation, 2) remote assistance for autonomous vehicles, and 3) remote driving training. Specifically, it offers a platform to control forklifts, yard trucks, and other robots, falling in the remote driving and remote assistance modes. E.g., Phantom Auto partnered with delivery service provider Postmates [33] to offer remotely operated deliveries, where autonomous vehicles would receive instructions or authorization from remote operators when they faced challenging conditions or to navigate the first and last dozen feet in a delivery. Phantom Auto operates in LTE, WiFi, and 5G networks, and adapts

dynamically to network conditions by using its patented platform.

Voysys [13] develops visual systems that enable the remote operation of machines, including vehicles. It offers mobility providers and fleet managers a platform to monitor and control autonomous vehicles through the streaming of video in "real time" even under unfavorable network conditions (e.g., public 4G/LTE networks). Voysys has partnered with companies such as Volvo, Einride, Ericsson, and the BT group.

Imperium Drive [14] offers a remote operation platform that allows service providers and fleet managers perform remote driving tasks. Among its services, Imperium Drive offers last mile delivery, shared mobility, and human supervision (i.e., remote assistance and monitoring) and intervention (i.e., remote driving) for fleets of autonomous vehicles. It considers the effect of varying network performance, and uses artificial intelligence to predict link conditions in order to adapt streaming and control services to the predicted network conditions, while also being able to respond to unexpected conditions through their link-aware streaming and control technologies (e.g., safe maneuvers are performed in the event of a sudden loss of signal).

2) NETWORK PROVIDERS

T-Systems, part of the German telecommunications company Deutsche Telekom, considers RORV as a stage towards full automation. It released a white paper [15] where it describes the feasibility of RORV remote driving in closed properties (e.g., yard trucks, parking lots), in public roads, and for use cases such as remotely-operated valet parking services, using 4G mobile networks. While their white paper considers 3G networks as very limited, and 4G environments as adequate under certain conditions (e.g., closed properties with good mobile coverage), it positions 5G as the technology which will empower the expansion of RORV deployments. Additionally, while T-Systems is part of a telecommunication operator, it has allied itself with companies such as Ottopia, which we will explore in section II-B3.

Telecommunication operator Telefonica and telecommunication infrastructure provider Ericsson have partnered in an effort to demonstrate that 5G networks are reliable for RORV in the remote driving mode. During a joint demonstration [16], they showcased 5G's ability to support the remote operation of a vehicle located in a test track from a stand located almost 100 km away (i.e., the distance between Barcelona and Tarragona in Spain). Telefonica and Ericsson have also partnered in the demonstration of a bus service, using Ericsson infrastructure and Telefonica as the network operator [34].

Also, Ericsson partners with other Swedish institutions and companies (e.g., Scania and the Royal Institute of Technology) in developing RORV systems [17], enabling the international transfer of knowledge.

3) VEHICLE AND SERVICE PROVIDERS

In this category, we list the commercial approaches to RORV coming from vehicle manufacturers and from mobility and transport service providers that rely on RORV. An example of an approach from a vehicle manufacturer is Nissan, which launched its Seamless Autonomous Mobility system [18], developed with NASA. It combines artificial intelligence with the support of a ROP that helps driving automation system make decisions when facing unpredictable situations. This service falls within the remote assistance mode of RORV, since the ROP does not perform any DDT sub-tasks.

Cruise [19] is a startup company that emerged from Y-Combinator that was acquired by General Motors and later co-financed by Honda, and announces itself as an autonomous driving service provider. However, its demos [35] show that a ROP (called a "safety operator") monitors the vehicle, and has the ability to bring the vehicle to a minimal risk condition. It is not clear, however, if this "safety operator" performs any DDT sub-tasks.

Aptiv [20], formerly known as Delphi and originally a spin-off from General Motors, acquired nuTonomy in 2017, while still under the Delphi brand. In 2020, Aptiv and Hyundai announced a partnership, re-branding nuTonomy as Motional [21], and started to develop RORV-assisted taxi services in Las Vegas in collaboration with Lyft, where DA-enabled vehicles will be assisted by a ROP, which will have the capability of redirecting a vehicle to a new path would it face an unusual scenario [36]. This places Motional in the remote driving and remote assistance modes of RORV.

RORV service providers are companies that offer services that rely on RORV systems either as their main business unit (e.g., a company that offers remotely driven freight services), or as part of their main service (e.g., a fleet of DA Level 4 taxis that relies on RORV capabilities to surmount unexpected situations). In other words, companies in this category offer services to end users (business-to-consumer), rather than to other companies (business-to-business).

An example of a fleet of DA Level 4 taxis supported by RORV systems is Waymo [22], a subsidiary of Alphabet Inc. (the parent company of Google), which offers taxi services

using DA Level 4 vehicles. While Waymo advertises its services as not requiring human input, it does rely on remote operators to deal with unexpected situations, e.g., when the vehicle encounters a closed road, it calls the *Fleet Response*, which is a remotely located set of specialists that provide high level input to the ADS [37]. This locates Waymo in the remote assistance and remote monitoring RORV modes.

Uber [23], a service that started as a ride sharing company and it now has strategic business units in the shipping and distribution sectors (e.g., from food delivery, couriers, and last mile transportation, to freight transportation), started working with RORV at different levels. Two patents [38], [39] registered to Uber or its subsidiaries, describe a telecommunications network and a remote assistance system for automated vehicles, which puts the efforts by Uber at least in the RORV remote assistance and remote monitoring modes.

Zoox [24], a subsidiary of Amazon that offers automated mobility in an as-a-Service model, operates taxi services without in situ drivers. It has a proprietary RORV systems to provide assistance to their DA-enabled vehicles should they encounter unexpected situations that require human input [40]. This puts Zoox into the remote assistance and remote monitoring modes of RORV.

Drive.ai started as a mobility provider in the Frisco, Texas area in the United States. It offered an DA-enabled vehicle that relied on a RORV system (called telechoice) that allowed the intervention of a ROP to deal with unexpected situations. The operator could provide both high level input (e.g., OEDR), and activate the brakes [41]. This puts Drive.ai in the remote assistance and remote fallback driving modes of RORV. The company was acquired by Apple in 2019 [25].

Vay [26] is a startup company from Germany, which offers a door-to-door car sharing system, i.e., a user orders a car to be delivered at a certain place and time by a ROP, the user drives the vehicle up to its destination, and leaves the parking task to the ROP. This puts Vay in the remote driving mode of RORV. In terms of business model and service development, Vay is past the seeding stage (above Series B funding), and is expected to use the data collected from its remotely and locally operated fleet to develop a fully automated service [42].

Einride is a developer of a driverless electric freight vehicle, who started hiring its first remote truck drivers in 2020 [27]. Remote operation capabilities seem crucial for operation of their trucks since there is no driver cabin in their vehicles.

C. STANDARDIZATION

Standards developing organizations (SDOs) at the international level work towards the harmonized operation of the systems that empower Connected, Cooperative and Automated Mobility (CCAM). Different regions in the world fall under the influence of different SDOs: the European Telecommunications Standards Institute (ETSI) for Europe, SAE for the Americas, Association of Radio Industries and

Businesses (ARIB) for Japan. Additionally, other SDOs and consortia regulate the operation of specific technologies, such as the Institute of Electrical and Electronics Engineers (IEEE) for 802.11 standards for wireless access, and the 3rd Generation Partnership Project (3GPP) — which includes several SDOs such as ETSI and ARIB — which develops protocols for mobile telecommunications.

ETSI, through the ITS Technical Committee (TC), has developed a set of standards that define the requirements and operation of Cooperative ITS. The ETSI ITS protocol stack defines the layers from application to access, providing for the use of different access technologies — WiFi and cellular — and the requirements for the applications that enable cooperative mobility: from road safety to traffic efficiency. However, there are not any specifications regarding RORV, although the goals of this TC include the development standards for remote assistance [43].

SAE has provided definitions and taxonomies on driving automation systems since the first release of SAE J3016 standard [4]. Its latest release, SAE J3016₂₀₂₁₀₄, continues to be the reference for the level of driving automation systems capabilities: both commercial and research applications refer to the SAE DA Levels when categorizing driving automation systems. It also provides the definitions for Remote User (i.e., remote driver, remote fallback-ready driver, and remote assistant/ driverless operation dispatcher), which we adapt in this work for the modes of RORV (i.e., remote driving, remote assistance, and remote monitoring). However, SAE J3016₂₀₂₁₀₄ only reaches the answer of what to do (e.g., when a DA-enabled vehicle fails within its ODD), but not how to do it (e.g., specifying an algorithm to call for assistance when the driving automation system fails within its ODD).

SAE and the International Organization for Standardization (ISO) released ISO/SAE 21434 : 2021 [44], a standard that specifies the requirements for the development, operation, and disposal of electrical and electronic systems in road vehicles in the scope of cybersecurity. It defines a framework and a common language for cybersecurity processes. However, it does not prescribe specific technologies or solutions, since it aims at the goal of adapting to the ever-changing threats for cyber-physical systems and networks that are at the core of CCAM.

As a result of the exploration of standards regarding RORV, we can identify that 1) SAE is the de-facto standard for driving automation systems, yet it does not regard RORV as DA, and it does not expect consistent input from ROPs at higher automation levels; 2) while ETSI standards are specific and in constant evolution (e.g., they now consider different access technologies), they more focused on cooperative mobility rather than on the automated part of CCAM; and 3) both SAE and ETSI emphasize the importance of cybersecurity and the need to account for the potential misbehavior of road users and adversarial entities. In summary, SDOs provide paths to follow in RORV, but do not prescribe explicitly a set of technological requirements in the same way they do for, e.g., cooperative mobility.

Therefore, standards specifically related to RORV are still largely undefined. However, it should be noted that there are already work towards regulating RORV, as summarized in [45].

III. AN EXPLORATION OF REMOTE OPERATION OF ROAD VEHICLES

In this section we explore the contributions of recent literature regarding RORV. Table 2 classifies the contributions from the different explored papers. The contributions are divided by the modes of RORV that we described in section I-A. We also divide contributions by the different network technologies used, in this case in two main categories: WiFi and cellular. For the case of cellular, when possible, we further indicate the specific technology and whether the work uses public or experimental networks. We also divide the contributions in the following categories according to the type of studies they present:

- 1) **Network measurements:** works that aim at measuring the feasibility of a network technology to achieve the required performance, e.g., the network requirements stated in section IV-A2.
- 2) **Human performance measurements:** works that evaluate the performance of ROPs (e.g., workload), and the effect of ergonomics (e.g., the use of display arrays, haptic feedback, headsets) in human performance.
- 3) **Simulations:** validation is performed in simulation setups for remote operation. Here, we account for different types of simulations:
 - a) *Focused simulations:* i.e., numerical analysis or simulations that model system under study partially (e.g., they evaluate an algorithm for driver selection without modeling the radio channel).
 - b) *System-level simulations:* setups that model the entire RORV system architecture (i.e., remote operation station, network, and vehicle).
- 4) **Prototypes:** the remotely-operated vehicle is a prototype, i.e., a vehicle in early stages of development that is not currently available to the public.
- 5) **Trials:** validation is performed in fully operational vehicles (e.g., passenger vehicles, trucks, shuttles) that have RORV capabilities. These trials can be performed in:
 - a) *Test Tracks:* tests are performed in purpose-built tracks that are commonly accessible to car manufacturers and research institutions.
 - b) *Public Roads:* tests are performed in roads that are accessible to the general public.

A. REMOTE DRIVING

Most works in the literature have focused on remote driving mode. There are several challenges on this mode since ROP is in control of most of the DDT, i.e., the ROP has to handle the longitudinal and lateral motion of the vehicle with or without assistance from other vehicle systems when the driving automation system finds a difficult situation. The related work can be categorized into four main topics, which

TABLE 2. Literature on remote operation of road vehicles.

Paper	RORV Mode			Component in Architecture			Study Type				
	Remote Driving	Remote Assistance	Remote Monitoring	HMI	Network	Vehicle	Network Measurements	Human Performance	Simulation	Prototype	Trials
Davis et al. [46]	✓			✓				✓	✓		
Chucholowski [47]	✓			✓				✓			
Graf et al. [48]	✓			✓				✓			
Graf et al. [49]	✓			✓				✓			
Hofbauer et al. [50]	✓			✓					✓		
Vozar and Tilbury [51]	✓			✓				✓	✓		
Cabral et al. [52]	✓			✓	LTE	✓			✓		
Hosseini and Lienkamp [53]	✓			✓					✓		
Hosseini et al. [54]	✓			✓					✓		
Kallioniemi et al. [55]	✓			✓				✓	✓		
Neumeier et al. [56]	✓				LTE		✓				
Neumeier et al. [57]	✓				LTE		✓	✓	✓		
Gaber et al. [58]	✓				LTE		✓				
Zhang et al. [59]	✓				4G, 5G, WiFi		✓				
Kang et al. [60]	✓				LTE, WiFi		✓				
Shen et al. [61]	✓			✓	WiFi, 4G, 3G	✓	✓				
Hosseini and Lienkamp [62]	✓				LTE		✓				
Juang [63]	✓		✓	✓	4G					✓	✓
den Ouden et al. [64]	✓				4G, 5G					✓	✓
Gnatzig, et al. [65]	✓				4G, 4G					✓	✓
Pyykönen et al. [66]	✓				4G		✓				
Zhou et al. [67]	✓				5G+					✓	
Perez et al. [68]	✓				4G, 5G+		✓				
Sato et al. [69]	✓			✓	WiFi					✓	✓
Liu et al. [70]	✓				5G		✓	✓		✓	
Gohar and Lee [71]	✓				Simulated				✓		
Gohar et al. [72]	✓				Simulated				✓		
Zulqarnain and Lee [73]	✓				Simulated				✓		
Saeed et al. [74]	✓				5G				✓		
Acharya et al. [75]	✓				Emulated				✓		
Tang et al. [76]		✓		✓					✓		
Gnatzig et al. [77]		✓		✓					✓		
Schitz et al. [78]		✓		✓					✓		
Schitz et al. [79]		✓		✓	✓ ‡					✓	
Kettwich et al. [80]		✓		✓				✓	✓		
Al-Taee et al. [81]			✓		GPRS						✓
Zhou et al. [82]			✓	✓						✓	
Medvedev et al. [83]			✓	✓							
Wang et al. [84]			✓	✓	GPRS					✓	

†[67] and [68] use experimental 5G networks, while [59] and [64] use public networks.
‡[79] performs a test in a full-sized vehicle but does not specify the network technology it uses.

are HMI, human factors, network feasibility, and system feasibility.

Work in the remote driving mode that address the vehicle are less common. As shown in Table 2, only two works that address the vehicle side of the architecture and it is only in tandem with the network and HMI parts. The work in [52] addresses two options for camera arrays, one with a fixed camera and another with a rotating camera that responds to input from the remote operator using a head-mounted device. The work in [61] similarly addresses the use of a stereoscopic camera, but its focus is on analyzing the feasibility of remote operation using low-cost equipment.

1) HUMAN-MACHINE INTERFACE (HMI)

In the remote driving mode, one of the main object of study we find in the explored works is the effect of remote driving scenarios on human workload — the mental and physical effort of a remote driver. Authors in the literature rely on questionnaires such as the NASA Task Load Index (or NASA-TLX) [85], which allows the subjective assessment of human performance of operators working with human-machine interfaces. It measures six dimensions: mental demand, physical demand, temporal demand, performance, effort, and frustration. The bulk of the works researching Human-Machine Interfaces aim

to mitigate the effect of, e.g., network lag, on remote drivers.

The work in [46] measures the effect of time lag in performance on a simulated driving task while proposing a mitigation alternative that they call predictive display. Their results show a degradation of the performance of the human-in-the-loop control tasks, and variable time lags equal to or larger than 700 ms may hinder an operator's ability to adapt. Similarly, authors in [47] conclude that time delays have a significant negative influence on driver performance in a simulated scenario. They also propose video frame prediction as a mitigation technique for network or processing-induced lags.

Furthermore, the work in [48] proposes the predictive corridor: predictive displays in combination with the concept of the *predictive corridor* (i.e., showing the ROP an area in which the DA-enabled vehicle will continue to travel in cases of unexpected network losses). To measure the effect of the predictive corridor in workload, the authors rely on the NASA-TLX questionnaire, but they also measure the face temperature and visual focus of their 32 participants. Furthermore, [48] evaluates the predictive corridor using objective metrics, in this case, Euclidean deviation, obtaining an improvement of 7.3% less deviation in an experimental evaluation with a constant driving velocity of 15 km/h and constant delays of 200 ms.

While using prototypes as validation, authors in [51] conduct an experiment aimed at modeling the effect of time delay on remote operation. They observe the tendency of drivers (assessing 31 voluntary subjects) to saturate game-pad inputs (i.e., moving a joystick as far right or left as possible) instead of relying on its sensitivity or granularity, which falls within the topic of haptic feedback as a mitigation for this tendency.

Driving simulators are the most common validation methods in HMI-focused research on remote driving. One well-established driving simulation environment for autonomous driving systems is CARLA [86]. From that starting point, the work in [50] proposes TELECARLA, an extension to CARLA that is aimed at remote driving scenarios over a network connection. Using video streaming software for camera data compression and transmission, and Robot Operating System (ROS) as an interface between the extension and CARLA, they test the performance of their extension in terms of scenario duration and vehicle collision rates. One of their conclusions is that they can use their extension in any driving simulator with a ROS bridge.

In studies about user experience, driving simulators are used in studies measuring the effect of network conditions on human performance, assessing the required setups for remote driving settings (e.g., camera and display positioning), and validating mitigation techniques for remote driving issues (e.g., the use of predictive displays). Regarding the effect of delay on human performance, works use varying driving simulation tool-kits, e.g., OpenROUTES3D [87] (used in [57]), SimCreator, a real-time simulation and modeling system (used in [46]), and a custom made environment based on

Java April Robotics Toolkit (used in [51]). Despite the varying use of tool-kits, the experiment setup tends to be consistent: delays are introduced (with different magnitude and frequency) and human performance is measured both objectively and subjectively. Finally, It can be gathered from these three samples that, even when open source tool-kits are available, researchers tend to create their own setups ([51], [57]), or rely on proprietary software ([46]).

In terms of the validation of remote driving setups, the work in [52] evaluates the viability of remote driving from the point of view of remote operators and passengers. Using different combinations of fixed and movable cameras and displays (e.g., AR glasses, tablets) and different delays, the authors measured the level of acceptance of remote driving by passengers when delays and steering angle errors are present. The authors in [53] and [54] use driving simulations to test the performance of a haptic feedback system that predicts a collision (i.e., to compensate for communication delays) and generates additional torque on the remote station steering wheel. Similarly, driving simulations are used to test the performance of mitigation techniques, such as the predictive display in [48], or the work in [55], where the driver's situational awareness is enhanced with the use of multi-modal feedback (visual, auditory, and haptic). The authors in [55] use a Unity-based custom-built simulator for an armored personnel carrier, and studied the effect of different combinations of feedback (e.g., visual and haptic clues to determine the slipperiness of the road).

Thus, we can conclude that there are open-source driving simulators that are highly validated (e.g., CARLA), and remote driving simulators are entering the scene (e.g. TELECARLA, OpenROUTES3D). The appearance of a dominant set of simulators (as is the case of OMNET++ and ns3 for network simulations) will provide researchers with opportunities to replicate experiments and benchmark results. However, due to the recentness of remote driving as a backup for automated driving systems, the literature exhibits a trend towards the use of custom-made simulation setups.

2) NETWORK FEASIBILITY

Network latency is one of the factors that affect RORV. The work in [2], focused on the remote operation of robots, proposes 170 ms as the threshold where latency starts to affect performance. Works researching RORV propose a maximum tolerable latency of 250 ms [56], along with the other performance requirements described in IV-A2. In this subsection, we explore works that measure network performance in remote driving and fallback driving scenarios.

The work in [70] refers to earlier works that state that network delays below 170 ms have mild influences in remote operation, while performance is significantly affected when network delays exceed 700 ms. By using network emulation, the authors explore the effect of constant and random delays in objective performance (i.e., lap times and cross-lane errors), and in driver workload. The results show that there is an effect from network delay, but this effect worsens when

the delay is not constant (i.e., constant latency is better than random delays).

Authors in [58] measure the performance of LTE networks from different operators (i.e., mobile network providers). Data collection was conducted in Cairo, with records of throughput in down-link and up-link along a public road using mobile phone terminals. They consider the possibility of switching providers, and using an algorithm to predict the next best providers using blind handover. By switching between providers, they postulate that network latencies can stay below 100 ms for 91% of the time, as opposed to 71% when using the single best operator.

The effect of uneven coverage and latencies is also explored in [59], where a fully automated vehicle yields control to a ROP when facing a challenging situation while driving in a closed industrial park. The prototype in this work has 4G, 5G, and WiFi connections that allow remote driving, and switches to manual operation (i.e., with an in-vehicle driver) when network losses exceed 10%.

The work in [60] measures network latency using WiFi (802.11n) and LTE networks and its ability to transmit video at different resolutions. The authors perform measurements by streaming video from a mobile phone. Their results show median latencies of 100 ms for LTE and 50 ms for WiFi, and postulate protocol overheads as an explanation for the difference (i.e., they only used one WiFi access point, so the overhead of hand-off is excluded).

The authors in [61] perform an evaluation of latency for WiFi, 4G and 3G networks as part of their work in analyzing the performance of off-the-shelf components for a RORV. While their measurements using WiFi-based networks could be used as a benchmark (i.e., they do not use DSRC, but WLAN technologies), it is their measurement of 4G and 3G cellular communications what makes this work relevant. Results show that 4G communications — with an average latency of 182.0 ms for video streaming, 107.2 ms and 110.3 ms for vehicle controls — fall within the parameters set as required in section IV-A2.

The work in [62] also performs network measurements as part of a bigger contribution for remote driving. The authors measure the performance of a commercial LTE network (i.e., ping round-trip times), and obtain an average delay of 138 ms, with maximums of 445 ms. These delays include the required times to encode video images from the vehicle, their transmission over LTE, and video decoding and visualization at the remote station.

The authors in [56] perform network measurements as part of a bigger effort to evaluate the feasibility of remote driving. In their previous work [57], they identified the effects of latency in remote driving using simulations, and in [56], they measure cellular network coverage and round-trip-times in roads in Germany. Using a smartphone and a trunk-mounted LTE gateway, they used ping, netradar and iperf3 to connect to servers in Frankfurt and Munich. Their results prompt them to conclude that teleoperation might not be feasible in certain scenarios where network coverage affects network performance. They propose *whitelisting* —

allowing remote driving only where network conditions are measured to provide sufficient performance. Their work in [56] provides an approach to whitelisting where a prior evaluation of coverage and a continuous measurement of network performance are completed in order to evaluate a route for remote operation and determine if it can be whitelisted.

In a similar fashion, the authors in [66] measure the current performance of 4G networks in combination with Mobile Edge Computing (MEC) servers. Using two full-sized vehicles (a car and a motorcycle) with 4G routers installed, authors measured the performance of a MEC-enhanced 4G network. Results showed an average latency between 100 and 200 ms, with maximums in the range of 1.5 s. Authors expect to obtain more promising results in future experiments using 5G networks.

Finally, authors in [68] evaluate the performance of 4G and 5G networks in remote driving contexts. Using measurements obtained in a cross-border corridor between Spain and Portugal, authors observe that 5G networks are not optimized for up-link contributions (e.g., to send sensor information or video streams), which might impair remote driving. However, the authors reach the conclusion that remote assistance and remote monitoring are feasible with the existing 5G architecture.

The work in [74] presents another evaluation of the technical feasibility of remote driving from the network perspective. Using ray-tracing software, data from the Google Direction API, and Matlab, they test different densities and carriers for deployments of macro and small Base Stations. Their results show that cellular support for remote driving is feasible but extremely challenging, since network deployment costs could grow to intolerable levels if remote driving is available everywhere.

A review of works that include network measurements in remote driving scenarios leaves us several key findings:

- 1) Commercial 4G networks have the potential to support remote driving applications in terms of latency and network stability.
- 2) Not many works use vehicular-grade equipment to perform measurements, and the bulk of works rely on measurements made using mobile phones.
- 3) Only three of the works ([56], [58], [66]) measure network performance in a wide area, while the rest stay within a restricted area with a particular coverage. Both works concur in that cellular network coverage is a challenge for remote driving, and propose — independently — a similar previous and continuous assessment of network conditions.

From these key findings, we obtain insights regarding the technological feasibility and the commercial potential of remote driving. First, a deployment for remote driving and fallback driving, under stringent bandwidth and latency requirements, can be possible using cellular networks. Yet, it would require the mobile network operator to guarantee a certain service level to offer, for example, a customized service with fully dedicated resources at certain times. One

option to provide for this scenario is network slicing [88], where mobile networks can reconfigure themselves at different levels to allocate resources from radio access to the core of the network. Second, the commercial potential of remote driving is focused mostly on scenarios where the operational costs can be absorbed by the activity, e.g., logistics and transportation companies that can translate these costs to their pricing schemes.

3) HUMAN FACTORS

The effect of latency on human performance is approached in the literature. The work in [70] explores the direct effect of latency in remote driving, and reach the conclusion that, while the workload is minimum when there is no latency, the difficult of driving with latency is almost twice as much in the mental demand, physical demand, effort, and frustration dimensions. Furthermore, the most demanding activity is when latency is not consistent, making the task more demanding than having a maximum but consistent delay.

The authors in [57], however, reach a different conclusion when measuring performance in a simulated environment. While using subjective assessment, they also perform an objective evaluation (e.g., measuring performance objectively in simulated driving and parking tasks), and compare it with other results in the literature. They identified that there is no difference in performance between constant and varying latency. Furthermore, one of their most interesting conclusions is that remote driving should only be performed by skilled and trained operators.

As an example of the last point, we find works in the literature that propose the use of different remote operators for different segments of a trip. First, the authors in [71] propose a heuristic remote driver algorithm, where they propose a set of potential drivers based on distance to the vehicle. Second, the work in [72] proposes a greedy approach to driver selection called Longest Advance First, where drivers are chosen according to the potential length of the segment they will cover and thus have fewer drivers in a trip. Finally, authors in the same team propose an algorithm called “Remote Driver Selection for Multiple Paths” in [73]. When compared to their greedy approach, the authors find a balance between latency and the number of required drivers to handle a Driving-as-a-Service operation. This series of works use mathematical focused simulations to evaluate their proposals, specifically using the Delaunay triangulation to model a road.

An analysis of works measuring human performance and driver selection in remote driving yields the following key points:

- 1) There is a general agreement in the use of the NASA-TLX questionnaire as a tool for subjective self-evaluation of human performance. However, only two sets of works ([48], [49], [57]) contrast these results to objective performance or workload tests.
- 2) Works agree in suggesting that delays have a negative effect on workload, with delays concurring with the delays postulated in section IV-A2.

- 3) When analyzing results from the evaluation of human performance and the previous evaluation of network performance, we can conclude that remote operation cannot be allowed in all roads (whitelisting and blacklisting) nor for all drivers (i.e., only trained remote operators).
- 4) Even with a pool of trained remote operators, driver selection is affected by the distance (either logical or physical) between the remote station and the vehicle (e.g., the selection occurs between drivers and also between remote operation centers). This, in turn, is affected by regulations (e.g., transnational driving) has an effect on business models. Both these challenges are addressed in Section IV.

4) SYSTEM FEASIBILITY

Network-specific simulations are less common in the literature on RORV, as opposed to the rest or CCAM, where well-established simulation tools (e.g., VEINS [89]), provide researcher with reliable testing environments. In remote driving, the work in [75] uses Mininet [90] — a Software-defined Network emulation tool — to propose a testing environment of remote driving software stack over lossless and lossy network conditions. They use Mininet and an electric vehicle to emulate remote fallback driving in conditions that are similar to those expected in cellular networks. This puts [75] in the system-level simulation category.

Prototypes are a form of validation for RORV where a physical vehicle, either full-sized or scaled down, is controlled by a remote driver over a network. Prototypes in the literature range from model cars (e.g., a 1:10 scale), small electric vehicles (e.g., golf carts), retrofitted road vehicles (e.g., vehicles with drive-by-wire capabilities that are equipped with remote driving hardware and software), and purpose-built vehicles (e.g., robotaxis). These prototypes are then tested in field trials, that are also divided into categories: trials on tests tracks, trials on public roads, and trials in closed properties.

In the model car category, we find the work in [70], where which measures the effect of delay on human performance. They use a 1:10 scale vehicle. On a similar note, the work in [67] uses a small robot that is driven remotely over a 5G network. The article describes the hardware setup (i.e., the robot, the remote station and the real-time control for the robot), as well as some target values for network metrics. However, the system they describe shows both the robot and the remote station connected to 5G modules, when a stationary system in a fixed location (such as the one described in the article) would be connected using wired alternatives.

The use of small electric vehicles is exemplified in [63]. The study proposes a compression algorithm for LIDAR data, and uses a golf cart running on a route inside a research campus to validate its performance over a 4G network. The results from this study, beside assessing their compression algorithm favorably, show the feasibility of remote driving over 4G networks at speeds up to 20 km/h.

In the full-sized vehicle category, we find the work in [64], which evaluates latency on 4G and 5G networks for remote driving use cases. The study uses two full-sized vehicles (Toyota Prius III and IV) running in a closed property — a parking lot close to a 5G deployment by Dutch telecommunications operator KPN — where remote drivers performed straight-line and slalom driving tasks. Results show that 5G allows remote driving at speeds below 40 km/h. In a similar fashion, the work in [69] uses a full-sized Toyota Estima to test remote driving under different delays to test the performance of a latency mitigation proposal — a visualization method which displays a line indicating the difference between the current vehicle position and the position that the driver sees in the display.

These two studies, [64] and [69] differ in a core issue: test-driver selection. While the work in [64] uses voluntary non-professional drivers (following a trend that is observed in studies of human performance from Table 2), the work in [69] highlights their use of professional drivers (Japanese Class 2 license holders, which allows for driving public transportation vehicles). However, their participants do not have experience in remote driving situations.

Finally, the work in [65] also uses a full-sized vehicle — an Audi Q7. In this work, an evaluation of remote driving over 3G and 4G mobile networks, the authors describe a setup for remote operation (i.e., workstation, vehicle systems, communications) and perform a performance evaluation in a 650 m long S-shaped test track. Results showed communication mean communication delays of 120.8912 ms, with maximums of 1299 ms, and yet the authors report that delays of 500 ms did not represent a problem for drivers at a speed of 30 km/h.

An exploration of validation studies that use simulations and prototypes (scaled and full-sized) in trials in roads and closed facilities yields the following key points.

- 1) While a wide variety of network simulation tools are available for connected mobility applications, especially those based on WiFi, this is not the case for remote driving applications.
- 2) Focused simulations are commonly found in the literature, especially those evaluating algorithms or mathematical models. However, the results of these works are seldom translated into more real scenarios (e.g., system-level simulations can approach real-world characteristics, including the concurrent effects stemming from mobility and radio propagation phenomena).
- 3) The use of scaled prototypes allow for the evaluation of the feasibility of remote driving in terms of network requirements. However, it is only with full-sized prototypes that real world factors (e.g., braking distances, responses from mechanical systems) can be accounted for. The studies that use full-sized vehicles ([64], [69]) are performed by or in association with corporate partners. The synergy between the industry and academia allows for better-equipped studies.

- 4) Most studies using prototypes are performed in closed properties (e.g., campus, parking lots), which are usually not open to public traffic. There lack of studies using prototypes for remote driving on public roads can be explained by the gray areas in regulation which also affect automated driving. These regulatory challenges are explored in [91].
- 5) The use of trained and untrained drivers is explored in these studies on trials. However, there is not a study which compares the performance of these two types of remote operators.

One insight that comes from the exploration of validation studies is that they focus on one of the three elements of design: technological feasibility — the other two elements being business viability and human desirability. As it is the case for automated driving [92], user acceptance is paramount for the success of remote driving, and a promising area for study is the validation of remote driving systems with real users in order to develop user-centered solutions to the problems to be solved by remote driving. This type of studies will answer questions on the type of users (e.g., direct, indirect, serial, environmental), their interactions, and their acceptance of remote driving systems.

B. REMOTE ASSISTANCE

Works in the literature covering the remote assistance mode of RORV follow a different pattern than those regarding remote driving. Due to the nature of remote assistance, where the DDT is performed by the vehicle and the ROP only provides or authorizes options to the automated driving system, e.g., goals or waypoints. Thus, phenomena such as the effect of latency in the successful performance of lateral and longitudinal motion control, since the automated driving system controls.

An early work that refers to the definition of a path for an automated driving system in the case of network losses is the *free corridor* in [76]. The free corridor consists of showing the driver the trajectory the vehicle would follow before stopping (i.e., a full braking distance ahead), and the driver is responsible for “keeping” that trajectory free of obstacles. Another similar approach is developed in [77], where the authors propose the *shared autonomy control* approach — the remote operator plans a path for the automated driving system to follow. Both works, [76] and [77], justify their proposals as mitigation for network delays or losses in remote driving scenarios, essentially postulating remote assistance as fallback for remote driving when automated driving systems can be relied upon (e.g., to avoid obstacles, or to stop in a safe place).

Authors in [78] and [79] build upon the concept of shared autonomy, which falls within the remote assistance mode. In [78], they describe an alternative to waypoint-based shared autonomy, where the remote operator is not responsible for creating a path that is collision-free, but rather of specifying an *admissible corridor*, which is a search space for the algorithm to determine collision-free paths. They simulate their proposal in MATLAB, and determine that the processing

time is in the range of 0.1 s. Then, in [79], authors use a real vehicle to test their proposal integrating the vehicle's automated driving system and their predefined admissible corridors. As the vehicle traverses the calculated path, vehicle sensors (e.g., LIDAR) detects obstacles that might have been previously hidden, and the calculated path is adapted in real time. Results from this latter work show that an optimized path can be calculated in 8 ms.

The work in [80] presents an extensive study on remote monitoring for public transportation vehicles (i.e., highly-automated buses). Using a simulated environment, authors test their proposed human-machine interface using expert participants (i.e., employees from public transport control centers) and evaluate their prototype usability and acceptance using subjective questionnaires (e.g., NASA-TLX). Their prototype consists of a set of screens that monitor the bus' activity and notify the operator if disturbances are detected. Then, the operator provides a solution (i.e., waypoints) for the bus to execute.

The exploration of works related to remote assistance yields the following key points:

- 1) Remote assistance is less explored in the literature than remote driving, and it is usually studied as a mitigation technique for problems identified in remote driving (e.g., latency, network losses).
- 2) Works are concentrated in specific research groups. For example, [78], [79], and [76], [77]. This allows for the tracking the evolution of a remote assistance mechanism, or the implementation or validation, such as [78] and [79], which departs from a simulation and ends with a test in a vehicle.
- 3) The scarcity of works in the remote assistance mode is an example of the disconnection between academia and industry, since the corporate approaches explored in section II-B rely on remote assistance and remote monitoring for fleet control rather than on the more demanding remote driving mode.

Finally, Table 2 shows that works in the Remote Assistance mode do not specify the network technology being used, and all but one use simulations as validation methods. Nevertheless, and considering the network performance requirements for Remote Assistance are less demanding than those for Remote Driving, we can postulate that existing, widely-deployed mobile network technologies (e.g., 3G, LTE) can support Remote Assistance even if latencies are high, since the all the vehicle requires is the input of a solution or the authorization for a calculated solution. However, even technologies that are deployed widely are not yet present on all roads at all times [93].

C. REMOTE MONITORING

Works in the remote monitoring mode of RORV fall close to works related to fleet management in contexts such as predictive maintenance, e.g., the work in [94], where data from the vehicle systems is sent to a central server where it is logged and analyzed in order to predict failures. For a work to be classified within the remote monitoring mode,

it must include live monitoring of the vehicle status by a remote operator.

An early work in the remote monitoring mode is [81], where the authors propose a system using an on-board computer (called on-board smart box) which connects to a remote server using GPRS communications. The on-board computer receives information from the vehicle sensors and is able to inform about malfunctioning vehicle parts, vehicle speed, and whether the speed limit is being exceeded (when compared against an allowed speed in a region that had been configured previously). The system was tested in an urban scenario in Amman, Jordan, and the results – according to the authors – demonstrate the robustness and efficiency of the system.

Authors in [82] use a remote monitoring application to test the interconnection between two heterogeneous network, 4G and FlexRay bus [95] (an alternative to CAN bus [96] for in-vehicle communications). Data from the FlexRay bus is converted and sent to a server using the 4G network. Then, an Android application uses an HTTP socket to retrieve information from the server. The data is then displayed as “normal” or “abnormal” in the application, reacting to parameters set previously (i.e., authors set an engine temperature below 95° as normal). This setup also has the capability of storing information for later analysis.

Another mobile application for remote monitoring is presented in [83]. In this work, authors design a battery monitoring system which monitors commercial vehicles (i.e., public transportation), and provides statistics about battery consumption, driver rating (e.g., energy consumption per kilometer), charging strategy computation, and a calculation of whether the vehicle will be able to complete the assigned route with the current battery load. This work, however, does not evaluate its performance in experimental conditions.

The work in [63], which also was analyzed in the remote driving mode, proposes a compression algorithm for the transmission of vehicle data using 4G networks. Their compression algorithm is able to reduce LIDAR information from 600 to 50.4 megabytes. This data, along with information from other vehicle systems is presented to a remote operator and also stored for historical analysis. As described in section III-A, this system was validated in field trials using a prototype in a golf cart in a campus.

Finally, [84] proposes a remote monitoring system based on CAN and GPRS. This application takes into account whether the vehicle is operating normally or if a fault is detected. If the vehicle is operating normally, data is sent to the remote server with a low frequency and including only key technical parameters. However, if certain thresholds are crossed, more data is sent to the remote server at a higher frequency. Finally, it also has an option to request data on-demand.

After a review of works in the remote monitoring mode, we find the following key points.

- 1) Live remote monitoring is widely used in commercial applications, and it is one of the core elements of fleet management in driverless scenarios. However,

aside from offline fleet management scenarios that do not relate to live remote monitoring (e.g., predictive maintenance), works from the academia do not explore remote monitoring as extensively as it explores remote driving.

- 2) Application-based remote monitoring applications send non-standardized information to their remote stations, i.e., they use different codification systems and send diverging information (e.g., some send information on whether doors are open or closed). Standardized messaging, that can be read by different operators, allows the interoperability of remote monitoring for fleets including various types of vehicles from different brands. E.g., a Cooperative Awareness Message [97] defined by ETSI is codified in ASN.1 and includes the status from different vehicle systems.
- 3) Works regarding fleet management, such as [94], prove that the disconnect between industry and academia is not irreconcilable. Further analysis shows that the collection systems used in [94] can potentially be extended for live remote monitoring. E.g., Volvo DynaFleet [98], which records statistics for later analysis and respond to on-demand requests, can potentially allow for live remote monitoring.

Finally, it is in the Remote Monitoring mode where we see that cellular networks are more widely used, and that the less stringent performance requirements allow for technologies such as GPRS to suffice. However, there is room for other CCAM technologies to allow cooperative monitoring, e.g., allowing the road infrastructure to detect a fault in a vehicle and alert other vehicles, for example, that a heavy vehicle coming downhill has faulty brakes. This would require the ability for a vehicle to disseminate information to its neighbors, and deployments where remote monitoring and DSRC coexist provide a platform to support those scenarios.

IV. CHALLENGES FOR REMOTE OPERATION OF ROAD VEHICLES

This section summarizes the lessons learnt from our survey and, based on them, identifies challenges for the research, development, and deployment of RORV. We begin with summarizing system requirements, which are derived from previous research results. We then discuss technical challenges and future research directions. Besides research and technical challenges, we also discuss non-technical challenges related to deployment, regulations, and business models.

A. SYSTEM REQUIREMENTS

1) REMOTE OPERATION STATION

Designs and requirements of remote operation station is an important factor in RORV, especially for types that require taking over the DDT. The HMI, which acts as a bridge between the ROp and vehicles, is one of the essential components within the remote operation station. Video feeds that are generated by the camera array in the vehicle and other

information are presented to the ROp via HMI. Depending on the required ergonomics, this can be done by using a single monitor, or an array that tries to replicate the conditions inside the vehicle. As we shown in our exploration in section III, HMI and remote operation station setups vary from tablet computers, over-the-counter equipment, to driving stations that use specialized hardware and emulate the conditions inside a vehicle.

Each operation mode requires varying control interfaces for the ROp to perform the remote operation tasks accordingly. For remote driving mode, the minimum interface must include controls for longitudinal and lateral motion, which can range from a game-pad (e.g., a video game controller where a joystick controls the steering and buttons control the throttle and braking) to a setup with pedals, steering wheels and haptic simulators. For remote assistance, where the vehicle motion is controlled by the ADS with the inputs provided or authorized by the ROp, additional equipment may be required to provide these inputs (e.g., drawing way points, accepting or denying authorizations with a click).

2) COMMUNICATION NETWORK REQUIREMENTS

The technology for enabling the remote operation of robots, and especially unmanned vehicles, permits the control of critical equipment at long distances. Military Unmanned Aerial Systems are controlled by military-grade air-to-ground communications which use different frequency bands (ultra-high frequency) and modulation schemes for short and long ranges, using direct data links and satellites [99]. However, these technologies are not suitable for the expected number of connected vehicles [100] within the following decades, which brings a question about the ability of current and future networks to support connected driving in general and RORV specifically.

The authors in [56] summarize the network requirements for the remote driving mode of RORV that involve performing the DDT: 3 MBit/s up-link and 0.25 MBit/s down-link, with a maximum tolerable network latency of 250 ms and a jitter below 150 ms are enough to control a remote vehicle safely. This difference stems from the data that has to be sent to the ROp, which consists of audiovisual feeds and sensor information. The effect of network induced latency and jitter is highlighted as one of the factors that impact human performance in the remote operation of robots [2], and has been measured in studies in the field of RORV, as we explore in section III.

While other operation modes of RORV may have less stringent requirements (since DDT is performed by ADS), demands on the network will increase due to the expected number of vehicles, and the fact that their ODD is expected to be in all roads at all times [93]. Our exploration on network performance yields these insights about network requirements:

- 1) Remote Driving can only be supported by cellular networks that are tailored for its stringent requirements. This tailoring can be achieved through network slicing [88], which means that only commercial

applications might be able to operate in the remote driving mode.

- 2) Remote assistance and remote monitoring, having less stringent requirements, could be achieved using cellular or DSRC technologies. Furthermore, the use of cooperative driving could enhance the possibilities for remote assistance and monitoring (e.g., by allowing vehicles to share information to enhance OEDR abilities and sharing information on obstructions and traffic disruptions, thus avoiding situations that the automated vehicle cannot solve by itself).

3) VEHICLES

The architecture in Fig. 3 reflects the generic elements of a RORV. Depending on the operation mode and the level of automation, vehicles can be equipped with different systems. The basic requirements for the vehicle side are the sensors that report the vehicle status to the ROP, and the actuators that control the vehicle motion depending on the input from the driving automation system or the ROP. For the case of SAE DA Level 0, these sensors and actuators do not have major influence in the DDT besides providing the driver with warnings. However, higher automation levels require sensors that can, e.g., detect obstacles, react to traffic signals, and provide real-time audiovisual feeds to the ROP. Furthermore, it is at lower levels of automation where tele-presence is crucial. Let us start by indicating that the field of view is fundamental even when the driver is in the vehicle, and that driver licenses require a minimum visual field of 120° for Group 1 drivers (i.e., motorcycles and automobiles), and 160° for Group 2 drivers (i.e., heavy goods vehicles and buses) [101]. This implies the use of camera arrays that allow at least for the same visual field without affecting the perspective (e.g., as opposed to what fish-eye or another wide angle lens does).

B. RESEARCH CHALLENGES

A comparison between Tables 1 and 2 exhibits the diverging interests in the research and development of RORV. On the one hand, commercial approaches appear to be better distributed among RORV modes, with remote driving and fallback driving being the sole mode of remote operation in only five out of twelve commercial approaches, and it is not considered in five approaches out of twelve that do consider remote assistance or remote monitoring. On the other hand, works from the academia related to remote driving have a ratio of 5:1 to either remote assistance or remote monitoring.

A further look at works analyzing remote driving ([52], [60], [65], [70], [48], [49], [57], [71], [53], [75]) shows that they propose scenarios where the remote operator takes over at least part of the DDT as the first fallback alternative for situations where driving automation cannot complete a task. In contrast, commercial alternatives usually fallback to remote assistance, where the operator only authorizes or provides options to the vehicle in the form of goals or waypoints.

We explain this difference in focus between commercial and academic proposals as a product of the general aim of academic works of breaking through challenges (e.g., the requirements for remote driving in terms of network performance) rather than working around them (e.g., looking for an alternative that can be deployed faster). However, it is important for the academia and the industry to work closely both in figuring out what future scenarios will look like and how to answer the questions stemming from present deployments, for example, whether remote driving is the optimal option for fallback when automation fails. In other words, researchers must think outside the box, but color inside the lines.

As an enabler for the last point, we consider that future lines of R&D should follow design principles based on user-centered co-design and co-creation [102]. Using these principles, we can ensure that the systems we develop be accepted by all the stakeholders: government agencies, transportation and logistic companies, remote operators, and end users. This way, the gap between what is designed and what can be actually used closes.

The majority of the research that was explored in this survey focuses on HMI and effects on human performance, which are mostly exploring feasibility and requirements for remote operation in different use cases. To tackle challenges related to communication delays and performance of ROP, recent research has suggested three main solutions: 1) optimizing video feeds (e.g., in [103] and [104]); 2) strategies for remotely operated vehicle to handle bad control commands (e.g., in [105] and [106]); and 3) improved feedback to the operator by means of different feedback modes (e.g., in [69] and [107]). In our opinion, we suggest that we could expect more of these approaches to be proposed in the future research field within the context of RORV, because a certain amount of delay and uncertainty will always remain in the system.

C. DEPLOYMENT

In section IV-A we show a list of requirements for remote operation, and we differentiate between modes that require remote operators to perform activities from the DDT and those that do not. Thus, the first challenge for the deployment of RORV is the availability of high-performing networks in those scenarios where remote operation is desired. The second challenge for the deployment of RORV stems from the hardware requirements for remote operation. Since all modes of RORV require at least a remote station with a display, it can be inferred that even if RORV-enabled vehicles are widely available, remote stations will not be ubiquitous. Additionally, and hand in hand with this last point, remote operation, and specifically remote driving, requires a set of abilities where not every driver with a normal permit will be able with the particular conditions of remote driving, and this set of skills changes for remote assistants and remote monitors. In this section, we explore each of these challenges in depth.

1) IS REMOTE OPERATION ON ALL ROADS AND AT ALL TIMES FEASIBLE?

According to [93], the goal of CCAM is to be present on all roads at all times by 2050. However, this ubiquity relies on the evolution of networking technologies and the reliability of automation. At that point, [93] states that vehicles will be able to 1) be aware and make others aware of their presence (i.e., cooperative awareness), 2) share what they see (i.e., collective perception), 3) share their intentions, and 4) coordinate their maneuvers (i.e., cooperative maneuvering). It is expected that, from point 2, 5G technologies will be widely available; and that from point 3 onward newer technologies will support CCAM applications (i.e., road safety, traffic efficiency, and other applications). These goals, however, might be hindered by factors such as network coverage and RORV service provider availability.

First, in terms of network coverage, a simple look at the available cellular coverage in the United States of America according to the OpenCellID project [108] shows that there are vast regions without network coverage, even from UMTS or CDMA technologies. This, in conjunction with the data from the International Telecommunication Union (ITU) report Information and Communication Technologies: facts and figures for 2021 [109], shows that LTE coverage is largely centered in urban areas, and that it took 6 years (from 2015 to 2021) for LTE to become the dominant technology, growing from 40% to 88% between 2015 and 2021. If we consider that 4G was released to the public in 2009, and that the first publicly available 5G services were launched in 2019, the availability of 5G and newer technologies in all roads at all times might not even be a real possibility.

Second, RORV service providers would have to offer remote operation services 24/7. This might hinder the potential for scalability for a single provider, even if the capability of driving automation system to deal with unexpected situations increases and only remote assistance or remote monitoring is required (i.e., if a single operator can manage a whole fleet of vehicles). This goes hand in hand with the deployment issues mentioned before: even if RORV-enabled vehicles are widely available, remote operation stations might not.

However, considering the potential for driving automation systems to operate correctly within an ODD, it might not be required to have RORV available at all times and in all roads, and if so, not under the stringent network requirements that remote driving and fallback driving have. As it was the conclusion of works measuring latency for remote driving applications, even 5G networks would require optimization to allow remote driving [68], but remote assistance — supported by high level ADS — could be bolstered by currently deployed network technologies ([76], [77], [78], [79]). Also, the concept of whitelisting [56] is an approach that addresses the fact that high-performing network technologies are mostly available in urban areas, where remote driving might be more on demand than on highways.

As a final note, as stated in [93], the road towards the full presence of CCAM in all roads at all times ends in 2050 at the earliest (Day 4). By then, the emergence of new technologies (e.g., 6G) could empower all the characteristics required for automated mobility and for fully-reliable RORV, for example, by reducing latency and improving reliability by creating a *virtual cable* [110]. However, this will all depend on the deployment and availability of these emerging technologies by the time Day 4 arrives.

2) CAN ANYONE BE A REMOTE OPERATOR?

Works from the academia [57] and examples from the industry [9] consider that remote operators, at least in remote driving scenarios, should be trained. This includes, both the training required to drive a vehicle of the required size (i.e., different requirements for cars, trucks, and buses), and the special training to deal with specific phenomena stemming from remote driving using networks (i.e., varying delays).

Remote assistants also have to undergo specific training, even if they are not responsible for activities in the DDT. This is supported by two facts: 1) the options provided or authorized to the ADS must comply with traffic laws and regulations (e.g., the remote assistant should not provide waypoints that would make the vehicle fall in a wrong-way driving infraction); and 2) the controls for remote assistance, even if the driver is an expert traffic controller [80] require training and adaptation.

Finally, regulations [91] support the notion that remote drivers must be licensed to operate regular vehicles. The study describes the existing regulations in the United States of America, and existing laws addressing remote driving require remote operators to hold a valid driver's license. However, some gray areas in these regulations are explored in depth in section IV-D.

D. REGULATORY CHALLENGES

The deployment of RORV and automated driving systems rises a series of questions regarding the regulatory framework for the presence of automated vehicles, remotely operated vehicles, and normally driven vehicles on the same roads at the same time. Liability in the case of an accident is one of the major questions addressed in works on the regulatory framework [111], i.e., who takes responsibility if a driverless, autonomous vehicle is involved in an accident: the owner or the manufacturer. The same question could be asked in a remote operation scenario, and [111] cites the examples of Italian, French, and Spanish laws, where both drivers and owners are liable to compensate if certain criteria is met (e.g., if the driver cannot prove he took every action to avoid a tort, or if the owner cannot prove that the vehicle was not moving with his consent). A conclusion of this study is that, at the European level, intervention is not only possible but necessary when adopting specific legislation regarding CCAM, specifically for remote and autonomous operation of vehicles.

In a similar fashion, [91] describes the gray areas in regulations within the United States: while state laws addressing remote driving require remote drivers to hold driving licenses, only Florida specifies that the license must be issued by a state in the Union, and that the remote driver must be physically located in the national territory. Furthermore, [91] describes the case for Alabama, where remote operators are required to undergo blood and urine tests in the event of a crash regardless of the jurisdiction in which the remote operator is present, and that fact yields two key points: 1) that laws will not permit everyone to operate a vehicle remotely, and full capabilities are required for remote operation (e.g., drivers cannot operate a vehicle while impaired), and 2) that laws can allow for business models where operators are outsourced abroad, yet jurisdiction might become a problem as it is for current business models empowered by the internet. Regulatory challenges, therefore, affect not only the deployment of RORV in terms of legality (i.e., allowing the remote operation of vehicles within and between regions, such as in the European Union), but also business aspects, such as the opportunity to tap into a pool of potential drivers in a remote labor market, which is explored in depth in section IV-D. Finally, the requirements to get a driver's license vary from country to country, e.g., countries where snow is a normal occurrence test a driver's ability to react to a slippery road, while those where snow is not common do not include these scenarios in driver's license testing.

The deployment of RORV as a support for existing business units (e.g., as a fallback for robotaxis), or as individual business units (e.g., offering RORV as-a-Service) involves challenges that affect business models in three main, interdependent areas: 1) operational expenses, 2) access to labor, and 3) scalability.

Among the most important operational expenses for a remote operation deployment are the cost of developing or acquiring the remote operation stack, the cost of using the remote operation stack (e.g., the cost of the mobile service or services), and the labor costs which will be addressed in depth in this section. While the cost for the stack can be dealt with through collaboration between companies (e.g., Einride and Voysys), the costs associated to mobile service subscriptions are more difficult to deal with. Commercial and academic approaches consider the use of multiple operators and selecting the best one at any given moment. Designated driver [9] uses a module that connects to up to eight mobile network operators, while the work in [58] addresses the possibility of switching operators in order to stay within the required latency values for remote driving. While a collaboration between companies to reduce the cost of acquiring remote operation stack is feasible, the collaboration between competing mobile network operators might be more difficult to achieve. However, the emergence of virtual mobile network operators offers an opportunity for remote operation service providers to hire core network infrastructure and services from different host operators and optimize their use

(e.g., by switching to the host with the best radio access at any given time).

Another effect of remote operation on business models is the access to more cost-efficient labor. Remote operation enables the possibility for drivers in one region to operate on vehicles located in a different one. This phenomenon is addressed both commercially and in the literature. On the one hand, Phantom Auto [12] explicitly highlights its potential to enable fleet managers to recruit drivers that work remotely, and thus mitigate regional or even national labor shortages, and by extension access qualified labor at a lower cost. On the other hand, [68] studies remote driving in an international corridor between Spain and Portugal, where not only there is a change in countries and operators (although roaming is possible, it does involve certain performance compromises, as analyzed in [112]), but the two countries also use two different languages. These factors affect the viability of remote operation as a business, since there is an intrinsic cost of training a roster of remote operators to be able to deal with regulations from different countries and regions (e.g., differences in language, driving sides, and signaling standards) potentially within the same workday or even simultaneously.

Finally, the combination of these factors (operation expenses and access to labor) with technological factors may also hinder scalability. The differences between physical and logical distances (e.g., network round-trip times) is one of the factors that affect scalability. The works in [71], [72], and [73] already consider that, for remote driving, a set of drivers has to take over the control of a vehicle at different times within one trip. This acquires more complexity when remote driving occurs between countries, even when data roaming is possible. As described in [112], the most common roaming configuration has data travel to the subscriber "home" network, affecting the performance of, for example, content delivery networks (i.e., the content is delivered from a server in the user's "home" network and not from a closer node). However, for the case of remote assistance, where low network delays are not crucial, scalability is easier to achieve, since a single remote assistant can control multiple vehicles in a fleet.

V. CONCLUSION

This article reviews the literature on RORV. After describing the different elements that compose a RORV deployment, we offered a classification for the different modes of Remote Operation depending on the level of input that comes from the remote operator. Following that classification, we have described relevant commercial approaches, followed by an analysis on how the research community has approached and validated RORV. These works show the progress in identifying and answering relevant questions from diverse areas ranging from the technological feasibility to the effect of remote operation in human performance and vice versa. However, this survey also points at the need for more work in modes of remote operation other than remote driving,

especially considering that remote monitoring and remote assistance are more relied upon by commercial approaches (i.e., mobility providers), and works regarding these two modes are less abundant. Also, other challenges leave more open questions, e.g., regarding regulatory and legal scenarios as well as business models that can either prompt or hinder the wide deployment of RORV systems.

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