Studying the Impact of Communication Disturbances on the Control of Remotly Driven Vehicle

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Report
of the
Graduation Project

Studying the impact of communication disturbances on the control of remotly driven vehicle

Etude de l'impact de perturbations de la communication sur le contrôle de véhicules commandés à distance

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1 Introduction

1.1 Final Study Project (PFE)

This report is one of the deliverables required to validate a Final Study Project (PFE), the ending project of the French engineering diploma. It has to present and detail a project conducted during at least 18 weeks and thus demonstrate the engineer competences acquired during the study. It leads to 3 of the 6 ECTs credits related to the PFE. It is evaluated by a professor of the computer science department of INSA Lyon.

The PFE is a major project conducted at the end of the engineering diploma, the French equivalent of a master. It must consist in an ambitious engineering work with computer science at the center of it. The PFE is realized in a host structure which may not be the home university. It is evaluated through this report, an oral presentation, a poster and the monitoring of professor from the INSA Lyon.

The PFE leading to this report started in 07/02/2022 and will be finished the 24/06/2022. It is conducted within RISE (Research Institute of Sweden) in Borås, Sweden. It is supervised by Mrs BIENNIER Frédérique,a researcher and professor at INSA Lyon, and M. Fredrik Warg, "Teknologie doctor" at RISE.

1.2 Project background

In the context of the development of Automated Vehicles (AV) [1] by several Swedish companies, the Einride start-up sales "pods" (trucks without cockpit) destined for the transport of containers [2]. The product has two main functions in development: autonomous and RD [3].

To put it in a nutshell, Remote Driving (RD) [2] is a vehicle functionality consisting in controlling it from the outside. A Remote Driving System (RDS) consists in a set of technologies which enable this functionality on a car. Nonetheless, we will simplify the terminology used in the report by mentioning RDS as a technology in itself. The physical set up of an RDS, implementing the RD functionality, is mainly composed a driving station, reproducing the one in a vehicle's cockpit, which receives information from a vehicle situated anywhere, so that a driver can safely control it. To conclude with the terminology, a Remote driving Vehicle (RDV) is a vehicle equipped with an RDS.

The most obvious advantage of this system is, first of all, to not have to move the driver itself when he is not the purpose of the travel (as in the case of trucks) without the disadvantages of

[1] Defined by the United States Department of Transportation as "[...] vehicles [...] in which at least some aspect of a safety-critical control function (e.g., steering, throttle, or braking) occurs without direct driver input. AVs may be autonomous (i.e., use only vehicle sensors) or may be connected (i.e., use communications systems such as connected vehicle technology, in which cars and roadside infrastructure communicate wirelessly)." [1].

[2] Also called "Teleoperation" [4] in the literature

security assessment of autonomous driving. Moreover, it would allow to keep all the professional drivers in a same location, to easily alternate between them so that they can rest, etc..

On this subject, the Einride company is in partnership with RISE (Research Institutes of Sweden), a Swedish public institute bringing together a set of national research institutes including a wide range of sectors. Among RISE's remit is supporting Swedish technological expertise by doing research, partnership, giving courses, etc.. It also includes certifying new technologies.

Except the partnership with Einride, RISE is also involved in the SCAT (Safety Case for Autonomous Trucks [5]) Swedish project and Verification and Validation of Automated Systems' Safety and Security, a project funded by the European Union's Horizon 2020 research and innovation program project with the aim of reducing time and cost of verification and validation (V&V) of automated systems with respect to safety, cybersecurity and privacy requirements.

Its responsibilities, competences, facilities and current projects give RISE a central place in the process of developing and putting into circulation vehicles equipped with new driving technologies. The institute is therefore at the origin of the proposal of this PFE, made alongside two other students, Fryderyk Marek Pryjma and Shrishti Trivedi, doing a master thesis under the supervision of three full time employees: Fredrik Warg, my supervisor and supervisor of the project, Ted Strandberg, engineer in « Functional safety », also supervisor of the project, and Martin Skoglund, doing a PhD in the Dependable Transport System unit, a co-supervisor. It seems relevant to warn against the risk of confusion for the reader between the two homonymous Fryderyk and Fredrik. The project grouping the supervisors and the three students, including me, will be called "RISE's project" or "thesis project" in the rest of the document.

1.3 Problem definition and methodology

One of the key factors of Remote Driving safety is the quality of communication. Indeed, as detailed later, drivers are combining a really large amount of rich information through different senses in order to properly control a vehicle [6]. The problems RISE wants to solve is therefore what effects a bad communication would have on the driving abilities of an operator and how can we evaluate the safety of a RDV with respect to that risk.

This problematic is wide in the extent that it depends a lot on the technologies used in the RDS. For this reason, the project aims at giving basis to the research by having a first general analytic approach of the problem, but first and foremost, by developing and testing an experimental protocol on both a physical and virtual car model, that can be reproduced later on real vehicles.

A first method to obtain meaningful results consists in isolating specific disturbances in the communication to be able to study and experiment there impact on the control of the vehicle. Moreover, the driving ability will be observed only through the ability to control the vehicle, to reduce the range of variables and capacities to evaluate, and to keep the most relevant and objectively observable ones. This will constitute the scope of the PFE.

1.4 Contributions

The work inside the RISE's project has been divided among the three students involved, including me, in the following way: Fryderyk Pryjma is focusing on the UX part of the experiment and the design of the tests, Shrishti Trivedi is working on the virtual experiment and I am more dedicated to the physical experiment and diverse technical aspects.

My contribution to the content of this project has thus been to develop and use the physical environment for the experiment in collaboration with Shrishti and Fredrik. But it has also been to help design the experiments themselves, to analyse the risks and impacts of disturbances and finally to bring a technical help to every matters linked to computer technologies.

Regarding the management of the project, I participated, alongside with the two other students to define the scope of our study, to organise it and to manage it all along. It has also so been a non negligible part of the work.

1.5 Report content

The body of this report is structured in two main logical parts and three main sections.

The first logical part, containing section 2, consists in describing and analysing the project environment and management. It is a post-formalisation with conceptual tools learned at INSA with the aim of giving a clear view of the project and capitalizing the experience. Moreover, even if the management of this small project of three persons wasn't the main goal of my PFE, it represents an interesting work we commonly did. This part also includes cultural aspects of the industry sector and of the work in Sweden, which are interesting and valuable learning from a PFE abroad.

The Second logical part focused on the content of the project. It has two sections. The first one, section 3, deals with a theoretical approach of the problem and gives an overview of the state of the art. The second one, section 4, details the experimental approach of the problem. It therefore presents most of the work performed during the PFE.

The references used for this report can be found at its end, as well as a glossary.

2 RISE's research project description and analysis

This part is dedicated to the description and analysis of the RISE's research project in which the PFE is included. A first subsection gives an insight of the societal, industrial and technological ecosystem around the project, which has created its need. The second subsection details the objectives of the project with respect to the needs. The third subsection introduces the different actors (persons or structures) who directly or indirectly contributed to the project. A fourth subsection describes the scientific and technical environment of the project. It is followed by a subsection defining exactly the problems solved and the scope of the project. The sixth subsection detailed the methodology followed in order to solve the previously detailed problems. A seventh subsection specifies the deliverables of the project. Finally, a last subsection details how did the group organised the work in order to produce the previously mentioned deliverables.

2.1 Background

International scale

The years 2010 witnessed a worldwide acceleration in the development of connected mobility and AV solutions, which are closely related. Indeed, after decades of research, in particular funded by the Defense Advanced Research Projects Agency (DARPA), and successful tests, 6 US states opened, in 2015, the public roads to AV testing. A year after, the EU commission started developing an innovation strategy for connecting and automated driving. The industry also started to organise itself with the creation of the 5G Automotive Association by AUDI AG, BMW Group, Daimler AG, Ericsson, Huawei, Intel, Nokia, and Qualcomm Incorporated in 2016. The same year, Toyota starts introducing automobiles equipped with Vehicle-To-Everything (V2X) technologies, implementing a standardize communication between a vehicle and outside equipments. In 2017 car companies started tests of entirely autonomous cars on public roads. [7] [8]

Swedish case

As mentioned in the introduction, the development of Automated Vehicles is notably very dynamical in Sweden. It is a part of a more general transition in the automotive industry, as says Joel Görsch, Investment Advisor, Automotive and Cleantech: "The automotive industry is undergoing a momentous transition, with Gothenburg taking the lead in many areas, such as electrification, autonomous technology, safety, and connected vehicles." [9]. We can define it as a transition toward the next generation of general public automotive technologies with the specificity of renewing more fundamental elements than the previous generation did, whether it is the energy used, the driving technologies or the vehicle's interactions. This transition is a turning point if we consider the decades of continuous improvement of the well known combustion engine vehicles.

This transition is, first of all, impulsed by the strength of the Swedish historical world class automotive industry. It is the result of a strategy consisting in developing innovative vehicles, which are more sustainable and easy to use, to maintain a good position on the future vehicle's market. There is also a political will to develop the Automated Vehicles sector, also considered by the authorities as full of innovative technologies valuable for a transition towards sustainable transportation. In this aim, the Swedish Government has authorized in 2016 the testing of AVs on the public road network [10][11]. It is thus possible to observe autonomous cars in Gothenburg from time to time. The Swedish Transport Agency is the institution that validates the trials on autonomous cars. Finally, this transition has also been allowed and encouraged by a national culture turned both towards innovation and towards sustainable development.

As Joel Görsch says, this transition is partly geo-localised in Gothenburg. Indeed, being the home of Volvo, Gothenburg is the centre of excellence regarding automotive in Sweden. The city nowadays hosts the headquarter of Volvo car, Volvo group (installed in the Lundby campus), Polestar, but also SKF, Zenseact (affiliated with Volvo to develop autonomous car), some of Einride's offices (company developing autonomous "pods"), etc.. RISE also participates to both the regional excellence and the transition of the automotive industry thanks to its expertise, but also to its facility Astazero in Borås [12]. Astazero is a large facility created in 2014 for driving tests and demonstrations, including the world's largest indoor track, used by Einride for its "pods". It was the first test facility to focus on automated driving vehicles [13].

Technological environment

The development of RDVs goes along with the one of AV. The RDVs are, therefore, also a part of the sub-mentioned transition. This inclusion and the relations between automated and RD can be detailed at several levels.

First of all, both technologies participate to the strategy, mentioned previously, consisting in developing very innovative vehicles. They can, indeed, both participate to the decrease of the energy consumption, to the safety improvement and to the extension of the use cases, or the optimization of the existing ones. For example, they both allow to remove the driver and the driving station from the car. By doing that, they give more autonomy to the vehicle, and thus, they allow to optimize its travels.

Secondly, the two technologies bring common technical modifications and technological additions to the vehicles. They both require to have a set of sensors and a computer, which handle the information from the sensors and which is able to physically act on the vehicle. They also both lead to a possible reorganisation of the vehicle's shape by removing the driving station.

Thirdly, the two technologies require to develop new safety and reliability specifications and V&V processes of them which are quite close from one technology to another. In particular RD technology may be needed for the safety of autonomous vehicle in the case of AV malfunction or failure. But it may also be needed in the V&V process of autonomous vehicle as the Swedish Transport Agency requires that "when tests are performed with an AV, there must be a physical driver inside or outside the vehicle" [10].

Nonetheless, development resources and legislation efforts have mainly been invested into AV. Indeed, exemption procedures to introduce vehicles, which do not comply to the existing legislation on the public roads, have mainly been thought for AV. Moreover the work for the development of type approval procedures[3] has been orientated toward AV. It is finally the same concerning safety standards such as ISO 26262 and ISO 21448. And yet, "While most of the teleoperation systems face similar challenges, the teleoperation of AVs is unique in its scale, safety requirements and system constraints." [14]

Furthermore, RDS's network fits in the development of Vehicle-To-Everything (V2X) technologies whose first standards were proposed in 2010.

In the light of those elements, the potential of RDVs, as well as the lack of dedicated research and legislation compared to autonomous driving ones, impels to study this technology.

2.2 Purpose

Firstly, this project addresses the needs of defining new specifications to guarantee that future RDS will be safe, secure and reliable with respect to Safety [4], Cybersecurity [5], Privacy [6] (SCP), which are the reference requirements for AVs. It means that SCP have to be qualified and have to have quantified indicators for RDS. In more concrete terms, the objective is here to answer the question: what are the potential unsafe aspects of RDS?

Secondly, the project addresses the need of developing systematic V&V methods [7] to properly quantify the SCP on a specific RDS. More practically, the question to answer is how can we evaluate those unsafe aspects of RDS?

For obvious reasons of time and resource limitations, those goals have to be restrained to a certain aspect of the RDS, which will be detailed in the problem definition. Moreover, by creating this project, RISE intended to set the basis of such a work. Going toward new V&V methods is the main priority. But in any case, no specification or V&V methods resulting from the project could be considered sufficiently reliable to assess a vehicle SCP.

[3]Official confirmation from a government or other body that a manufactured item meets required specifications. Oxford languages

[4]"The ability of a system to avoid injury, serious injury, or death." [15]

[5]"The ability of a system to avoid unauthorised access, use, or modification." [15]

[6]"The ability of a system to avoid disclosure of sensitive data." [15]

[7]From a general perspective, a method corresponds to a particular procedure for accomplishing or approaching something, especially a systematic or established one [16]

2.3 Actors

Several entities and persons have inspired, motivated, initiated and then contributed to the RISE's project.

Einride

The Einride company can be seen as an indirect actor of the project. As a matter of fact, through their partnership, they collaborate with some employees of RISE, including Ted Strandberg, who supervises our project. They are also users of the AstraZero facility owned by RISE. Finally, they develop the example of technology our project aims at studying. Unfortunately, no meeting could have been organized with them before the writing if this report.

The product's developed by Einride, whose technology is within the scope of our study, is called "pod" [2]. Presented in 2017 [17] it consists in an electric truck without cockpit controlled remotely. It evolved in 2018 with an autonomous version, and the same year, a remote driven version was allowed to drive inside a company facility in Sweden. Einride nowadays aims at validating the security of its pod in the autonomous and remotely driven modes so that they can be used in the same conditions as common trucks.

RISE

The RISE structure has been hosting the project, initiated by its employees.

RISE is a state-owned research institute and "innovation partner" [18] created in 1997 to group a set of smaller Swedish research institutes. Its headquarter is located in Gothenburg, but it has facilities in more than 25 cities of Sweden, and several others in Europe, including France. The institute employs almost 3000 people. It has a really large range of missions, roles, activities, partnerships and fields of expertise [19]. Indeed, its objectives at the national level is to guaranty international technological competitiveness of Sweden and to participate in a national sustainable growth. In order to do so, RISE is doing industrial and technological research, but it also performs tests, certification and training courses. The institute thus collaborates with the industry, the academic and the public sector. Its field of expertise has five divisions: Bioeconomy and Health, Built Environment, Digital Systems, Materials and Production, Safety and Transport.

The RISE project is a collaboration between two units in the department of Electrification and Reliability which is a part of the Safety and Transport division: Dependable Transport Systems (to which Fredrik Warg is attached) and Safe Control Systems (to which Ted Strandberg is attached) [20]. These two units are the ones financing the project. The first one has edited this PFE's contract. The result of this specific project will contribute to RISE's expertise, but also to other project RISE is invested into.

Figure 1: Einride's pod photography

The first one it the Safety Case for Autonomous Trucks [5] (SCAT) [5]. It is a Swedish project, in collaboration with French structures, founded in 2020 by Vinnova and coordinated by RISE. Ted Strandberg is involved in this project. It aims at contributing to the development of safe remote assisted truck operations at a higher velocity than the current one, and in more complex situations. The problem is handled at both a technical and legal point of view. Tests are notably realized on Astazero facility. "One of the areas that have been investigated is the requirements on communication to ensure safe remote operation. The experiments conducted in the thesis projects provide further insights into how to evaluate the human machine interaction, and in particular the impact of communication limitations or disturbances, on a remote driver." Fredrik Warg detailed.

Another important linked project is the Verification and Validation of Automated Systems' Safety and Security (VALU3S) [21], founded by the European Union's Horizon 2020 research and innovation programme through the Key Digital Technologies Joint Undertaking (KDT JU) [22]. This project is conducted at the scale of 24 industrial partners, 6 research institutes and 10 universities. Starting from the observation of the dynamic and increasingly complex development of automated systems, VALU3S "aims to design, implement and evaluate state-of-the-art V&V methods and tools in order to reduce the time and cost needed to verify and validate automated systems with respect to safety, cybersecurity and privacy (SCP) requirements." [8].

Those methods and tools are evaluated through 13 use cases in 6 domains [23] among which the "Car teleoperation" [9] conducted by Roboauto [24], a company developing non-hardware dependant technologies to remotely control vehicles via LTE cellular network or Wi-Fi connection. Fredrik details that "The focus for the use case in the VALU3S project is specifically safety evaluation of the transmission line, e.g., decreased throughput or increased latency or cybersecurity attacks. Several V&V methods are used including penetration testing and different types of simulation.".

Furthermore, RISE has developed, for this project, a method called Human Interaction Safety Analysis (HISA) which analyses the Human Machine Interaction (HMI) with automated or RDSs safety. This systematic analysis method can be used both during the design phase and for V&V [25].

Thanks to this expertise, several employees of RISE participated in the project, outside Fredrik Warg and Ted Strandberg: Martin Skoglund, Marvin Damschen and Rickard Häll from the Dependable Transport Systems unit.

Student team

Finally, two students have been involved in this project with me: Shrishti Trivedi in Embedded Systems Master of science at KTH, Stockholm, and Fryderyk Marek Pryjma in Master of Computing Sciences, Human-Technology Interactions at Tempere University .

2.4 Framework

The PFE has been conducted both remotely and in the offices of RISE in Borås (50 min from Gothenburg). The campus in Borås hosts several departments of the Safety and Transport division of RISE. It includes the following divisions: Measurement Science and Technology, Fire and Safety, and Electrification and Reliability, the department containing the Dependable Transport Systems and Safe Control Systems units. The project has therefore been conducted into a rich research environment.

One main lab has been made available to the project. It contained all the required material, including a driving station, car models and there parts components, both personal and experimental computers, and a set of common manufacturing and DIY tools. An outside test field was also made available and were used to the driving tests.

The duration of the project is one semester.

2.5 Problem definition

To achieve the goal of developing new specifications and V&V methods for RDS, we have to face the problem of evaluating the impact of the new technologies introduced in an ordinary vehicle on its driving functionalities and, consequently, on the SCP requirements.

The technological step between an ordinary vehicle and a remotely driven one mainly consists in reproducing the vehicle HMI and the vehicle environment but outside of it, . In order to do so, there is a need of connecting the new HMI to the vehicle through a network.

The figure 2 illustrates the technological changes done by representing the technical/physical architecture of a RDV and the one of an ordinary one. We can observe that the new HMI created has to convey a lot of information that were previously directly conveyed by the vehicle and the environment of the vehicle. In a functional implementation of this RD physical architecture, the most critical element therefore seems to be the network infrastructure for several reasons, revealed by a quick risk analysis.

First of all, because of the use case, the infrastructure is geographically dispatched, which complicates its instantaneous management. Second, one can reasonably consider relying on external operators in case of an international deployment of the technology. Consequently, there is a loss of control over the safety of this part of the infrastructure. Third, the perfect redundancy (information going from the vehicle to the driving station through several channels without common infrastructures) of a long distance communication is difficult to consider. By consequence, it is probable that all the information, which is conveyed in an ordinary vehicle through several channels, goes through the same channel at certain portions of the infrastructure. To conclude, there is a high risk of unstable network performances. As mentioned in a reference scientific article studying latencies during teleoperation of AV, "To enable teleoperated systems, two main problems have to be solved: Safely controlling the vehicle under latency and [...]" [14].

For all those reasons, the safety, security and reliability of the RDS are studied only regarding communication problems.

On one hand, the communication problems already cover an extremely wide domain at the scale and complexity of such an infrastructure. Therefore, in this project, communication problems are reduced to communication disturbances that we can define as deviations from a nominal state of communication. This term allows to focus more on certain phenomenon appearing in the network and their impacts, rather than on the cause of their appearance, which is not the subject. The term is also relatively generic, thus, we can later on precisely define the disturbances depending on the network modified characteristics. Their magnitude can also be chosen and quantified in order to observe stable and measurable impacts. Finally, we will be able to reproduce the precisely define disturbances. Furthermore, two main communication's functions can be distinguished in the system: sensor communication (all the information given by the car to the driver) and actuator communication (orders sent by the driver to the car) [14]. As

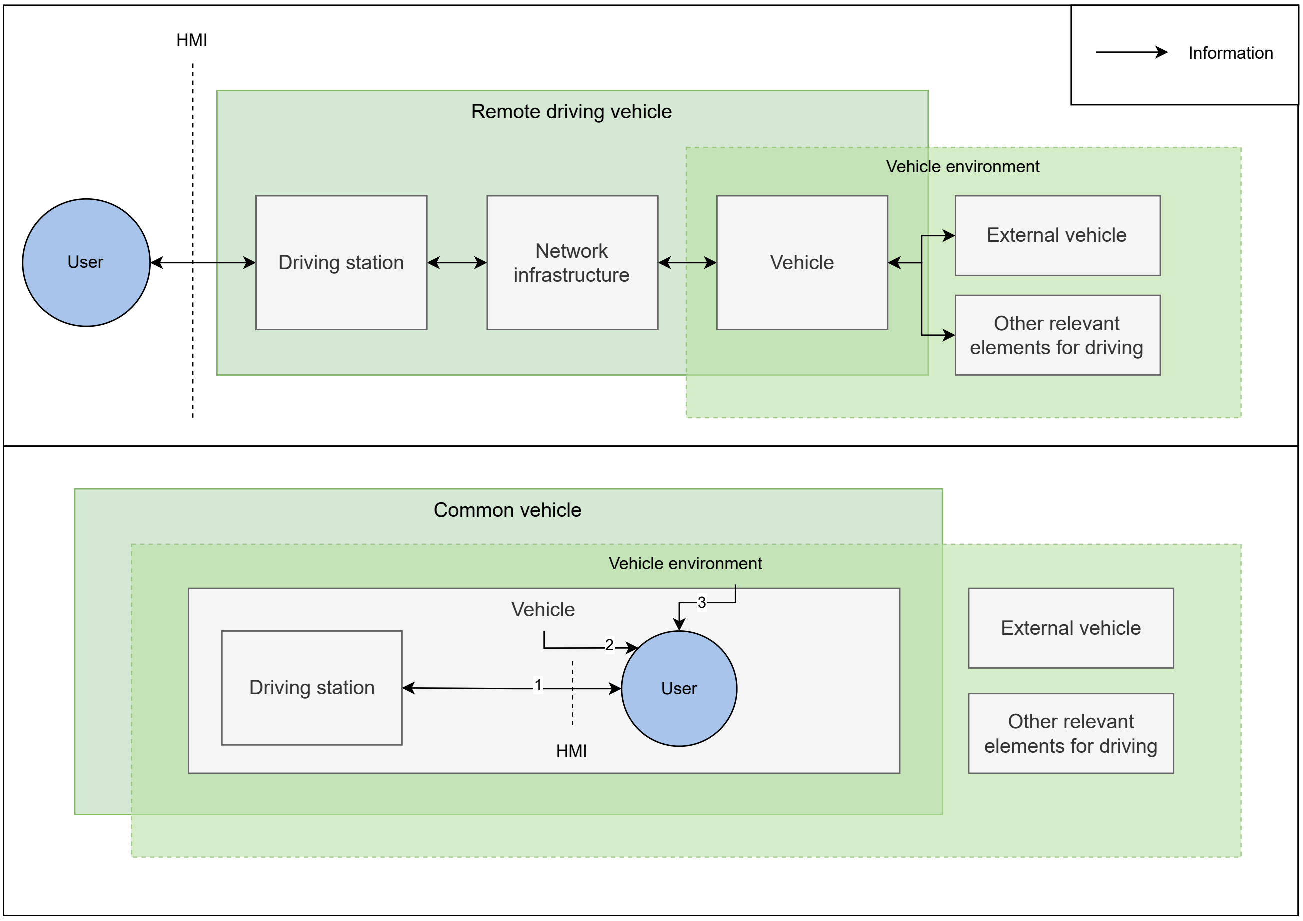

Figure 2: Comparison between the technical/physical view of the conceptual architecture of an ordinary vehicle and a remotely driven one.

(1) Information sent from the user to the driving station through joysticks, and the other way around through the displays, but also the haptic return of the steering wheel and the pedals, etc. .

(2) Information conveyed by the sound of the vehicle, the kinetic of the vehicle (general movement, vibrations,...), the rearview mirrors, the potential smell of a misused engine, ...

(3) Information given by the sound of the environment, the direct vision of it, etc..

it appeared to be much more complicated to meet safety requirements of the people and the material during experiments of disturbances on the actuator communication, this project focus on the sensor part. It indeed seemed more tactical to firstly implements easily realisable tests on the set up, and moving on to harder ones later.

On the other hand, the potential impacts of such disturbances are also very diverse. For this reason, the project focus on the control of the RDV and not, for example, on the driver feelings as excess stress, ill-being or excessive tiredness. This will allow to define a reduced set of metrics for the specifications. The project also mainly focuses on the impacts of such disturbances for the Safety requirements of the system. Those reductions of the subject are needed for the quality and validity of the results. They define the scope of the PFE.

Finally, the problems encountered have been formalized by the team through research questions to guide the work:

- What kind of communication disturbances can happen in a RDV infrastructure?
- What is the risk of appearance of such disturbances?
- What impact does it have on the control of the vehicle?
- Can it makes remote drivers not having control of the vehicle?
- How to test human performance of RD under network disturbances?
- Can a simulator be used for those tests?
- To what extent can the results from RD simulation tests can be used to improve the design of the system?
- How does video quality affect safe driving?

2.6 Methodology

The general process of V&V[8] of a new technological system [9] can be decomposed of four main phases (see synthesis table 1):

1. **Exploration: V&V methods development**. This phase is dedicated to the development of the V&V methods for the new system. It, first of all, consists in a theoretical analysis of the system, and in experiments conducted in a physical or a simulated prototype of RDS, which doesn't need to be advanced but only to have the main system functionalities. This phase relies on the scientific process of hypothesis verification with the aim of learning some underlying principles from the outcomes. It allows to distinguish variables and select the relevant ones for the final V&V methods. The concept of failure doesn't apply to the experiments. Engineering analysis tools are, of course, also necessary to analyse the system.

[8] Backed by the development process

[9] to differentiate with a new product implementing an already known technological system

2. **Development: method improvements**. This phase consists in using the methods and analysis extracted from the previous phase for the development of the RDS in the industry or in research. The tested system is a prototype intended to become a sold product. The V&V methods themselves are tested on a realistic model, but in a controlled environment. They can later be improved. This phase can be distinguished from the previous one because the process followed is not scientific anymore but correspond to engineering development processes. The tests follow a relatively fixed methodology, specific results are expected, or at least the quantities are known, and pre-defined metrics are used. The tests are models designed from the previous experiment. They have pass or fail criterion.

3. **Real case tests**. The RDS, very close to a product to be sold, is tested in a real environment.

4. **Authorities Verification and Validation**. The products is verified and validated according to the mature developed methods.

Phase	Exploration	Development	Real case tests	Verification and Validation
Aim	v&v methods development	Help to system development and method improvement	Advanced system testing	Approval for the market
System	Non commercial destined functional prototype	Commercial destined functional prototype	Commercial destined functional product	Product to be commercialized
Environment	Controlled	Controlled	Real	Controlled and real
Tester	R&D laboratories	R&D laboratories	R&D laboratories	Authorities

Table 1: Synthesis of the different phases of the V&V process for new technological systems.

Judging from the system complexity, but first and foremost, judging the unknown entire set of technologies that will be chosen in the industry, this project aims at participating in the phase 1 of the sub-mentioned process by answering the research questions listed in part 2.5.

Several evaluations of the system, among which some of them are experimental, are conducted in order to answer these research questions.

To formalize the specification of the evaluations, the VALU3S initial multidimensional layered framework [26] (figure 3) will be used. The final version of this framework is a work in progress. We also use a proposal for the classification of methods for V&V of SCP of Automated Systems [15].

With this analysis grid, it has been proposed to realize the five following evaluations of the system during the project:

- **Physical experiment without fault injection**. The experiment is an in-the-lab evaluation conducted on an artificial metal grid field. The prototype of V&V methods will be applied to a minimalist open-source based technological system without a full scale. Hence, the studied RDS will be constructed by RISE from top to bottom with the objectives of:

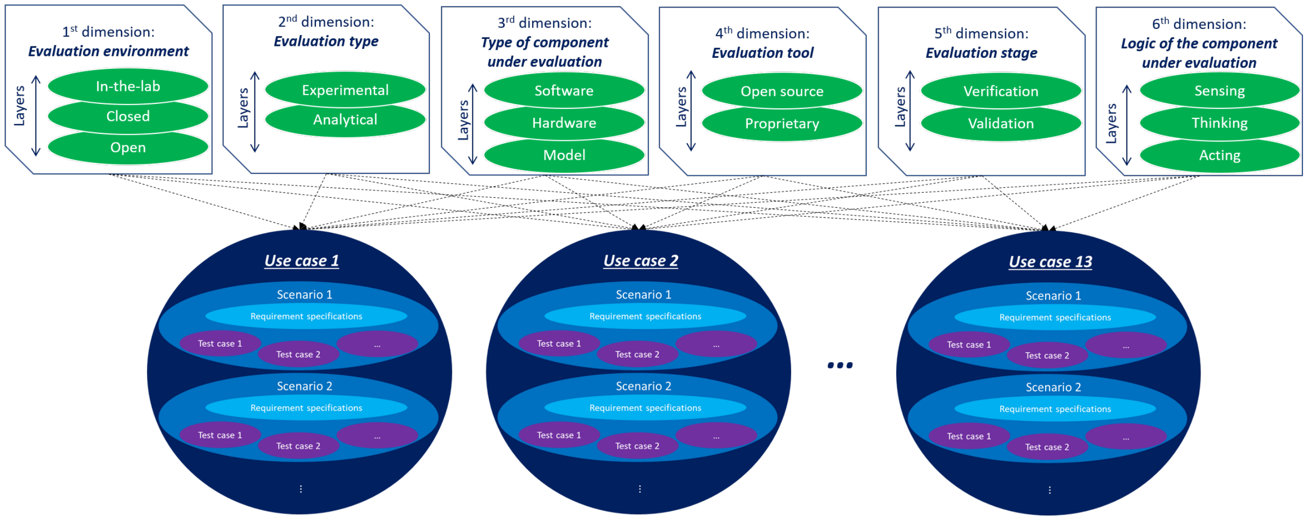

Figure 3: VALU3S initial multidimensional layered framework

- Mastering the all system
- Having a reliable tool, implementing all the fundamental functionalities of a RDS but only them, to conduct the experience
- Having the capacity to compare and generalise the results

This experiment aims at defining a baseline of the use of the RDV in optimal conditions. It can, therefore, be categorized in the Testing method type[10]. Both software and hardware components, which logical role is sensing (video streaming of the RDV) or acting, are evaluated.

- **Physical experiment with fault injection**. The experiment is similar in every point to the previous one, except that we artificially introduce disturbance to observe their impact on the system. It is therefore a method of type FI[11]

- **Simulation experiment without fault injection** This experiment is conducted in a simulator instead of a physical RDV. Using a simulator allows to do more diverse and exhaustive experiments on the vehicle control. Some aspect of the experiments are also more realistic because it allows to use a full scale simulated vehicle on simulated public road. This method has already been employed to study the FI impact into an Advanced Driver Assistance System (ADAS) at RISE [27] and in a study which test the AV resilience [28]. The simulator uses the HMI as the physical RDS and the experiment without FI also aims at giving a baseline of the use of the simulator before introducing disturbances. This method is an in-the-lab experimental evaluation of sensing and acting simulated components, that is to say, a model of the physical components. Consequently, it enters in the Simulation[12] method category.

[10] "when system execution under certain conditions is checked before operation."[15]
[11] "When some phenomenon is introduced in a system to analyse its response."[15]
[12] "When the behaviour of a model of a system is studied."[15]

- **Simulation experiment with fault injection** The same experiment is reproduced, but this time with a FI to simulate communication disturbances in the system.
- **Analytic evaluation** Finally, an analytical evaluation of type Semi-formal [13] will be conducted on the hardware and software sensing and acting components of the system.

A more detailed explanation of the methodology of the experiments I participated in, including the use cases, scenarios and metrics used, can be found in part 4.

2.7 Expected deliverables: Product Breakdown Structure (PBS)

The deliverables of the project are:

- D1. Functional, complete and reliable physical experiment set-up reproducing a RDV
  - D1.1. Software
    - D1.1.1. Dispatched software components for the remote control of the vehicle (already existing, the onboard module is maintained, not the workstation module)
    - D1.1.2. Dispatched software components for the video streaming of the vehicle front camera
    - D1.1.3. Onboard software component for the video recording of the top camera
    - D1.1.4. Workstation software component for the joystick handling (already existing, not maintained)
    - D1.1.5. Configured computer workstation for driving station handling and network configuration
  - D1.2. Hardware
    - D1.2.1. Driving station: screen and joystick connected to the system
    - D1.2.2. Miniature vehicle model: raspberry pi, top camera, front camera, wifi antenna, GNSS antenna, VESC motor controller, etc. (Already built example existing)
    - D1.2.3. Network infrastructure for a 50m distance wifi network: wifi antenna, repeater.
    - D1.2.4. Computer workstation
- D2. Functional, complete and reliable simulation experiment environment reproducing a RDV (part of those elements were already functional and only needed to be properly integrated in the system):
  - D2.1. Software:
    - D2.1.1. Parameterized CARLA simulator

[13] V&V methods that exploit some structured means but without a full mathematical basis.

    - ∗ D2.1.2. Configured computer for driving station handling and CARLA simulator hosting
  - D2.2. Hardware :
    - ∗ D2.2.1. Driving station
    - ∗ D2.2.2. Computer workstation

- D3. Application for drivers reaction baseline evaluation
- D4. Architecture description of the RDV
- D5. Description of the simulated environment
- D6. Conducted experiments, there results and result analysis.
  - D6.1. Physical experiment without FI
  - D6.2. Physical experiment with FI
  - D6.3. Simulation experiment without FI
  - D6.4. Simulation experiment with FI
- D7-9. A scientific report on the study from each student, focusing on its specific questions, containing the description of the scientific method followed, the experiment protocol, the result and result interpretation.

No deliverable concerning the project management were expected.

2.8 Work organisation and distribution: Work Breakdown Structure (WBS) and Organisational Breakdown Structure (OBS)

The project has been organized according to the general project lifecycle presented in fig. 4. The succession of phases 2 and 3 has been realized 2 times: the first time to study and work on the system and experiments without FI, the second time to introduce FI both in the theory and in the experiments.

The different tasks performed to achieve the project deliverables are presented in the following tables (tab. 2,3,4,5,6,7,8,9). Activity D2.2 is not mentioned as its tasks are common to those realized for deliverables D1.2.1 and D1.2.4. Some deliverable don't have corresponding tasks as there were already existing (see indication in the deliverables), even if they were not deployed.

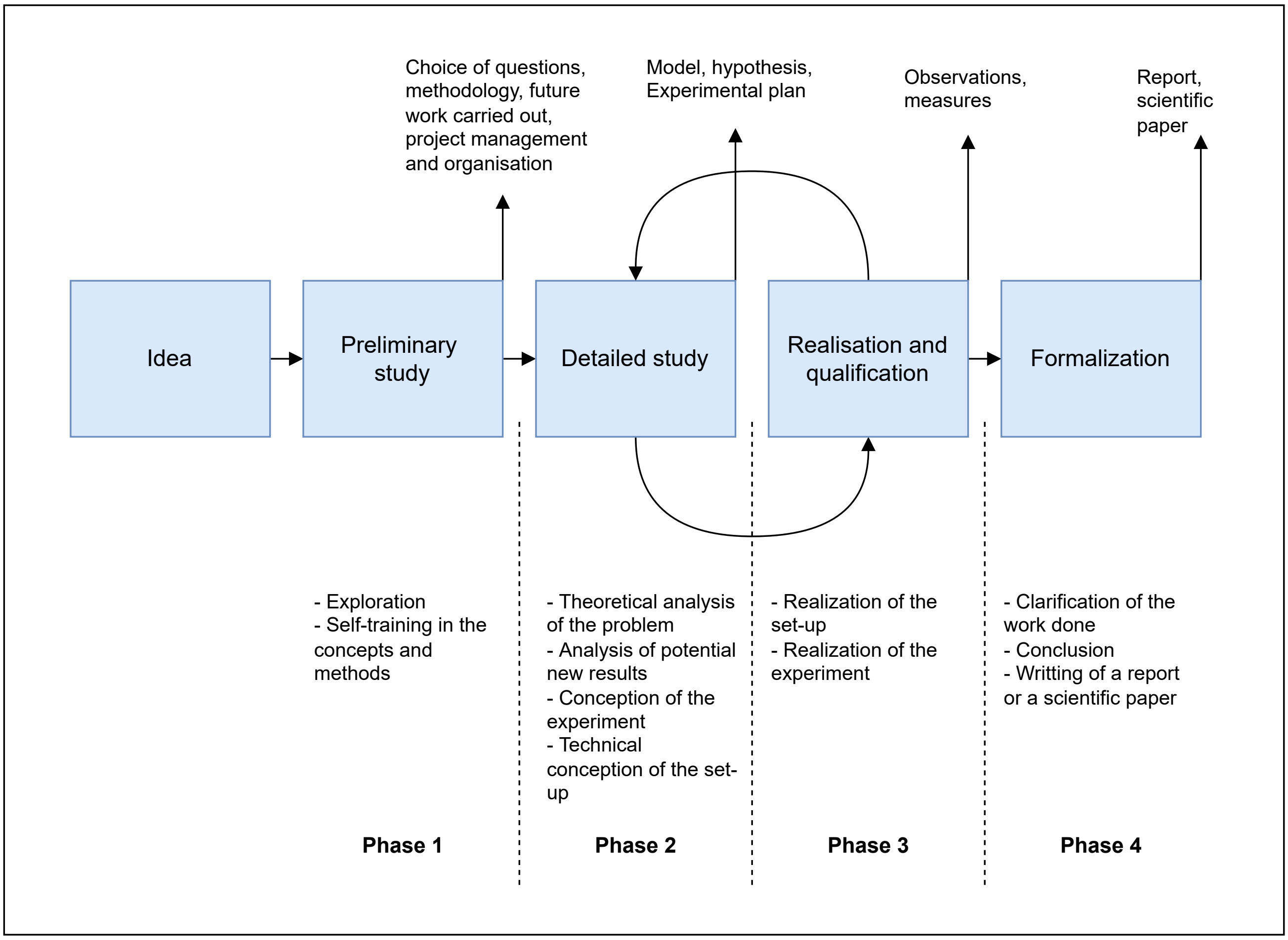

Figure 4: General scientific project life-cycle

Family	Identifier	Task
Study	D1.1-S1	SFG of software components for physical experiment set-up
Study	D1.1-S2	SFD of software components for physical experiment set-up
Realization	D1.1.2-R1	Coding of the software components for the front camera video streaming
Realization	D1.1.3-R1	Coding of the software component for the top camera video recording
Realization	D1.1.4-R1	Modification of the workstation application to handle the joystick
Realization	D1.1.5.-R1	Workstation computer configuration
Acceptance Testing	D1.1.-AT1	Software components deployement and scenarios test

Table 2: Activity D1.1. Software components of the physical experiment set-up

Family	Identifier	Task
Study	D1.2.1-S1	SFG-SFD of hardware components for the driving station
Acceptance Testing	D1.2.1-AT1	Driving station connection and scenarios test
Study	D1.2.2-S1	SFG of hardware components for the vehicle prototype
Study	D1.2.2-S2	SFD of hardware components for the vehicle prototype
Realization	D1.2.2-R1	Vehicle prototype building
Acceptance Testing	D1.2.2-AT1	Scenario-based test of the vehicle prototype
Study	D1.2.3-S1	SFG-SFD of the network infrastructure
Realization	D1.2.3-R1	Network set-up
Acceptance Testing	D1.2.3-AT1	Network system and scenario-based test, quality measurements
Realization	D1.2.4-R1	Workstation computer configuration
Acceptance Testing	D1.2.4-AT1	Scenario-based test of the computer workstation

Table 3: Activity D1.2. Hardware components of the physical experiment set-up

Family	Identifier	Task
Study	D2.1-S1	SFG of the CARLA simulation and CARLA environment
Study	D2.1-S2	SFD of the CARLA simulation and CARLA environment
Realization	D2.1-R1	Parametrization of CARLA simulator, coding of specific parts, computer workstation configuration
Acceptance Testing	D2.1.-AT1	CARLA simulation scenario-based test

Table 4: Activity D2.1. Software components of the simulation experiment

Family	Identifier	Task
Study	D3-S1	SFG of the application
Study	D3-S2	SFD of the application
Realization	D3-R1	Coding of the application
Acceptance Testing	D3-AT1	Application scenario-based test

Table 5: Activity D3. Application for drivers reaction baseline evaluation

Family	Identifier	Task
Study	D4-S1	Architecture design file writting

Table 6: Activity D4. Architecture description of the RDV

Family	Identifier	Task
Study	D5-S1	Simulated environment file writting

Table 7: Activity D5. Description of the simulated environment

Family	Identifier	Task
Study	D6.1-S1	Physical experiment without FI conception
Realization	D6.1-R1	Physical experiment without FI preparation
Acceptance testing	D6.1-AT1	Pilot test
Income	D6.1-I1	Physical experiment without FI realization and result collection
Income	D6.1-I2	Result analysis
Study	D6.2-S1	Physical experiment with FI conception
Realization	D6.2-R1	Physical experiment with FI preparation
Acceptance testing	D6.2-AT1	Pilot test
Income	D6.2-I1	Physical experiment with FI realization and result collection
Income	D6.2-I2	Result analysis
Study	D6.3-S1	Simulation experiment without FI conception
Realization	D6.3-R1	Simulation experiment without FI preparation
Acceptance testing	D6.3-AT1	Pilot test
Income	D6.3-I1	Simulation experiment without FI realization and result collection
Income	D6.3-I2	Result analysis
Study	D6.4-S1	Simulation experiment with FI conception
Realization	D6.4-R1	Simulation experiment with FI preparation
Acceptance testing	D6.4-AT1	Pilot test
Income	D6.4-I1	Simulation experiment with FI realization and result collection
Income	D6.4-I2	Result analysis

Table 8: Activity D6. Conducted experiment and there results

Family	Identifier	Task
Study	D7-9-S1	Report writting

Table 9: Activity D7-9. Scientific report

Finally, The work has been divided in the following way between the three students (under the supervision and co-supervision of Fredrik Warg, Ted Strandberg and Martin Skoglund, and with the help of the other members of the Dependable Transport Systems unit):

- Shrishti Trivedi has focused her work on the simulation part of the study.
- Fryderyk Pryjma has been working on the human factor in our study.
- I have concentrated my work on the physical part of the study.

The consecutive work organisation (updated a posteriori) is presented in the annexed GANTT diagram (fig. 7). The tasks have been attributed in the diagram to the students responsible for it. The diagram therefore doesn't represent the numerous collaborations.

3 Informatic technologies for RDVs: State of the art

This part aims at giving a theoretical insight of the system before getting into experiments. It is not an exhaustive specification or conception file, but it synthesizes the main technological aspects of , the one relevant to the research questions. Thus, a first subsection gives a precise definition of the system studied. A second subsection details the functional requirements that this system has to meet. A third section presents the categories of use cases of the system, and the consequent benefits it represents. A fourth section details the network infrastructure the system has to rely on. Finally, a fifth section presents the architecture that as been designed for a future system implementation and illustrates it with some existing models.

3.1 Definition

5G Automotive Association (5GAA) distinguishes three types of activities in the driving tasks which they hierarchy [29]:

- Strategic level operation: "travel planning (e.g. to define driving goals and choose the route or mode), considering available options, costs and risks involved."
- Tactical level: "e.g. speed selection, lane selection, object and event response selection, and manoeuvre planning."
- Operational level: "e.g. longitudinal and lateral control as well as object and event detection and classification."

This analytical framework is interesting in the case of combining a RD technology to an AV technology, because it allows to categorize the task distribution between the two technologies. For example, in the case of a car equipped with an onboard autonomous system, the RDS could be used at a Strategical level only. It is also interesting when considering companies' infrastructures which could be developed around RD services. Indeed, there is a need to specify the work of the operator relative to the onboard driver or autonomous system. There is also a need to define the capacity of the infrastructure to handle RDS mode switch. Finally, this hierarchy in the driving tasks is interesting to evaluate the impact of a RDS on the driving capabilities. This last aspect is the one we will be interesting in in this study. Indeed, the aim is not to evaluate a commercial service infrastructure, but the safety of the system. Because of this subject delimitation, we will only study the case of a remote driver operating the three levels of the driving task, but we will use these distinctions to observe the driving tasks most impacted by communication disturbances.

Therefore, as detailed in the previous parts, a RDS is here considered as a coherent set of technologies, which allows, in relation with the vehicle technologies, a pre-existing network and classical road infrastructures, to fulfill every task of driving while being away from the driven vehicle. We can distinguish three main subsystems in a RDS: the driving station, the vehicle and the communication network. Tele-operated vehicle is a synonym that can be found in the literature.

3.2 Functional requirements

As the purpose of the study isn't to do retro-engineering, but to make a theoretical analysis of the system, we'll settle with the main functional requirements of the system presented in tab. 10. We can also already propose standards functional safety requirements (tab. 11) based on the related technologies developed ones and especially, based on the guidelines on the exemption procedure for EU approval of AV [30].

Subsystem	Functional requirements
Driving station	Receiving all the information necessary to perform the tasks of driving a specific vehicle
	Presenting to the driver those information in such an ergonomic way that he can perform these tasks safely
	Collecting the driver's orders and all the information to safely perform them
	Communicating those information to the vehicle
Vehicle	Collecting all the information necessary for a remote driver to perform the tasks of driving
	Sending those information
	Receiving the orders from the driver
	Executing the orders of the driver
Communication network	Enabling the communication in both directions between a driving station and a vehicle in such a way that driving tasks can be performed

Table 10: Remote Driving System functional requirements

3.3 Use cases and benefits

When considering a RDS with a central three levels driving operator (whether he is a human or a machine), two main use cases of this technology appear:

1. A specific localization of the competences to drive a vehicle in a certain domain.
2. The lack of need to transport the driver with the vehicle.

Those two cases are not contradictory but independent. The first case occurs, first of all, when an AV reaches the limit of its Operational Design Domains[14] (ODD). In that case, if the vehicle has to continue outside of the ODD of the AV or if it cannot turn back into it (e.g. problems during an autonomous system test), then a remote operator is needed. Malfunctions are also included in the limit of the ODD if the AV doesn't have the capacity to handle it itself. But this

[14] "Description of the conditions in which an AV (AV) is designed to operate safely" [31]

Subsystem	Functional safety requirements
Driving station	Collecting all the information necessary to guaranty the subsystem normal operation
	Detecting system malfunctioning or exit from the system Operational Design Domain from those information and the one sent by the vehicle
	Collecting proof of the driver invovlment in the driving tasks
	Sending alert to the vehicle and it's environment in case of malfunctioning or exit from the Operational Design Domain of the system
	Sending order to the car to go into minimal risk state in case of driver non-involvment into the task, critical malfunctioning of the system or critical system Operational Design Domain
	Updating the system
Vehicle	Collecting all the information necessary to guaranty the subsystem normal operation
	Detecting system malfunctioning or exit from the Operational Design Domain of the system from those information and the one sent by the driving station
	Sending alert in case of the detection of system malfunctionning or exit form the Operational Design Domain
	Placing itself into a minmial risk state in case of critical system malfunctioning, critical exit from the Operational Design Domain or reception of the order to do so from the driving station
	Sending alerts to the driving station and the environment in case of minimal risk state procedure
	Saving the recent information allowing an evaluation of the normal operation of the system and a correct driver behaviour
	Calibrating and synchronizing the sensors and actuators
	Updating the system
Communication network	Communicating Quality of Service related information

Table 11: Remote Driving System functional safety requirements

case can also occurs with human drivers on board, for multiple reasons, whether it is because a construction truck has to be manoeuvred in a tricky situation (e.g. a mine, a construction site with a complex ground) or because a non-professional car driver is in a situation he cannot handle (e.g. private parking optimization requiring to have a global vision of the cars inside). In all those cases, a more competent, or more informed operator could take the control of the vehicle.

The second main use case is when the driver himself doesn't need to travel. We can easily find examples in the professional world: carriage of goods, automated factory parking, public transportation, valet parking, taxis, etc. But there are also some use cases for individuals: transport of personal belongings, etc. The moral aspect of some use cases, such as remotely driving the children to their grandparents instead of going with them, is left to other studies.

In comparison to the common vehicles, remotely driven ones require a more complex infrastructure on top of the existing one (detailed later on). The actors behind the service of driving a remote vehicle are therefore more numerous. To the vehicles constructors, dealers, rental companies, repairer, regulator, owner, to the road constructor, operator and traffic authority are added the RD service provider, the driving station owner, the (MNO), the potential professional drivers providers, etc. The number of scenarios derived from the main use cases is therefore very important. Notably, several questions concerning the system specifications and standards have to be raised in the case of multiple MNOs, RD service providers, Original Equipment Manufacturer (OEM) or Road Traffic Authority (RTA).

In the light of those use cases, the benefits of the RD technology appear to be:

- Drivers safety and comfort improvement
- logistic optimization
- Consumption optimization Decrease of human workload

3.4 Network infrastructure

As shown in fig. 2, a RDS has to rely on a network infrastructure to fulfill its main functionalities. But, as the RDS has to recreate the environment of the vehicle, it is relevant for it to integrate information from other communication channels than the RDS one, in addition to the vehicle sensors. In particular, information shared by other users of the road infrastructure or by the infrastructure itself. The technology enabling those communications have been developed relatively at the same period as RD under the name of Vehicle-To-Everything (V2X) or Intelligent Transport System (ITS). As it covers a large range of the technological needs to build a RDS, the latter has to be thought as integrated into V2X. The 5GAA proposed infrastructure to commercialize RDV relies on V2X standards.

V2X, defined as "communication between a vehicle and any entity that may affect, or may be affected by, the vehicle." [32], is used in general public vehicles since 2016, when it appeared on Toyota cars. As part of the connected mobility and AV transition, the benefits presented are ones again safety improvement, energy reduction, use cases optimisation and extension.

Five sub-communications, corresponding to five types of entity that may affect, or may be affected by the vehicle, compose V2X:

1. Vehicle to infrastructure(V2I)
2. Vehicle to Network(V2N)
3. Vehicle to Vehicle(V2V)
4. Vehicle to Pedestrian(V2P)
5. Vehicle to Device(V2D)

Among them, V2N would be a direct component of RDS core functionality, while the other ones can be integrated into advanced functionalities such as driving assistance, enhanced interactions with the environment (e.g. V2D for communication with traffic safety officers) or safety functionalities (e.g. redundancy of the network thanks to different communication channels, malfunction alerts sent to the environment).

Two different implementations of V2X based on two different technologies, resulting in competitive standards have been developed:

- **WLAN-based**. A Wireless Local Area Network (WLAN)[33] is a wireless network within the geographic area whose scale is between a home and a campus (LAN). This technology supports V2I and V2V communication. The specifications of a WLAN-based V2X were first published in the 2010 version of IEEE 802.11p technical standard [34]. IEEE 802.11 is a very common standard for WLAN defined by the professional association Institute of Electronical an Electronics Engineers[35]. One of the well known technology derived from the IEEE 802.11 standard is the Wi-Fi[36], which notably allows interoperability of the devices into a WLAN. IEEE 802.11 standard defines protocols of the physical (layer 1) and data link layers(layer 2) of the Open Systems Interconnection model (OSI). The IEEE 802.11p is an amendment to IEEE 802.11 dedicated to vehicles applications. A European standard for communication between vehicle has been built based on this one: the ETSI ITS-G5. This communication relies on radio transmission medium using radio waves of the electromagnetic radiation within the frequencies of the 5.9 GHz band (e.g. 5.850–5.925 GHz in the USA) composed of 10MHz bandwidth channels in the case of the IEEE 802.11p standard.
- **Cellular-based** (C-V2X). A cellular network is a type of wireless communication network that can be distributed over a large area divided into cells with specific receivers each [37]. This concept is the basis of commercial mobile networks whose version names are well known nowadays (1G to 5G...). This mobile network is also based on the radio transmission medium, whose frequencies are divided between cells. Since the second version, the networks have become digital. This technology supports V2I and V2V but also V2N communication. The first C-V2X standard has been published in 2016 by the 3GPP consortium as a LTE (Long Term Evolution), which is the norm of a 4th generation cellular

network[32][38]. A new release of C-V2X standard handles 5G network. In this standard, the V2I and V2V communications use a special interface to directly exchange information between equipment without passing through a base station. The allowed radio frequencies are the same as for 802.11p based system.

3.5 Architecture

The objective of this subsection is to describe the architecture of a target RDS, which is therefore not existing. We make the choice of considering this system as being used in open public areas, for a generic commercial use, that is to say, without specific actors providing and using the .

Except for the network infrastructure a RDS has to rely on, no specific application architecture has been found in the literature. It appears that the technology is not mature enough to see common solutions emerging. As a consequence, there is no point in presenting a so-called state of the art application architecture. Nonetheless, the application architecture implemented for the experiments will be presented in the following section.

On the contrary, a generic physical architecture emerges from the different work around this technology. The figure 5 illustrates it. The architecture presented implements a Cellular based V2X network. It is based on several works analysed, and notably the one of 5GAA[39]. The physical aspect of the network infrastructure is not represented as it depends on its generation.

Different HMI and vehicle characteristics are studied and proposed by companies. Among them, we can, for example, notice the different choices of actuators in the driving station made by Einride and Roboauto companies (fig. 6). Those main differences in HMI impact a lot the safety of the system, and therefore, the capacity of generalizing our results. This reinforces the choice of a minimalist set up for the experiments.

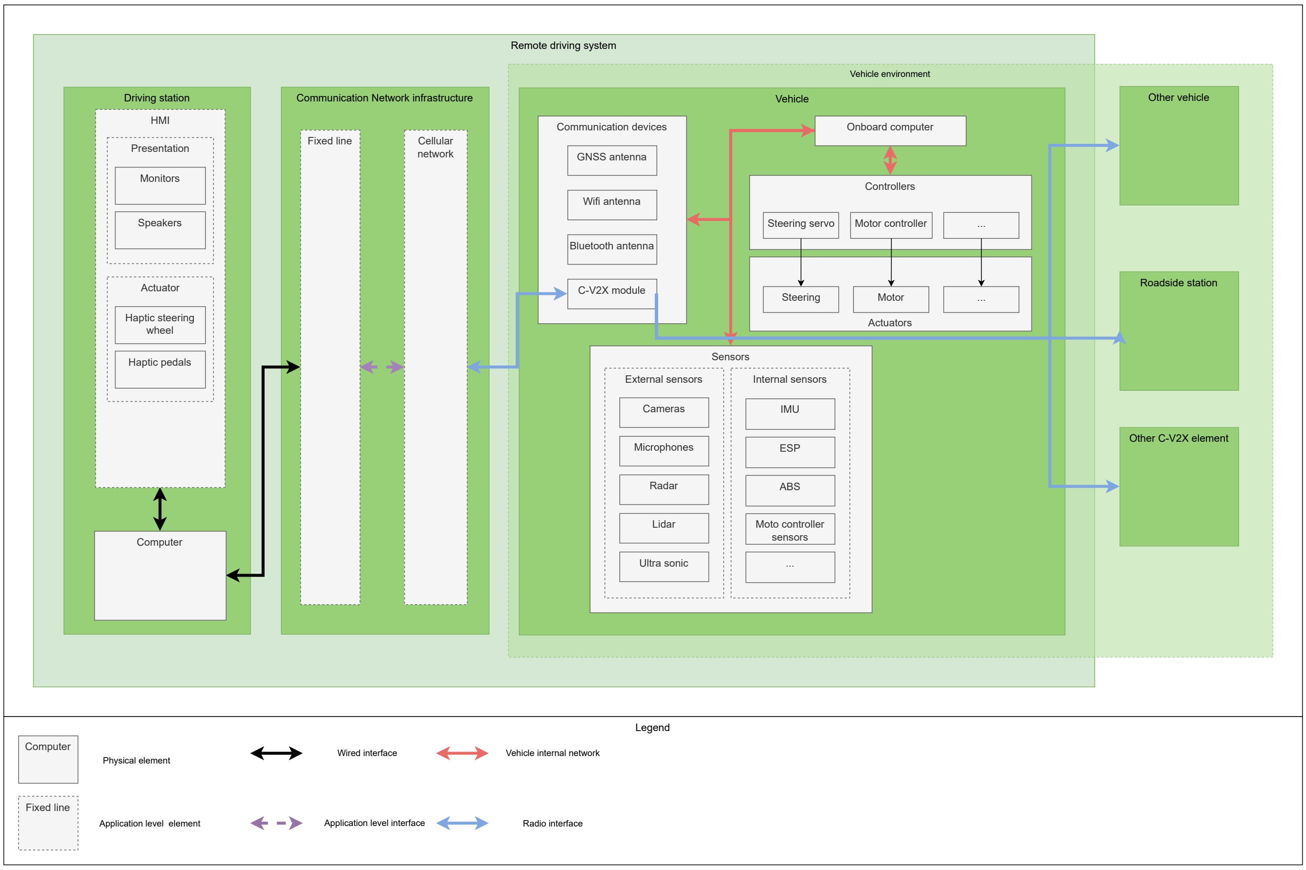

Figure 5: Physical view of the conceptual architecture of a Remote Driving System with a C-V2X communication network

4 Experiment

This section deepen the physical experiment with FI (set up common to the physical experiment experiment without FI), the one I have mostly contributed to during this PFE: the physical experiment with and without FI. The second one has been prepared but not realized at the moment of the report writing.

4.1 Purpose

Let us recapitulate the background of the experiment to introduce its purpose. RDV is a new promising technology in development with huge Safety, Cybersecurity and Privacy issues that haven't been handle yet. It therefore requires, both for its industrial development and the authorities control of the technology, to develop new specifications and V&V methods to check those specifications in order to guarantee the security, safety and reliability of the system with respect to SCP.

(a) Roboauto driving station[40]

(b) Einride driving station[41]

Figure 6: Comparison between Roboauto and Einride driving station HMI

This project participate to the first phase of the VV method development with a focus on what appear to be the most risky aspect of the system: the communication between the vehicle and the driving station. Moreover, only the safety requirement is studied.

A conceptual tool for the impact study of the system communication's problems has been defined: the disturbances of communication (deviation from nominal functioning), we study it as the cause of system non-safety. We can distinguish three main parameters that decrease network quality : bandwidth, latency and jitter[15] [14]. They respectively introduce a restriction on the amount of data transmitted, a delay in the communication and loss of transmitted data. The physical experiments therefore aim at measuring the impacts of those three disturbances on precise aspects of RD safety.

[15] "Deviation from true periodicity of a presumably periodic signal, often in relation to a reference clock signal." [42]

4.2 Methodology

FI is used to replicate the previously mentioned communication disturbances: reduction of data transmitted, delay and data loss. We use the tool NetEM to emulate delay and packet loss on the communication interfaces and Token Bucket Filter (TBF) to limit the bandwith. The system between the conceptual layer in which the faults are be injected and the conceptual layer of the observable impacts is treated as a black box of unknown behaviour.

The faults are injected while experimental subjects are asked to realize precise tasks grouped into scenarios with the RDV. The scenarios are defined based on the Swedish driver license evaluation (see tab. A.2). The terms Carla and Carlos respectively define the simulation and physical set up.

The driving abilities are measured during the tasks, based on metrics defined in the tables in appendix A.2.

The subject tested are RISE employees because of facility access constraints.

4.3 Protocol

The protocol mainly consists in:

- introducing a tested subject to the set up
- allowing him to train and get use to the set up
- explaining the scenario to follow
- starting the scenario, the data recording and introducing disturbances at defined moment
- ending the scenario and prepare for another subject

4.4 Setup

4.4.1 Experimental System (ES) architecture

The objective of the physical set-up was to use minimalist open source technologies which would be reliable enough so that the FI could be differentiated from nominal operating. Photo of the set up can be found in the appendix (fig. 11d).

4.4.2 Environment

The environment of the test consist into an outdoor flat metal grid close to the driving station.

4.5 Limitation and difficulties

Judging from the first tests realised, the main difficulty and limitation of our tests are the nominal quality of the communications.

5 Conclusion

To conclude on this work, a very large questioning field has been dealt with during this project. Looking at scientific papers, it appears that the subject of the PFE gathered several research questions which therefore wasn't deepen enough (vehicles technical and legal requirements, methods, RDV end-to-end latency, ...). Nonetheless a theoretical and practical work useful for RISE could have been realized. Moreover, it allowed to learn about many different domains. Finally, working inside RISE has been a really interesting experience itself.

A Appendix

A.1 GANTT chart

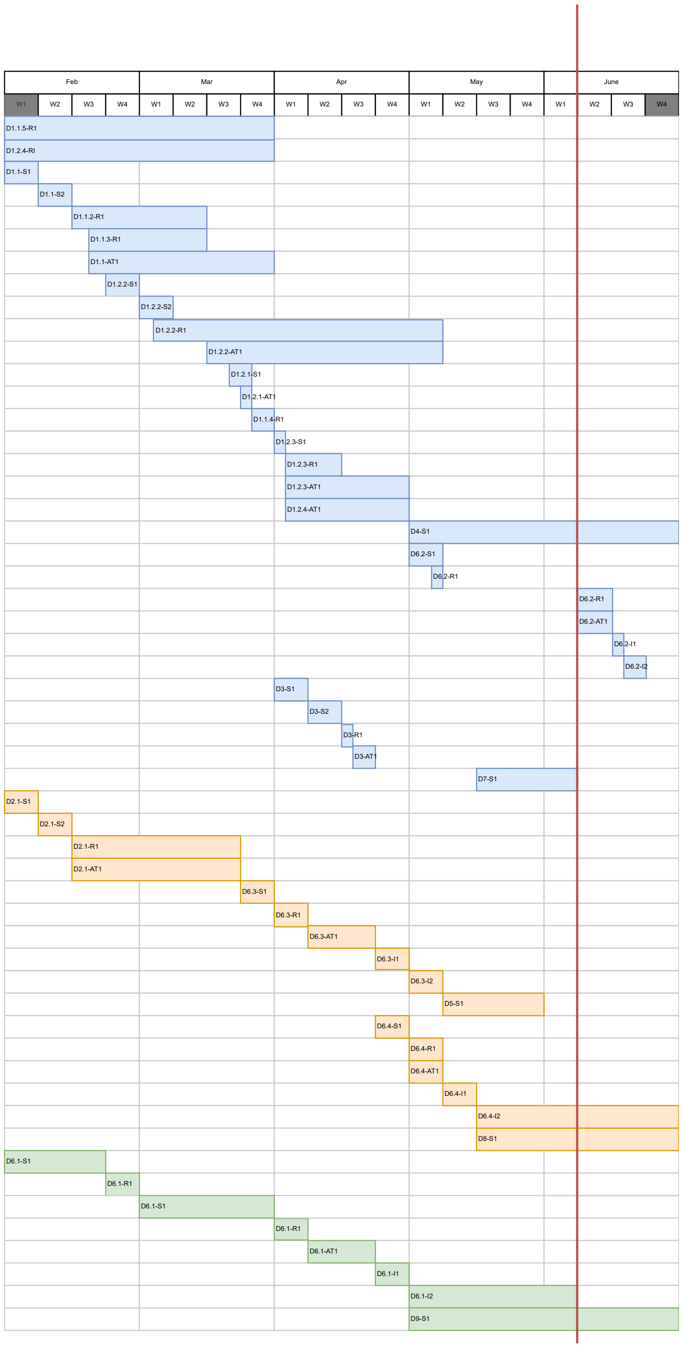

Figure 7: A posteriori GANTT chart of the project

A.2 Tests methodology

Experiments								Output variables								
									A	B		C	D	E	G	H
								Basic driving abilities (metrics)	Knowing its position on the roads network	Staying on the road		Following lane centering	Avoiding obstacles	Maintaining safe distance	Controlling steering action	Controlling acceleration/brake
Elements of the swedish driving test (scenarios tested)		Hypothesis on the direct impact of fault injection in the video streaming on for an ideal set up	Hypothesis on the direct impact of fault injection in the car control commands for an ideal set up	Possibility to test with the actual set up				Definition	Distance ranges between the position of the car and the driver's believed location on a map that represent degrees localisation abilities	Time spent on or out of a road delimitation	Number of lane invasion	Difference of distances between the car and each border of the road	Projection of the distance between the car and the obstacle on a boolean space : d>0 = True, d<=0 = False	Distance ranges between the car and the obstacles that represent degrees of danger	/	/
				Carla		Carlos		Unit	degree	second	/	meter	Boolean	degree	/	/
1	Driving position	x	x	x	No fault injection impact	x										
2	Emergency stop	x	yes	x	No realistic enough breaking system	x	No break on the car									
3	Parking	yes	yes	x	No rear views	x	No rear views									
4	Reversing	yes	yes	x	No rear view is not available	x	No rear view is not possible									
5	Hill start	x	yes	v	Yes, the town has a flyover	x	flat environment and no break									v
6	Three-point turn	yes	yes	x	No rear views	x	No rear view mirror									
7	Pulling away from the kerb	yes	yes	x	No rear-view mirror	x	No rear view mirror									
8	Using the controls	x	x	x		x										
9	Unprotected road users	yes	yes	?		v	Yes but a rear-view mirror is missing			v	v		v	v		
10	Driving in lane	yes	yes	v		v				v	v	v				
11	Changing lane	yes	yes	v		v				v	v	v				
12	Intersections	yes	yes	x		x	No rear-view mirror and no break									
13	Signal-controlled junctions	yes	yes	x		x	No dynamic signal									
14	Roundabouts	yes	yes	x		x	No roudabout on the field									
15	Passing stationary vehicles	yes	yes	v		v							v	v		
16	Driving in built-up area	yes	yes	v		v				v	v	v				

17	Independent navigation	yes	yes	x		x	Not enough complex road network, not enough road signals		v	v	v	v				
18	Driving Through roadworks	yes	yes	x		x										
19	Railway and/or tram crossings	yes	yes	x		x										
20	Driving on narrow and/or windind roads	yes	yes	x		v				v	v	v				
21	Motorways, expressways or similar	yes	yes	x		x										
22	Trunk road access	yes	yes	x		x										
23	Turning off trunk roads	yes	yes	x		x										
24	Driving on trunk roads	yes	yes	x		x										
25	Overtaking	yes	yes	?		?										
26	Meeting oncoming traffic	yes	yes	x		x										
27	Reduced visibility and darkness	yes	yes	v		x			v	v	v	v				
28	Hazardous and slippery road conditions	yes	yes	x		x										

Figure 8: Tests scenarios and metrics conception.

Experimental scenarios			Carla experiment	Carlos experiment
1	Overtaking a stationary object	Driving Abilities	D, E	D, E
		Test Setup	A static vehicle would be placed in one of the roads, and the driver is supposed to overtake the vehicle	A static object representing a vehicle would be placed in one of the road and the drive is supposed to overtake the vehicle
		Measurement set up	Check longitudnal safe distance maintained ahead of the vehicle. Use varying degrees of safe distance (5m most safe, 2m safe yet the boundary level of being safe and so on...). Similarly we can also check for latitudnal safe distance that is the distance maintained on the sides. - programmed in the script and saved in log files	Check longitudnal safe distance maintained ahead of the vehicle. Use varying degrees of safe distance (5m most safe, 2m safe yet the boundary level of being safe and so on...). Similarly we can also check for latitudnal safe distance that is the distance maintained on the sides. Marks can be put (using tapes) to easily see at which degree the vehicle overtake the static object from a zenital point of view.
2	Driving on a curved road (right and left turns)	Driving Abilities	B,C	B,C
		Test Setup	A curved course is shown to the driver who has to follow it	A curved course is shown to the driver who has to follow it
		Measurement set up	The number of lane invasions, how long does the vehicle stay outside the lane and number of collisions. - programmed in the script and saved in log files	The number of lane invasions, how long does the vehicle stay outside the lane and number of collisions. Manually counted from the videos
3	driving on a narow road	Driving Abilities	B,C	B,C
		Test Setup	x	The subject drives through the narrow road.
		Measurement set up	x	Time during which the subject was outside the lane : video
4	Driving between two vehicles	Driving Abilities	B, D and E	x
		Measurement set up	Two cars would be placed on a multi-lane highway and the subject is supposed to drive through the middle road.	x
		Metrics	The safety distance, any collision would be recorded in log file.	x
5	Independent Navigation	Driving Abilities	x	?
		Test Setup	x	?
		Measurement set up	x	?

Figure 9: Test scenarios

A.3 Set up

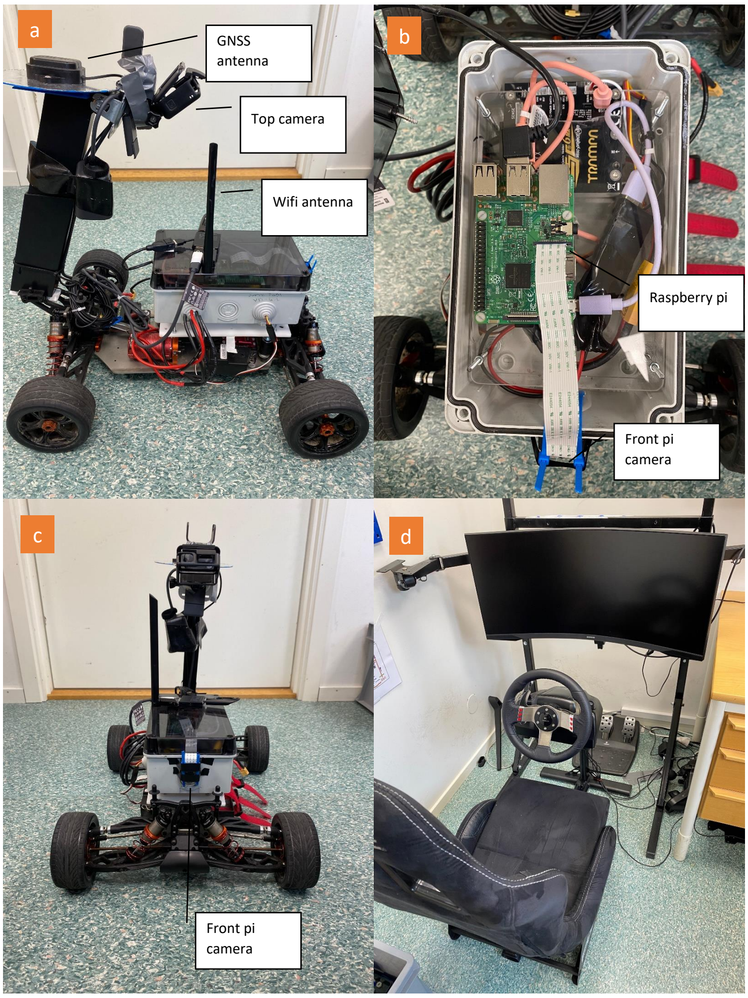

Figure 10: Physical set up

(a) Side view of the vehicle prototype

(b) Side view of the vehicle prototype

(c) Front view of the vehicle prototype

(d) Remote driving station

B References

[1] *Intelligent Transportation Systems - Automated Vehicle Research*. [Online]. Available: https://www.its.dot.gov/automated_vehicle/ (visited on 05/27/2022).

[2] *The autonomous Pod*, en. [Online]. Available: https://www.einride.tech/pod (visited on 05/26/2022).

[3] *Remote Pod Operation*, en. [Online]. Available: https://www.einride.tech/remote-pod-operation (visited on 05/26/2022).

[4] J.-M. Georg and F. Diermeyer, "An Adaptable and Immersive Real Time Interface for Resolving System Limitations of Automated Vehicles with Teleoperation," in *2019 IEEE International Conference on Systems, Man and Cybernetics (SMC)*, ISSN: 2577-1655, Oct. 2019, pp. 2659–2664. DOI: 10.1109/SMC.2019.8914306. [Online]. Available: https://ieeexplore.ieee.org/document/8914306/authors.

[5] *Safety Case for Autonomous Trucks*, en. [Online]. Available: https://www.ri.se/en/what-we-do/projects/safety-case-for-autonomous-trucks (visited on 05/27/2022).

[6] A. Bjornberg, "Shared Control for Vehicle Teleoperation with a Virtual Environment Interface," en, M.S. thesis, KTH Royal Institute of Technology, Jun. 2020. [Online]. Available: https://www.diva-portal.org/smash/get/diva2:1504690/FULLTEXT01.pdf.

[7] *Self-driving car*, en, Page Version ID: 1090614684, May 2022. [Online]. Available: https://en.wikipedia.org/w/index.php?title=Self-driving_car&oldid=1090614684 (visited on 05/30/2022).

[8] *About Us – 5G Automotive Association*, en-US. [Online]. Available: http://5gaa.org/about-5gaa/about-us/ (visited on 05/30/2022).

[9] *Automotive use cases | VALU3S*, en-US. [Online]. Available: https://valu3s.eu/automotive-use-cases/ (visited on 05/27/2022).

[10] *Automated vehicles - Transportstyrelsen*, en, Nov. 2021. [Online]. Available: https://www.transportstyrelsen.se/en/road/Vehicles/self-driving-vehicles/ (visited on 05/26/2022).

[11] *Automated vehicles – will Sweden be left behind?* en-US, Mar. 2022. [Online]. Available: https://www.wistrand.se/en/germany-and-france-at-the-forefront-regarding-legislation-on-automated-vehicles-will-sweden-be-left-behind/ (visited on 05/30/2022).

[12] *Automated vehicles are more than self-driving cars*, en. [Online]. Available: https://www.ri.se/en/what-we-do/our-areas/automated-vehicles (visited on 05/26/2022).

[13] *Swedish state and industry back autonomous vehicle testing facility*, en. [Online]. Available: https://www.computerweekly.com/news/252456030/Swedish-state-and-industry-back-autonomous-vehicle-testing-facility (visited on 05/30/2022).

[14] J.-M. Georg, J. Feiler, S. Hoffmann, and F. Diermeyer, “Sensor and Actuator Latency during Teleoperation of Automated Vehicles,” in *2020 IEEE Intelligent Vehicles Symposium (IV)*, ISSN: 2642-7214, Las Vegas, USA, Oct. 2020, pp. 760–766. DOI: 10.1109/IV47402.2020.9304802. [Online]. Available: https://ieeexplore.ieee.org/document/9304802.

[15] J. L. de la Vara, T. Bauer, B. Fischer, *et al.*, “A Proposal for the Classification of Methods for Verification and Validation of Safety, Cybersecurity, and Privacy of Automated Systems,” en, in *Quality of Information and Communications Technology*, A. C. R. Paiva, A. R. Cavalli, P. Ventura Martins, and R. Pérez-Castillo, Eds., vol. 1439, Series Title: Communications in Computer and Information Science, Cham: Springer International Publishing, 2021, pp. 325–340, ISBN: 978-3-030-85346-4 978-3-030-85347-1. DOI: 10.1007/978-3-030-85347-1_24. [Online]. Available: https://link.springer.com/10.1007/978-3-030-85347-1_24 (visited on 05/31/2022).

[16] *METHOD | Meaning & Definition for UK English | Lexico.com*, en. [Online]. Available: https://www.lexico.com/definition/method (visited on 05/28/2022).

[17] *Einride*, en, Page Version ID: 1085150763, Apr. 2022. [Online]. Available: https://en.wikipedia.org/w/index.php?title=Einride&oldid=1085150763 (visited on 05/27/2022).

[18] *RISE*, en. [Online]. Available: https://www.ri.se/en (visited on 05/27/2022).

[19] *Research Institutes of Sweden (RISE)*, en, Page Version ID: 1070900716, Feb. 2022. [Online]. Available: https://en.wikipedia.org/w/index.php?title=Research_Institutes_of_Sweden_(RISE)&oldid=1070900716 (visited on 05/27/2022).

[20] *Rise overall organisation description.* [Online]. Available: https://www.ri.se/en/about-rise/organisation (visited on 05/27/2022).

[21] *About the project | VALU3S*, en-US. [Online]. Available: https://valu3s.eu/about-the-project/ (visited on 05/27/2022).

[22] *ECSEL JU becomes KDT JU | KDT JU.* [Online]. Available: https://www.kdt-ju.europa.eu/ (visited on 05/27/2022).

[23] “V&V methods for SCP evaluation of automated systems,” en, p. 174,

[24] *Roboauto homepage*, en. [Online]. Available: https://roboauto.tech/ (visited on 05/27/2022).

[25] F. Warg, M. Skoglund, and M. Sassman, “Human Interaction Safety Analysis Method for Agreements with Connected Automated Vehicles,” in *2021 IEEE 94th Vehicular Technology Conference (VTC2021-Fall)*, ISSN: 2577-2465, Sep. 2021, pp. 01–07. DOI: 10.1109/VTC2021-Fall52928.2021.9625202.

[26] *The VALU3S ECSEL Project: Verification and Validation of Automated Systems Safety and Security*, May 2020. [Online]. Available: https://valu3s.eu/wp-content/uploads/2020/12/paper_1_values_paper_pp.pdf.

[27] M. Maleki and B. Sangchoolie, "SUFI: A Simulation-based Fault Injection Tool for Safety Evaluation of Advanced Driver Assistance Systems Modelled in SUMO," en, in *2021 17th European Dependable Computing Conference (EDCC)*, Munich, Germany: IEEE, Sep. 2021, pp. 45–52, ISBN: 978-1-66543-671-7. DOI: 10.1109/EDCC53658.2021.00014. [Online]. Available: https://ieeexplore.ieee.org/document/9603599/ (visited on 06/01/2022).

[28] S. Jha, S. S. Banerjee, J. Cyriac, Z. T. Kalbarczyk, and R. K. Iyer, "AVFI: Fault Injection for Autonomous Vehicles," in *2018 48th Annual IEEE/IFIP International Conference on Dependable Systems and Networks Workshops (DSN-W)*, arXiv:1907.01038 [eess], Jun. 2018, pp. 55–56. DOI: 10.1109/DSN-W.2018.00027. [Online]. Available: http://arxiv.org/abs/1907.01038 (visited on 06/01/2022).

[29] *Tele-operated Driving (ToD) – Use Cases and Technical Requirements – 5G Automotive Association*, en-US. [Online]. Available: http://5gaa.org/news/tele-operated-driving-tod-use-cases-and-technical-requirements/ (visited on 06/04/2022).

[30] , *GUIDELINES ON THE EXEMPTION PROCEDURE FOR THE EU APPROVAL OF AUTOMATED VEHICLES*, Feb. 2019.

[31] L. Fraade-Blanar and M. A. Holliday, *How States and Localities Might Approach Operational Design Domains for AVs*, en, Aug. 2020. [Online]. Available: https://www.rand.org/blog/2020/08/how-state-and-local-governments-might-consider-approaching.html (visited on 06/04/2022).

[32] *Vehicle-to-everything*, en, Page Version ID: 1074358483, Feb. 2022. [Online]. Available: https://en.wikipedia.org/w/index.php?title=Vehicle-to-everything&oldid=1074358483 (visited on 03/04/2022).

[33] *Wireless LAN*, en, Page Version ID: 1086674048, May 2022. [Online]. Available: https://en.wikipedia.org/w/index.php?title=Wireless_LAN&oldid=1086674048 (visited on 06/04/2022).

[34] *IEEE 802.11p*, en, Page Version ID: 1090262789, May 2022. [Online]. Available: https://en.wikipedia.org/w/index.php?title=IEEE_802.11p&oldid=1090262789 (visited on 06/04/2022).

[35] *IEEE 802.11*, en, Page Version ID: 1089752758, May 2022. [Online]. Available: https://en.wikipedia.org/w/index.php?title=IEEE_802.11&oldid=1089752758 (visited on 06/04/2022).

[36] *Wi-Fi Alliance*, en, Page Version ID: 1090153134, May 2022. [Online]. Available: https://en.wikipedia.org/w/index.php?title=Wi-Fi_Alliance&oldid=1090153134 (visited on 06/04/2022).

[37] *Cellular network*, en, Page Version ID: 1090516328, May 2022. [Online]. Available: https://en.wikipedia.org/w/index.php?title=Cellular_network&oldid=1090516328 (visited on 06/04/2022).

[38] *LTE (réseaux mobiles)*, fr, Page Version ID: 191705600, Mar. 2022. [Online]. Available: https://fr.wikipedia.org/w/index.php?title=LTE_(r%C3%A9seaux_mobiles)&oldid=191705600 (visited on 06/04/2022).

[39] T. Linget, “Safety treatment in connected and automated driving functions report,” 5GAA Automative Association, Munich, Germany, Technical, Mar. 2021, p. 106. [Online]. Available: https://5gaa.org/news/sticad-safety-treatment-in-connected-and-automated-driving-functions/.

[40] Roboauto, *Teleoperation*, May 2020. [Online]. Available: https://www.youtube.com/watch?v=KgzhBLcpPEI (visited on 06/05/2022).

[41] Einride, *Einride | The world’s first Remote Pod Operator completes her training*, Mar. 2022. [Online]. Available: https://www.youtube.com/watch?v=5EVOS7vOegQ (visited on 06/05/2022).

[42] *Jitter*, en, Page Version ID: 1083080321, Apr. 2022. [Online]. Available: https://en.wikipedia.org/w/index.php?title=Jitter&oldid=1083080321 (visited on 06/06/2022).

[43] *OSI model*, en, Page Version ID: 1089978937, May 2022. [Online]. Available: https://en.wikipedia.org/w/index.php?title=OSI_model&oldid=1089978937 (visited on 06/04/2022).

C Glossaries

Glossary

Automated Vehicles "Automated vehicles are those in which at least some aspect of a safety-critical control function (e.g., steering, throttle, or braking) occurs without direct driver input. Automated vehicles may be autonomous (i.e., use only vehicle sensors) or may be connected (i.e., use communications systems such as connected vehicle technology, in which cars and roadside infrastructure communicate wirelessly)." [1].. 3, 6, 7

Final Study Project Ending project of the french engineering diploma.. 3

Human Interaction Safety Analysis Safety analysis method focusing on the interaction between humans and vehicles with driving automation or remote driving systems.. 11

Key Digital Technologies Joint Undertaking EU-driven public-private partnership funding innovation in electronic components and systems [22].. 10

Open Systems Interconnection model "conceptual model that describes the universal standard of communication functions of a telecommunication system or computing system, without any regard to the system's underlying internal technology and specific protocol suites." It is composed of 7 layers from the physical transmission of information to the highest level of abstraction: physical, data link, network, transport, session, presentation, application. [43]. 27

Operational Design Domains "description of the conditions in which an autonomous vehicle (AV) is designed to operate safely. This might include requirements about the environment (e.g. the vehicle can only function on clear days, on highways, not on one-way streets, etc.), maneuvers (e.g. no left turns across traffic), particular parts of particular cities, and even driver involvement. Essentially, ODDs define where the AV can drive based on the system's capabilities."[31]. 24

Remote Driving Also called "Teleoperation" in the literature, Remote Driving is a vehicle functionality allowing to fulfill all the tasks of driving while being away from the controlled vehicle.. 3, 4

Remote Driving System Set of technologies which implement the remote driving functionality on a vehicle.. 3

Remote driving Vehicle Vehicle equipped with a remote driving system.. 3

Research Institute of Sweden State-owned research institute and "innovation partner" created to group a set of smaller Swedish research institutes in various domain [18].. 3

Safety Case for Autonomous Trucks [5] Swedish project in collaboration with french structures which aims at contributing to the development of safe remote assisted trucks operations at a higher velocity than the current one, and in more complex situations.. 4, 10

Vehicle-To-Everything "communication between a vehicle and any entity that may affect, or may be affected by, the vehicle."[32]. 8, 26

Verification and Validation of Automated Systems' Safety and Security Project funded by the European Union's Horizon 2020 research and innovation programme project **noauthor_valu3s** It "aims to design, implement and evaluate state-of-the-art VV methods and tools in order to reduce the time and cost needed to verify and validate automated systems with respect to safety, cybersecurity and privacy (SCP) requirements." [8].. 4, 10

Acronyms

5GAA 5G Automotive Association. 23, 26, 28

AV Automated Vehicle. 3, 6–8, 12, 16, 23, 24, 26

DARPA Defense Advanced Research Projects Agency. 6

FI Fault Injection. 16–18, 22, 29, 31

HISA Human Interaction Safety Analysis. 11

HMI Human Machine Interaction. 11, 12, 16, 28, 30

KDT JU Key Digital Technologies Joint Undertaking. 10

LTE Long Term Evolution. 11, 27

MNO Mobile Network Operator. 26

ODD Operational Design Domains. 24

OEM Original Equipment Manufacturer. 26

OSI Open Systems Interconnection model. 27

PFE Final Study Project. 1, 3–6, 9, 11, 14, 29, 32

RD Remote Driving. 3, 7, 12, 14, 23, 26, 30

RDS Remote Driving System. 3, 4, 8, 11, 12, 14–16, 23, 24, 26–28

RDV Remote Driving Vehicle. 1, 3, 4, 7, 8, 12, 14, 16–18, 23, 26, 29, 31, 32

RISE Research Institute of Sweden. 1, 3–11, 15, 16, 31, 32

RTA Road Traffic Authority. 26

SCAT Safety Case for Autonomous "pods". 4, 10

SCP Safety, Cybersecurity and Privacy. 8, 11, 12, 15, 29, 43

V2D Vehicle to Device. 27

V2I Vehicle to infrastructure. 27, 28

V2N Vehicle to Network. 27

V2P Vehicle to Pedestrian. 27

V2V Vehicle to Vehicle. 27, 28

V2X Vehicle-To-Everything. 6, 8, 26–28

V&V Verification and Validation. 4, 7, 8, 11, 12, 14, 15

VALU3S Verification and Validation of Automated Systems' Safety and Security. 10, 11, 15, 16