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The role of 5G network technology in the evolution of local mobility with a particular focus on Autonomous Vehicles.

Supervisor

Linus Brunnström – GU

Paolo Spagnoletti – LUISS

Student

Gian Marco Di Lascio

MATR: 720021

Co – Supervisor

Luigi Laura – LUISS

Graduate School

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LIST OF ABBREVIATIONS

AD: Autonomous Drive

ADS: Automated Driving System

AV: Autonomous Vehicle

CA: Certification Authority

C – V2X: Cellular Vehicles to Everything

DDT: Dynamic Driving Task

DSRC: Direct Short-Range Communication

eMBB: enhanced Mobile Broad Band

GII: Global Innovation Index

HV: Human-driven Vehicle

ICT: Internet Communication Technology

IEEE: Institute of Electrical and Electronic Engineers

IoT: Internet of Things

ITS: Intelligent Transportation System

MANETs: Mobile Ad-hoc NETworks

mMTC: massive Machine Type Communication

ODD: Operation Design Domain

OEDR: Object and Event Detection and Response

OEMs: Own Equipment Manufacturers

OU: Onboard Unit

RSU: Road-Side Unit

SAE: Society of Automotive Engineers

URLLC: Ultra Reliable Low Latency Communication

VANETS: Vehicular Ad-hoc NETworks

VCC: Vehicular Cloud Computing

V2I: Vehicle-to-Infrastructure

V2N: Vehicle-to-Network

V2V: Vehicle-to-Vehicle

V2X: Vehicle-to-Everything

3GPP: 3rd Generation Partnership Project

ABSTRACT

Autonomous vehicles would be increasingly present in urban environments in the future and companies are currently developing competences in order to successfully commercialize these products. Considering AVs, connectivity is a concept that is always more related to mobility, thus network communications technologies would have an important role in the deployment and functioning of these vehicles. Given that 5G is progressively diffusing, this thesis aims at developing a clear understanding on which are the benefits of relying on the fifth generation of ICT in the perspective of mobility. Furthermore, also the OEMs' perspective and the Policymakers' perspective are considered, due to the relevance of their positions in the AVs market. In addition, in the perspective of AVs' deployment, Hybrid ITS are described focusing on the two technologies that represent the most feasible solution to ensure V2X communication, which is key in relation to AVs. This thesis also aims at gathering the various knowledge on the topics under study, considering that the literature resulted to be fragmentated and/or it didn't include 5G. For this reason, the present research maintains the focus on 5G implications in relation to AVs and the related technologies and concepts.

The qualitative study has been conducted during 2021 and, due to restrictions to prevent Covid-19 outbreak, all interviews has been conducted remotely. Respondents works all for Swedish organizations that operate in sectors linked to 5G and AVs, thus providing important and practical consideration on the relation between 5G and autonomous drive.

Findings show how 5G represents one the enabling technologies when it comes to AVs, but it is not sufficient by its own to accelerate the deployment of these vehicles. There are other key technologies and challenges that should be overcome in order to boost AVs commercialization, both in the perspective of the authorities in the mobility field and in OEMs' business decisions. In addition, the coexistence of DSRC and C-V2X turned out to be central for AVs functioning, especially in urban environment. Nevertheless, 5G brings important enhancements, compared to previous generation of ICT, such as network slicing, URLLC and bandwidth, that represent relevant aspects in the perspective of AVs' reliability and operability.

Keywords: 5G, AVs, DSRC, C-V2X, ITS, Hybrid ITS, Cloud, Edge-Computing, Infrastructure, Policymakers, OEMs.

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Gian Marco Di Lascio

1) INTRODUCTION

The purpose of this chapter is to introduce the topic of the research. This section has been divided in six parts: research background, research problem, research purpose, research question, research boundaries and thesis structure.

1.1) RESEARCH BACKGROUND

Generally, it can be observed that every 10 years, the network technology changes, with a new generation that brings considerable enhancements respect the previous ones (Guevara and Cheein, 2020). At present, the state of evolution has reached the 5th generation. Strictly related topic to the communication technologies is the Internet of Things (IoT), which can be defined as "global infrastructure for the information society, enabling advanced services by interconnecting (physical and virtual) things based on existing and evolving interoperable information and communication technologies" (ITU, 2012). Considering the abovementioned definition from the International Communication Union, it is possible to extend the concept of IoT also to vehicles, especially considering the great volume of data produced by vehicles' on-board sensors. Nevertheless, the evolution status of already commercialized vehicles, in the perspective of IoT, is still far from its potential. This is particularly true if it is considered that the overall value generated by an individual product is enhanced if it is connected to related product, thus becoming part of an ecosystem (Wortmann and Flüchter, 2015).

This interconnectivity and exchange of information among vehicles, known as Vehicle to Vehicle (V2V) communication, are important elements associated to autonomous vehicles (AVs). The ability of exchanging information in a network of smart vehicles, would allow to coordinate the entire traffic flow, increase passengers' safety, reduce congestions, and other benefits (Gerla et al, 2014).

In a boarder sense, AVs are associated to a wider perspective of communication, that enriches the variety of counterparts in the network ecosystem in which AVs represent a key element. The communication paradigm that would characterize the future mobility can be seen as a Vehicle to Everything (V2X), which consists in the possibility of exchanging information not only among vehicles, but also between vehicles and other elements present in the urban context.

By the passing of the time, the integration between vehicles and network technologies has become deeper and it would continue to be developed. The co-evolution of these two concepts would lead to an increasing variety of services that would enrich transportation system's potentialities and a change in the habits of citizens inside, as well as outside, urban areas. Previously, the data generated by on-board sensors was exclusively used for the vehicle's own needs but, as already mentioned, soon the information that a vehicle needs in order to operate in the maximum efficiency and safety would be gathered also from external sources. The overarching network infrastructure would be represented by network technologies. In this regards, 5G network entails important features that have the potential to accelerate the deployment of AVs. A more complete reflection on 5G characteristics that would improve mobility services would be analyzed in the following sections.

1.2) RESEARCH PROBLEM

Autonomous vehicles represent a considerable step forward in the evolution of mobility. Customers are getting more familiar with advanced systems that are meant to ensure a higher degree of safety during a journey in a vehicle, especially cars. The pace of development of these automated safety features could be higher among car manufacturers because each producer invests in maintaining a more advanced position compared to its main competitors. As mentioned, 5G represents a key aspect to keep into consideration while developing new functions for automotive vehicles.

The already existing literature seems quite fragmentated and incomplete on certain aspects of how the concepts of AVs and 5G can be implemented. Some researchers have proposed different models to solve specific AVs' system failures, and again some of them didn't included a reflection on 5G role in the potential solution of critical situations for AVs functioning in an urban environment. Additionally, it is important to consider that many studies on AVs have been conducted previous the development of 5G network technology, or in particular moments in time where this communication technology was not sufficiently diffused and understood.

1.3) RESEARCH PURPOSE

Considering the previous paragraphs, the purpose of this thesis is to provide a detailed overview on the way the diffusion of 5G can affect the development and functioning of AVs. More precisely, the focus of the research would be on trying to provide practical understanding of how the evolution a network technology is influencing the features and functions of AVs, especially in urban areas. In this regard, it is worth mentioning that particular attention would be kept in considering the "transitionary" phase, between the current situation and the future environment in which most of vehicles on our roads would be automated and autonomous and realistically, no human intervention would be needed for these vehicles to complete tasks. The mixed traffic environment would persist for a long period, indeed according to the Institute of Electrical and Electronic

Engineers (IEEE), mentioned by (Hu et al., 2020), the coexistence of human-driven vehicles (HVs) and AVs would persist at least until 2040, moment in which the IEEE predict that around 75% of vehicles in the traffic flow would be autonomous. Having in mind this forecast, it can be seen the relevance of the mixed traffic environment described, and the way in which AVs interact not only with other self-driving cars, but also with human driven vehicles, which is realistically a more complex and less predictable interaction. With that been said, this work aims to provide insights on how 5G, and in general network communication technologies, can be used to increase the overall efficiency of AVs.

Moreover, the thesis has the objective of identifying which are the challenges in the implementation of a 5G as an overarching infrastructure that can be used to convey all the data in the ecosystem of AVs, as well as trying to provide feasible solutions.

1.4) RESEARCH QUESTION

Considering what has been outlined so far, it is possible to link it with the overarching research question that would guide the development of this thesis. More precisely the main research question would be the following:

"What expected role would have the diffusion of 5G network technology in the deployment of autonomous vehicles in the perspective of local mobility in urban contexts?"

It is worth precising that with the term *"mobility"* the researcher intends to mainly focus on AVs given that this sort of vehicles are the ones that more deeply can be affected by 5G, and in general the features of network technologies, compared to vehicles that are still manually driven. Additionally, given the fact that the autonomous driving technologies are in an embryonal stage, the researcher, in developing the work, would consider not only fully autonomous vehicles, but also vehicles that are in some sort "hybrid", in the sense that they can operate autonomously in some environments (i.e., highways), while still needing a human operator in the rest of the range of usages.

For the purpose of a more complete analysis of the topics under study, the overarching research question is divided in two additional sub-research questions:

SRQ1: "*Which are the most relevant benefits that the use of 5G network technology, as overarching communication infrastructure, could have in relation to the deployment of AVs in an urban environment?"*

SRQ2: "*Which are the main challenges that could be faced while trying to advance the deployment of AVs also relying on 5G network technology? Which could be the most feasible solutions to these challenges?"*

Considering the abovementioned research questions, in is worth being more precise in defining the perspective under which the problem would be analyzed. In this regard, the researcher aims to develop finding mainly in the perspective of the automotive industry. More precisely, the research would be oriented towards the development of a framework that could be used by automotive manufacturers in order to have a more complete understanding on the characteristics of the relationship between AVs and 5G. Moreover, the findings of this research could realistically be applied for future generations of network technologies, at least as a starting point.

The target of this thesis is thus any automotive manufacturer which is planning to develop, or is already developing technologies for AVs deployment, and that is interested in enriching its understanding on how network technologies, specifically 5G, could influence and facilitate the functioning of AVs in urban contexts. In addition, this work also aims to provide practical considerations and solutions for policymakers that operate in the mobility field can consider while establishing strategies for the deployment of AVs in an urban mobility environment.

1.5) RESEARCH BOUNDARIES

This research would be conducted predominantly with a focus on the area of Gothenburg. More precisely, interviews would realistically be held with professionals working in Gothenburg, or in general in Sweden. This is derived by the fact that the researcher would rely on the consulting agency named First-to-Know, based in Gothenburg, in the identification of the best profiles to be contacted with the aim of organizing an interview.

This methodology choice, would undoubtedly create some sort of biases, especially considering the reflections developed by interviewees on the tackled concepts. Nevertheless, there are two aspects that could be considered in assessing the quality of the research in the perspective of the data gathered.

Firstly, according to Visual Capitalist (Visual Capitalist, 2021) Sweden is the second most innovative country on Earth. Sweden figures second in the world ranking also according to the Global Innovation Index (GII) (World Intellectual Property Organization, 2019). Considering these two recognitions of innovation attitude, it is possible to conclude that the results of interviews would be highly effective in giving a deep understanding of the dynamics that guide the topics under study, contributing to produce quite generalizable result.

Secondly, Sweden has shown a consistent interest in mobility innovation, both in the sustainability perspective as well as in the technological one. A relevant example, that in linked also to the main area of study of this thesis, is represented by the so called “Drive Sweden Innovation Cloud” which is a cloud-based platform developed by Drive Sweden. Drive Sweden is a strategic innovation program which has the goal of creating and implementing new mobility solutions through a connected and automated transport system (drivesweden.net). Drive Sweden Innovation Cloud re-enters in one of the 5 thematic areas of the Drive Sweden program, as it focuses on the digital infrastructure required for future mobility solutions and AVs' efficient and secure functioning.

The Drive Sweden program shows the Swedish society's commitment in the innovation of mobility, as well as its interest in exploiting new technological innovations to accelerate the development and implementation of new mobility services.

1.6) THESIS STRUCTURE

In this section a general overview of the structure of thesis is presented, giving a brief description of what each section deals with. The structure in which the research is presented is the following:

- Introduction
- Literature review
- Methodology
- Empirical Findings
- Discussion
- Conclusions

2) LITERATURE REVIEW

This chapter aims at presenting the most relevant literature on the topics under study, hence providing the current understanding on the relevant concepts related the implication of the use of 5G for the deployment and functioning of AVs. The chapter has been divided in four section: 5G, Autonomous Vehicles, Technology Implementation and OEMs' organizational perspective for AVs deployment.

2.1) 5G

In this section the most important aspects of the fifth generation of ICT are described to provide a comprehensive understanding of which are the characteristics of 5G that most benefit AVs. The three parts in which this section is divided are: Introduction on 5G, Application Scenarios, and Internet of Things and Network Slicing.

2.1.1) INTRODUCTION ON 5G

The term 5G refers to the 5th generation of mobile wireless technologies and it entails important characteristics that would increase the potential number and reliability of network technologies. As mentioned by an Ericsson paper written by Osseiran et al. (2020), the time span after which the previous network technologies have been replaced is around 7 to 10 years. Additionally, this new ICT (Information and Communication Technology) generation has been developed also considering the expected growth in the amount of data that would be transferred in the upcoming years, as well as the increase in the number of connected devices that would need a communication infrastructure to send and receive information. Panwar et al. (2016) use the abbreviation 3D to regroup three elements that have boosted the development of 5G: Device, Data and Data transfer. In addition to the just mentioned 3D, there are other trends that triggered the need for an enhancement of the ICT infrastructure: a better optimization of energy consumption and ubiquitous connectivity. The first trend can be associated with a cost optimization for the service providers, that are experiencing in the most recent times an increase in the demand thus their expenditures are rising. Moreover, a better energetic consumption results in a longer battery life, which is something that customers would like to experience (European Parliament, 2016). Another wish of customers, that can be associated to the second abovementioned trend, is represented by the fact that personal devices are always connected, at any moment. This concept can be translated in ubiquitous connectivity.

"Providing connectivity to everyone and everything, everywhere and every time."

(Institute of communication and connected systems)

This expression, used in relation to the concept of ubiquity associated to 5G, entails its ability of enabling a "total" connectivity experience, in the sense that devices would be constantly connected, independently to the place and moment, overcoming issues related to the density of devices connected to the same network.

The concept of ubiquitous connectivity re-enters in the *user-centric view* mentioned by Panwar et al. (2016), which the authors present with other two views addressed by 5G: *service-provider-centric* and *network-operator-centric*. Each of these three views is associated to a characteristic of 5G that would ultimately allow to satisfy the requirement of that view. As already mentioned, the *user-centric view* can be satisfied thanks the ability of 5G to provide a ubiquitous type of connection.

The *service-provider-centric view* is associated by Panwar et al. (2016) to the Intelligent Transportation System (ITS), sensors and mission-critical monitoring and tracking services. Thus, the just mentioned perspective, is strongly linked to the area of research of this thesis. The key feature of 5G that would allow this view is zero latency. This concept would be further analyzed in the following chapters, but it is worth presenting it as an enabling element for those services with zero delay tolerance. In this regard, the target level of latency is 1ms (Panwar et al., 2016, Osseiran et al., 2020, Agyapong et al., 2014). This level of low latency would be reached thanks to a faster connection speed, which is approximately 10 to 100 times higher than previous ICT (Thalesgroup.com).

The last view mentioned by Panwar et al., (2016) is more oriented toward the overall ecosystem, considering the energetic efficiency, scalability, and secure communication infrastructure. In this perspective, it is worth mentioning the activity of the 3rd Generation Partnership Project (3GPP) which is a group of telecommunications standards development organizations. The 3GPP measures progresses of its standards not in generations but in "releases" that, as stated by 3GPP (3gpp.org), aim at ensuring a backwards and forwards compatibility. Additionally, releases contribute to the standardization process and, particularly considering 5G, the standardization effort has been divided in two different phases, realized with three releases (Osseiran et al., 2020). The first phase, operationalized with Release 15, the organization focuses on the fundamental 5G building blocks. Release 16 and 17 aims at consolidating and enhancing the previously established standards.

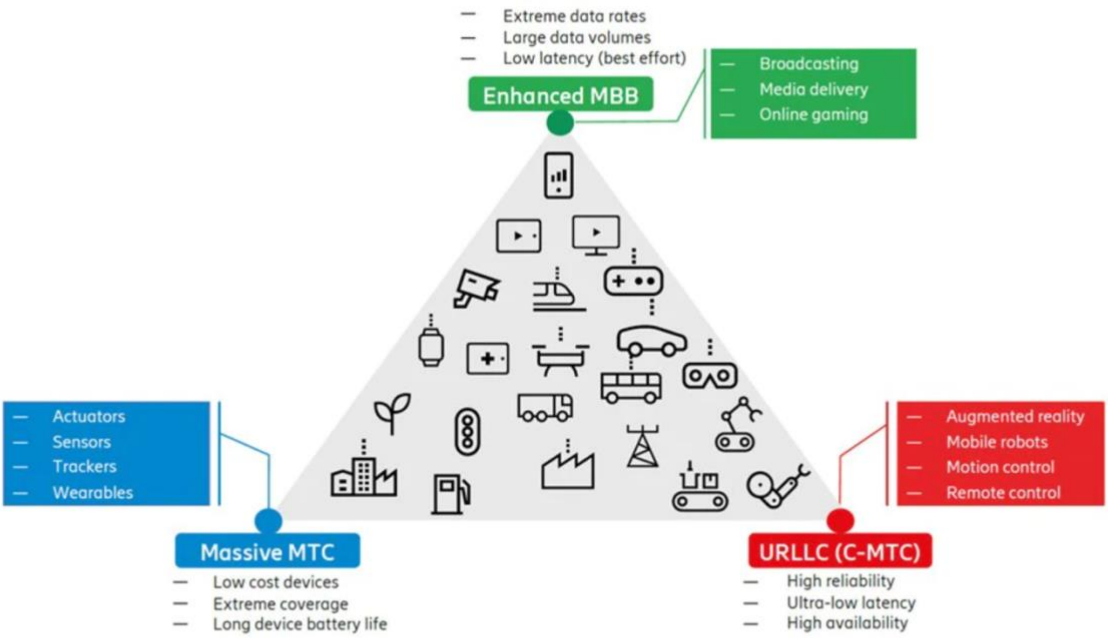
The application scenarios would be analyzed in the next section, but it is important to consider the economic relevance of this ICT in a broad sense. In a briefing of the European Parliament (2016) it is highlighted how the ICT sector contributed for 4% to the European GDP and that half of the productivity growth is associated to investments in these technologies. In the same briefing it has been noticed that 5G has the potential of creating new jobs and new business models, that ultimately would contribute to the overall wealth of a population. The European Parliament (2016) has explained that new mobile technologies have contributed on average between 2% and 4% to the growth of GDP. It can be derived that Europe commitment in the development and deployment of 5G is serious and oriented toward the establishment of a competitive advantage. It can be derived that the European Union is prone to promoting the diffusion of this ICT.

2.1.2) APPLICATION SCENARIOS

In considering the possible application scenarios, 5G's main use cases can be divided into three groups (IMT Vision, 2015). This differentiation has been made according to the connectivity requirements that the applications that re-enters in a group mainly rely on. The authors also associate each category to a human-centric or a machine-centric perspective, thus highlighting in some sense if a category would mainly benefit human users or if it is more oriented towards the technical functioning of machines. This last distinction is mainly done for the purpose of clearer differentiation, because in concrete applications there wouldn't be a sharp distinction, in the sense that the enhancements and new features of machines are realistically oriented to provide a better and easier experience to customers. The concepts of human-centric and machine-centric can be more clearly separated from the technical point of view.

The connectivity requirements aspects that guided the classification of Osseiran et al. (2020) are: enhanced mobile broadband (eMBB); massive machine type communication (mMTC); ultra-reliable low latency communication (URLLC). eMBB is the category which has the most human-centric perspective between the three and it refers to the large amount of data transferred and to the speed by which this information is sent. The other two category are more oriented toward machine-centric use cases. Osseiran et al. (2020) define the focus of mMTC as providing connectivity to small and not so complex devices, for example sensors, which send and receive data not on a regular basis. While presenting URLLC, the authors pointed out that the main concerns in use cases connected to it are reliability and latency. In addition, the concept of reliability in this context is represented by the ability of successfully transferring the required data in a defined time length. The following figure (Figure 1) presents a visual representation of the abovementioned classification.

Figure 1 – 5G application scenarios

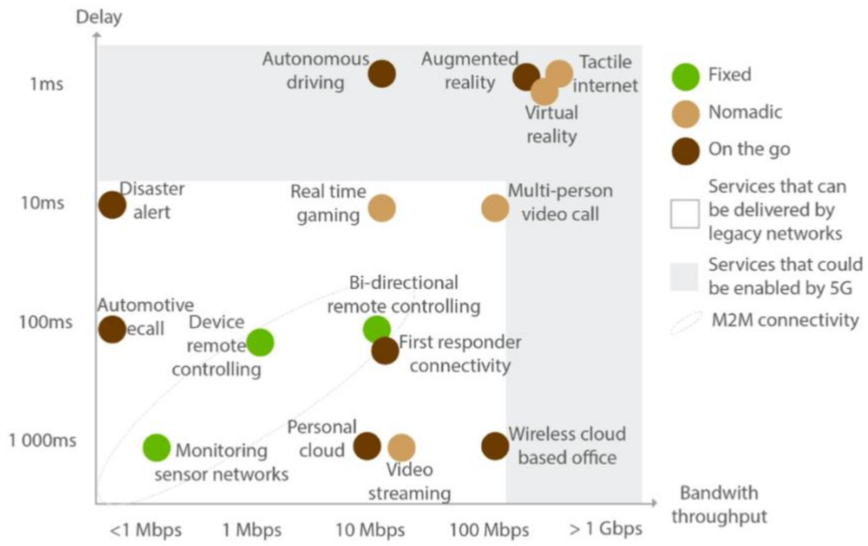


https://www.ericsson.com/en/reports-and-papers/white-papers/5g-wireless-access-an-overview

As can be visually seen, most of the use cases are not place in the vertices but inside the triangle, or at least on the sides. This simple consideration brings to the fact that use cases in which 5G would be required, on most occasions, imply a certain mix of the three connectivity features described before.

Considering the scope of this research, the connectivity aspect that seems to fit the most is represented by URLLC. This consideration is derived by the fact that URLLC implies a particular focus on latency and reliability, which are two concepts strictly linked to each other, and particularly important while considering AVs. Additionally, AVs can be associated also to eMBB, specifically considering the need for the vehicles to continuously send and receive data. The following figure (Figure 2) is presented to provide an overview on the application scenarios, considering also how the current generation of ICT is adopted. The use cases are positioned in the graph according to two dimensions, which are latency and bandwidth throughput, allowing an easier identification of the technical requirements of a specific scenario.

Figure 2 – Application Scenarios considering latency and bandwidth throughput



https://www.ericsson.com/en/reports-and-papers/white-papers/5g-wireless-access-an-overview

The extremely low latency that characterize 5G would significantly benefit the urban mobility, especially considering safety aspects for passengers. In order to provide a practical and concrete understanding of the implication of latency it is worth mentioning a brief and simple example.

“A car running at 100Km/h will move 27.6m every second, or 2.7cm every millisecond. If the road sensors capture an unexpected event on the road, <1ms network latency means that the information would reach the car from the cloud in a time frame that corresponds to less than 1 meter motion.”

(thalesgroup.com)

The relation between latency and distance travelled by a vehicle is thus particularly significant while dealing with AVs, especially considering passengers safety. The 1 millisecond (ms) reaction time of the vehicle allowed by 5G represents a significant improvement compared to 4G for example. This is particularly true having in mind the abovementioned example and the latency difference between the two generation of ICT. More precisely, 4G has a latency of 50ms, while 5G 1ms. Contextualizing this difference in the meters traveled by a vehicle before receiving the actual input from an external source, it can be seen that a reaction distance of approximately 50m compared to 1m is a significant improvement in terms of safety. A similar confront can be done comparing the 1ms latency of 5G and the human reaction time (in some sense, human reflexes are a form of latency). In this regards the speed by which an input from the human eyes is processed by the brain is approximately 10ms (Jansen and Beaton, 2021) which is higher than 5G latency. In conclusion, the reaction speed enabled by the 5th generation of ICT is higher than our natural reflexes, resulting in a safer urban mobility experience.

2.1.3) INTERNET OF THINGS AND NETWORK SLICING

Internet of Things (IoT) can be defined as a network of interconnected objects. Patel et al. (2016) enrich the perspective of IoT with a further and more precise analysis, dividing this concept into three type of relationships that could occur in this paradigm: People-to-People, People-to-Machine/Thing, and Machine/Thing-to-Machine/Thing. Heterogeneity in the type of connections and in the requirements of devices is increasing with the passing of the time, and this progressive diversity requires more features of the ICT, which are energy efficiency, speed, security, and reliability (Patel et al., 2016). The just mentioned needs match with the characteristics of 5G, that has been described in the previous section. In this regard, Palattella et al. (2016) puts particular emphasis on three specific features of 5G that represents the enablers of an advanced IoT ecosystem compared to the one possible with previous generations of ICT: increased data rate, reduced end-to-end latency and improved coverage.

Patel et al. (2016) provide an architectural description of IoT functioning, identifying different layers of technologies that would be interconnected to complete the "ecosystem" and to ensure the correct interchange of information. The lower layer is mainly represented by sensors which, as pointed out by Patel et al. (2016), are what translate the natural, "real world" inputs into digital data. The second layer consists in gateways and networks, that represent the transport mean for the information gathered by sensors. Considering the progressive increase in the number of sensors, hence the volume of data generated, 5G would enable a quicker and more reliable transfer of this sort of information, especially considering the low latency and bandwidth characteristics. The last layer has been presented by Patel et al. (2016) as the management service, that consists in the decision-making phase during which data are interpreted. In this step, some sort of rules should be defined, and analytical tools should be adopted to contextualize information and to ensure that the need for a specific use case are met.

As already mentioned, the number of connected devices is predicted to grow exponentially in the near future, which is also something that triggered the need for a new ICT which could replace the current ones with the aim of representing the communication infrastructure for the increasing number of connections. Another concept already presented while talking about 5G is *ubiquity*, which is something that could also be associated to the characteristics of IoT that 5G would allow. In this regard, it is important to introduce the so-called *network slicing*.

Network slicing represents the main enabler of network service coverage and for tailored and customizable network services for specific application scenarios (Zhang et al., 2017, Rost et al., 2016, Jiang et al., 2016). A similar description has been given by Li et al. (2017), particularly when considering network's *slices* as portions of a wider network that have been adapted to the particular requirements of specific use cases. Furthermore, network slicing is related to the concept of network *virtualization*, which allows a flexible management of the network to create multiple heterogeneous and service-specific virtual network that rely on the same substrate network (Li et al., 2017).

Network slicing represents an important aspect to take into consideration in the perspective of this thesis, particularly referring to the fact that it would allow AVs to have a dedicated "*slice*", of the overarching network, that could have the specific features that would maximize the efficiency and reliability of it as a communication infrastructure.

2.2) AUTONOMOUS VEHICLES

This section aims at presenting the nature of autonomous vehicles and describe which are the most important aspect linked to them. A particular focus has been placed upon the communication that these vehicles could established with other devices given that it is one of the key aspects to consider when it comes to driverless vehicles. The three parts in which this section is divided are: Definition and Levels Classification, Internet of Vehicles and, Vehicular Networks and Cloud.

2.2.1) DEFINITION AND LEVEL CLASSIFICATION

To present the concept of Autonomous Vehicles it is worth starting from the definition and the classification in levels. The most authoritative resource for this purpose is represented by the Society of Automotive Engineers (SAE), especially thanks to the J3016 standard. AVs are vehicles equipped with an Automated Driving System (ADS) which is defined as the hardware and software that are collectively capable of performing an entire Dynamic Driving Task (DDT) (SAE, 2018). Additionally, the DDT is contextualized associating it to an Operational Design Domain (ODD), which can be seen as a specific environment in which the vehicle is operating.

The classification in levels proposed by SAE (2018) has been guided by three main parameters: DDT, DDT Fallback and ODD. DDT Fallback refers to a failure in performing a driving task, and it is specific to a particular domain. The role of recovering from a DDT Fallback could be associated to the human driver or to the automated systems, it depends on which level is considered. Furthermore, DDT are divided into two sub-tasks: sustained lateral and longitudinal vehicle motion control and object and event detection and response (OEDR) (SAE, 2018). The ability by the ADS to perform one of both these two sub-tasks contributes to a more precise differentiation among the different levels. To provide a clearer understanding and more schematic representation of the characteristics and roles associated to the driver and to the ADS, the following table (Table 1) has been used.

Table 1 – Different AVs levels

Level	Name	Narrative definition	DDT		DDT fallback	ODD
			Sustained lateral and longitudinal vehicle motion control	**OEDR**		
Driver* performs part or all of the *DDT						
0	**No Driving Automation**	The performance by the *driver* of the entire *DDT*, even when enhanced by *active safety systems*.	*Driver*	*Driver*	*Driver*	n/a
1	**Driver Assistance**	The *sustained* and *ODD*-specific execution by a *driving automation system* of either the *lateral* or the *longitudinal vehicle motion control* subtask of the DDT (but not both simultaneously) with the expectation that the *driver* performs the remainder of the *DDT*.	*Driver* and *System*	*Driver*	*Driver*	Limited
2	**Partial Driving Automation**	The *sustained* and *ODD*-specific execution by a *driving automation system* of both the *lateral* and *longitudinal vehicle motion control* subtasks of the *DDT* with the expectation that the *driver* completes the *OEDR* subtask and *supervises* the *driving automation system*.	***System***	*Driver*	*Driver*	Limited
***ADS* ("*System*") performs the entire *DDT* (while engaged)**						
3	**Conditional Driving Automation**	The *sustained* and *ODD*-specific performance by an *ADS* of the entire DDT with the expectation that the *DDT fallback-ready user* is *receptive* to *ADS*-issued *requests to intervene*, as well as to *DDT performance-relevant system failures* in other *vehicle* systems, and will respond appropriately.	*System*	***System***	*Fallback-ready user (becomes the driver during fallback)*	Limited
4	**High Driving Automation**	The *sustained* and *ODD*-specific performance by an *ADS* of the entire *DDT* and *DDT fallback* without any expectation that a *user* will respond to a *request to intervene*.	*System*	*System*	***System***	Limited
5	**Full Driving Automation**	The *sustained* and unconditional (i.e., not *ODD*-specific) performance by an *ADS* of the entire *DDT* and *DDT fallback* without any expectation that a *user* will respond to a *request to intervene*.	*System*	*System*	*System*	**Unlimited**

Pag. 19 (SAE J3016, 2018)

As can be seen in the table above, until level 4 ADS is constrained to a specific ODD, hence to a specific environment, with specific rules. Currently, the majority of commercialized vehicles re-enter in the level 2 category, thus the ADS can perform only a portion of the driving tasks, but the driver still has to take control over the system in the majority of driving scenarios. Considering ADS level 3 and 4, the vehicle can perform all the driving tasks by its own, the difference occurs when there are some performance relevant system failures (SAE, 2018): level 4 ADS can recover from fallback situation automatically, while the driver intervention is needed for ADS level 3.

2.2.2) INTERNET OF VEHICLES

The concept of Internet of Things already mentioned while dealing with 5G, could be applied also in the mobility perspective. The paradigm of interconnected devices, that mutually exchange data with the aim of enhancing the overall efficiency of the ecosystem which they are part of, is something central for developing an Intelligent Transportation System (ITS). ITS refers to the implementation of Internet and Communication Technologies (ICT) in the mobility infrastructure with the aim of improving safety and the overall efficiency of the transportation system (Vanderschuren and McKune, 2011, Guevara et al., 2020).

The implementation of ICT on the transportation system is linked to the fact that, in order to reach the objectives associated to a more intelligent mobility, it is key to ensure the realization of three main communication paradigms: vehicle-to-vehicle communication (V2V), vehicle-to-infrastructure (V2I) and vehicle-to-everything communication (V2X). The exchange of information requires some rules in order to be effective, some protocols that guide the communication between the various elements of the ITS (Arena & Pau, 2019). As already mentioned in the chapter that introduced 5G, as well as by Arena & Pau (2019), an important effort in the standardization process has been carried on by 3GPP, which is setting rules and promoting the acceleration of the diffusion of ICT. The objectives of the different standards developed in this context is to reach a faster speed in the exchange of information, to increase the coverage of ICT and to ensure a more stable connection in areas with high density of connected devices. It is worth describing the three communication paradigms to have a comprehensive overview on the different ways in which vehicles can interface between each other and with the other devices that form the ITS.

Vehicle-to-vehicle (V2V) communication essentially consists in the wireless data transmission between vehicles (Arena & Pau, 2019). Each vehicle is thus capable of exchanging information with others, independently. The concept of independency has been considered also by Arena & Pau (2019), especially while describing the advancement of wireless connection, thus a virtual infrastructure, rather than a physical one that relies of wires, which is a more constraining one, in term of complexity, cost and efficiency. The virtual interconnection among vehicles enriches the number of services that passengers could use, and the overall safety of the experience. This is particularly true considering that a vehicle which is not connected to others can only rely on the information produced by on-board sensors. On the other hand, a network of vehicles would enable them to complement the self-generated information with the data gathered by the other elements of the network, resulting in a more efficient and safe experience.

Vehicle-to-Infrastructure V2I is the communication paradigm that allows vehicles to interact with the overall road system, exchanging data with other smart elements that are present in an operational environment (Arena & Pau, 2019). V2I is an extension of V2V, in the sense that in-transit vehicles can rely on additional information, which are associated to the overall condition of mobility is a specific area.

Vehicle-to-everything V2X is a wider communication paradigm, in which re-enter the two previously described. As considered by Arena & Pau (2019), V2X as the main objective of increasing the safety of pedestrians, specifically allowing an interconnection between in-transit vehicles and the smart devices carried by pedestrians, such as smartphones.

Gerla et al. (2014) provide interesting considerations regarding the data generated by vehicles and their relevance. More precisely, related to the just described communication paradigms, is the concept of “time-space validity” (Gerla et al. 2014), that consists in the fact that the data gathered by a vehicle have a particular spatial scope of interest, in the sense that they represent relevant information only for the vehicles/devices in a specific area. Additionally, the time dimension refers to a temporal scope of the necessity of specific information, which would have its relevance in a defined time length. It is important to consider that the time-space dimensions may vary in accordance with the nature of the information. Moreover, in understanding the vehicles’ interaction attitude it is useful to cite the “content-centric networking”, that refers to the fact that the priority in the communication among vehicles is placed upon the content, the information itself, not on the source of that information (Gerla et al., 2014).

The exchange of information among vehicles, as well between vehicles and other devices that constitute the operational context in which AVs would operate, could be benefited using 5G in the communication infrastructure, especially considering the speed by which data could be transferred. This is particularly true in a dynamic driving environment in which reaction time is a central aspect to consider in order to guarantee the maximum safety of passengers and pedestrians.

2.2.3) VEHICULAR NETWORKS AND CLOUD

Extending the perspective on Internet of Vehicles described in the previous paragraph, it important to introduce the concept of Vehicular Networks and Vehicular Cloud. It is worth precising that with Vehicular Networks are intended the Vehicular ad-hoc Networks (VANETs) which can be defined as networks specifically designed to allow exchange of data between vehicles and other devices in the transportation environment, incorporating the three communication paradigms described before (V2V, V2I and V2X) (Boukerche & De Grande, 2018, Abdelhamid et al., 2017, Papadimitratos et al., 2009, Amadeo. et al., 2016, Silva et al., 2016). VANETs are derived from MANETs (Mobile ad-hoc Networks) in which nodes are represented by vehicles (Boukerche & De Grande, 2018, Eze et al., 2016). Considering this derivation, by describing what MANETs are, it is possible to understand how these networks could be applied in a mobility context. MANETs consist in wireless networks in which the nodes can communicate directly with each other, without an intermediary phase, hence a node acts both as a receiver as well as a source of data. The communication between nodes, given the fact that is direct, is constrained by the spatial dimension, as already mentioned while presenting the Internet of Vehicles. This constraining condition could be overcame with the use of additional nodes in the network (or, in the case of VANETs, other vehicles) that in some sort act as amplifiers that contribute to satisfy the data needs of a receiving node. This feature could be once again associated to the Internet of Vehicles, especially while dealing with "content-centric network": the priority is placed upon the actual information, not on the source. The wireless transmission represents an advantage considering the overall architecture of MANETs, hence VANETs, because it allows nodes to be able to communicate while been in motion. Considering the wireless communication among vehicles, it is allowed by the IEEE 802.11p protocol (Boukerche & De Grande, 2018, Eze et al., 2016).

The VANETs' architecture is composed by three elements (Boukerche & De Grande, 2018):

- Onboard Units (OU) which are all the built-it components of vehicles that are responsible for collecting information related to the status of the vehicle. Moreover, OU can communicate the gathered data to other vehicles or, in general, to other elements of the network.

- Road-Side Units (RSU) which, as pointed out by Boukerche & De Grande, (2018), are key network components, especially considering the V2I perspective. RSU are fixed-location components of the network and have the function of providing information that vehicles cannot directly gather themselves, such as traffic congestions or accidents, and then distribute this information to interested vehicles.

- Certification Authority (CA) that has the objective of maintaining the security of VANETs (Mejri et al., 2014) by assessing the validity of the information diffused in the network.

The concept of VANET can be aggregated to Cloud Computing in order to obtain the Vehicular Cloud Computing (VCC) (Boukerche & De Grande, 2018), which allows to gather, allocate and use in the most efficient way vehicles' on-board resources (Olariu et al., 2011, 2013). Cloud Computing, in general, can be interpreted in the possibility of exploiting external computational power and storage space, this is particularly true while considering the Mobile Cloud Computing, which is a paradigm in which re-enter smartphone as beneficiary devices. On the other hand, Vehicular Cloud Computing could be seen as the inverse of Mobile Cloud Computing, in the sense that VCC rely on the fact that underutilized on board resources of a vehicles may be used by other ones (Hussainn et al. 2012, Boukerche & De Grande, 2018), this deep difference between the cloud computing associated to mobile devices and the one that characterizes Internet of Vehicles can be associated to the built-it computational power of vehicles themselves.

2.3) TECHNOLOGY IMPLEMENTATION

In this chapter would be discussed some considerations relative to the ways in which 5G could be implemented in an AVs ecosystem and how it could complement the other technologies on which AVs rely on to operate. Considering the nature of ICT, 5G enhancements are mainly oriented to the communication paradigms according to which AVs would interface to the other components of the Intelligent Transportation System, hence dealing with V2X. In this regard, there are two main technologies that could enable vehicles to communicate, which are Dedicated Short Range Communication (DSRC) and Cellular Vehicle to Everything (C-V2X). The description and the comparison between these two alternatives would be provided, also trying to identify which is the most suitable solution to be implemented in AVs. A more detailed overview on millimeter wave would be provided to highlight the most relevant characteristics of this technology in relation to the mobility perspective. The two parts in which this section is divided are: Wireless Communication Technologies: DSRC and C-V2X, Hybrid ITS: Coexistence of DSRC and C-V2X.

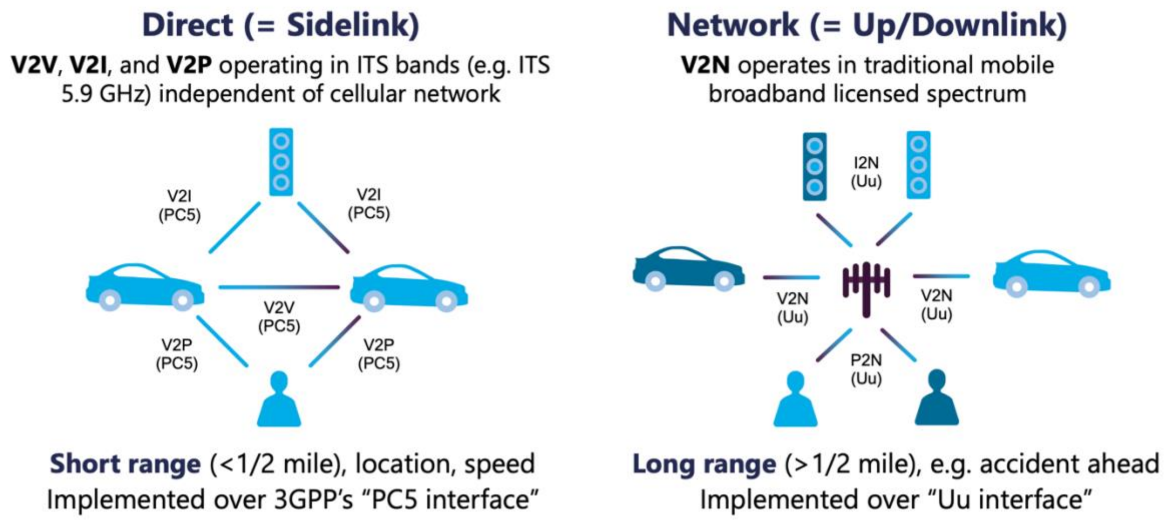
2.3.1) WIRELESS COMMUNICATION TECHNOLOGIES: DSRC AND C-V2X

A key enabling aspects of an ITS is represented by the interconnectivity between vehicles and other devices, which could be vehicles, smartphones, RSU, etc. All these connections re-enters in the V2X perspective, that was presented in prior sections. There are two wireless communication technologies that would allow an efficient data transfer in V2X, thus representing an essential factor for AVs deployment: Dedicated Short-Range Communication (DSRC) and Cellular Vehicle-to-Everything (C-V2X) (Kiela et al., 2020, TechVison Group of Frost&Sullivan, 2017). It is worth precising the standards on which these two technologies rely on. DSRC has be developed starting from IEEE 802.11p, which is an amendment to the IEEE 802.11 standard (Kennny, 2011, Kawser et al., 2019, Ghafoor et al., 2020) while C-V2X standard was developed by 3GPP with Release 14 (Flore, 2016). Additionally, for what concerns the DSRC there are two variants of the IEEE 802.11p standard, one adopted in the USA and the other in EU, which are not compatible with each other thus requiring different equipment (GSMA, 2017).

Both are VANETs, and one of the first distinction between them is represented by their operational range: DSRC has a short-medium range while C-V2X has a long range. An important consideration is that the operational range of DSRC is variable, mainly related to line of sight (Southwest Research Institute, 2018, TechVison Group of Frost&Sullivan, 2017). This limitation could create issues in the efficient communication among vehicles, especially in an urban environment. In this particular context, the exchange of information among vehicles that rely on DSRC is likely to be constrained by blind spots and buildings, and in general other obstacles. However, 5G could also be sensitive to propagation issues in an urban environment, in which the signal could lose its power while coming up against an obstacle. In this regard, the main difference in the two technologies could be identified in the fact that, as considered by TechVison Group of Frost&Sullivan (2017), C-V2X relies on the network infrastructure while DSRC doesn't. This important distinction leads to consider the characteristics of the concrete usage of the two technologies in vehicular communication.

DSCR and C-V2X have both differences and similarities. As just mentioned, one of the most relevant differences is represented by the technology used to transmit information from a device to another. DSRC send and receive information through a paradigm similar to Wi-Fi (Kenney,2011), which can be seen as peer-to-peer communication. On the other hand, C-V2X rely on the network infrastructure. One of the main implications of this different communication approach is the fact that C-V2X is very much dependent on the actual presence of the network, while DSRC communication is not affected by the absence of network coverage. However, as considered by Gulia (2020), there is a communication mode for C-V2X, named "Mode 4", thanks to which cellular communication could be maintained in absence of network, thanks to sidelink communication called PC5, that is designed to function on 5.9 GHz band.

Figure 3 - C-V2X complementary communication modes



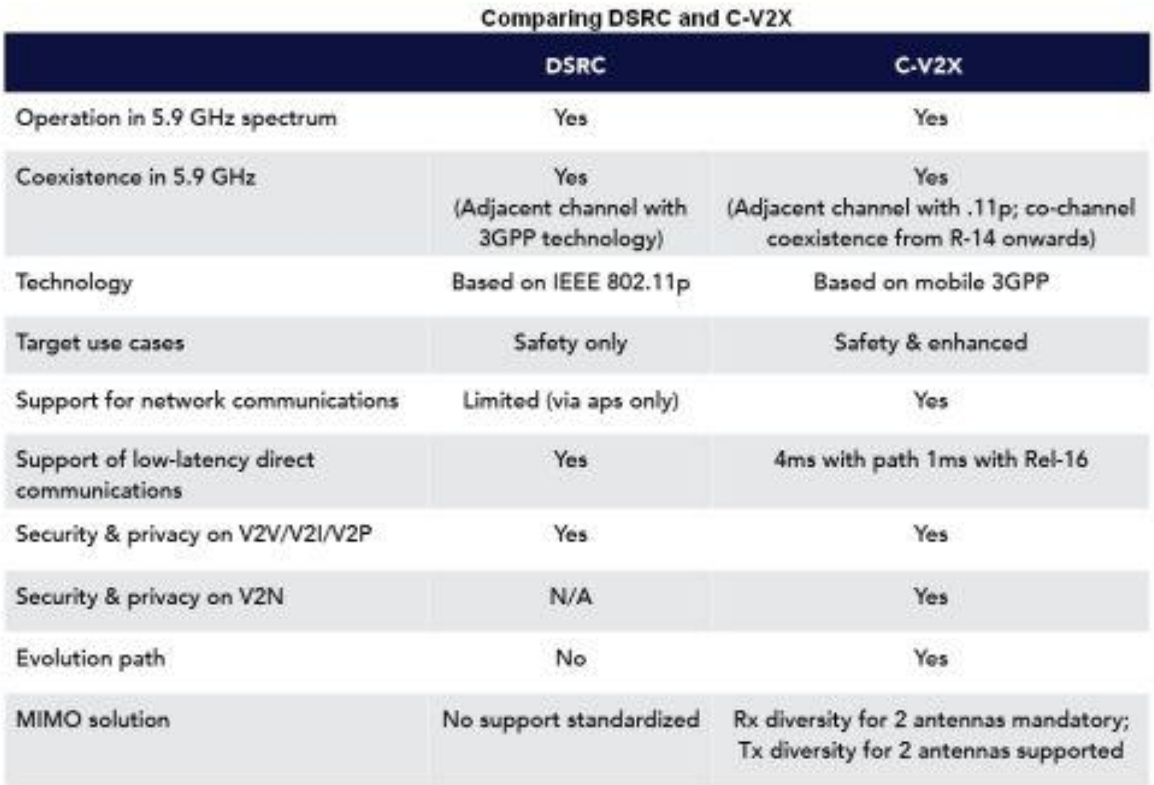
Slide 7, 5G Automotive Association, pioneering digital transformation in the automotive industry, 2019 https://5gaa.org/wp-content/uploads/2019/02/5GAA-IOO-Webinar-Presentation-April-16-Updated.pdf

Considering the above illustration, it can be seen a comparability between DSRC and C-V2X in the "Sidelink" communication, given that in this case the cellular communication will operate without relying on the network connection and it would mainly be oriented to comparable use cases as the ones of DSRC. In this perspective, one of the key differences between the two communication technologies discussed in this section is represented by the fact that DSCR allows only Direct communication while C-V2X extends the communication possibilities also to the network, thus it adds V2N as communication paradigm.

However, it is important to consider that DSRC is a more mature technology, having been developed and tested for approximately a decade since the moment in which this research is conducted (Southwest Research Institute, 2018, TechVison Group of Frost&Sullivan, 2017), while the vehicular cellular communication has been introduced more recently. This different maturity stage is an important implication, specifically considering the fact that potential problems in the functioning of these technologies would imply concrete risks for passengers as well as all other humans in the road environment. Thus, it could be argued that the DSRC represents the current best option for what concerns the Direct (Sidelink) communication, at least for the moment in which this research is being conducted.

Nevertheless, C-V2X has similarities in relation to DSRC (Gettman, 2020, Southwest Research Institute, 2018). The table (Table 2) below provides a comparison between the two communication technologies described in this section.

TABLE 2 – Comparison between DSRC and C-V2X



Comparing DSRC and C-V2X

	DSRC	C-V2X
Operation in 5.9 GHz spectrum	Yes	Yes
Coexistence in 5.9 GHz	Yes (Adjacent channel with 3GPP technology)	Yes (Adjacent channel with .11p; co-channel coexistence from R-14 onwards)
Technology	Based on IEEE 802.11p	Based on mobile 3GPP
Target use cases	Safety only	Safety & enhanced
Support for network communications	Limited (via aps only)	Yes
Support of low-latency direct communications	Yes	4ms with path 1ms with Rel-16
Security & privacy on V2V/V2I/V2P	Yes	Yes
Security & privacy on V2N	N/A	Yes
Evolution path	No	Yes
MIMO solution	No support standardized	Rx diversity for 2 antennas mandatory; Tx diversity for 2 antennas supported

https://ytd2525.wordpress.com/tag/v2i/

As can be seen from Table 2, DSRC and C-V2X have similar characteristics but it can be derived that cellular communication seems more promising and effective, especially considering two differences. The first one is the target use cases. In this regard, DSRC is a technology particularly oriented toward critical-safety applications, those use cases in which the low latency (thus reaction time) is a key factor for ensuring a safe and reliable functioning of a vehicle. However, C-V2X could also meet the specifications for safety use cases, especially when it is associate to 5G that, as already mentioned in previous sections, represents a considerable evolution in the latency perspective. Moreover, given that cellular communication extends the range of the communication paradigms also to V2N, it introduces a wider spectrum of use cases.

In order to provide a more complete overview on the applications that both technologies have, some of the use cases described by Southwest Research Institute (2018) would be mentioned. These use cases are presented in a list to provide a clearer overview. It is worth precising that Southwest Research Institute (2018) bases its description of the applications scenarios considering LTE C-V2X, which implies a more relevant latency gap from DSRC compared to 5G C-V2X. Nevertheless, C-V2X applications presented are mainly derived from the fact that C-V2X implies network connectivity.

Some use-cases of C-V2X:

- Recommended speed to reduce congestion: this implies a harmonization of the speed of vehicles in a defined area with the purpose of ensuring a faster traffic flow. The two main information required are traffic and weather conditions. It is underlined by Southwest Research Institute (2018) that for proximity adjustments, latency is a key aspect to take into consideration.

- Enhanced situational awareness: it implies that vehicles could receive information related to the surrounding environment, for example when there is a modification of the road conditions that a vehicle is approaching, which has been detected by other vehicles. It is important to consider the "real-time" aspect of the exchange of information. This is especially relevant when there are new and unpredicted road situations.

- Emergency vehicle operations: the ability of warning vehicles that are transiting in a specific area about the presence of an emergency vehicle. This could ensure a more fluid and faster transiting of the emergency vehicle in the road environment.

- Information sharing: this consists in providing vehicles the ability of exchanging information with each other. The information could be the ones of on-board sensors or for example the information related to the road condition to vehicles behind them.

Some use-cases of DSRC are:

- Emergency Electronic Brake Light: which consists in the notification of a hard braking to upcoming vehicles. It is linked also to the next use-case.

- Forward Collision Warning: it contributes to prevent or mitigate the severity of crashes between vehicles thanks to ability of identifying the risk of an impact between vehicles.

- Spot Weather Impact Warning: drivers are notified of weather conditions of the area that they are approaching, that might imply a different driving behavior

In general, the use-cases described by Southwest Research Institute (2018) in some senses are mainly focused on the technologies themselves, and their capabilities. More precisely, in the presentation, the researcher has noticed that the authors do not particularly consider the concept of autonomy, in the perspective that vehicles don't intervein themselves, but it would be human drivers who would take decisions. This aspect does not undermine the validity of the concepts presented, because the mentioned paper provides a valid description of DSRC and C-V2X.

Another relevant aspect that has been summarized in Table 2 is represented by the evolution path of the two technologies. DSRC seems not to have an evolution path while C-V2X does. This difference could be linked mainly to the fact that cellular communication allows vehicles to be connected also to the network (V2N) thus ensuring a wider range of services and application scenarios. Moreover, cellular technologies have more application than DSRC, in many other sectors. It can thus be derived that the use of cellular communication for V2X would create the possibility for more integration with service providers in the mobility context. This aspect of C-V2X would result in a more pronounced gap from DSRC. It can be thus assumed that cellular vehicle communication is the best option for the development of an ITS, but the current situation is more oriented on using both technologies. This coexistence will be described in the following section.

2.3.2) HYBRID ITS AND COEXISTENCE OF DSRC AND C-V2X

As described by Kelia et al. (2020), Hybrid ITS networks are designed starting from a combination of DSRC and C-V2X. It is worth mentioning that a hybrid network could be designed in different ways, according to devices' interconnections. The two variants are: Hierarchical hybrid ITS and Flat hybrid ITS.

In a hierarchical network, devices have access to certain features, can send/receive specific information thanks to the classification in levels, that could be public transport, personal transportation and other. While considering hierarchical networks, a further distinction can be made:

- Dynamic Hierarchical Hybrid ITS: in which the levels of devices inside the network could be reassigned in accordance with network conditions. In these networks, an important concept is represented by the "main device", which is an intermediary node with the aim of regulating the network workload and manage connections of the other devices. An important task that could be performed by a main device is the fact that it allows devices of different groups to communicate with each other. In a dynamic network C-V2X is used for communication between main devices and base stations, between main devices and between main devices and regular devices. On the other hand, DSRC would manly be used for allowing communication between devices in the same group (Kelia et al.,2020).

- Static Hierarchical Hybrid ITS: which implies less flexibility in the reallocation of resources, given that levels are fixed. C-V2X network is used to ensure the communication between public transport and services, while DSRC would be the choice for communication between personal transportation as well as between personal transportation and public transport.

The alternative to hierarchical networks is Flat Networks, in which the interconnection between devices is not limited a priori by the architectural design of the network itself. The connection type is flexible and would be determined by the network conditions. In this sense, if a device uses C-V2X as default communication technology, in a flat network it could switch to DSRC according to network conditions.

The concept of hybrid ITS could be linked to the topic of coexistence between DSRC and C-V2X as communication technologies in the mobility environment. One of the issues to be solved in order to allow the joint use of these two technologies is connected to the spectrum, and in the way in which it would be shared by these communication technologies. As suggested by GSMA (2017) regulators should maintain a neutral approach, in the sense that they should not take actions that would advantage the usage of a technology over another. This neutral approach can be seen in the fact that regulators such as the European Union have allocated the 5.9GHz band for ITS purposes, resulting in the fact that both DSRC and C-V2X have the same rights over this spectrum range (5GAA, 2018). This natural approach in the spectrum perspective by regulators results in a relevant issue to be sold to allow DSRC and C-V2X to functions in a manner that would ensure safety and efficiency: *co-channel interference*. In this regard, 5GAA has proposed an approach to potentially solve this issue, which consists in three steps (5GAA, 2018).

- STEP 1: in this initial phase the proposed solution consists in a priori agreement on how to allocate 10 MHz for each technology at the extremes of the spectrum range in order to avoid any potential interference in the middle part of it thus decreasing the co-channel interferences between the two technologies.

Figure 4 - Step 1 proposed co-existence approach

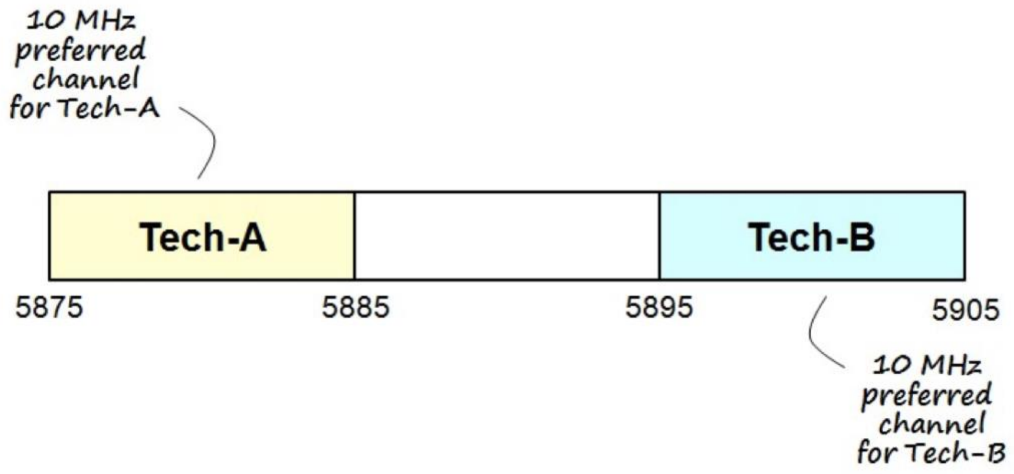


Figure 1, 5GAA (2018), https://5gaa.org/wp-content/uploads/2018/10/Position-Paper-ITG5.pdf

- STEP 2: during this phase, the proposed solution in order to extend the operation range of the spectrum for the two technologies consists in the so called "*detect-and-vacate*" (5GAA, 2018). In this step, each technology would still operate without issues in its dedicated 10 MHz allocated spectrum. The major step forward is represented by the fact that DSRC or C-V2X spectrum is not just confined inside the ranges agreed in STEP 1, but each of them has the possibility to also use the middle range if needed. This is possible only if an activity of the other technology is not detected.

Figure 5 - Step 2 proposed co-existence approach

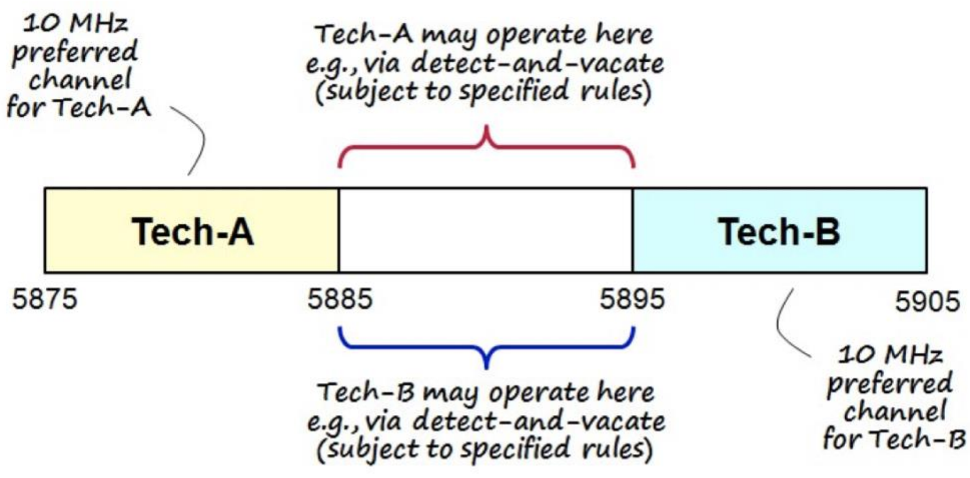


Figure 2, 5GAA (2018), https://5gaa.org/wp-content/uploads/2018/10/Position-Paper-ITG5.pdf

- STEP 3: this last phase represents an extension of STEP 2 in the sense that it would result in a more effective usage of the spectrum available, particularly when there is only one technology in a defined geographic area (Gulia, 2020). Once again in this phase both technologies would rely on "*detect-and-vacate*" as decision-making paradigm while trying to extend their operation range.

Figure 6 - Step 3 proposed co-existence approach

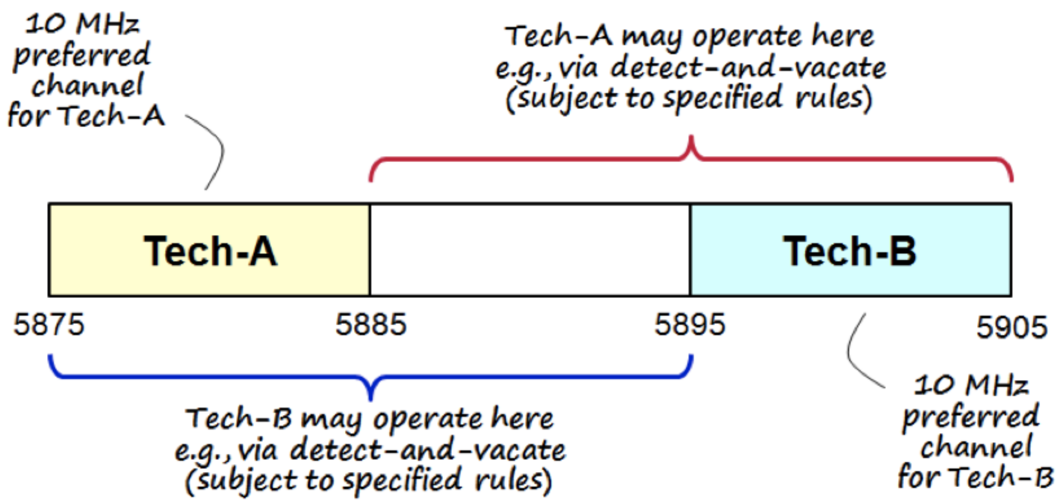


Figure 3, 5GAA (2018), https://5gaa.org/wp-content/uploads/2018/10/Position-Paper-ITG5.pdf

It is worth considering that the coexistence between DSRC and C-V2X seems to appear as a process oriented to the establishment of cellular communication as the predominant technology to ensure V2X, and that DSRC and other similar technologies could represent the supporting foundation to further implement C-V2X. Moreover, since cellular V2X is a more scalable technology and, in perspective, it could represent the base for enhanced services. Additionally, an important aspect to consider is that C-V2X seems to be a more suitable technology in dense scenarios, as it could be an urban environment. With the progressive deployment of 5G and with further tests, C-V2X would gain more maturity and reliability. Moreover, cellular communication based on 5G network has proven to have a consistent better performance in some key areas for AVs' functioning (5GAA, 2018).

What seems to be the most suitable solution at the moment for implementing 5G in AVs is the joint use of both DSRC and C-V2X technologies. By doing so, it would be possible to rely on an already mature technology (DSRC) while testing and developing the potential future communication technology (C-V2X) used to deploy vehicles with a higher degree of autonomy.

2.4) OME'S ORGANIZATIONAL PERSPECTIVE FOR DEVELOPING AUTONOMUS VEHICLES

Organizational landscapes in the automotive industry are changing especially because the more technological solutions imply the presence of new actors and organizations that weren't previously present inside this industry. This is mainly due to the progressive technological complexity of vehicles. In this perspective vehicles manufacturing firms could need to reshape the way in which they are designing collaborations with other actors, with the aim of increasing the potential success of their products. In this sense the concept of innovation ecosystem is becoming important especially in relation to AVs' deployment. The literature review on this topic also considers the Volvo's AD program as an example of the emergence of innovation ecosystem in the automotive industry.

2.4.1) VOLVO AD PROGRAM AND THE EMERGENCE OF AN INNOVATION ECOSYSTEM

The Volvo AD program started as an internal project, but it has become a perpetual evolving program with new partnerships overtime. The aim of this program is to acquire technological resources and competencies given that automotive firms are increasingly been challenged by the competition of technology firms that has crucial knowledge in software development and AI (Pushpananthan & Elmquist, 2019). With the AD program Volvo has three main goals: resources, competences, and commercialization. As underlined by a respondent in the study of Pushpananthan & Elmquist (2019), the technology development by itself is not enough to ensure commercialization. In this regard, the interconnection with partners like Uber, which develop its self-driving system on Volvo's base cars, increased the commercialization possibilities in the ride sharing market (Pushpananthan & Elmquist, 2019).

In the spectrum of the Volvo AD program, a particular relevance could be place upon the relationship between Volvo and Zenuity, which was created in 2017 as a result with a joint venture with Veoneer, a major automotive supplier of safety electronics, ADAS and AD (Pushpananthan & Elmquist, 2019). Zenuity was created with the purpose of externalize the software development for AD. The relationship between Volvo and Zenuity was not like the usual joint venture one, which implies a hierarchical control of the parent company (Volvo) over the joint venture (Zenuity) and an independency between the core businesses of the two firms (Pushpananthan & Elmquist, 2019, Hagedoorn, 2002). Indeed, Zenuity was independent from Volvo and it does not have to exclusively supply its parent company, but it has as potential customers also other Own Equipment Manufacturers (OEMs). In addition, the core business of the joint venture has a relevant influence over the core business of Volvo. The significant implication is that the hardware system supplied by Volvo and the software system supplied by Zenuity need to be integrated, thus implicitly leading to a modular system that can be used also by other actors to develop complementary products (Pushpananthan & Elmquist, 2019).

The relationship that has been established between Volvo and Zenuity could be defined as *symbiotic* (Pushpananthan & Elmquist, 2019, Davis et al., 2011), thus a symbiotic joint venture, which brings Volvo not to adopt a closed technology platform, and to increase the modularization, due to the deep interdependencies associated to its bond with the joint venture company, that ultimately facilitated the inclusion of a bigger variety of actors that supply complementary products, enhancing the overall attractiveness of Volvo's ecosystem (Pushpananthan & Elmquist, 2019).

Modularity represented a crucial factor to allow Volvo to extend the range of collaborations it could establish and, most important, all parties involved had the interest of increasing the value of the core platform and of the network they are part of, which also implies an effort in boosting the commercialization of AVs. In this regard, the AD program, during its evolution, assumed the shape of an innovation ecosystem (Pushpananthan & Elmquist, 2019). In this ecosystem, Volvo can be identified as the keystone firm, whose role is to integrate the solutions developed by actors inside the network, ensuring the platform modularity and managing activities coordination (Brem et al., 2016, Gawer et al., 2014, Iansiti et al., 2004, Jacobides et al., 2018).

In conclusion, the research conducted by Pushpananthan & Elmquist (2019) has showed how, in the scope of AVs, the choice of creating a symbiotic joint venture by the parent company (in the case of the study an OEM) results in the development of an innovation ecosystem in which the automotive manufacturer becomes the keystone firm. Additionally, the study has highlighted the importance of modularity in the perspective of the innovation ecosystem as a mean for increasing the attractiveness of the overall network as well as enhancing the commercialization process of complex products i.e., AVs.

3) METHODOLOGY

In this chapter the various choices related to the methodology by which the research h has been conducted are presented, in order to provide to the reader a clearer understanding on this study. More precisely, the four parts in which this chapter is divided are: Research Design, Research Strategy, Data Collection Method and, Data Analysis.

3.1) RESEARCH DESIGN

A research design provides a framework for the collection and analysis of data. A choice of research design reflects decisions about the priority being given to a range of dimensions of the research process (Bryman & Bell, 2011). In relation to this study the research design that was considered more appropriate for its characteristics is the cross-sectional design. In trying to study which role 5G network technology could play for local mobility in urban context the generalizability of findings is important, thus the focus is not placed on the specific context in which the subjects that would participate to the study belong to, or their characteristics. What is more relevant for the purpose of this research is to derive general findings from the thoughts and reflections of participants. This need is met by the cross-sectional design in a more appropriate way than the other research designs. Moreover, another consideration for which a cross-sectional design seems preferable is represented by the time dimension. Precisely, by adopting this type of research design, data would be gathered in a single point in time (Bryman & Bell, 2011). It is worth mentioning that the time span during which data would be collected would approximately be 3 months. This is related to the fact that the main source of data are interviews, thus it would not be plausible to collect all the data needed for the research in a very restricted amount of time. Nevertheless, the researcher aims to complete the data collection process as soon as possible. In relation to the topic of the study, the time dimension is sufficiently relevant, due to the pace by which new technologies are developed. In collecting data in a short time span, would ensure the decrease of the potential risks that "older" data would lose their value. The considerations just mentioned reinforce the appropriateness the cross-sectional design.

The most feasible alternative to the cross-sectional design is represented by the multiple case study, which re-enters in the comparative research design category, that embodies the logic of comparison between two or more cases to increase the understanding on a particular phenomenon (Bryman & Bell, 2011). Multiple-case study design and cross-sectional design both identify multiple cases as source of data. Nevertheless, they differ in the ultimate objective of the research. More precisely, the main difference that guided the choice of the cross-sectional design, rather than the other, is that the multiple case study is focused on the cases, on their specific characteristics and on highlighting the differences among them (Bryman & Bell, 2011). On the other hand, the cross-sectional design places the emphasis on generating general findings out of the data gathered from cases.

3.2) RESEARCH STRATEGY

The research strategy represents the approach taken in order to conduct the research (Bryman & Bell, 2011). There are two general research strategies which can be followed, qualitative or quantitative, each one with different characteristics. It is important to consider that a quantitative research would produce more objective findings, in the sense that the sample of the population is generally greater, there are fewer potential biases induced by the researcher and the overall way in which data are collected and analyzed is more standardized. The qualitative research strategy, on the other hand, is characterized by a more in-depth analysis on a smaller sample of cases/subjects, with the aim of developing a more complete understanding of the phenomena under study.

In developing this work, a qualitative approach would be followed. The choice of this strategy is related to the nature of the topic of the thesis and the research question. More precisely, in analyzing which are the new implication of 5G network technology diffusion for the local mobility and the deployment of AVs, the main benefits and challenges associated the introduction of 5G in this field of research and the other related topics, it is important to ensure a wider understanding though in-depth data collection and analysis. For this reason, it is relevant to emphasize the importance of words rather than numbers as source of data, which is a characteristic of a qualitative research strategy.

Moreover, though an epistemological orientation named *interpretivism*, the qualitative strategy emphasizes the way in which individuals interpret their social world (Bryman & Bell, 2011). *Interpretivism* is in line with the research question, given that by following this approach it is possible to understand personal opinions and reflections of participants in relation 5G and mobility, and how these two concepts could be interlinked.

Qualitative research strategy is also associated with the ontological position of *constructionism* (also called *constructivism*) which assert that social phenomena and their meaning are continuously being accomplished by social actors (Bryman & Bell, 2011). According to *constructionism*, the research always presents a specific version of the social reality, rather than a definitive one (Bryman & Bell, 2011). This dynamic changing of the reality best fits with the phenomena that would be studied in this research. Indeed, it is important to consider that the way in which mobility and 5G would evolve is a dynamic process, for the nature of the technologies implied and the dimension of the ecosystem represented by urban areas.

For what concerns the relationship between theory and observations, there are two general alternatives: *inductive* and *deductive*. A qualitative strategy is generally connected to the *inductive* approach (Bryman & Bell, 2011), which is also appropriate for the purpose of trying to identify how 5G network would be implemented in smart cities. An *inductive* approach seems to be preferable also considering that, due to the relative novelty of the diffusion of 5G network technology, the tentative of developing some sort of theory after the analysis of concrete observations could be the most straightforward path.

Nevertheless, it is worth mentioning that, as highlighted by Bryman & Bell (2011), the *inductive* approach does not exclude the *deductive* one, actually the latter is generally present. In this regard, it is important to also consider that, given the importance and the economic relevance of the two main phenomena under study, 5G and mobility, the research that has been conducted results to some extend in the development of some "theoretical" frameworks. Thus, in relations to the strategy described, a literature review would be conducted in order to identify the current understanding of the relationship between 5G network technology and mobility, and, in addition, interviews would be set up in order to have the chance to spot new findings and develop new considerations, that would enrich the current knowledge on the research topics. In conclusion, the approach that seems more appropriate to follow is the *abductive* one, which combine the *inductive* and the *deductive* ones, and that would lead to a more complete overview of the topic of the research.

The choice of a qualitative research strategy is also connected to the research purpose of this study. More precisely, this research would be exploratory, indeed its objective is to investigate new concepts and create new findings, which can be associated to the *inductive* approach mentioned above, as well as with the cross-sectional design described in the previous paragraph.

Even though the qualitative research strategy is the most appropriate choice for this study, it entails some limitations that it is worth mentioning. In particular, there could be some biases associated to the researcher, for example the choice of the interviewees and the way in which information would be interpreted. Additionally, the result of a qualitative study could be difficult to replicate, given that the predominant source of data is represented by interviews and their subjective interpretations and opinions.

3.3) DATA COLLECTION METHOD

For the purpose of this study, two sources of data have been used, in order be able to develop a more complete overview on the research topic.

3.3.1) Primary data collection

The primary data consists in data directly collected by the researcher (Bryman & Bell, 2011) and they are data gathered for the specific research problem, using collection methods that most appropriately fit the needs of the research (Hox & Boije, 2005). For this research primary data is represented by interviews. In qualitative research there are two possible alternatives for what concerns the structure of interviews. The first option is represented by unstructured interviews that could be compared to informal chat (Bryman & Bell, 2011). The other possible path to follow in the interview process consists in semi-structure interviews, which are characterized by more detailed questions on a specific topic and by a more standardized approach while conducting interviews.

Having in mind the previous features of these two alternatives and the research question, semi-structured interviews is considered the most suitable choice, also in accordance with the research design adopted, because they allow a sufficient level of structure while gathering information, resulting in a more consistent set of data to use for the analysis. More precisely, the choice of this type of interviews has been driven by the fact that the use of an interview guide would allow to follow a common order of question during interviews (Bryman & Bell, 2011). The order in which questions would be asked, in the opinion of who writes, is something that could be relevant, in the sense that it should be designed with the aim of stimulating the emergence of findings and associations between concepts. Additionally, by asking the same critical questions to the different interviewees, it would be possible to gain a broader perspective on relevant aspects.

Furthermore, semi-structured interviews leave space for some more tailored questions, in relation to some specific considerations developed by an interviewee. This level of flexibility of the conversation would give the possibility to deal with new topics previously not considered and to further investigate on them. By stressing this point, the interview guide would be continuously revised to include some new questions that an interviewee has stimulated and that are considered relevant to develop a more complete understanding on the phenomena under study. Moreover, this sort of strategy allows to let the interviewees have an active role in the data collection process. The proactive participation of respondents is particularly important for the purpose of this research because the expertise of interviewees is the main source of data that would be used to elaborate conclusions.

Connected to the choice of the semi-structured interviews, a purposive sampling approach would be use in the selection of respondents. The goal of purposive sampling is to sample cases/participants in a strategic way, so that those sampled are relevant to the objective of the research, and it is particularly indicated when the objective of the research is enough clear since the beginning (Bryman & Bell, 2011). In trying to find the most appropriate interviewees the researcher would also rely on the Swedish consulting organization named First-to-know, which has a sufficient level of experience in innovation management and that could help to identify the most valuable personalities whose expertise and experience in 5G and mobility would contribute to produce findings with the highest possible quality. Particular attention would be placed upon their background, on their current position in their organization, and on the organization itself as well.

The interviews have been held only online, through tools like Zoom and Teams, depending to the preferences of the respondents. The researcher aims to mainly use Zoom given that he is particularly familiar with its interfaces and because the service provides an easy-to-use recording function, that would be determinant in facilitating the transcription process. In this regard, to all interviewees was asked the permission to record the meeting, explaining that the recording would only be used for the purpose of the transcription. After a respondent has expressed his/her willingness to be recorded, the recoding would be started. The following step is represented by a brief description of the overall project. Subsequently, the actual interview starts, in accordance with the interview guide.

Table 3 – Respondents of the various companies

INTEEVIEWEES	***COMPANY***	***POSITION***	***DATE***	***METHOD***	***LENGHT***
Interviewee A	*Einride*	*Senior Logistics Strategist*	*29/03*	*Zoom*	*32min*
Interviewee B	*Drive Sweden*	*Chairman*	*13/04*	*Teams*	*31min*
Interviewee C	*Swedish Transport Administration*	*Head of Investigation on Digitalization of the Transport System*	*27/04*	*Zoom*	*45min*
Interviewee D	*Carmenta Automotive*	*Vice President of Development*	*27/04*	*Zoom*	*34min*
Interviewee E	*Telia*	*5G and Dedicated Network Evangelist*	*06/05*	*Zoom*	*30min*
Interviewee F	*-Volvo Cars* *-Telematics Valley*	*-Strategy and Innovation* *-President of the board*	*19/04*	*Teams*	*35min*

Produced by the author (2021)

3.3.2) Secondary data collection

As mentioned by Johnson (2014) secondary data consist in the review and evaluation of previously collected data in the area of interest of the research that is being conducted.

Secondary data would be collected from literature review. In this regard, there are two different approaches by which literature review can be performed: *systematic* review and *narrative* review. *Systematic* review is characterized by a more "scientific" attitude towards the literature review, in the sense that the researcher defines a set of inclusion and exclusion criteria that would be followed during the review (Bryman & Bell, 2011). The use of this approach would ensure a higher degree of replicability, but the *systematic* review also presents limitations when the boundaries of the subject under study are more prone to change, a characteristic that can be associated to the relationship between 5G and mobility. Moreover, the *systematic* review is more focused on the technical aspects by which the research has been done, rather than on its interpretation (Bryman & Bell, 2011). Considering the criticisms of the *systematic* review mentioned above, the most valuable approach to perform the literature review for this research is represented by *narrative* review. As highlighted by Bryman & Bell (2011), *narrative* review is particularly suitable for qualitative research, which are associated mainly with an *inductive* approach. For the literature review of this work, a *narrative* approach has been chosen, because given that this research would follow mainly an *inductive* approach, it would have been problematic to use the *systematic* review, since it implies that theory is already in place and that it would guide the definition of the inclusion and exclusion criteria for the literature review (Bryman & Bell, 2011). Additionally, the researcher considers very realistic that new or more specific topic would emerge during the literature review, following a narrative approach it would be efficient to include them in the study.

The secondary data would be gathered mainly from online libraries (LUISS and Gothenburg university) and from reports of relevant organizations. Particular attention would be played in relation to the source, with the aim of deriving information from reports and articles published on this field of study by authoritative publishers. Additionally, the time factor would be considered as well. More in detail, the year in which a particular article/report has been published is considered relevant and would be taken into consideration. Given the rapid evolution that could be associated with the topic of this research, it is important not to take for granted information that is presented in not very "recent" works, because generally it could be assumed that some conditions could have changed or are changing in the moment in which this research is developed. This is particularly true when dealing with a relatively new technology like 5G, thus older works could present finding that, at the time in which this study is conducted, may have a different relevance in comparison to the moment of their publishment. For this reason, while performing the literature review, a constant comparison among the sources would be made, to identify similarities and differences, with the aim of ending up with more consistent results.

3.4) DATA ANALYSIS

To perform the analysis of the data gathered from the interviews thematic analysis would be used. This analysis technique is one of the most used for qualitative research and it consists in analyzing patterns in qualitative data, in terms of uncovering major themes, that would be used to build the final conclusions and to try to answer the research question (Bryman & Bell, 2011). The process of which thematic analysis can be divided in three phases.

The first step is represented by initial coding, which consists in breaking down data into smaller codes that are building block of the analysis (Bryman & Bell, 2011) and that should emerge directly from the transcriptions of the interviews. The coding tasks would be done after each interview, with the aim of comparing the similarities and differences in the codes emerged from the various transcriptions. This continuous coding process would be done also for the purpose of continuously updating the interview guide, with new questions on relevant topics that weren't previously considered. There are different alternatives in coding in thematic analysis, but the one that the researcher is more prone to use is the so called "*color coding*". It consists in highlighting, directly on the text (in the case of this research, the interviews' transcriptions), with different colors, the quotes that can be associated with a specific code. One of the advantages that this way of coding could bring is that it prevents the fragmentation of the transcriptions. The fact the original structure of the transcriptions could be maintained could mitigate one of the limitations of the thematic analysis, which is the loss of context as a consequence of the fragmentation of the text (Bryman & Bell, 2011).

The second phase of the thematic analysis is represented by the formation of themes, by aggregating various related codes. Themes represent a higher level of abstraction than initial codes. During this step, codes would be compared, to find similarities between them that would lead to the formation of themes. A valid method for the identification of themes could be seen in the frequency by which specific codes are repeated across the different interviews (Bryman & Bell, 2011). After themes have been identified, the researcher would revise them in order to test their relevance for the purpose of the research and to find potential association patterns that would lead to the formation of aggregate themes (regrouping two or more themes), that would be ultimately used in trying to answer the overarching research question.

Thematic analysis could entail more disadvantages, in addition to the loss of context already mentioned. A relevant one is the fact that the transcriptions are very time consuming but, given that they represent the main source of data starting from which the analysis would be carried on, the time required could not be saved. Additionally, another disadvantage associated to this analysis technique is that it could be influenced by some researcher's bias, mainly in the coding or in themes formation.

It is important to notice that the analysis process, particularly coding, would be done in continuous comparison with the data emerged from the literature review. The aim of this comparison is to identify similarities and discrepancies between the new data generated by interviews and the data already collected by other sources, which could improve the reliability of the results of the analysis.

4) EMPIRICAL FINDINGS

The empirical findings section, for the purpose of clarity and to provide a comprehensive understanding to the reader, has been divided in two sections. The first one is dedicated to an overview of the organizations that are represented in this study. The second section is dedicated to the presentations of the actual findings that emerged from the data collection.

4.1) COMPANIES THAT PARTICIPATED TO THE STUDY

It is important to consider that for the purpose of this research the companies represented by interviewees operate in different areas of the autonomous vehicles' topic. More in detail, given that the subject under study represents a merge of the interests of organization that operates in different sectors. Having in mind this consideration, the fact that different organizations have been involved during the data collection process would contribute to generate a more complete set of information on which the analysis process has been conducted.

Moreover, in briefly describing each company, a focus on the automotive sector has been maintained, especially on AVs and 5G when it is possible. This allows the reader to develop a better awareness on how each organization is committed to the topic under study, and how they could be linked to each other.

Overall, the information related to organizations has been derived from the respective web pages.

4.1.1) EINRIDE

Einride is a company founded in 2016 with a vision that can be divided in two main drivers: the first one is related to the perspective that autonomy and electrification could bring new opportunities for enhancing the future of mobility, with the aim of contributing to the definition of a better future; the second driver in related to sustainability and the decrease of emissions in the environment.

Einride operates in the carries sector and in this regards it has 3 main focal areas of competence, that ultimately merge in the offer of the organization. There is digitalization, in which reenters the position of the company that the development of an intelligent and interconnected ecosystem is crucial for the enhancement of mobility. The other two area of specialization are electrification and automation.

The company is currently using trucks with a level of automation which is up to 4. These vehicles are completely electric, which means that the environmental impact of their use is exponentially lower than traditional vehicles that continues to rely on fossil fuels. Moreover, these Einride's trucks also rely on 5G as communication technology to operates.

4.1.2) DRIVE SWEDEN

Drive Sweden has already been mentioned in the Research Boundaries section of this thesis, but in this occasion a more detailed overview of what it represents is provided.

Drive Sweden is a strategic innovation program launched by the Swedish Government and it is an ecosystem of partners that jointly aim at creating an innovative transportation system by looking at new solutions in the mobility field. Once again, digitalization and automation are crucial drivers behind the project and they guide the efforts of the parties involved, in order to maximize the benefits and the innovation apport that the work put in place by Drive Sweden's partners. From an organizational perspective, the project counts approximately 150 partners, and it adopts a cross-sectorial collaboration between business, society, and academia.

Moreover, Drive Sweden has conducted pilots in a variety of scenarios related to the digital infrastructure for passengers and freight transportation. In addition, it has defined the requirements that the just mentioned infrastructure should have for supporting the initial commercial services in a smarter transportation system, with more advanced and interconnected vehicles.

4.1.3) SWEDISH TRANSPORT ADMINISTRATION

The Swedish Transport Administration is the authority that issues permissions for trial operations with automated vehicles on public roads or in general in confined areas. This regulatory role has been assigned to this agency by the Swedish Government, given that the government has expressed its interest in promoting the development of the transportation system on the country level.

For example, the Swedish Transport Administration has been the authority in charge of evaluating and giving permissions for trials of the trucks developed by Einride and that would be used by the German logistic company DB Schenker, with which Einride has a partnership.

The just mentioned example involve another organization that has participated in the data collection, whose role in this trial will be subsequently taken into consideration to enrich the understanding on how the activities of the different organizations are interlinked in the deployment of connected and automated vehicles.

4.1.4) CARMENTA AUTOMOTIVE

Carmenta was founded in 1985. At the beginning the company has worked with Swedish Air Force and other aviation projects. This experience has led to the consolidation of knowledge in geospatial situational awareness data. At present the company operates in three areas: Geospatial Technology, Public Safety and Automotive.

Particularly considering Carmenta Automotive, the company provides infrastructural products that contribute to enhance the situational awareness of connected and automated vehicles. For the sake of clarifying what the company does in the automotive sector, as well as underlying which is the specialization of its knowledge, it is worth describing the two products that it offers.

Carmenta TrafficWatch is a cloud-based service that monitors each vehicle, collecting dynamic and static data, as well as environmental information, and then automatically issuing safety instructions that aim at improving safety and efficiency of an AV's driving. More precisely, TrafficWatch collect situational awareness data from connected sources to ensure that automated vehicles have "beyond line of sight" capabilities.

Carmenta Control Tower complement TrafficWatch, especially in the decision-making process and in the real-time integration with other parts of the fleet management center.

4.1.5) TELIA

Telia is a multinational telecommunication company that has shown interest and commitment in the automotive industry, indeed one of the sectors in which the organization operates is "transport and logistics". Telia offers a comprehensive solution named "Telia Connected Vehicles" which is a service designed for logistics, which has proven to perform good considering that its version designed for public transport is already implemented on 60% of Sweden's public buses. In addition, this platform for connected vehicles allows Telia's clients to do fleet management and to oversee on every connected vehicle, preventing breakdowns while keeping track of the status of devices.

Moreover, to mention an example previously presented, Telia has partnered with Ericsson as 5G network provider for the pilot that of autonomous trucks of Einride, with the partnership with DB Schenker.

Furthermore, Telia is one of the companies involved in the so called "5G Ride", an initiative that aims to boost the deployment of AVs connected to the network through 5G.

4.1.6) VOLVO CARS

Volvo Cars was founded in 1927 and the central principle of its vision has been since its birth to ensure safety for people inside but also around its product. The company has expressed its commitment in promoting autonomous driving, since it believes that this technological advancement in the transportation industry could really contribute to ensure a safer environment and to decrease the number of accidents by eliminating human mistakes. Furthermore, Volvo Cars foresees big opportunities in this upcoming business and the company has also demonstrated with its 360c autonomous concept, that this technology has the potential to really revolutionize our habits and the ways in which we use our cars.

Additionally, the company has underlined that the future of the automotive industry would be characterized by fully electric and connected vehicles, also in line with emergent customers' needs. More precisely, car ownership seems not to be the first choice of customers, who would probably prefer to have a temporary access to a vehicle when and where they want.

Volvo Cars also promote innovation, mainly thanks to the "Volvo Cars Tech Fund", which make strategic investments in new ideas and technologies related to the mobility field. Generally, Volvo Cars is committed to boost the deployment of innovations from different actors and it's open to gather technologies from outside the boundaries of the company.

4.2) FINDINGS FROM THE COLLECTED DATA

In this section, the findings that emerged from the collected data are presented. It is possible identify six main themes, that would be further discussed in the discussion chapter. The parts in which this section is divided are: Key 5G characteristics and other core on-board technologies for AVs' deployment; Infrastructural considerations and requirements; Role of Cloud and Edge-Computing; Hybrid Transportations System: DSRC and C-V2X; OEMs' perspective; Policymakers' perspective.

4.2.1) KEY 5G CHARACTERISTICS AND OTHER CORE ON-BOARD TECHNOLOGIES FOR AVS' DEPLOYMENT

While considering the keys feature of 5G compared to the previous generations of ICT, all interviewees have agreed upon the fact that the most significant enhancements that the fifth generation of network technologies brings is represented by the ultra-low latency and the ability of ensuring bandwidth for specific use cases. The ultra-low latency that 5G guarantees is particularly important when it comes to safety-critical real-time-applications that where not possible with 4G. Volvo's interviewee has also provided a ranking of the three main pillars of 5G. More precisely, the first most important has been identified in the latency performance of that network, that would ensure a faster reaction of vehicles in safety and efficiency perspective. The second most important characteristic is the high-speed internet, while the least important is the low energy consumption. More in detail, Volvo's respondent has argued that low power consumption still maintains its importance, which is mainly related to the off-board devices in the mobility environment i.e., road-side-units. 5G ultra-low latency holds its importance also when it comes to remotely control driverless vehicles, as mentioned by Einride's respondent. As he has underlined, this use cases are not possible using 4G, given that to ensure safety and efficiency of vehicles remotely controlled the latency performance guaranteed by 5G is key.

Generally, interviewees mentioned that also 4G could be theoretically feasible for some autonomous drive use cases, but then they have reasoned on the fact that in the perspective of an increasing number of connected vehicles and on the fact that 4G would not be reliable when it comes to urban environments. In tackling this topic, interviewees have highlighted how the possibility of having a dedicated bandwidth is a crucial feature that makes 5G stand out in comparison to 4G. This dedicated bandwidth is particularly important in the connected vehicles perspective because it implies a considerably better coverage than 4G, also derived from the fact that there would be much less interferences and conflicts for bandwidth, ultimately improving the reliability of the network.

"…if your vehicle is close to football game, for instance, where there are 50.000 people attending game, it's not going to work properly because there won't be enough bandwidth…"
(Swedish Transport Agency Administration, talking about 4G)

Furthermore, the interviewee that works for the Swedish Transport Administration has considered another interesting, yet relevant characteristic that highlights the importance of 5G in the scope of mobility. He has mentioned how 5G opens new possibilities for a higher precision positioning. In developing his reasoning on positioning, he has provided two cases in which the enhanced 5G performance compared to GPS could really represent a step forward the present status of positioning technologies. The first example regards line-changing maneuvers, that positioning through GPS couldn't really ensure, while using high precision 5G positioning they becomes possible. Additionally, referring particularly to the urban environment, the interviewee has considered that 5G positioning could help to overcome the "*urban canyon*" problem, which is the loss of GPS signal due to the interferences related to building like skyscrapers.

Interviewees has generally extended the reasoning on connectivity and AVs by considering that vehicles would not solely rely on network connection to operate, in the sense that vehicles should be able to handle situations in which there is no connection, or more in general occasions in which the conditions of the network would not allow an efficient and safe functioning of them. The respondent working for Einride provided an example of this scenario, by also considering that potential drawbacks of using 5G for AVs functioning would not be due to the 5G itself but to occasional events that alters the latency in the network i.e., bursts of high latency. When this happens vehicles should be able to take the safest decision given the environment in which they are operating in the moment of the disconnection. The capability of operating also offline is mainly enabled by other on-board technologies, which can be identified in sensors and the software. All interviewees have described sensors as one of the key elements, given that they would provide to a vehicle the awareness of the surrounding by producing data that would be ultimately used by the software in the decision-making process.

Overall, has highlighted by one of the respondents, vehicles relying just on sensors would not be efficient enough because the connection to the network enrich the vehicles' ability to understand the context in which they are operating also because the network extends the situational awareness beyond the line-of-sight, which is one of the constraints of operating offline.

"You need to have connected vehicles to make them enough. efficient. You can make safe, fully, autonomous vehicles, but they will not be able to drive quickly or fast enough because you need to put on the safety measures all the time."

Another interesting consideration associated to the network connection, as well as computational power, has been done by Eirnride's respondent, who reasoned on the fact that machine-learning could represent a crucial aspect in the mobility perspective of connected vehicles. More in detail, the experience that could be developed by vehicles is exponentially quicker that the one that human drivers could have.

"That type of experience gathering is extremely powerful when it comes to autonomous, because if you take your driving license when you're 18 and you drive for 30,000 hours during your lifetime you will accumulate 30,000 hours of experience. But if there are 30,000 autonomous cars, or even cars with sensors out there, they will gather the same experience in one hour."

In this perspective, the higher the number the connected vehicles the quicker the experience gathering for a single vehicle would be.

In conclusion, all the respondents have agreed on the fact that 5G, would be required in the perspective of the future mobility, but it is one of the of the key technologies on which AVs would base their functioning.

4.2.2) INFRASTRACTURAL CONSIDERATIONS AND REQUIREMENTS

"…if you have connected vehicles that could get the information also from infrastructure and from outside, in that way you can create an enough safe and efficient system."

One of the most common distinctions among the different interviews has been the one between the physical infrastructure and the digital one. Dealing with the two perspective on the infrastructural topic there are different implications but ultimately it can be derived that both holds a crucial importance for creating an optimal environment for the operational needs of AVs. Furthermore, some of the interviewees have distinguished confined areas and public areas, providing thoughts on the differences between them. Moreover, most of respondents have also provided considerations on which could be the infrastructural differences between urban areas and rural ones and highways.

Starting from the physical infrastructure, interviewees as generally highlighted that the overall quality of roads, markings and the other elements should be ensured to facilitate the awareness of vehicles that are approaching a specific piece of road. Moreover, the respondent who works for Volvo Cars has particularly stressed an interesting aspect that the physical infrastructure should have in the perspective of the future transportations system in which AVs navigate, which is the homogeneity, that would enhance the efficiency of AVs' functioning. The homogeneity considerations could be also extended to the morphology of the environment in which vehicles would operate, that plays a role in overall efficiency of the vehicles functioning. Einride's respondent highlighted the difference between how cities are designed in the USA and in Europe: the biggest difference, that would have an impact on AVs functioning is represented by the fact that in US cities have a more regular and geometrical design, which results in an easier awareness of the surrounding for vehicles, thus more efficiency, while European urban areas are characterized in general with a more irregular layout that historically derives from the older moment in which the city has been built. Having in mind this consideration about the actual design of urban environment, in the future there will be much more attention on how to effectively build urban areas.

According to most interviewees, the starting point in developing knowledge about the AVs functioning, also in relation to 5G, is represented by test environments, which are confined contexts in which the sufficient operational requirements for the efficient functioning of vehicles could be crated, one of which is the full coverage. Nevertheless, as considered by Volvo respondent, creating an ad-hoc infrastructure rises the amount of investments, especially in sensors and in preparing the area.

Investments has been considered by most of the interviewees as one of the most relevant issues while dealing with the infrastructural perspective, because they are no more restricted to the actual physical elements of the transportation system, but they could be extended also to the emerging digital infrastructure, which is something that is key in the eyes of respondents. As underlined by those respondents that have discussed this topic, the digital infrastructure requires investments to be developed, while keep investing in the physical one. As noticed by Drive Sweden's interviewee investments in this digital side of the ITS would be less costly, in proportion, compared to the efforts for maintaining the actual roads in good quality or to even create new ones.

Moreover, while still considering the digital infrastructure, it is essential to provide vehicles the ability of understanding the rules of the ODD that they are approaching. As underlined by the respondent working for the Swedish Transport Administration, *"you should supply the same you can see as a human, but digitally"* and the effort should be also made to develop a *"digital twin"* infrastructure, that would allow vehicles to understand the rules of the surrounding context, being able to behave in the proper manner. This is true also when there are events like road works: it is essential to notify the vehicles of their presence, how the road condition has changed and in general provide them with all the visual information that a human driver can recognize. With 4G it is possible to send information to vehicles, but the interviewee highlights that 5G would be required especially in urban areas, where the density of devices and the competition for bandwidth is more pronounced. In this regard, 4G could still maintain its usefulness mainly in the countryside, or in general in areas in which bandwidth could be ensured. This joint use of 5G in urban areas and 4G in rural areas, or in general contexts outside cities, seems feasible considering the reasoning of Volvo's respondent. More precisely the interviewee explained that to have a full coverage, or realistically a coverage that is close to it, a lot of base stations are required when it comes to 5G. With that in mind, the investment to ensure full coverage on i.e., a highway would be higher, in proportion, that the one that would be made in a city. This is due to the fact that in the urban environment there would be more people to finance it. The potential use of 4G in external areas of cities implies that safety protocols for autonomous driving shouldn't be based only on 5G, to guarantee security also when the vehicle uses other cellular connection. Investments in urban areas are more justifiable because the network connection would satisfy more use cases and users.

Moreover, this consideration seems to be confirmed also be the thoughts expressed by the respondent working for the Swedish Transport Administration, who mentioned the fact that the increasing number of connected devices trigger the need of having "*multi-sensors poles"*, devices that merge more sensors, and in general can produce more information, than they can do at present. This trend derives from the fact that "*We can't have one device for one thing anymore because there will be too many devices when you go into the future IoT."*

Generally, interviewees have agreed on the fact that when it comes to the infrastructural perspective the main challenge is represented by the identification of the right business model and "*who is going to pay for what*". Nevertheless, starting investing is essential to create the basis for AVs' deployment.

"…it's a chicken and the egg problem because vehicles manufacturers won't necessarily add features to their cars and trucks that would take advantage of that unless they know that the infrastructure is there, on the other side of that coin infrastructure providers won't build that unless they know that someone is using it."

4.2.3) ROLE OF CLOUD AND EDGE-COMPUTING

Overall interviewees have expressed different considerations on this topic, nevertheless there are also common thoughts about the ways in which cloud and other related concepts could be implemented. Generally, different focuses can be identified while dealing with cloud, which brings benefits in the scope of an ITS with an increasing number of AVs: situational awareness and computational power.

According to the respondent that works for Volvo Cars, when it comes to the cloud, cloud-to-cloud communication seems to be good enough, thus in this perspective there would be more connected infrastructure, that doesn't necessarily imply that vehicles will directly communicate with every roadside unit. Furthermore, the cloud would also enhance traffic management tasks which, would be even more data driven.

"Volvo is already sensing slippery roads, for example. If it's slippery, the car will say, "oh, it's slippery here", and then it will send that to the back-end Cloud at Volvo and Volvo Cars will send that to other vehicles that are approaching the sleepery area."

The just mentioned quote could be further explained thanks to the reasoning of the respondent, who highlights that, at present, information that comes from the cloud are more oriented to provide a better situational awareness to the driver, while in the future it would be the vehicle itself that would provide to take actions to maximize safety in a specific context, thus cloud's information would be mainly oriented to the AVs with the aim of increasing its awareness of the surrounding and *"…it could perhaps adjust some parameters for safety: distance to vehicles and stuff like that"*. This proactive approach of vehicles to the events of the environment in which they are operating or which they are approaching results in a better overall user experience for passengers, which could have a pleasant and safe ride. Additionally, as agreed by most of respondents, 5G low-latency characteristics would benefit the on-board experience also when it comes to infotainment, which is something that is increasingly more data intensive.

Overall, 5G would enhance cloud capabilities and thanks to the higher bandwidth and the lower latency, it is possible to develop new features and improve the current ones. An interesting consideration has been done by the interviewee working for Einride, who has associated the so called "*Parkinson's Law*" to this topic. More precisely, he has expressed his conviction that 5G would be maxed out with functionalities to the point in which it will not be more sufficient to support all of them and the need of the next generation of network technologies would be required.

A topic that most of interviewee has considered more important than the cloud itself, is the concept of edge-computing, that would be improved thanks to 5G. According to respondent working for Telia, there are different issues related to edge computing and they will trigger business opportunities as well. One of the questions that interviewee reasoned on is *"How close should we get to vehicles?"*. Respondent has also underlined that in this context operators would likely have a very important role. Given the fact that the understanding of how edge-computing could be implemented in the scope of transportation is not defined yet, the potential roles that the different actors would have is still unclear. Following the reasoning of the respondent, the automotive industry actors would probably focus on ensuring V2V communication, while the other communication paradigms would be taken care by actors whose businesses are closer to the telecommunication industry. Generally, edge-nodes have been seen by Telia's respondent as the potential solution to problems like delays, security, network slicing, etc.

One of the main reasons that has been identified why edge-computing would represent a more significant enhancement than cloud and cloud-cloud computing consists in the fact that, according to Drive Sweden's interviewee, there isn't the necessity for a vehicle to send requests to the cloud to perform some sort of actions, specifically the ones that requires a slower reaction time. In this perspective, the sources of the majority of information needed to perform these computational tasks are roadside units and in general all the devices present in the environment in which vehicles operate.

The concept of remotely locating the computational power required for vehicles to function in a safe and efficient manner could be linked also to quantum computing, something that was expressed by Einride's respondent. More precisely, the interviewee has considered that we are approaching quantum computing and the power of these devices could also be used in the ITS. The importance of network technologies is highlighted by the fact that it will not be possible to install a quantum computer on each vehicle, thus the requests of vehicles would be performed off-board.

Some of the respondents have added that the cloud could be used also to give permissions to vehicles that are approaching a specific area. These permissions could be given if a vehicle respects certain parameter or if it has specific on-board technologies.

4.2.4) HYBRID TRASPORSTATION SYSTEM: DSRC AND C-V2X

"There's a lot of discussions [...]. The two camps are quite far apart from each other and maybe the solution is some sort of hybrid solution that combines the best of the two worlds."

Overall, all respondents have agreed on the fact that when it comes to V2X both technologies are needed, at least at the current state. Nevertheless, some interviewees have also highlighted how the C-V2X represents a better solution to be implemented because it has the potential to be more efficient, both in its reliability and from an economic point of view. The reasons for promoting a hybrid solution derive from the fact that both technologies have features that would benefits mobility when it comes to AVs, especially in urban environment. One of the reasons behind the need of the joint use of them can be identified in the importance of information for AVs. More precisely, as mentioned by Carmenta Automotive's respondent, vehicles just need information, independently from their source.

"From that perspective it doesn't matter where it comes from and to be able to guarantee that you have enough information for automated driving you need to have both ways to communicate."

Generally, interviewees highlighted how DSRC seems to be a better solution is specific urban hotspots i.e., intersections, given that while establishing a direct Wi-Fi communication between roadside units and vehicles it is possible to guarantee a very low latency and a reliable exchange of information. Nevertheless, all respondents have agreed on two main downsides that this technology entails, and that could be seen as two factors that establish C-V2X as an overall better technology that need to be implemented: line of sight constraints and infrastructural costs.

Firstly, DSRC given its characteristic of being a peer-to-peer communication technology, it doesn't enable to overcome physical constraints in the exchange of information. With these consideration in mind, it seems to be the preferable choice especially for interceptions, given that vehicles could directly receive information from i.e., traffic lights, other vehicles, in a reliable way. Secondly, the costs perspective associated to DSRC is strictly linked to the fact that the correct functioning of this technology implies the need of a considerable amount of roadside units, to provide all the information needed by vehicles. This investment, as expressed by Volvo Car and Swedish Transport Administration's respondents, could be feasible and more justifiable in urban areas, but when it comes to rural areas, areas with a lower traffic affluence or even highways, it would be too costly to ensure a full coverage.

"From the Swedish Transport Administration our statement basically is that we're going to focus on cellular communication to distribute information to the vehicle. I think the think also the Finns and Norwegians made the same kind of statement because they are similar geographically. I suppose one reason also why we have been focusing on cellular information in Sweden is because we have Ericsson obviously, which is a very big international company that does supply the equipment."

The just mentioned quote from the Swedish Transport Administration's respondent, is linked to the fact that C-V2X is much more efficient than its Wi-Fi based counterparty, because it enables to cover bigger geographical areas in a cheaper way, ensuring coverage to vehicles. Especially looking at operational environments outside cities, C-V2X represented the path to follow for cost efficiency and coverage. These two benefits can be seen also in the reasoning of Volvo's interviewee, who explained how cellular vehicle communication could rely on an already well-established cellular infrastructure. C-V2X is possible also with 4G but, as highlighted by the respondent, when it's based on 5G new features would be possible. Furthermore, extending the considerations of infrastructure and costs, to his eyes there isn't the need of investing to heavily of DSRC given that the communication infrastructure is already there, so it would result in doubling the infrastructure. Nevertheless, as considered by Drive Sweden's respondent, the considerable amount of investments made in developing DSRC would have an impact on the speed in which 5G will be rolled out.

Moreover, the other limitation associated to DSRC, which is line-of-sight constraints, could be overcame with C-V2X. More precisely, given that this technology relies on cellular network it enables to exploit cloud services to provide vehicles with a more complete situational awareness: vehicles could receive information not only on what is happening in their immediate distance, but they can actually have data about upcoming events, road conditions or traffic, being able to perform a more efficient decision-making process, thus ultimately improving safety and user experience.

An additional reason why 5G, and in general cellular, seems to be a preferable choice is highlighted by the respondent working for Volvo, who reasoned on the fact that, since it is a more ubiquitous technology, it would be more scalable, and it would be easier to adapt it overtime when newer generations will be deployed.

4.2.5) OEM'S PERSPECTIVE

From interviewees' discussions has emerged that 5G wouldn't create many big challenges for automotive manufacturers, also when it comes to AVs. Generally, respondents have considered that, given that OEMs are currently relying on 4G to enable communication capabilities to their products, in doing the upgrade to the fifth generation of network communication technologies there wouldn't be many difficulties. According to those interviewees that have tackled these considerations, it is mainly a matter of investing on new technologies that would ensure a 5G connection. Nevertheless, as mentioned by Volvo Cars' interviewee, in the past there were very few features of vehicles that uses the communication link, but with the new platforms most of vehicles' use cases would be related to the network communication.

"I don't see as much challenges as opportunities by using technology like five year. Of course, there are challenges […] because this is an adoption of a new technology, so there will be instances when it doesn't work as expected and something needs to be fixed […] but that's always the case when you bring something new into the equation."

Keeping the focus of investments, Volvo Cars' respondent has explained that the costs associated to 5G chipsets are much higher than the technological components associated to the previous generations of communication technologies. Additionally, when it comes to the development cycle, another aspect mentioned is the timing of investments in 5G chipsets. The respondent has underlined how investing later would have a positive impact on the kind of specifications and the prices manufacturers would get. Moreover, given that the new vehicles platforms would be more oriented to connectivity than the past, there would be potential challenges in ensuring that all the new components that needs to be associated to connectivity work in the proper manner. So generally, the increased complexity of vehicles is something that OEMs should manage.

As mentioned by the interviewee working for Drive Sweden, vehicles will be certainly equipped with 5G modules but the speed by which 5G would diffuse won't make a big difference in the deployment of AVs, because it will mainly enhance the information exchange process and the infotainment in vehicles. Bigger challenges are related to more technically advance technologies though. Moreover, also Telia's respondent has said that major challenges for OEMs in relation to 5G and their vehicles are not strictly linked to the technological perspective, rather it would be more challenging to develop an efficient business model and business ecosystem. He as further argued that OEMs, in the perspective of communication infrastructure are looking for collaborations with operators, and even other actors. In the perspective of the business ecosystem, there is an imbalance in the dimensions of OEMs, which are generally global, and operators, that in most cases don't equal the market scope of automotive manufacturers. Furthermore, extending the considerations of the potential issues derived from the relationships with other actors for AVs deployment, as mentioned by Carmenta Automotive's interviewee, OEMs could face challenges also from the legal part, in the sense that competent authorities could pretend that vehicles send information about the nature of the on-board technologies, to provide, or eventually deny, permissions to approach a specific area.

Overall, from the data collection it has emerged that most of the challenges in the deployment of AVs by OEMs is not strictly related to 5G, or cellular communication in general, but they are mainly due to the business model perspective, from an organizational point of view, and to more advanced technologies than 5G itself.

4.2.6) POLICYMAKERS' PERSPECTIVE

Dealing with policymakers in the mobility field, interviewees that have expressed their thoughts on this topic have reasoned on different challenges that should be solved to promote deployment of AVs. It was a common consideration the 5G will work just fine and it would be harmonized. More precisely, as underlined by Volvo Cars' respondent, there is a lot of standardization going on among countries and it wouldn't create many difficulties. On the other hand, as highlighted by the interviewee, a much bigger challenge is represented by the harmonization of the regulations and laws, which ultimately have deep implications for autonomous drive. This sort of alignment of the rules represents a more complex problem given that it should not only be done on a macro level i.e., country level, but also on the micro level, i.e., among cities. This will increase the complexity of the regulatory efforts to create a homogenous regulation set for autonomous drive. The solution to this challenge is in the hand of competent authorities, given that OEMs can't solve it.

The importance of the role of regulators is particularly underlined by Telia's respondent, who expressed his conviction that regulators would contribute to determine how the market would evolve, as well as influencing how the different actors that have a stake in this business would shape their business model. More precisely, the interviewee focuses his attention especially on the spectrum and how it could be managed by competent authorities.

"[...] Who is owning it? Who can buy it? Who can use it? How should it be deployed in different areas: if it's combined areas or public areas?"

The respondent highlights that there are many organizations that have a great interest in understanding how this spectrum would be managed, to be able to figure out how they could develop their ecosystem and relationships.

"Laws are written for vehicles with drivers."

With the just mentioned quote, Einride's interviewee reflects on another relevant aspect related to the challenges that could be seen both from the side of regulators and the side of AVs' developers. Laws define dispositions related to vehicles that still have a driver, or more in general passengers on board. This implies that, when it comes to vehicles that operate autonomously without any human user inside them, it is important to find solutions to ensure that the same actions that could be normally performed by a user could be done even if a vehicle has no passengers. This is probably one of the challenges that organizations that uses this sort of AVs would face. Laws are there and should be respected. On the other hand, it could be derived that regulations are moving forward with a slower speed than technology, yet they maintain their importance and it seems that it is the technology that should adapt to them. Einride's respondent has also underlined that as long as it is possible to do the same actions in specific situations, there wouldn't be great difficulties.

Another area in which regulators should intervein is represented by the management of the vast amount of information that is increasingly characterizing the transportation system. In this perspective, Carmenta Automotive's respondent has considered data filtering and data fusion as two important aspects to consider in order to enable the correct and safe ride by AVs. Furthermore, given the importance of information and their big volume, also cybersecurity is something that is becoming central in the mobility perspective, as considered by Volvo Cars' interviewee, and it's something that authorities should handle. Regulators should also define how all the different information would be manage: which could be kept by OEMs, which should be shared, etc.

Overall, there are different area in which policymakers are required to intervein and to manage, mainly in relation to the vehicles' side and to the information's side. As emerged from interviews, the major challenge related to the network infrastructure consists in how the spectrum would be managed, given that 5G itself is supposed to be harmonized without particular difficulties.

5) DISCUSSION

In this section the results of the thematic analysis would be discussed. The same main topic of the empirical finding would be followed. In this section a comparison with the literature review would be done in all the occasions in which there a correspondence between it and the collected data is found. The data analysis presentation has been divided in 5 section: Key 5G characteristics and other core on-board technologies for AVs deployment, Infrastructural considerations requirements, The role of cloud and edge-computing, Hybrid transportation system: DSRC and C-V2X, OEMs' perspective, Policymaker's perspective.

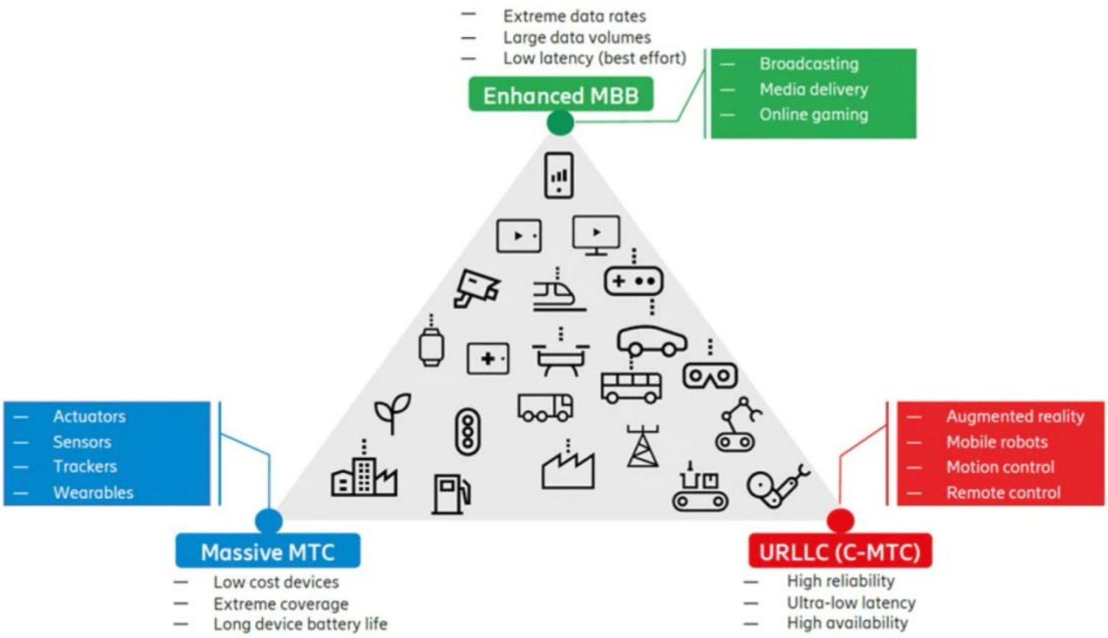
5.1) KEY 5G CHARACTERISTICS AND OTHER CORE ON-BOARD TECHNOLOGIES FOR AVS DEPLOYMENT

From the data analysis it has emerged that 5G represents one of the enabling core technologies when it comes to AVs' deployment, for its characteristics. In addition, its importance for mobility use cases is also represented by the kind of enhancements that it brings, especially compared to the previous generations of ICT. More precisely, interviewees have compared it to 4G which, from the data analysis, seems to maintain its relevance, at least for the current moment, in AVs applications. Moreover, during the analysis it has also emerged that 5G alone is not enough to accelerate the deployment of AVs.

The data analysis has shown that the most important characteristic associated to 5G, especially compared to 4G, is the ultra-low latency. The relevance of this feature in the perspective of the future mobility, and for the development of an ITS, is in line with the work of Panwar et al. (2016), who underlined how a critical requirement for the ITS, sensors, and mission-critical tracking, is the "*zero-latency*". Furthermore, latency considerations derived from the analysis can be also linked to the classification presented by Osseiran et al. (2020), that distinguishes between URLLC, eMBB and mMTC. By analyzing the gathered data, it is clear that the URLLC stands out as a key feature, especially considering that the authors associate the reliability of the connection to the ability of ensuring a secure data transfer in a short time span.

In extending the reasoning on the triangular classification provided by Osseiran et al. (2020), it is possible to identify a ranking, based on the importance of the three 5G characteristics. This ranking has been discussed by the respondent working for Volvo Cars, who has agreed on the centrality of low latency, and he has further discussed that the second most relevant feature is represented by high-speed internet, while the least important is the low power consumption. High-speed internet in the Osseiran et al. (2020) work is represented by eMBB, while the low power consumption is the mMTC. For the purpose of clarity, the visual representation provided by Osseiran et al. (2020) is presented again.

Figure 1 – 5G application scenarios



https://www.ericsson.com/en/reports-and-papers/white-papers/5g-wireless-access-an-overview

The ranking provided by the Volvo Cars' interviewee in reflected also in the figure, in which it can be seen that autonomous drive can be found in between URLLC and eMBB. The importance of these two characteristics is mainly linked to the on-board technologies, while the mMTC would benefit sensors, and other devices, that are not on the vehicles itself.

Moreover, the data analysis has shown that 5G represents a crucial enhancement also in relation to remote controlling vehicles, which is once more aligned with the considerations developed by Osseiran et al. (2020) in relation to URLLC. More in detail, Einride's respondent and the Swedish Transport Administration's one have reasoned on the aspects of remoting controlling vehicles that are associated to 5G's reliability and latency characteristics, highlighted by Osseiran et al. (2020), and underline how 5G could improve network communication technologies performance. As pointed out by its interviewee, Einride has level 4 autonomous trucks and it uses 5G to take over the control on them when it's needed, since the latency that 5G enable is crucial for that use case. Swedish Transport Administration's respondent has, on the other hand, mainly expressed considerations about reliability that 5G connection could guarantee, compared to 4G. More precisely, he has reasoned on the fact that if vehicles transit in an area with a high density of connected devices, it could be expected that 4G would not work properly, given that there is not enough bandwidth.

Another relevant characteristic of 5G that aligns the collected data with the literature review is its ubiquity, which recover a central role in the mobility perspective, since, as highlighted by respondents, the IoT perspective could be extended also to vehicles.

As discussed in the literature review, the concept of ubiquity could be associated also to network slicing, which is the ability of dedicating a portion of the network for specific use cases (Zhang et al., 2017, Rost et al., 2016, Jiang et al., 2016, Li et al., 2017). From the data analysis, it has emerged that network slicing is key when it comes to AVs and ITS, since it enables the possibility of guaranteeing coverage and connection to vehicles, avoiding inferences and competition for bandwidth. In this sense, 5G results a considerable enhancement in the AVs perspective because it enables an overall better coverage, especially in urban areas where there is a much denser environment and competition for bandwidth is more pronounced. From the analysis, the density of devices seems to be one of the key aspects that would stimulate the need of 5G in the mobility perspective, given that 4G could be still used for many use cases associated to AVs, the denser the network is, the less effective and reliable 4G would be.

Nevertheless, as already mentioned, 5G diffusion is not a sufficient condition for boosting the deployment of AVs. In this section, other core on-board technologies are considered, while other concepts would be discussed in the following sections. From the data analysis, there are two major technologies that need to present in an AV: sensors and software. There is also the cloud, but it would be discussed in a dedicate paragraph given that is can be seen more an off-board resource, and additionally for the purpose of clarity is worth describing it by alone.

During the analysis, while dealing with sensors and software, as well as 5G, it has been noticed a correspondence with the architectural description of IoT provided by Patel et al. (2016). More in detail, the authors identified three layers. The first layer is represented by sensors, which generate data of the surrounding environment. The second layer consists in the network, which is used to transport information. This layer can be associated to 5G. The third layer is described by the authors as the management service, in which reenters the decision-making process. From the literature review, this concept is quite general, but from the analysis of the collected data, the decision-making task seems to be associated mainly to the built-in software, thus it is possible to associate it to the third layer identified by Patel et al. (2016).

From the analysis of the data, it is possible to derive additional considerations on sensors and software. More precisely, all respondents have underlined that 5G, even though it is supposed to improve considerably the coverage, it could be realistically expected that network connection wouldn’t be always available, or it would experience bursts of high latency. In the occasions, in which AVs couldn’t rely on internet connection, sensors and the software become the key technologies to ensure safety. In this perspective, it is worth considering that the analysis of data showed that AVs could function, and are expected to function, even without connection to the network, yet network is needed to have vehicles that are also efficient.

A new benefit that 5G brings in the perspective of AVs, which isn't present in the literature review, is represented by positioning precision, which was discussed by the Swedish Transport Administration's interviewee. The respondent has highlighted two particular improvements compared to the GPS technology currently used: line changing maneuvers and "*urban canyon*" problem. The first one, consists in the higher precision in understanding in which line of a road a vehicle is, to perform in a more precise, thus safer, way the change of the line. The second benefit is related to the fact that, with the use of 5G it is possible to overcome the interreference problems that GPS could have, especially in urban environment where there are building that could decrease the signal.

In conclusion, another key technology is represented by machine-learning, that Einride's respondent links to the computational power. A correspondence with the literature review can be found in the concept of VCC, that implies that the underutilized computational resource of a vehicles could be used by other vehicles that require it (Hussainn et al. 2012, Boukerche & De Grande, 2018). The machine-learning could be also associated to the concept of "time-space validity", discussed by Gerla et al. (2014), which implies that the information gathered by vehicles could be used by others and, depending to the nature of the information, it maintains its relevance for a specific time span and/or for a specific area. This exchange of resource by vehicles would provide a better understanding of the environment and could help to share "*experience*".

5.2) INFRASTRUCTURAL CONSIDERATIONS REQUIREMENTS

In the literature review, the infrastructure has been mainly considered in relation to the V2I communication paradigm, thus in the perspective of the RSU that would enable the extension of V2V communication, to provide vehicles with more information than the ones that they could gather themselves. From the analysis of the collected data many additional concepts have emerged, not only in relation to the virtual infrastructure but also to the physical one. Nevertheless, it could be found some correspondences to some of the topic presented in the literature review.

One of the topics that could be see also in the collected data is the importance of being able to provide vehicles with the possibility of interpreting the "real world", expressed by Patel et al. (2016) while dealing with the lower layer of IoT. The authors mainly focus on sensors, but from the data analysis it can be derived that the understanding of the physical environment is not just limited to the work of on-board sensors, but is could be extended also to infrastructural elements, which ensure that vehicles can "*see what a human driver could*". More precisely, this could be resume in the creation of "*digital twins*", translations of the real-world inputs into digital inputs so vehicles can have a more complete situational awareness of the surrounding environment. Particularly referring to the words of the interviewee working for the Swedish Transport Administration, it can be derived that these "*digital twins*" should be dynamic, in the sense that when there are changes in the conditions of the road, it should be possible to enable vehicles to understand that. The respondent has provided the example of roadworks to motivate his reasoning: when there are some works on the road AVs should be alerted about that, probably though digital signs.

Similarly to what considered by Arena & Pau (2019) while dealing with the virtual infrastructure, from the collected data it could be understood that the digital infrastructure development would be characterized by more cost efficiency than the physical one. In this perspective, a recurrent topic while considering the infrastructural viewpoint are investments. More precisely, the collected data showed that, when it comes to investments, one of the major issues consists in understanding who is going to pay for what. This derives from the fact that the number and nature of actors that would be involved in the mobility industry is raising, and the business opportunities are vast. Overall, it seems that when it comes to the network connection operators would recover a key role in developing the digital infrastructure.

From the analysis, 5G coverage didn't seems to be a challenge from the infrastructural viewpoint. This consideration decreases the relevance of the potential coverage issues related to 5G propagation sensitivity, considered in the literature review during the comparison between DSRC and C-V2X. According to collected data, coverage would be ensured thanks to the investments in antennas, especially in urban environments. The investments in antennas inside cities would be justified by the many use cases that they could have, and in general by the fact that there are more people financing their diffusion. On the other hand, 5G coverage could be probably too costly to implement in rural areas, or in general in areas with lower traffic volumes. In this perspective, 4G seems to maintain its importance as network communication technology in these contexts.

5.3) THE ROLE OF CLOUD AND EDGE-COMPUTING

From the analysis, two main concepts have emerged in relation to the external computational tasks required by AVs: cloud-computing and edge-computing. The collected data show that the most important in the perspective of 5G and AVs is edge-computing, thus decentralized computation. Nevertheless, cloud-computing still maintains its relevance, but for applications in which reaction time isn't that much critical.

While dealing with edge-computing, there could be seen a correspondence with VCC, which implies that the underutilized computational resources of a vehicle could be used by another vehicles (Hussainn et al. 2012, Boukerche & De Grande, 2018). The reasoning on VCC could be further extended considering the analysis of collected data. More in detail, according to the interviewee working for Telia, edge-computing could represent a solution for issues like delays, network slicing etc. In this perspective, the characteristics of 5G would ensure more evident enhancements, given that the lower latency that it brings would guarantee a faster exchange of information, and an overall more efficient edge-computing.

On the other hand, what isn't considered in the literature review on VCC is edge-computing performed not by vehicles, thus by devices more distant to vehicles themselves. In this sense, it is worth considering the reasoning of Einride's respondent, who introduced the concept of quantum computing as potential solution for computational need of vehicles. In this case, a quantum computer could physically be built on vehicles, but it would be located elsewhere in the network. Given the great amount of data exchange, 5G features would ensure a more reliable communication between nodes. Furthermore, edge-computing in general would probably be critical also because the bult-in computational power of vehicles wouldn't be enough when the volume of data would reach some levels. Nevertheless, the ways in which edge-computing could be implemented are still unclear given that it is very much an early-stage technology.

When it comes to cloud-computing, the analysis showed that it's a technology which is more mature and already implemented in the mobility sector, but it wouldn't be as important as edge-computing for AVs deployment. Cloud-computing would be probably continuing to be used like in the current time, thus as storage space and as a service that would provide vehicles with information mainly related to road conditions, and in general for traffic management services. At the moment, information is mainly delivered to the driver, while in the future it would potentially be the vehicles itself that would intervein on certain parameters to maximize safety. Moreover, it seems that 5G diffusion wouldn't benefit cloud-computing in the same intensity as it would for edge-computing. This is mainly related to the sort of information that these two computational technologies would use. From what emerged from the analysis, cloud-computing would be mainly use for less real-time applications.

5.4) HYBRID TRANSPORTATION SYSTEM: DSRC AND C-V2X

While considering the key differences between the two technologies, there is a strong alignment of the data analysis and the literature review. The analysis showed that one the biggest limitations associated to DSRC is represented by the line-of-sight constraints and the fact that it is peer-to-peer. Similar considerations are present also in the literature review, when it has been discussed that DSRC's operational range could vary in relation to the physical morphology of the area in which the technology is used (Southwest Research Institute, 2018, TechVison Group of Frost&Sullivan, 2017). In the literature it has been also considered that with 5G there could be issues related to operational range, mainly associated to propagation issues, nevertheless coverage would be ensured especially in urban areas thank to the use of a vast amount of antennas.

Furthermore, the analysis showed that the correct functioning of DSRC is very much dependent on the presence of RSU, due to the peer-to-peer communication which characterize Wi-Fi based technologies. In this perspective, it could be done once more the distinction between urban areas and the ones outside cities. In an urban environment, it is predictable that there would be a great implementation of RSU, that could support this sort of data exchange, while outside cities, it would be too costly to implement them on roads to ensure full coverage. Coverage is one of the key differencies between these two technologies, and from the analysis of data it can be derived that C-V2X would be supported and would function over wider geographical areas and in the areas in which there aren't RSU because, as also mentioned in the literature review, it relies on network connectivity rather than peer-to-peer communication.

Moreover, there are relevant differencies also in the potential use cases. In this perspective, it could be seen a close association with what interviewees have reasoned on and some of the use cases presented by Southwest Research Institute (2018). Some of use cases already described in the literature review are mentioned with the aim of extending the reasoning on them considering the data analysis.

- Recommended speed to reduce congestion: this implies a harmonization of the speed of vehicles in a defined area with the purpose of ensuring a faster traffic flow. From the analysis it could be further argued that, thanks to network connectivity vehicles can receive information from the cloud in relation to the congestion's conditions. Furthermore, the information about congestions could be use also for traffic management and fleet management.

- Enhanced situational awareness: it is meant the fact that vehicles could receive information related to the surrounding environment and the "real-time" aspect of the data transferring. From the analysis, the situational awareness is one of the major aspects that differentiate C-V2X over DSRC, mainly because cellular technologies add to the potential communications that vehicles can have also V2N. The communication to the network would ultimately introduce the possibility for vehicles to receive information about the characteristics of the environment that they are approaching during their path, without being constrained to line-of-sight communication which is on the other hand something associated to DSRC.

- Emergency vehicle operations: the ability of warning vehicles that are transiting in a specific area about the presence of emergency vehicles. This could ensure a more fluid and faster transiting of an emergency vehicle in the road environment. In this perspective, Telia's respondent mentioned that emergency services in relations to the spectrum of communication. In addition, Swedish Transport Administration's interviewee has considered that C-V2X could benefit the way in which emergency vehicles operates. Overall, there haven't been collected much information about this use case, nevertheless, is could be expected that the communication between passengers' vehicles and emergency ones would help to smooth emergency vehicles' operations.

- Information sharing: this consists in providing vehicles the ability of exchanging information with each other. The information could be the ones of on-board sensors or, for example, the information related to the road conditions to vehicles behind them. From the analysis, it could be seen a relationship in the fact that OEMs, thanks to their clouds, can provide this kind of information, gathered by some vehicles, to other vehicles that are approaching a specific area. This use case seems to be once more possible thanks to the V2N communication that characterize C-V2X, rather than DSRC.

Considering DSRC on the other hand, the analysis of the collected data highlighted how it would be realistically used mainly in intersections, or in general hotspots of a city that have similar characteristics to intersections. This consideration leads to the fact that the different use cases proposed by the Southwest Research Institute (2018) reenters in the contexts in which DSRC would be implemented, according to the collected data. Furthermore, what seems to create a stronger confirmation of what is considered in the literature review on the use cases of DSRC, consists in the fact that applications such as *Forward Collision Warning* and *Emergency Electronic Brake Light* entail the need of very low latency and a reliable connection between devices, which are two aspects that could be associated to DSRC in this specific case. In addition, it could be considered that DSRC has a shorter operational range than C-V2X, thus it seems feasible to use it in situations in which the distance among devices is short.

Overall, C-V2X represents a better solution than DSRC. As already mentioned, it enables to exploit V2N communication, which is not possible with DSRC. As discussed in the literature review, particularly by Gulia (2020), C-V2X could be used also in absence of network thanks to sidelink communication called PC5, that is designed to function on 5.9 GHz spectrum. Moreover, as confirmed also by the data analysis, C-V2X is a more scalable technology than DSRC, and it is possible to leverage on the already existing cellular infrastructure rather than creating a new one dedicated for the Wi-Fi based communication.

Even though C-V2X seems to be the best choice in the future perspective, DSRC maintain its importance. This consideration derives from the fact that it is a technology that has been developed for a longer time (Southwest Research Institute, 2018, TechVison Group of Frost&Sullivan, 2017), which implies that it would be mainly used in sidelink communication, at least at the moment. DSRC maturity seems to be reflected also in the collected data, given that a recurrent advantage of this technology is reliability and low latency performance, that respondents have associated to it.

At the current state, the most feasible choice, according both to the literature review and the data collection analysis, seems to be the joint use of DSRC and C-V2X, to exploit the best from both technologies. The analysis highlighted how DSRC represents the best alternative to be implemented especially in intersections, while C-V2X could be used to cover all the remaining use cases, leveraging also on the enhanced efficiency that could be reached with V2N. Considering the collected data on the potential current coexistence of these two technologies, it could be found a connection with the *Dynamic Hierarchical Hybrid ITS*, mentioned in the literature review related to how a hybrid ITS could be. As already mentioned, in a dynamic network C-V2X is used for communication between main devices and base stations, between main devices and between main devices and regular devices, while DSRC would manly be used for allowing communication between devices in the same group (Kelia et al., 2020). In this perspective, the concept of *"same group"* seems to be associable to specific hotspots in an urban environment, i.e., intersections. C-V2X would be used to ensure the other information exchanges. Information represents a crucial aspect for AVs, and one of the reasons to rely on both DSRC and C-V2X consists in the fact that, as long as information is provided to vehicles, it doesn't matter the source from which they come. The importance of information for AVs can be also seen in the literature related to VANETs, especially in the "*content-centric networking*" concept that refers to the fact that the priority in the communication among vehicles is placed upon the content, the information itself, not on the source of that information (Gerla et al. 2014). From the analysis of the data, it could be derived that hybrid ITS would be realistically present mainly in urban environments, given that the investments in RSU in external areas of cities, and in vast geographical spaces, seems to be not feasible from an economic point of view. Furthermore, data show that C-V2X can manage AVs requirements in less complex environments such as rural areas or on highways.

5.5) OEM'S PERSPECTIVE

From the analysis of data, it has emerged that, 5G would represent a big concern for automotive manufacturers, since it is something that would be taken care of mainly by other actors in the market, probably by operators. 5G would be there and OEMs would use it. Probably, one of the challenges related to 5G for automotive firms consists in the timing of the investments, as was specified by the Volvo Cars' respondent. In this perspective, it is a matter of deciding when it is the right moment to invest in 5G chipsets, for example. This would be influenced by the kind if specifications required, given that the latter the investments on this technology are done, the better specifications and price firms would get.

Furthermore, by comparing the literature review and the data analysis, two major challenges could be identified, that are linked to each other as well: product architecture and business ecosystem.

From the product architecture perspective, Volvo Cars' interviewee provided the most relevant thoughts. More precisely, vehicles are getting ever more complex products, with each part that is required to be connected to the rest of the architecture, thus not just functioning independently. In this sense, the connection links of vehicles would increase their importance as a mean of enabling other components of the device to be connected to the network. Vehicle's platforms need to be developed to ensure that new connection needs are fulfilled.

A relationship between vehicles' platform and the business ecosystem challenge can be found, especially by considering the AD Volvo program presented by (Pushpananthan & Elmquist, 2019). More in detail, the literature review on this business initiative created by Volvo highlighted how modularization revealed to be a key factor for the development and commercialization of AVs. This is particularly true considering that thanks to the modular architecture, a product platform results to be more attractive for other actors, which is ultimately something that Pushpananthan & Elmquist (2019) considered central in creating a sustainable business ecosystem. In the perspective of AVs deployment, it could be derived that OEMs would experience great advantages in opening up their platforms to external actors, mainly because all the competences needed when it comes to AVs couldn't realistically be developed inside the boundaries of the same organization. As described in the literature review, Volvo developed a joint venture with Zenuity to outsource the software development process. The nature of the relationship led to the creation to an innovation ecosystem, that ultimately enhanced the attractiveness of the overall ecosystem, in which Volvo is the keystone organizations. In this perspective it could be derived that, for AVs development and deployment, modularization is a key aspect to consider by OEMs, especially those that intend to rely on other organizations as products/service suppliers. Moreover, OEMs as keystone organizations needs to be committed to ensure that their business ecosystem would operate optimally, also in the perspective of its extension and strengthening.

5.6) POLICYMAKER'S PERSPECTIVE

The collected data highlight how 5G standardization would not represent a big issue for regulators, because there is already a big effort in harmonizing it by competent organizations. In this regard, there is an alignment with the literature review, specifically when the role of 3GPP is discussed in relation to 5G. As considered by Osseiran et al. (2020), 5G standardization process has been divided in three *Releases*, hence there is already a good effort. 3GPP also aims at ensuring a backwards and forwards compatibility (3gpp.org), and this could be linked to the scalability concept already mentioned.

As can be derived from the collected data, as well as from the literature review, policymakers in the mobility field should take some positions, especially when in comes to the 5.9 GHz spectrum, which has been allocated for ITS applications. As highlighted by Telia's respondent, this is one of the key aspects on which authorities should intervein in order to define the evolution of the market, given that actors that have their stakes in the business opportunities related to AVs could take more accurate business decisions, also when it comes to alliances and other relationships with other organizations. Additionally, has mentioned in the literature review, the 5.9 GHz spectrum has been allocated to ITS applications in a general way, thus both DSRC and C-V2X have the same rights over it, and the major issue that could be identified in this perspective is the *co-channel interference*. As recommended by GSMA (2017), policymakers should maintain a neutral approach.

From the analysis, two other challenges could be considered: harmonization of regulations and information management.

As already mentioned, 5G would be harmonized across different geographical areas, different countries, and continents. On the other hand, the same is not true when dealing with laws and regulations. There could be many differences, even subtle, and even from city to city that contributes to increase the complexity of the norms related to vehicles. In this perspective, Volvo respondent suggested that regulatory authorities should intervein to mitigate the differences in the laws, to obtain more homogenous regulations, that would ultimately benefit AVs functioning.

Policymakers, as emerged from the analysis, should also intervein when it comes to information management, especially considering that AVs would produce and require a considerable bigger volume of information to function, thus authorities need to manage the way in which these data are used. Furthermore, regulators should define which information needs to be shared by OEM or their vehicles, also to guarantee security. In this regard, policymakers could allow, or even deny, the access of a vehicles to a specific area according to the information that vehicles themselves share with them about the actual capabilities and technologies that the devices have.

6) CONCLUSIONS

In this final section there would be provided a brief overview on this thesis, and there would be provided potential answers to the main research question and to the two sub-research questions. Lastly there would be proposed considerations for future research on the field of this work.

6.1) CONCLUSIONS OVERVIEW

As mentioned in the paragraph 1.1, 5G is strictly linked to the concept of IoT, which implies interconnectivity and exchange of information, and in which also reenters the concept of AV and autonomous drive. More precisely, vehicles are becoming more and more connected, and they are exchanging an increasing volume of data, and in this perspective ICT like 5G would have a key role for their wireless connectivity features and their performance. Moreover, while dealing with AVs the concept of V2X as communication paradigm is central, given that it enables vehicles to communicate with all those devices that would be present in the ITS, and would be enhanced by using 5G, especially considering C-V2X. The economic relevance of the upcoming business opportunities related to autonomous drive is particularly important and there are many actors and organizations that are putting their stakes in this sector.

As considered in paragraph 1.2, the literature on the coexistence of 5G and AVs resulted to be fragmentated. Some authors have tried to develop models to overcome to some specific AVs failure, yet some of them haven't considered 5G in their research works. Another consideration that could be done regarding the existing literature is that there are many researches that have been conducted in the past, that could have been biased by a not complete enough understanding of 5G and AVs. Additionally, there haven't been found many papers that have focused also on the urban environment as an operational context for AVs, and the implications that it could have in the overall understanding of the phenomenon under study.

Considering the potential limitations identified in the current literature, the researcher intended to enrich the understanding on the relationship between 5G and AVs by conducting interviews with people working for companies that are committed to the two main topics under study, with the aim of providing a concrete and clear understanding about them.

In order to reach the objective of this thesis the main research question is:

"What expected role would have the diffusion of 5G network technology in the deployment of autonomous vehicles in the perspective of local mobility in urban contexts?"

For the purpose of a more complete understanding of the concepts, the overarching research question would be divided in two additional sub-research questions.

"Which are the most relevant benefits that the use of 5G network technology, as overarching communication infrastructure, could have in relation to the deployment of AVs in an urban environment?"

"Which are the main challenges that could be faced while trying to advance the deployment of AVs also relying on 5G network technology? Which could be the most feasible solutions to these challenges?"

6.2) FIRST SUB-RESEARCH QUESTION

The first sub research question, mentioned in the previous paragraph is:

"Which are the most relevant benefits that the use of 5G network technology, as overarching communication infrastructure, could have in relation to the deployment of AVs in an urban environment?"

As emerged from the analysis, there are some key benefits related to 5G, compared to previous generations of ICT, nevertheless 4G seems to maintain its relevance in the AVs' perspective. Overall, 5G is a better network technology for the reasons that would be discussed in this paragraph.

The first one is the ultra-low latency, that would enable a considerable faster data transfer compared to previous ICT. Latency has been highlighted as crucial, especially when it comes to real-time applications of the technology, hence when the reaction time needed is very low. In this perspective, 5G represents the best choice also in relation to remote controlling vehicles from a big distance, which is an application in which latency plays a central role in the efficiency and security of operating a vehicle. The use case that would be enhanced by the URLLC characteristic of 5G is also represented by edge-computing, which emerged as a key aspect to consider in the perspective of AVs' functioning. This is particularly true given that, the built-it computational power represents an important resource for AVs, but it could be also externalized in order to be performed elsewhere. This externalization of the computational power seems to become a requirement for the ITS especially when the number of vehicles would increase, and in general when the volume of data exchanged and needed to perform the decision-making process would increase considerably. Edge-computing capabilities and applications would be improved with 5G, as well as the next generations of ICT, especially because the low latency performance would enable a considerably quicker data transfer between nodes. As emerged during the analysis, edge-computing could be also seen as a potential solution in issues like network slicing.

Furthermore, network slicing has emerged as one of the core concepts that 5G introduce, and that would have deep implications for AVs' deployment. More precisely, it implies that there could be portions of the network that are dedicated for specific use cases, resulting in a high reliability of the network. In the mobility perspective, there is the 5.9 GHz spectrum that has been allocated specifically for ITS proposes.

The reasoning on reliability could be extended to the bandwidth, and the fact that, especially in urban environment, 5G represents a much better solution compared to 4G given that bandwidth could be more efficiently ensured, also thanks to less interferences. From the analysis it has emerged that the density of devices would increase the performance gap between 5G and 4G, more precisely 5G ensures a much better coverage in denser areas than 4G can do. The need of 5G in urban areas is also derived from this consideration.

Another important benefit that the use 5G in the mobility perspective brings, is the higher precision positioning. The level of precision and reliability that are associated to 5G compared to GPS, enable to perform more efficiently and in a safer way line-changing maneuvers, for example. Furthermore, the signal is less subjected to interferences, especially in urban areas, where there is the so-called *"urban-canyon"* problem.

Nevertheless, it is worth considering that it has emerged that there is the need of other technologies to support AVs' deployment, and that 5G is one enabler among many. These core technologies are sensors, software and cloud.

Sensors ensure that vehicles can gather information on the real world and software allows vehicles to interpret this information and take decisions. The information collected by vehicles themselves could be complemented by the data that they receive from the cloud. Overall, the key concept is the ability of ensuring the more complete and precise situational awareness possible.

Network connectivity has emerged to essential in relations to AVs, mainly due to the efficiency benefits that it entails. It has emerged that AVs could operate safely and in security even without network connection, but it turned out that they wouldn't be efficient enough.

6.3) SECOND SUB-RESERCH QUESTION

The second sub-research question considered in this study is:

"Which are the main challenges that could be faced while trying to advance the deployment of AVs also relying on 5G network technology? Which could be the most feasible solutions to these challenges?"

In relation to 5G, one of the potential issues that could be associated to it, especially in urban areas, is the ability of ensuring full coverage, which could be also linked to the 5G signal propagation sensitivity. Overall, from the analysis it turned out that it isn't a relevant problem, given that it is a matter of investing in many antennas to ensure an approximately full coverage inside a city. The amount of investments, in this regard, could be seen as an issue as well, but it has emerged that it would be economically justifiable to invest in many antennas in urban context since the use cases that they are going to serve for are numerous, beyond the mobility perspective, thus there would be a big number of people that are going to finance that.

The challenges about investments could be also identified, in general between OEMs and infrastructure providers. Given that OEMs don't invest at least there is an infrastructure, and infrastructure providers do not invest until there are vehicles that would use their infrastructure. Nevertheless, there is the necessity of starting investing. The novelty of AVs' business opportunities, and the fact that this sector is attracting organizations previously not involved in the automotive market, increase the complexity of identifying "who is going to pay for what".

Another issue could be represented by how the 5.9 GHz spectrum would be managed, given that it is central when it comes to V2X technologies. Moreover, there are many actors in the market that have their interests in this spectrum, also in the perspective of developing alliances and business models. As emerged from the analysis, there is no clear position by authorities yet, and a lot of discussion is still ongoing.

Furthermore, in extending the potential challenges that authorities in the mobility field could face, in addition to the spectrum management, there is the harmonization of regulations. More precisely, there is a big difference, also on the micro level, among laws in the mobility sector. The harmonization, in the perspective of autonomous drive, would result in a less complex environment to navigate in, even in the occasion of moving from one city to another.

The other challenge related to policymakers is represented by how information in the ITS would be managed. This derives from the fact that vehicles would rely on an increasing amount of information to operate, thus authorities need to figure out how to ensure cybersecurity and how to define which information should be shared by vehicles, also to be able to give hypothetical permissions

Considering the perspective of OEMs, there are challenges associated to product's architecture, which is becoming more complex and characterized by more interconnected components. In this regard, the number of components that should be associated to the communication link is increasing. Moreover, manufacturers could face the challenge of timing, also in the perspective of the specifications that they could get from suppliers.

Another relevant, challenge associated to the development and deployment of AVs is related to how organization could organize their businesses and what kind of relationships they should develop with other actors. As emerged from the literature review, business ecosystems and modularization of the product's platform are two key organizational aspects that OEMs should take into consideration, with the aim of gathering new competences and creating an ecosystem in which they represent keystone firms. The overall attractiveness and value of an organization's ecosystem increase with the progressive extension of its boundaries.

Lastly, focusing on the hybrid transportation system characterized by the coexistence of DSRC and C-V2X, the major concern that has emerged is the "*co-channel interference*" that results from the equal rights of the two technologies over the 5.9 GHz spectrum, which could potentially solve by following the three steps proposed in the literature review.

6.4) MAIN RESEARCH QUESTION

The main research question of this study is:

"What expected role would have the diffusion of 5G network technology in the deployment of autonomous vehicles in the perspective of local mobility in urban contexts?"

As already mentioned, 5G network technology alone will not contribute to accelerate the deployment of AVs. Nevertheless, it represents a crucial enhancement in the mobility perspective. Thanks to its characteristics it introduces new possibilities, such as network slicing and edge-computing, that are two key concepts in the perspective of autonomous drive. Furthermore, especially in urban areas, 5G is predicted to be required because, given the high density of devices, 4G would probably not be a reliable network communication technology. Furthermore, 5G would represent the overarching communication mean of C-V2X technologies, that has emerged to represent the potential future enabling technology for V2X, which is key for an ITS with AVs.

6.5) FUTURE RESEARCH PROPOSALS

The research has shown that 5G would be one of the central technologies on which AVs would be rely, but not the only one. The majority of uncertainties emerged during this study has been related to the business opportunities and the role that the different actors that have their interest in the AVs sector could have, as well as how policymakers could intervein in order to stimulate the deployment of autonomous drive.

With that in mind, in the future there could be the need to investigate more on OEMs organizational possibilities in the perspective of developing business ecosystems and in general in the way that they could increase their commercialization chances of AVs.

The second proposal regards the regulatory point of view, and more precisely how policymakers in the mobility field could overcome some of the challenges that has emerged from this study, or other not considered, with the ultimate focus of defining the path to follow also by the other organizations, such as OEMs.

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UNIVERSITY OF GOTHENBURG
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The role of 5G network technology in the evolution of local mobility with a particular focus on Autonomous Vehicles.

Supervisor

Linus Brunnström – GU

Paolo Spagnoletti – LUISS

Student

Gian Marco Di Lascio

MATR: 720021

Co – Supervisor

Luigi Laura – LUISS

Graduate School

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INTRODUCTION

RESEARCH BACKGROUND

Dealing with 5G, it has been considered also the topic of Internet of Things, which is progressively extending its relevance and in which it is possible to also identify Internet of Vehicles. This derives from the fact that vehicles are getting more connected and are exchanging an increasing amount of information.
AVs are associated to a wider perspective of communication, that enriches the variety of counterparts in the network ecosystem in which AVs represent a key element. The communication paradigm that would characterize the future mobility can be seen as a Vehicle to Everything (V2X), which consists in the possibility of exchanging information not only among vehicles, but also between vehicles and other elements present in the urban context. By the passing of the time, the integration between vehicles and network technologies has become deeper and it would continue to be developed. The co-evolution of these two concepts would lead to an increasing variety of services that would enrich transportation system's potentialities. The overarching network infrastructure would be represented by network technologies. In this regards, 5G network entails important features that have the potential to accelerate the deployment of AVs.

RESEARCH PROBLEM

The research problem consists in the fact that the already existing literature resulted to be fragmentated, in the sense that papers presented some solutions to very specific problem without reasoning on other implication. Other works didn't consider 5G, thus the considerations developed could have been different if this ICT would have been considered. Having in mind these criticisms to the literature, this thesis aims to provide a complete understanding on which are the dynamics that are present when dealing with the use of 5G as network technology for AVs functioning. Furthermore, it is worth mentioning the fact that the technological advancements proceed at a very fast pace, thus past years works may result partially outdated.

RESEARCH PURPOSE

Considering the previous paragraphs, the purpose of this thesis is to provide a detailed overview on the ways the diffusion of 5G can affect the development and functioning of AVs. More precisely, the focus of the research would be on trying to provide practical understanding of how the evolution a network technology is influencing the features and functions of AVs, especially in urban areas.
Overall, the different characteristics of 5G would be considered and their potential benefits for an ITS would be discussed, with the purpose of highlighting the central concepts that would help to identify which are the implications that 5G would have in these regards, as well as underlining the most relevant differences with the previous generations.

Additionally, this work has the objective to identify which are the main challenges associated to the diffusion of both 5G and AVs, considering the perspective of OEMs and Policymakers.

RESEARCH QUESTION

Considering what has been outlined so far, it is possible to link it with the overarching research question that would guide the development of this thesis. More precisely the main research question would be the following:

"What expected role would have the diffusion of 5G network technology in the deployment of autonomous vehicles in the perspective of local mobility in urban contexts?"

It is worth precising that with the term *"mobility"* the researcher intends to mainly focus on AVs given that this sort of vehicles are the ones that more deeply can be affected by 5G, and in general the features of network technologies, compared to vehicles that are still manually driven. For the purpose of a more complete analysis of the topics under study, the overarching research question is divided in two additional sub-research questions:

SRQ1: "*Which are the most relevant benefits that the use of 5G network technology, as overarching communication infrastructure, could have in relation to the deployment of AVs in an urban environment?"*

SRQ2: "*Which are the main challenges that could be faced while trying to advance the deployment of AVs also relying on 5G network technology? Which could be the most feasible solutions to these challenges?"*

The target of this thesis is thus any automotive manufacturer which is planning to develop, or is already developing technologies for AVs deployment, and that is interested in enriching its understanding on how network technologies, specifically 5G, could influence and facilitate the functioning of AVs in urban contexts. In addition, this work also aims to provide practical considerations and solutions for policymakers that operate in the mobility field can consider while establishing strategies for the deployment of AVs in an urban mobility environment.

RESEARCH BOUNDARIES

This thesis has been conducted mainly focusing on Sweden given that the identification of the best profiles for interviewees has been done also with the help of First-to-Know, which is based in Gothenburg, hence the network that the company has is mainly composed by Swedish people. Additionally, the choice of Sweden has been done also because this country is considered to be one of the most innovative in the world (Visual Capitalist, 2021, World Intellectual Property Organization, 2021), and its commitment in the automotive

innovation, as well as AVs development, is remarkable considering the fact that there are many initiative and pilot related to autonomous drive.
Having in mind this information, the quality and relevance of the findings that emerged from this study could be ensured, considering the experience of the selected respondents.

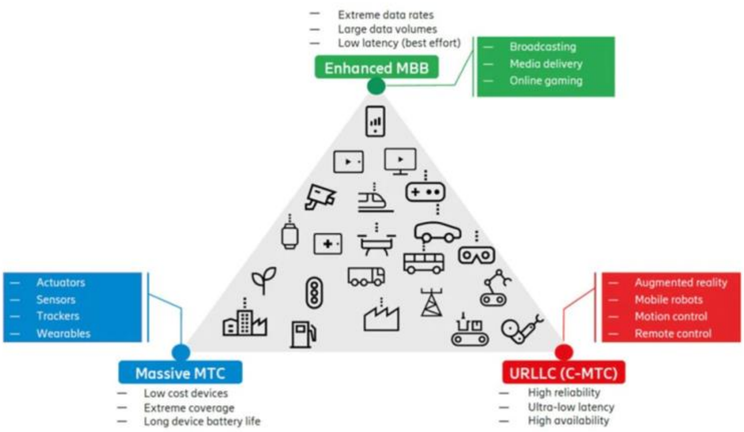
LITERATURE REVIEW

This chapter aims at presenting the most relevant literature on the topics under study, hence providing the current understanding on the relevant concepts related the implication of the use of 5G for the deployment and functioning of AVs.

5G

5G is a network technology whose development has been driven by increasing amount of connected devices and by the vast amount of transferred data. Panwar et al. (2016) use the abbreviation 3D to regroup three elements that have boosted the development of 5G: Device, Data and Data transfer. In addition to the just mentioned 3Ds, there are other trends that triggered the need for an enhancement of the ICT infrastructure: a better optimization of energy consumption and ubiquitous connectivity. The concept of ubiquity associated to 5G, entails its ability of enabling a “total” connectivity experience, in the sense that devices would be constantly connected, independently to the place and moment, overcoming issues related to the density of devices connected to the same network. 5G would represent an enhancement in relation to ITS’s services thank to the latency that it ensures. More precisely, when it comes to intelligent mobility and connected AVs latency is a crucial aspect to take into consideration, given that delays in the data transferring would compromise safety and efficiency of these vehicles. Considering 5G application scenarios it is possible to identify three key connectivity requirements (Osseiran et al., 2020): enhanced mobile broadband (eMBB); massive machine type communication (mMTC); ultra-reliable low latency communication (URLLC). In the perspective of this research the most important connectivity aspect is represented by URLLC.

Figure 1 – 5G application scenarios



As already mentioned, vehicles connectivity could be associated to IoT, and in this regard it possible to talk about Internet of Vehicles. The architectural description of IoT provided by Patel et al. (2016) finds a correspondence also with Internet of Vehicles. More precisely the three layers in which the architecture is described are: sensors, gateways and networks, and the management service.

Network slicing represents the main enabler of network service coverage and for tailored and customizable network services for specific application scenarios (Zhang et al., 2017, Rost et al., 2016, Jiang et al., 2016). It represents an important aspect to take into consideration in the perspective of this thesis, particularly referring to the fact that it would allow AVs to have a dedicated "*slice*", of the overarching network, that could have the specific features that would maximize the efficiency and reliability of it as a communication infrastructure.

AUTONOMOUS VEHICLES

Autonomous vehicles can be classified in different levels, up to level 5 of autonomy. According to (SAE, 2018), the different parameters to consider in order to classify vehicles are: DDT (sustained lateral and longitudinal vehicle motion control, and object and event detection and response), DDT Failbacks and ODD. This classification also enable to understand which would be the role of the driver during a ride and in which occasion he should take over the control of the vehicle form the system.

When it comes to ITS of connected vehicles, the objective of developing a smarter mobility is particularly linked to the ability of ensuring the presence of three main communication paradigms among vehicles: Vehicle-to-Vehicle; Vehicle-to-Infrastructure; Vehicle-to-Everything.

These paradigms ensure that vehicles are capable of receiving and sending a complete set of information with the other devices that compose the ITS. Information results to be key for the development of an ITS and there are two aspects that could be linked to AVs.

The first one is the "time-space validity" that consists in the fact that the data gathered by a vehicle have a particular spatial scope of interest, in the sense that they represent relevant information only for the vehicles/devices in a specific area (Gerla et al., 2014). Additionally, the time dimension refers to a temporal scope of the necessity of specific information, which would have its relevance in a defined time length. Moreover, in understanding the vehicles' interaction attitude it is useful to cite the "content-centric networking", that refers to the fact that the priority in the communication among vehicles is placed upon the content, the information itself, not on the source of that information (Gerla et al., 2014).

All the interactions that vehicles would have inside an ITS could be linked to the concept of VANETs, which can be defined as networks specifically designed to allow exchange of data between vehicles and other devices in the transportation environment, incorporating the three communication paradigms (V2V, V2I and V2X) (Boukerche & De Grande, 2018, Abdelhamid et al., 2017, Papadimitratos et al., 2009, Amadeo et al., 2016, Silva et al., 2016). This ad-hoc network would benefit by the adding of new devices inside them, especially considering the fact that the peer-to-peer communication that characterize them represent a constraining condition, that could be overcome when there is a sufficient amount of vehicles. This derives from the fact that the source of the information is less important of the information itself, thus the key task inside VANETs is the ability of ensuring that information is correctly transferred. The interactions among vehicles is not just limited to the exchange of information but it could be used also to perform computational tasks thanks to Vehicular Cloud Computing, that implies that underutilized on-board computational power could be used by other vehicles according to their needs (Hussainn et al. 2012, Boukerche & De Grande R., 2018)

TECHNOLOGY IMPLEMENTATION

Considering the importance of V2X paradigms in the perspective of and ITS, there are two main technologies that could enable it: DSRC and C-V2X. There are some key differences that should be considered in order to understand how they could be used. Firstly, DSRC is a Wi-Fi based communication technology (Kenney, 2011), hence it enable peer-to-peer information exchange (Southwest Research Institute, 2018, TechVison Group of Frost&Sullivan, 2017). This represents on the biggest downsides of DSRC, given that it is constrained by line-of-sight communication. On the other, hand C-V2X relies on cellular technologies, thus it enable beyond line-of-sight communication, also introducing the possibility of using V2N, which would ultimately enhance the situational awareness of vehicles given that they can receive information from more connected devices. Nevertheless, DSRC has been developed for a longer time, resulting in a more mature technology. Overall, DSRC seems not to have an evolution path while C-V2X does. This difference could be linked mainly to the fact that cellular communication allows vehicles to be connected also to the network (V2N) thus ensuring a wider range of services and application scenarios. Moreover, cellular technologies have more application than DSRC, in many other sectors

TABLE 2 – Comparison between DSRC and C-V2X

Comparing DSRC and C-V2X

	DSRC	C-V2X
Operation in 5.9 GHz spectrum	Yes	Yes
Coexistence in 5.9 GHz	Yes (Adjacent channel with 3GPP technology)	Yes (Adjacent channel with .11p; co-channel coexistence from R-14 onwards)
Technology	Based on IEEE 802.11p	Based on mobile 3GPP
Target use cases	Safety only	Safety & enhanced
Support for network communications	Limited (via aps only)	Yes
Support of low-latency direct communications	Yes	4ms with path 1ms with Rel-16
Security & privacy on V2V/V2I/V2P	Yes	Yes
Security & privacy on V2N	N/A	Yes
Evolution path	No	Yes
MIMO solution	No support standardized	Rx diversity for 2 antennas mandatory; Tx diversity for 2 antennas supported

https://ytd2525.wordpress.com/tag/v2i/

DSRC is mainly linked to real-time application, in which latency and reliability that this technology ensures represent determinant factors to consider. On the other hand, C-V2X, thanks to the possibility of exploiting network connection enables to rely on more services and use cases, which would ultimately enhance vehicles' efficiency.
The most feasible solution in order to ensure V2X communication is the joint use of both DSRC and C-V2X, hence developing a hybrid transportation system. The major challenge in this regard is represented by the "co-channel interference", due to the fact that both technologies have the same rights over the 5.9GHz spectrum that has been allocated for mobility purposes. In this regard, 5GAA has proposed an approach to potentially solve this issue, which consists in three steps (5GAA, 2018).

OME'S ORGANIZATIONAL PERSPECTIVE FOR DEVELOPING AUTONOMUS VEHICLES

The Volvo AD program, presented by (Pushpananthan & Elmquist, 2019), showed that form an organizational point of view one of the most important aspect for an OEM to consider when it comes to AVs development and commercialization is represented by modularization. Thanks to it, the attractiveness of the product's platform increases contributing to create an interest also in other actors. This is crucial because dealing with AVs new competences are needed and OEMs have difficulties in developing all the needed experience inside their boundaries. Modularization contributes also to the creation of an innovation ecosystem (Pushpananthan & Elmquist, 2019) in which Volvo is the keystone firms and it should act in order to maximize the value of its business network.

METHODOLOGY

RESEARCH DESIGN

In relation to this study the research design that was considered more appropriate for its characteristics is the cross-sectional design. In trying to study which role 5G network technology could play for local mobility in urban context the generalizability of findings is important, thus the focus is not placed on the specific contexts in which the subjects that would participate to the study belong to, or their characteristics (Bryman & Bell, 2011). What is more relevant for the purpose of this research is to derive general findings from the thoughts and reflections of participants. This need is met by the cross-sectional design in a more appropriate way than the other research designs.

RESEARCH STRATEGY

In developing this work, a qualitative approach has been followed. The choice of this strategy is related to the nature of the topic of this thesis and the research question. More precisely, in analyzing which are the new implications of 5G network technology diffusion for the local mobility and the deployment of AVs, the main benefits and challenges associated the introduction of 5G in this field of research and the other related topics, it is important to ensure a wider understanding though in-depth data collection and analysis. For this reason, it is relevant to emphasize the importance of words rather than numbers as source of data, which is a characteristic of a qualitative research strategy.

DATA COLLECTION METHOD

For the purpose of this study, two sources of data have been used. The primary data consists in data directly collected by the researcher (Bryman & Bell, 2011) and for this study it is represented by interviews. Semi-structured interviews is considered the most suitable choice, also in accordance with the research design adopted, because they allow a sufficient level of structure while gathering information, resulting in a more consistent set of data to use for the analysis. Additionally, by asking the same critical questions to the different interviewees, it would be possible to gain a broader perspective on relevant aspects. Furthermore, semi-structured interviews leave space for some more tailored questions, in relation to some specific considerations developed by an interviewee. This level of flexibility of the conversation would give the possibility to deal with new topics previously not considered and to further investigate on them. Connected to the choice of the semi-structured interviews, a purposive sampling approach would be use in the selection of respondents. Interviews have been held only online, through tools like Zoom and Teams, depending to the preferences of the respondents. In trying to find the most appropriate interviewees the researcher would also rely on the Swedish consulting organization named First-to-know, which has a sufficient level of experience in innovation management and that could help to identify the most valuable personalities whose expertise and experience in 5G and mobility would contribute to produce findings with the highest possible quality. Nevertheless, the majority of respondents have been selected and contacted by the researcher alone.

The secondary data would be gathered mainly from online libraries (LUISS and Gothenburg university) and from reports of relevant organizations. A *narrative* approach has been followed since it particularly suitable for an *inductive* research and when it is not so straightforward to identify exclusion criteria (Bryman & Bell, 2011).

DATA ANALYSIS

To perform the analysis of the data gathered from the interviews thematic analysis would be used. The first step is represented by initial coding, which consists in breaking down data into smaller codes that are building block of the analysis (Bryman & Bell, 2011) and that should emerge directly from the transcriptions of the interviews. The coding tasks would be done after each interview, with the aim of comparing the similarities and differences in the codes emerged from the various transcriptions. There are different alternatives in coding in thematic analysis, but the one that the researcher is more prone to use is the so called "*color coding*". It consists in highlighting, directly on the text (in the case of this research, the interviews' transcriptions), with different colors, the quotes that can be associated with a specific code. One of the advantages that this way of coding could bring is that it prevents the fragmentation of the transcriptions. The fact the original structure of the transcriptions could be maintained could mitigate one of the limitations of the thematic analysis, which is the loss of context as a consequence of the fragmentation of the text (Bryman & Bell, 2011).The second phase of the thematic analysis is represented by the formation of themes, by aggregating various related codes. During this step, codes would be compared, to find similarities between them that would lead to the emergence of themes. It is important to notice that the analysis process, particularly coding, would be done in continuous comparison with the data emerged from the literature review. The aim of this comparison is to identify similarities and discrepancies between the new data generated by interviews and the data already collected by other sources, which could improve the reliability of the results of the analysis**.**

EMPIRICAL FINDINGS AND DATA ANALYSIS

Form the data collection and analysis it has emerged that 5G has important benefits for autonomous drive, especially compared to 4G. It is worth considering that 4G still maintain its relevance and it would be realistically be used to support AVs functioning, but mainly in areas outside cities. It has emerged that 5G seems to be required in cities because of the high density of devices and the competition for bandwidth. Especially on bandwidth, 5G enable to have a dedicated portion of the network specifically allocated for autonomous driving use cases, thanks to *network slicing*. In addition, 5G entails improvement of latency and positioning. High-precision positioning resulted to be a considerable enhancement especially in urban areas, where current GPS signal could face more interferences due to the *urban canyon* problem. Overall, interviewees have agreed on the fact that vehicles must be able to handle themselves situations in which there is no network connection, so sensors and software technologies have to be able to manage these situations. These offline capabilities derives from the fact that network connection couldn't be ensured all the time. Nevertheless, 5G coverage wouldn't be so challenging to be ensured, especially in urban areas where it is all a matter of investments and, given that there are a lot of people financing 5G diffusion in cities, coverage will be there. In extending the reasoning on investments, from the analysis it has emerged the one of the central challenges when it comes to the infrastructural perspective is the identification of "*who is going to pay for what".* In addition, it is possible to distinguish physical infrastructure and digital one. The physical infrastructure should be maintained in a good status because it contribute to the correct functioning of vehicles and their awareness of the context in which they are operating. Considering the digital infrastructure, it needs to be developed and designed, with the aim of creating a *digital twin* of the physical one, in a way that it is possible to provide vehicles with the same information that a human driver could detect. In general, the infrastructure should be designed to ensure that vehicles have the best situational awareness possible in order to have a great amount of information according to which taking their decisions. The reasoning on situational awareness and network connectivity can be further extended by considering cloud-computing. As emerged for the analysis, it is something important to take into consideration when dealing with connected AVs, especially because the cloud contribute to provide information about what it's happening in areas that vehicles are approaching, which could be the conditions of the roads, the status of congestions, and other data that would ultimately ensure a more complete understanding of a vehicle's path. Nevertheless, the introduction of 5G would benefit in a more pronounced way edge-computing, which is something that would be realistically be exploited for real-time applications and, according to Telia's respondent, it is something that could help to solve problems like delays and network slicing. It is worth precising that edge-computing is a very early-stage technology thus it was not possible to develop an extensive understanding of its implications.

Considering DSRC and C-V2X, it has emerged that both technologies are needed at the moment, especially in urban environments, given that cities are characterized with many hotspots in which DSRC could be used, such as intersections. DSRC's latency and reliability characteristics would be mainly used in contexts in which peer-to-peer communication could be ensured and real-time use cases are required. Overall, all respondents have agreed on the fact that C-V2X is a better solution in the long term, especially because it enables to overcome line-of-sight constraints associated to DSRC, it's a more scalable technology because it is possible to leverage on an already existing cellular network, and it entail the possibility of providing vehicles with a more complete situational awareness. The hybrid ITS that is considered to be the most appropriate, comparing the literature review and the data analysis, is represented by the Dynamic Hierarchical Hybrid ITS.

Considering the perspective of OEMs, it has emerged that there aren't many challenges associated to 5G implementation. Probably the most relevant issue for manufacturers is represented by the timing of investments because it would influence the nature of specifications and the prices that OEMs would get. The two major challenges that could be identified are product architecture and business ecosystem creation, which are ultimately linked to each other. When it comes to the product architecture, OEMs should put more effort than in the past in trying to design vehicles in which a lot of components are interlinked, also in the perspective of the connectivity link to the network. Moreover, automotive manufacturers should extend the boundaries of their business networks with the aim of attracting new actors. This is particularly important in the perspective of AVs commercialization given that the set of competences and knowledge needed is getting wider and it would be not feasible to try to develop everything inside a single organization. What seems to be the conjunction element between product architecture and innovation ecosystem is represented by *modularization*.

Considering the policymakers' perspective, it has emerged that 5G harmonization wouldn't be so challenging given that there is a lot of standardization going on at the moment. A bigger challenge is represented by the harmonization of the regulations, especially considering that they could differ also on the micro level. Furthermore, it is worth considering that regulators should also manage how the 5.9 GHz spectrum would be used, because by clarifying the different rights over this spectrum, actors that have their interests in developing their businesses also in accordance to how this spectrum would work could take business decisions and create relationships with other organizations. Additionally, another relevant task of regulators is represented by the information management and security.

CONCLUSIONS

In presenting the answers to the research questions, the researcher decided to start from the two sub-research question and then concluding with the main research question of the thesis.

FIRST SUB-RESEARCH QUESTION

The first sub research question, mentioned in the previous paragraph is:

"Which are the most relevant benefits that the use of 5G network technology, as overarching communication infrastructure, could have in relation to the deployment of AVs in an urban environment?"

The first one is the ultra-low latency, that would enable a considerable faster data transfer compared to previous ICT. Latency has been highlighted as crucial, especially when it comes to real-time applications of the technology, hence when the reaction time needed is very low. In this perspective, 5G represents the best choice also in relation to remote controlling vehicles from a big distance, which is an application in which latency plays a central role in the efficiency and security of operating a vehicle. The use case that would be enhanced by the URLLC characteristic of 5G is also represented by edge-computing, which emerged as a key aspect to consider in the perspective of AVs' functioning. This is particularly true given that, the built-it computational power represents an important resource for AVs, but it could be also externalized in order to be performed elsewhere. This externalization of the computational power seems to become a requirement for the ITS especially when the number of vehicles would increase, and in general when the volume of data exchanged and needed to perform the decision-making process would increase considerably. Edge-computing capabilities and applications would be improved with 5G, as well as the next generations of ICT, especially because the low latency performance would enable a considerably quicker data transfer between nodes. As emerged during the analysis, edge-computing could be also seen as a potential solution in issues like network slicing. Furthermore, network slicing has emerged as one of the core concepts that 5G introduce, and that would have deep implications for AVs' deployment. More precisely, it implies that there could be portions of the network that are dedicated for specific use cases, resulting in a high reliability of the network. In the mobility perspective, there is the 5.9 GHz spectrum that has been allocated specifically for ITS proposes. The reasoning on reliability could be extended to the bandwidth, and the fact that, especially in urban environment, 5G represents a much better solution compared to 4G given that bandwidth could be more efficiently ensured, also thanks to less interferences. From the analysis it has emerged that the density of devices would increase the performance gap between 5G and 4G, more precisely 5G ensures a much better coverage in denser areas than 4G can do. The need of 5G in urban areas is also derived from this consideration.

Another important benefit that the use 5G in the mobility perspective brings, is the higher precision positioning. The level of precision and reliability that are associated to 5G compared to GPS, enable to perform more efficiently and in a safer way line-changing maneuvers, for example. Furthermore, the signal is less subjected to interferences, especially in urban areas, where there is the so-called *"urban-canyon"* problem. Nevertheless, it is worth considering that it has emerged that there is the need of other technologies to support AVs' deployment, and that 5G is one enabler among many. These core technologies are sensors, software and cloud. Sensors ensure that vehicles can gather information on the real world and software allows vehicles to interpret this information and take decisions. The information collected by vehicles themselves could be complemented by the data that they receive from the cloud. Overall, the key concept is the ability of ensuring the more complete and precise situational awareness possible. Network connectivity has emerged to essential in relations to AVs, mainly due to the efficiency benefits that it entails. It has emerged that AVs could operate safely and in security even without network connection, but it turned out that they wouldn't be efficient enough.

SECOND SUB-RESERCH QUESTION

The second sub-research question considered in this study is:

"Which are the main challenges that could be faced while trying to advance the deployment of AVs also relying on 5G network technology? Which could be the most feasible solutions to these challenges?"

In relation to 5G, one of the potential issues that could be associated to it, especially in urban areas, is the ability of ensuring full coverage, which could be also linked to the 5G signal propagation sensitivity. Overall, from the analysis it turned out that it isn't a relevant problem, given that it is a matter of investing in many antennas to ensure an approximately full coverage inside a city. The amount of investments, in this regard, could be seen as an issue as well, but it has emerged that it would be economically justifiable to invest in many antennas in urban context since the use cases that they are going to serve for are numerous, beyond the mobility perspective, thus there would be a big number of people that are going to finance that.

The challenges about investments could be also identified, in general between OEMs and infrastructure providers. Given that OEMs don't invest at least there is an infrastructure, and infrastructure providers do not invest until there are vehicles that would use their infrastructure. Nevertheless, there is the necessity of starting investing. The novelty of AVs' business opportunities, and the fact that this sector is attracting organizations previously not involved in the automotive market, increase the complexity of identifying "who is going to pay for what". Another issue could be represented by how the 5.9 GHz spectrum would be managed, given that it is central when it comes to V2X technologies. Moreover, there are many actors in the market that have their interests in this spectrum, also in the perspective of developing alliances and business models. As emerged from the analysis, there is no clear position by authorities yet, and a lot of discussion is still ongoing.

Furthermore, in extending the potential challenges that authorities in the mobility field could face, in addition to the spectrum management, there is the harmonization of regulations. More precisely, there is a big difference, also on the micro level, among laws in the mobility sector. The harmonization, in the perspective of autonomous drive, would result in a less complex environment to navigate in, even in the occasion of moving from one city to another. The other challenge related to policymakers is represented by how information in the ITS would be managed. This derives from the fact that vehicles would rely on an increasing amount of information to operate, thus authorities need to figure out how to ensure cybersecurity and how to define which information should be shared by vehicles, also to be able to give hypothetical permissions

Considering the perspective of OEMs, there are challenges associated to product's architecture, which is becoming more complex and characterized by more interconnected components. In this regard, the number of components that should be associated to the communication link is increasing. Moreover, manufacturers could face the challenge of timing, also in the perspective of the specifications that they could get from suppliers. Another relevant, challenge associated to the development and deployment of AVs is related to how organization could organize their businesses and what kind of relationships they should develop with other actors. As emerged from the literature review, business ecosystems and modularization of the product's platform are two key organizational aspects that OEMs should take into consideration, with the aim of gathering new competences and creating an ecosystem in which they represent keystone firms. The overall attractiveness and value of an organization's ecosystem increase with the progressive extension of its boundaries. Lastly, focusing on the hybrid transportation system characterized by the coexistence of DSRC and C-V2X, the major concern that has emerged is the "*co-channel interference*" that results from the equal rights of the two technologies over the 5.9 GHz spectrum, which could potentially solve by following the three steps proposed in the literature review.

MAIN RESEARCH QUESTION

The main research question of this study is:

"What expected role would have the diffusion of 5G network technology in the deployment of autonomous vehicles in the perspective of local mobility in urban contexts?"

As already mentioned, 5G network technology alone will not contribute to accelerate the deployment of AVs. Nevertheless, it represents a crucial enhancement in the mobility perspective. Thanks to its characteristics it introduces new possibilities, such as network slicing and edge-computing, that are two key concepts in the perspective of autonomous drive. Furthermore, especially in urban areas, 5G is predicted to be required because, given the high density of devices, 4G would probably not be a reliable network communication technology. Furthermore, 5G would represent the overarching communication mean of C-V2X technologies, that has emerged to represent the potential future enabling technology for V2X, which is key for an ITS with AVs.

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