LAPIN AMK
Lapland University of Applied Sciences

SOLUTIONS NEEDED FOR INDEPENDENTLY MOVING VEHICLES AND POSSIBLE APPLICATIONS OF THIS TECHNOLOGY

Zhdanov Evgenii

Bachelor's Thesis
School of Business and Culture
Degree Programme in Business Information Technology
Bachelor of Business Administration

2019

LAPIN AMK
Lapland University of Applied Sciences

Abstract of Thesis

School of Business and Culture
Degree Program in Business
Information Technology

Author Evgenii Zhdanov Year 2020
Supervisor Yrjö Koskenniemi
Commissioned by
Title of Thesis Solutions Needed for Independently Moving Vehicles and Possible Applications of This Technology
Number of pages 42

Autonomous vehicles are a set of technologies currently in its development and testing stage with a considerable potential for improving transportation safety and positively affect the quality of life for the majority of people. However, the technologies used for the implementation of self-driving are very highly sophisticated and required the further development of other technologies, such as Lidar, Radar, Cameras, and Neural networks.

This thesis aimed to define the concept of autonomous vehicles, analyze the current development stage, and describe use cases for this technology. The desk study methodology was used in order to collect and analyze the most relevant data gathered by companies testing the actual self-driving vehicles on the roads nowadays. This research produced relevant data and analysis of the hardware and software in the self-driving vehicles but did not provide the process of implementation for the actual self-driving vehicle.

The results demonstrate that self-driving technology nowadays is not ready for the consumer market or business-to-business sales. This technology is yet in the testing stage due to its high standards for the safety and complexity of law processes and bureaucracy applied. Additionally, the study represented potential technologies that could possibly be implemented and testing processes in different companies.

Key words self-driving, autonomous vehicles, independently moving

CONTENTS

SYMBOLS AND ABBREVIATIONS

RQ	Research Question
RCA	Radio Corporation of America
AI	Artificial Intelligence
AV	Autonomous Vehicle
SaFD	Safety First For Automated Driving
SAE	The society of Automotive Engineers
TOPS	Tera operations per second
FCA	Fiat Chrysler Automobiles

1 INTRODUCTION

1.1 Background and Motivation

There are more than 1.2 billion cars in the world. Almost a billion of these cars are passenger cars, 335 thousand are commercial (statista.com, 2015). It is a well-known fact that the number of cars growing every year, which makes transportation problems, as well as negatively affects ecology by producing Co2. However, humans do need transportation services on an everyday basis. The situation is not likely to change without new technologies or laws.

The car market is full of different models and car manufacturers from all over the world. Vehicles are beneficial in everyday human life, and they give people the ability to move from one place to another fast. Cars are saving time and let people move long distances. However, the car needs a driver, which makes it less time-saving and more expensive. The driver should always be focused and in control of the situation while driving the vehicle. In addition, a person first needs to get a driving license to be allowed to drive a car on the road. It limits the number of activities a driver could do during the transportation process and limit the circle of people who could use personal vehicles due to a lack of driving license.

Today, over forty IT and vehicle companies are working on solutions for autonomous driving vehicles (CB Information Services, 2020). It is going to change the industry of transportation and affect many other industries that depend on logistics services (Tarutin, 2018). The companies are developing their hardware and software solutions for vehicles. The self-driving technology is going to make a new market and establish the industry around this technology. These companies are developing self-driving technology today, investing in the future to obtain significant profits from a newly established market.

Self-driving vehicles can orientate on the road using different sensors, such as cameras, GPS, and Lidar sonars, Radars. Significant IT and vehicle companies

such as Waymo, General Motors, Nissan, Uber, Mercedes, BMW, Ford, and others already started to test autonomous vehicles. Some companies already got permission to test their autonomous cars on public roads (GreyB Services, 2020). This fact shows us the current progression of technology. Dangerous vehicles would never be allowed on the public roads for testing.

At present, self-driving cars are not legal everywhere in the world. Only some list of countries allowed testing self-driving vehicles. For example, in the USA, each state has its laws about self-driving cars. Some states do not allow any autonomous vehicles on the roads. Other states ask companies to get a permit at first that given after tests and only if the vehicle and company comply with all the legal rules and laws provided by the state. (GreyB Services, 2020.)

The motivation for conducting this research is to explore the current situation in the area of autonomous vehicles and discuss possible technology implementation of such vehicles. The legitimacy of self-driving vehicles in different countries discussed to show the government interest in driverless vehicles implementation in different countries. The researcher aims to explore the area of self-driven cars and find the best technology solutions in the field of autonomous vehicles nowadays.

1.2 Research Objectives and Scope

The objectives of this research are to explore the area of self-driving vehicles nowadays and find the standard solutions used in most of them. The research provides an overview of the technologies used in self-driving vehicles, hardware, and software. Besides, the current and possible levels of self-driving cars technologies nowadays and in the near future discussed.

The research does not include the implementation of self-driving technology in the real vehicle due to the complexity of such technology, costs, and time limitations. However, the technology implementation pitfalls are listed, overviewed, and discussed. The information about pitfalls during the

implementation accumulated from the reports and articles made by companies who implemented and testing the self-driving technology

1.3 Research Questions

The three research questions (RQ) are presented and described next. The research questions are the following:

- RQ 1: What is the current situation in the field of autonomous vehicles, and what essential technologies are applied?

This research question is targeting on familiarizing the reader with the current state of this field and describe the leading technologies used in this field for making self-driving vehicles.

- RQ 2: What hardware and software are used to make self-driving vehicles and how they work with cars?

The second question is aims at analyzing the work of self-driving cars on the level of software and hardware and tell more about the solutions used by companies in that field nowadays.

- RQ 3: What is the potential of the use of autonomous vehicles, and how will it improve the near future of transportation?

The third research question aims to analyze the near future of autonomous vehicles and to find possible affection on the economy because of the implementation of self-driving technology in vehicles.

1.4 Research Methodology

This study uses the exploratory research method based on reviewing and analyzing literature and data from publicly available resources. This

methodology is used since the field of autonomous vehicles develops rapidly and accumulates new data. Companies improve technologies and software frequently, which generates a lot of data to analyze. Many companies are gathering and publishing data about their projects based on real vehicles that are currently in use on the real roads frequently. All the data used in this research are up to date and covered by the research topic.

Due to the fact that self-driving technology is relatively new and currently in the development process by multiple technological and vehicle companies, it is getting frequent media coverage and publications. This is the reason why data been collected by conducting desk research. The source materials consist of electronic sources such as Google Scholar, Google search, ACM electronic library, an e-library of Lapland University of Applied Sciences, and multiple articles and e-books.

1.5 Thesis Structure

The thesis work is divided into six main chapters. Chapter one is an introduction that describes the background information, objective, and scope that presents the research questions, methodology, and this sub-chapter with the thesis structure. The second chapter is aimed at familiarizing the reader with the essentials of autonomous machines, history, and the current situation in the field, followed by an article about laws and the future of self-driven vehicles. Chapter three provides a more in-depth explanation of hardware and software needed to implement the self-driving technology. Chapter four, with three example companies, represents the testing and validation methodologies for self-driving vehicles. Chapter five represents the public opinion about self-driving vehicles based on statistical data and surveys. Chapter six is a conclusion it includes the results and the direction for further research.

The structure of the thesis aims firstly to introduce reader the field of autonomous vehicles, so even the people who never heard about this technology before would learn and understand the background before taking a

more thorough look at each technology in the example self-driving vehicle. The thesis structured this way to obtain the best experience of reading it.

2 FIELD OF AUTONOMOUS VEHICLES

2.1 Structure and Introduction

The essentials explanation of the technologies is described first. The short history of self-driving vehicles and the industry provided and reviewed secondary. Lastly, the current situation within the area of the autonomous vehicles will be reviewed.

Many big companies are implementing projects with autonomous vehicles nowadays (CB Information Services 2020). There is plenty of successful examples that are currently being developed and gradually improved. Behind the term of autonomous vehicles first of all comes the set of technologies and programs working together and influencing the actual vehicle, giving it the understanding of the current situation on the road and making the probability calculations to take the decisions based on the information gathered from the sensors and the calculations.

2.2 Essentials of Autonomous Machines

The transportation technologies invented over the centuries mostly aimed at improving the quality of human life through delivering certain items, services, or people. Starting from the simple wheel, all the way to the planes, and possibly future space ships that will deliver humanity on the other planets, always all the created vehicles needed the person who would control everything, they are called a driver or a pilot. That means whatever vehicle that is, a space ship, or a cart with the horse. It needs a human driver or pilot sitting inside, traveling with the vehicle over the whole trip. All of this raises the main problem that autonomous technology designed to solve. Autonomous vehicles technology aims to replace the human driver and provide a better experience of transportation by making all the driving work instead of the human (NHTSA, 2020). By replacing the human work, this technology will lower transportation prices as well, because instead of paying to the driver, the owner of such a car can make it ride itself, paying just for upkeeping all the hardware in it (GreyB

Services, 2020). Finally, the technology had progressed to a level that made it possible for a computer to monitor the road situation and control the vehicle based on specific rules using the set of sensors and hardware-based calculations.

The self-driving vehicles do not only refer to the cars on the roads but can also be used in many different industries for robotics, farming, productions, and other possible uses. The technology itself could be possibly implemented in most of the vehicles that have enough space on it for sensors and inside for hardware needed for calculations (Nvidia Corporation, 2020). That means it is possible to turn many machines into smart self-driving vehicles. It could increase the level of automation for many industries, improving business profits, and reducing the number of accidents happening to employees by reducing the number of employees needed for work. (GreyB Services, 2020.)

The self-driving technology may be described as a set of hardware made of different sensors and software combinations based on neural networks that, first of all, calculate probabilities and takes the decision basing on previously learned data. The car-vision is much better than a human vision. The vehicle receives all the data from cameras, lidars, long-range, short-range, and articulating radars on Figure 1. These sensors send the data to the computer that processes trough the neural network and takes the decisions according to results (General Motors, 2018). This cycle happens multiple times every second. The actual numbers depend on each system and the processing power of a particular computing unit. However, the general rule, more often it the cycle repeats, better.

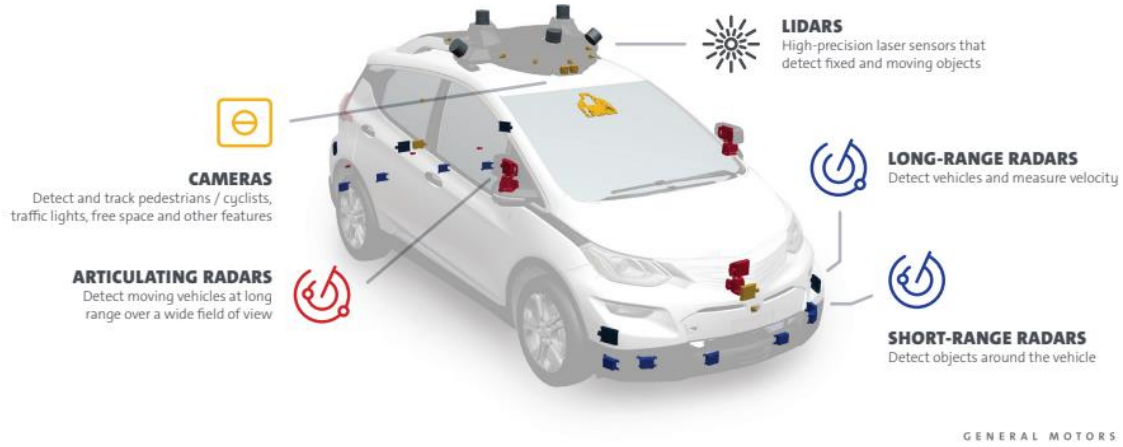

Figure 1. General Motors Self-driving Vehicle (General Motors, 2018)

It is not as simple as just placing the sensors on the car, hardware with software inside, and the car drives itself. Each camera, Lidar, and Radar should have a specific position to get the best possible picture of what is happening around the car (Yandex, 2019). The companies that develop self-driving car technologies lead all the possible tests and calculations to find the best position for each sensor. Figure 2 represents the positions of cameras on the self-driving car designed and made by Yandex.

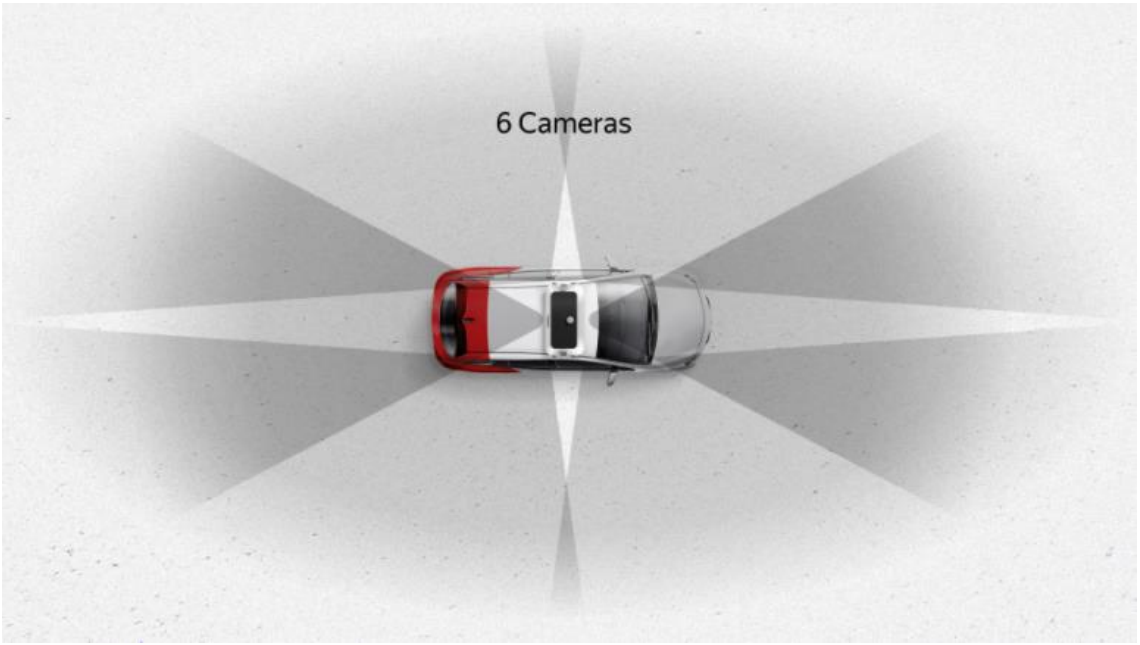

Figure 2. The Camera Positions On the Self-driving Car (Yandex, 2019)

2.3 History of Autonomous Vehicles

According to the article by David Baker from the San Francisco Chronicle, the first presentation and the concept of the ‘self-driving’ car shown on The Futurama exhibit 1939 World’s Fair. This car was made by “General Motors teams with famed designer Norman Bel Geddes” as the vision into the future (Baker, D. 2017). There have been many other car concepts and even prototypes over the years, but most of them have been based on the specially prepared embedded roadway, the technological limitations made it impossible to develop the car-vision that would let the vehicle detect the obstacles and road without radio signal in them. Today technology allows the vehicle to see any objects, using cameras, radars, and lidars. Even understand what those objects are, using the neural networks.

Multiple companies from all over the world tried to invent the self-driving car since the first prototype shown in 1939. The idea of a fully autonomous vehicle traveled over time and changed into something to fit the current needs of users. In 1958 Nebraska Department of Roads implemented the unique 120 meters of the road with electric circuits to lead the public tests on the highway outside Lincoln. Chevrolet passenger cars got equipped with radio Corporation of America (RCA) radio receivers and different mechanisms to control the car. As well, a panel with lights and sounds used. This car was not a self-driving vehicle as people know it today. It was an experiment to prove that a car might be controlled by the radio signals from the electric circuits implemented into the road. This system worked by flashing the lights and sounds to communicate with the driver. (The Lincoln Journal Star, 2017.)

However, the scope of engineers changed. Instead of designing the road to communicate with the vehicle, they decided to design the smart car, to ride on existing roads. Mostly because it is not possible to transform all the road networks, it would require significant investments that the government cannot provide. That is how the ancestor of car-vision developed. In 1980 Ernst Dickmanns and his team developed the first robotic car-vision and installed it in

a Mercedes-Benz to test it on the public streets in the city. This Mercedes-Benz is shown in Figure 3.

Figure 3. The Original Photo of Ernst Dickmanns Mercedes-Benz With Car-Vision (velocetoday.com, 2014)

The modern self-driving cars as the set of sensors and hardware, software based on neural networks combination only started to appear around in the first decade of 21 century. The idea behind modern self-driving cars is the same as before, but instead of remaking the whole road-system to fit the needs of auto-pilot, modern cars designed to be able to ride on the actual roads using its sensor systems and neural networks. The Guardian article was written in 2015, saying that from 2020 all people will become a permanent backseat driver, supposed to predict that self-driving vehicles will become accessible for the majority of people in 2020 (Guardian News & Media Limited, 2015). However, this prediction did not happen yet. Self-driving vehicles are still rare on the streets of cities. Such technology as autonomous vehicle is not easy to implement on public roads due to many reasons. The car is still a few tons of metal riding around a lot faster than a human can walk. According to the World Health Organization, in the car-to-car crash, the fatality risk for the vehicle driver and its passengers on the speed 65 km/h approximately equal to 85% (WHO, 2020). This means even at low speed, the probability of a fatal accident is very

high. This is why important to discuss the legal and moral aspects of self-driving cars, which discussed in detail later in this thesis.

2.4 Self-driving Cars Nowadays

Nowadays, the technologies used in self-driven vehicles are currently in the stage of active development. That is already possible to meet a self-driving car on the street of the big cities or even order it as taxi. So, for example, Waymo founded in 2009 as the Google Self-Driving Car Project. Waymo has over ten years of experience with self-driving cars, slowly growing its base of self-driving cars on the streets of the USA. However, there always was a safety driver on the driver seat until 2017. In 2017 Waymo did as they mention ”the world’s first fully self-driving trip on public roads” (Waymo LLC, 2017), which opened a whole new page of self-driving cars testing. Right now, anyone could order a self-driving taxi without a safety driver. This option is available in the USA, the Arizona state, Pheonix East Valley. All needed is a smartphone with Waymo One application to order the taxi, interface represented in Figure 4. This feature could let any person experience self-driving cars, to show that it is not a privilege; it is the future that is already close enough to ride it.

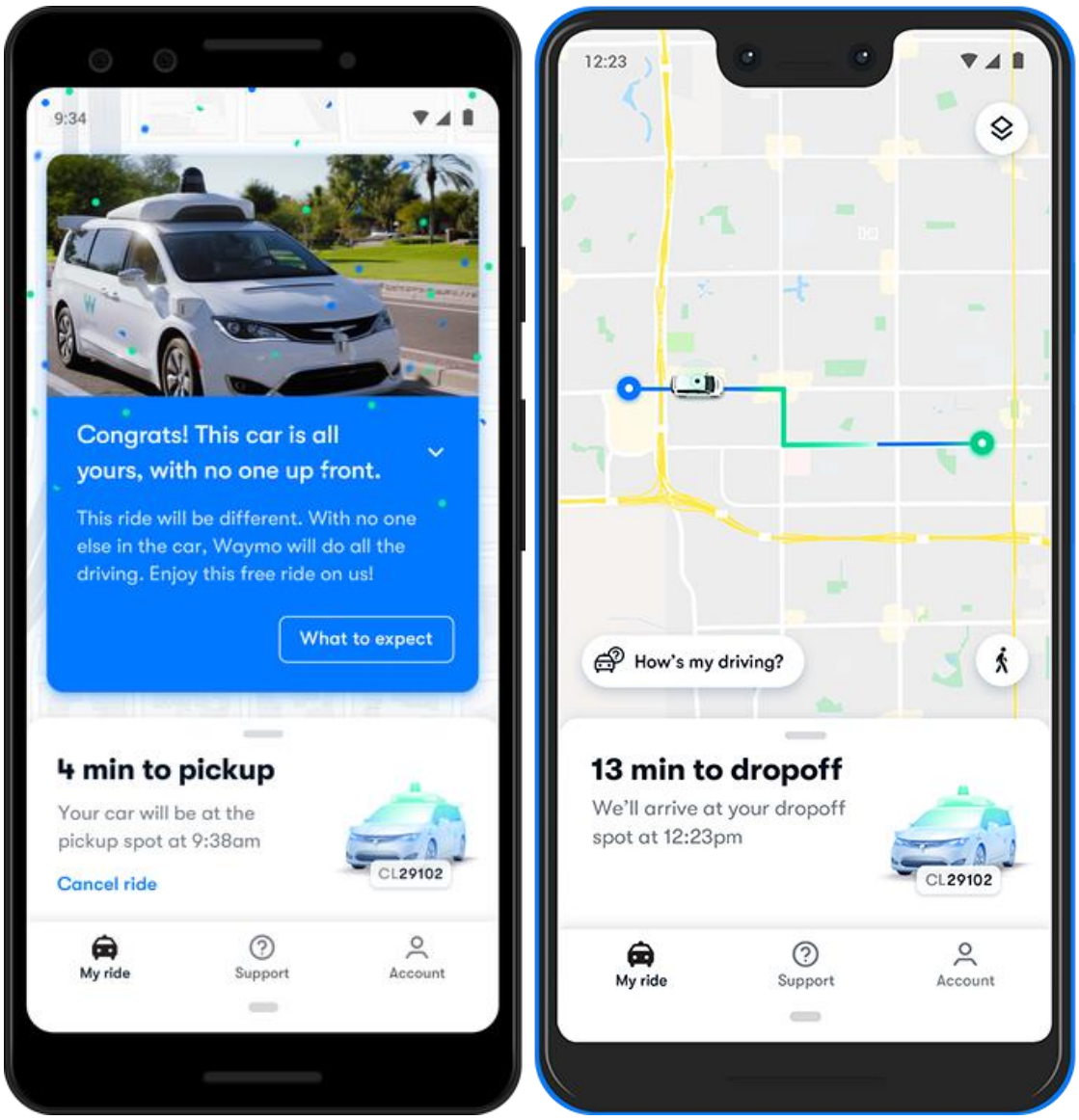

Figure 4. The Interface in the Application When Fully Self-driving Taxi Car Ordered (Waymo LLC, 2019)

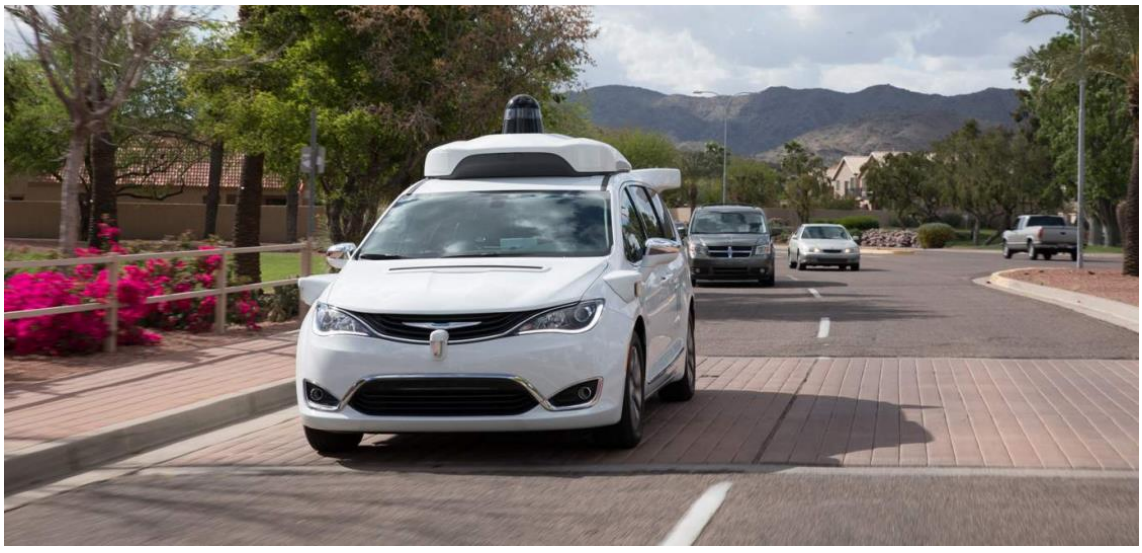

Figure 5. Waymo Self-driving Car on the Road (Waymo Safety Report, 2020)

However, Waymo is just one of many companies contributing to self-driving technology development. Many companies from all over the globe are nowadays participating in self-driving cars testing for a different purpose. Multiple companies reviewed later in this thesis as an example. Self-driving technology is a field for investments nowadays to gain profits in the future.

2.5 Laws and Liability

Since the very initial stage of self-driving technology development, the question is still not answered fully “When a self-driving car crashes, whose fault is it?” (Kreindler & Kreindler LLP, 2020). March 2018 became the first big accident on public roads in the USA, the state of Arizona, with the participation of a self-driving car made by Uber. According to Forbes Media self-driving vehicle of Uber killed a pedestrian, which caused laws and liability questions to rise again (Fernandez, 2020). Self-driving cars are learning every day, driving the roads themselves. However, usually, there is a safety driver whos work is to watch the road and take over the AI in an emergency case. In that particular case, the blame divided between all parties, Uber, driver, the car, victim, and the state of Arizona (Fernandez, 2020). The self-driving technology progress being slowed down by the legal reasons, due to the unique type of that technology. The world is not ready for self-driving cars. It takes time to prepare the practice and systems, to include that type of vehicle into the rules and laws.

2.6 Future of Self-driving Cars

The future of self-driving cars is not clear for ordinary people. There are many proposals about this topic from many specialists and consulting companies. According to McKinsey.com, «up to 15 percent of new cars sold in 2030 could be fully autonomous» (Gao, P., Kaas, H-W., Mohr, D., Wee, D., 2016). However, there are many factors which involves on autonomous vehicles. The first one is the human factor. Many people like to drive a car by themselves, but

it depends on many conditions and options connected to the style of driving. For example, in a traffic jam, it will be easier and more comfortable to transfer driving responsibilities to the car itself. Another example, clear road with high-speed limit, someone can get much more fun and excitement to drive by himself/herself. Summing this issue, the human being would like to choose how to operate it in each situation, use the machine help, or do it manually. Probably, the self-driving car will have both operational styles.

The second proposal is that self-driving cars will change the actual legislative system and way of living in cities. With the introduction of this kind of technology, theoretically, it could be allowed to use a self-driving car without driving license or use these cars even when the person has alcohol intoxication as well as for people who are physically unable to drive the vehicle. Moreover, it could change the car parking situation. The car will find the parking place by itself for personal cars or could even drop off the passenger and continue to drive to find another passenger until it needs a recharge in the case for taxi. It could massively optimize car traffic in big cities. The driverless cars can optimize the process of coming to work and returning, and save approximately an hour each day. (socialtables.com, 2020.)

The third prediction is that self-driving cars could reduce the fuel consumption of on-road vehicles. “The researchers determined that even a small percentage of autonomous vehicles (5 percent) could have a significant impact in eliminating waves and reducing the total fuel consumption by up to 40 percent and the braking events by up to 99 percent” which also means it will reduce the CO2 emissions which could have a positive impact on the ecology and improve the quality of air in big cities. (Leong, J., 2018.)

The fourth prediction of using self-driving cars is about saving human lives, U.S. National Highway Traffic Safety Administration (NHTSA) reports that the human driver causes 94 % of all serious car crash accidents (NHTSA’s National Center for Statistics and Analysis, 2015). According to the World Health Organization, around 1.35 million people die in road accidents yearly, which is approximately 3700 deaths every day (WHO, 2018). The primary goal is to reduce human

input in driving activity to improve safety on the roads. It could minimize the chances of human mistakes and reduce deaths, injuries, economic damage.

2.6.1 Potential Technologies to be Implemented in Self-driving Cars

The possible solutions and features that might be implemented in the future for autonomous vehicles is the fantasy-related topic, so this is the future vision of what technologies should appear in self-driving cars in the nearest future. All these technologies will improve the self-driving technology. The list of possible technologies gathered from different resources and articles.

Automotive Cybersecurity is an essential part of development. Nowadays, self-driving cars are not as popular and often still controlled by the human safety driver. However, level 4 automotive self-driving car is controlled by computer basically, and it will be connected to the world wide web eventually so that it could be in danger of hackers attacks. The security of the vehicle should take a critical part of the self-driving vehicle and guarantee the integrity of the vehicle. (Wood, 2019, 23.)

The car must be fully functional even without good road contact. Today, there is no self-driving car that could go off-road, which might become a problem. For example, snow covers up lane dividers or white stripes, and the car does not know where and how to operate without such information. There should be technology to be able to drive without good road contact. The real automotive cars should be able to navigate and drive in extreme weather conditions, without any road. This technology might be a part of Level 5 automation for self-driving vehicles.

Vehicle-to-vehicle (V2V) communication. This technology would allow self-driving cars to exchange information about the current situation on the road by broadcasting and receiving messages from other smart or self-driving vehicles on the road. This feature would require appropriate software, that would send the information about the road situation to other vehicles. The technology

already being developed and might appear in self-driving cars soon. (NHTSA, 2020.)

The self-driving car could be a part of more significant ecosystems. As a part of the city ecosystem, autonomous vehicles could get new functionality. This technology could optimize big cities' car traffic, as well as improve public transportation services. As an example, parking could send actual information about the availability of places to cars, and after analysis, the car will move to the closest one.

Additionally, it could be useful to have a streamlined process for sending the car to repairing service automatically. The car should analyze data from sensors and notify if something wrong. Then, the owner could let the car make an appointment and go to the service itself, in the best time, without an owner. After the repair is complete, the car should come back to its parking place.

2.6.2 Future of transportation services

There is no doubt that this technology will change the entire delivery and transportation services. New technologies have already come to business. A good example is a delivery robot made by Amazon shown on Figure 6. It is like a small autonomous vehicle, full of sensors, just like the actual self-driving cars. These robots are small enough to use sidewalks. For the moment, it is all in the testing stage, but similar projects already announced by other companies, which means it could become a new way of delivery in the nearest future. This delivery bots could lower the price for delivery. The business owner does not have to hire a worker, buy a car, pay the fuel anymore. These bots are already working and delivering amazon orders to customers in Washington state, USA. As said the vice president of Amazon Scout ”The future is right around the corner, and we couldn't be more excited” (Scott, 2019). (Vincent, J. 2019.)

Figure 6. Amazon Scout Delivery Bot (Amazon 2019)

A second good example of future transportation that is starting nowadays is the project from Waymo Via. This project is creating self-driving trucks. Nowadays, many people are engaged in the transportation process, every single truck needs a driver, and it passes over a thousand kilometers a day. Even with all assistance technologies, the driver has to be alert during the driving time and have to do most of the work manually. Waymo Via is here to solve that problem, and they made a self-driving truck for that. Technically, these trucks using all the same technologies as Waymo One self-driving cars, that riding now in the cities. However, software a little modded to understand the truck-specific, such as blind spots, braking, and turning fully loaded truck and trailer. These self-driving trucks are already testing on public roads in California, Arizona, Georgia, and Atlanta in the USA. (Waymo LLC, 2020.)

3 HOW SELF-DRIVING VEHICLES WORK, HARDWARE AND SOFTWARE

3.1 Hardware and Software Background and Levels of Automation

Neural networks, in combination with sensors, are the central systems that let the self-driving cars see, think, learn, and move in almost countless scenarios of the road situations. It is an unbelievable route from a regular car without any electronics, to a fully-self driving car. So, in that part of the thesis work, the technologies used in autonomous cars will be discussed. The most important parts of any self-driving vehicle, or simply what makes a car a self-driving.

In 2019 eleven companies participated in the development a principle rules for self-driving cars industry-wide. This document called ”Safety First For Automated Driving” or shortly SaFD, it describes how cars should be developed and tested, to comply with the safety measures pointed out in the documentation. This document advocates ”The Twelve Principles of Automated Driving”(SaFD, 2019), those are as follows:

- Safe operation
- Operational design domain
- Vehicle operator-initiated handover
- Security
- User responsibility
- Vehicle-initiated handover
- Interdependency between vehicle operators and automated driving systems (ADS)
- Safety assessment
- Data recording
- Passive safety
- Behavior in traffic
- Safe layer

All these principles described more deeply in the SaFD, with argumentation and technical information. Nowadays, software and hardware created by companies who participated in the creation of that document are checked for compliance with principles and tested using the techniques described in SaFD and ISO 26262 documentation.

To understand how the software that makes a car “self-driving” firstly, it is essential to mention the levels of automation. The society of Automotive Engineers (SAE) defines multiple levels of automation, starting with Level 0, which is entirely manual and ending on Level 5, which is full driving automation. Figure 7 provides a visual representation of automation levels. (SAE International, 2019.)

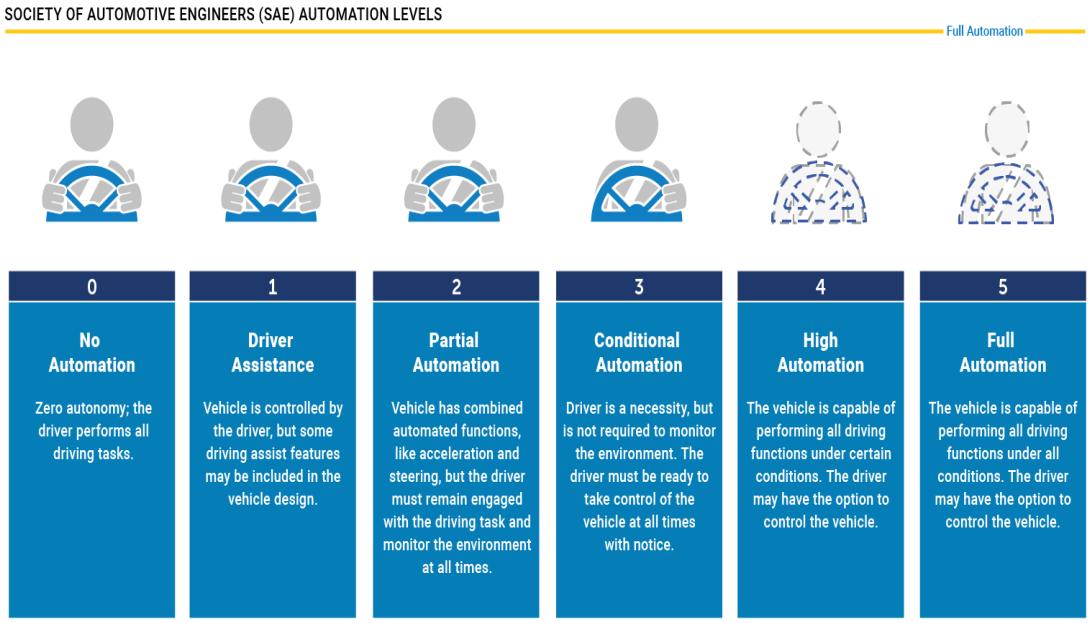

Figure 7. Levels of Driving Automation According to SAE International (National Highway Traffic Safety Administration, 2020)

- Level 0 no automation
- Level 1 automation, vehicle-controlled by the driver, with small assistance in steering and acceleration
- Level 2 partial automation is like an original autopilot system on Tesla cars. The car could take safety actions, but the driver always has to be in alert.

- Level 3 automation still needs a human driver, but the driver passes the significant tasks to the vehicle self-driving system. Cars with such automation levels are not able to drive itself under specific traffic or weather conditions.
- Level 4 automation cars are almost fully self-driving vehicles that able to drive itself all the time without human input but could be programmed to avoid unmapped areas or to drive in certain weather conditions.
- Level 5 automation is an ultimate level of automatization that does not need a human driver at all and designed to drive itself all the time.

3.2 Hardware in self-driving vehicles

In order to navigate and find its way on the road, self-driving cars using multiple hardware solutions, from locating sensors to hi-end computers running neural networks, all of this hardware may be different. It all depends on the car producer. There are a few types of companies working on self-driving vehicles, several companies buying ready solutions, and implement it inside their vehicles with some minor modifications. At the same time, some other companies prefer to develop fully custom hardware and software solutions from scratch, to improve the system performance and get more control over the whole system.

Self-driving vehicles have many different hardware solutions, most of which aimed at “seeing”, calculating and predicting the road situation based on data learned before. Just like the human being has eyes to see and brains to analyze, autonomous cars using a set of sensors and powerful computers. It makes a kind of Computer Vision. It is important to take a closer look at actual technologies used in self-driving cars hardware-wise.

As an example, the Waymo self-driving car will be taken. Some hardware decisions may be different for different companies, but key technologies are the same. The reason Waymo is chosen as an example is that this particular company is the first one to reach 20 million miles of autonomous driving and is one of the leading companies in the self-driving cars industry (GreyB Services, 2020).

Cameras are one of the many technologies used to participate in “computer-vision”. Cameras are placed all around the car, overlapping the fields of view. According to Satish Jeyachandran, the Head of Hardware in Waymo, “Our latest long range cameras and 360 vision system now see much farther than before, allowing us to identify important details like pedestrians and stop signs greater than 500 meters away.”. This means each Waymo car has an excellent camera view that could see much better and wider than a human can ever see. Figure 6 represents the camera viewing angles, as well as it is possible to see from the picture, that on the front a couple of long-range cameras, that allows a car to see the signs and pedestrians that are half of the kilometer away.

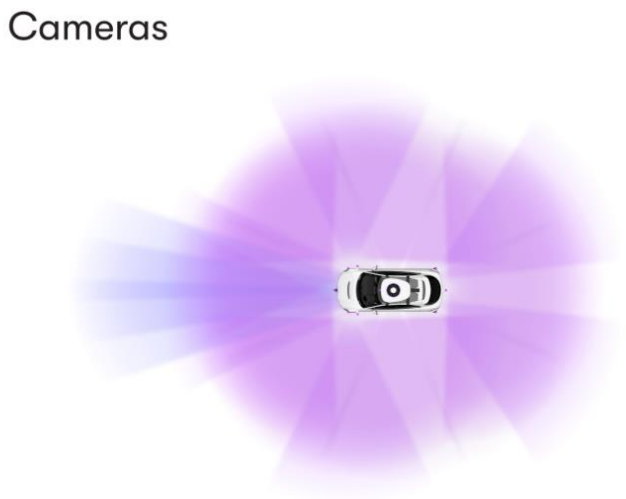

Figure 6. Visual Representation of Camera Viewing Angles and Overlapping (Waymo LLC)

However, cameras are not the only decision. Cameras are good at day time and in suitable weather conditions, but in the dark and with adverse weather conditions, performance drops down to almost zero and makes this technology almost useless for guidance on the road (Waymo LLC, 2020). This why self-driving vehicle needs some other technologies as well.

Other technologies in self-driving vehicles work even at night. This technology called Lidar, it uses a laser beam to reflect it from objects for detection. In self-driving vehicles, this technology used to build a 3D model of surroundings, allowing the vehicle to gather information about objects size and distance to object. In Waymo cars, Lidar can see objects as far as 300 meters away, with a 360-degree field of view around the vehicle represented in Figure 8. (Waymo LLC, 2020.)

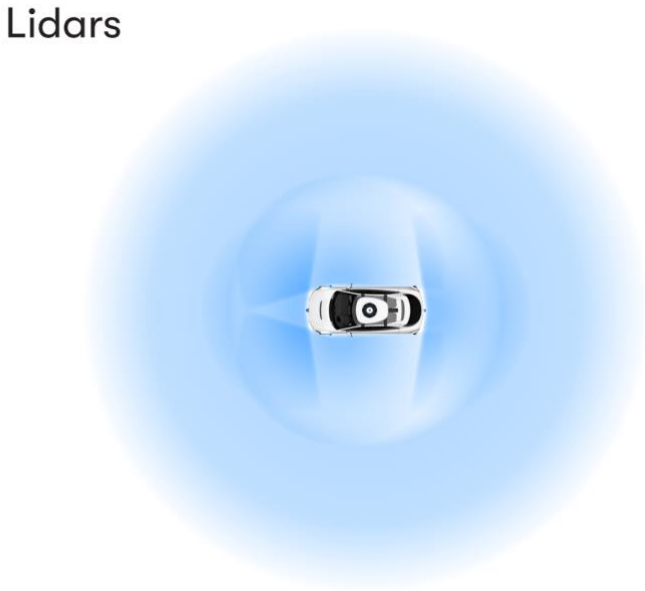

Figure 8. Visual Representation of Lidar Viewing Covering in Waymo Self-driving Vehicles (Waymo LLC)

According to Satish Jeyachandran, Lidar is “one of the Waymo Driver's most powerful sensors”, which makes it one of the essential sensors for self-driving vehicles. Waymo cars as well equipped with perimeter lidars that placed on the

vehicle sides to improve the coverage of blind spots and detect the close objects. (Waymo LLC, 2020.)

However, next in the list is Radars. It uses radio waves to detect objects. This technology used in many different industries, as well as in self-driving vehicles now. Radar working together with cameras and Lidars on Waymo self-driving vehicles. While Lidar makes the 3D picture of the area, helping to understand objects around the vehicle, and cameras helps us to understand surrounding, the Radar helps to understand the velocity of the objects as well as provides a higher resolution than Lidar, but with a lower field of view. The visual representation of Radar shown on Figure 9. Radar's unique ability is to see even in adverse weather conditions like fog, rain, snow. Radar cannot see closer objects, so it cannot replace Lidar on closer distances. (Waymo LLC, 2020.)

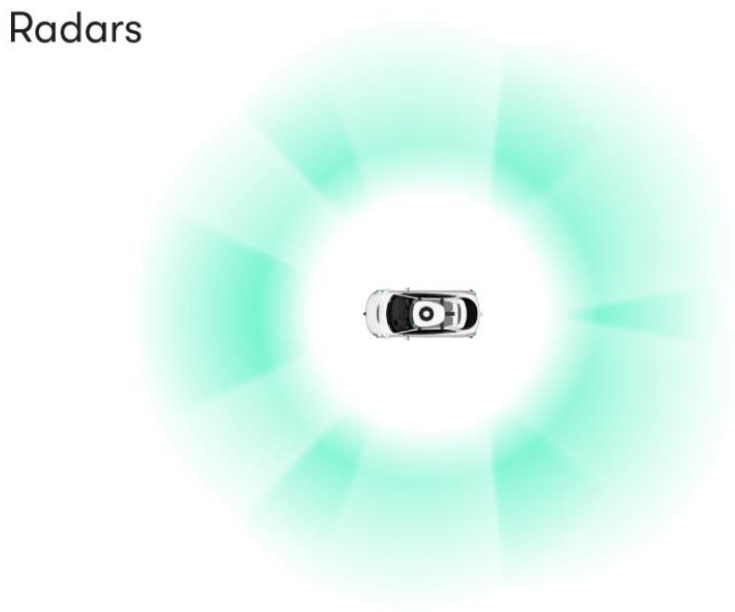

Figure 9. Visual Representation of Radar Work Area on Waymo Self-driving Vehicles (Waymo LLC)

This combination of sensors is the most popular in the self-driving vehicle nowadays. However, there are also other types of sensors in use by other companies, such as ultrasonic sensors and other experimental solutions, but so

far the combination of camera, Lidar and Radar are most usable in industry. Usually, sensors integrated into the car with the calculation of best viewing positions for every single technology to gain the best viewing for cameras, Lidars, and Radars. All of these sensors are working together, gathering information, and sending it over to a computer for further analysis and calculations based on that data.

The computing unit is not any less critical than sensors that gather all the data. This computer is getting a massive amount of data to calculate and make decisions in real-time. It is essential to have a very powerful computing platform that could do it in real-time without any delays. Any delay in calculations could be deadly. It is a matter of safety. For calculations, there is a couple of ready solutions out on the market nowadays, one of the most popular provider of computing platforms for autonomous vehicles is NVIDIA with their world's first Xavier and Pegasus processors for autonomous driving vehicles. It designed for the DRIVE AGX platform that processes all the data from sensors and localizes the vehicle on the map. These processors aimed primarily on neural networks and deep learning with the performance of 320 TOPS (tera operations per second), which is 320 trillion operations per second for Pegasus, and 30 TOPS for Xavier. Pegasus computing unit is a high-performance AI computer aimed at working with neural networks and designed to run on the fully automated Level 5 vehicle. Xavier computing unit designed for Level 2 and 3 automation. This computing platforms able to perform all the needed calculations for self-driving cars nowadays, of course, it is possible to run neural networks on other types of hardware, but this processor specially designed for running a neural network, with excellent performance. (NVIDIA Corporation, 2020.)

All this hardware makes the self-driving vehicles possible. Every company passed a long way in hardware development to make self-driving vehicles possible. It is not only about the hardware itself, but also about positioning it and integrating it into existing vehicle models. While most vehicles are not yet fully automated, it is essential to let the safety driver see the situation on the road clearly, without putting sensors over the windows and make this vehicle comfortable to use.

3.3 Software in Self-driving Vehicles

Self-driving vehicles are a combination of hardware and software. It is essential to have a good software in the center or self-driving car since this is what responsible for safety and decisions made by the vehicle. Software is made of multiple technologies, as said in GM safety report “No one technology makes this “brain” work. Instead, computers use a combination of systems that work safely together”. In this part of the thesis, the technologies used in vehicles will be discussed.

The software in General Motors self-driving vehicles made from many technologies and systems that are connected and depend on each other, according to safety report those are as follows:

- Safety
- Behavioral Control
- Machine Learning
- Simulation
- Perception
- Localization
- Mapping
- Planning
- Remote Assistance
- Controls
- Dispatch and Routing
- Networking

Safety first, it is an essential part of the computer technologies and systems for decision making in critical situations, it is important to create self-driving vehicles thinking about safety as the main factor. Each company using many different methods for safety-testing the systems and software, it will be discussed more deeply later in this thesis work. (General Motors, 2018, 6.)

Behavioral control uses information from multiple systems and technologies, such as planning, safety, and controls, to analyze it and provide the best ride

experience and comfort for other road users by providing predictable behavior for human drivers. Machine Learning is the next technology on the list. It let the vehicle learn and improve itself. This technology is getting information about road objects and the picture of the world around from Perception system, analyzing information, and learning. Simulation is one of the best ways to test and improve vehicle abilities safely. The vehicle is making a virtual driving simulation, learning, and gathering experience in the virtual world. For example, Waymo declares that their vehicles passed over 5 billion miles in simulation. Perception is a software system that is responsible for detecting and classifying objects on the road. This system is also detecting the speed of objects, their heading, and acceleration. Perception helps the vehicle to find a difference between pedestrians, motorcyclists, and cyclists that could look similar sometimes, but their behavior is very different, which helps to find the difference. (Waymo LLC, 2018, 15.)

Localization shown on Figure 10 is the critical system in a self-driving vehicle. This system helps the vehicle to localize itself on the road and let the vehicle for understanding the surroundings and structures. It helps the vehicle to detect lining on the road, signs, and other important infrastructure on the road. A vehicle matching the environment with HD maps to position itself on the map with high accuracy. (Akbarzadeh, Sheng, Marr, 2020.)

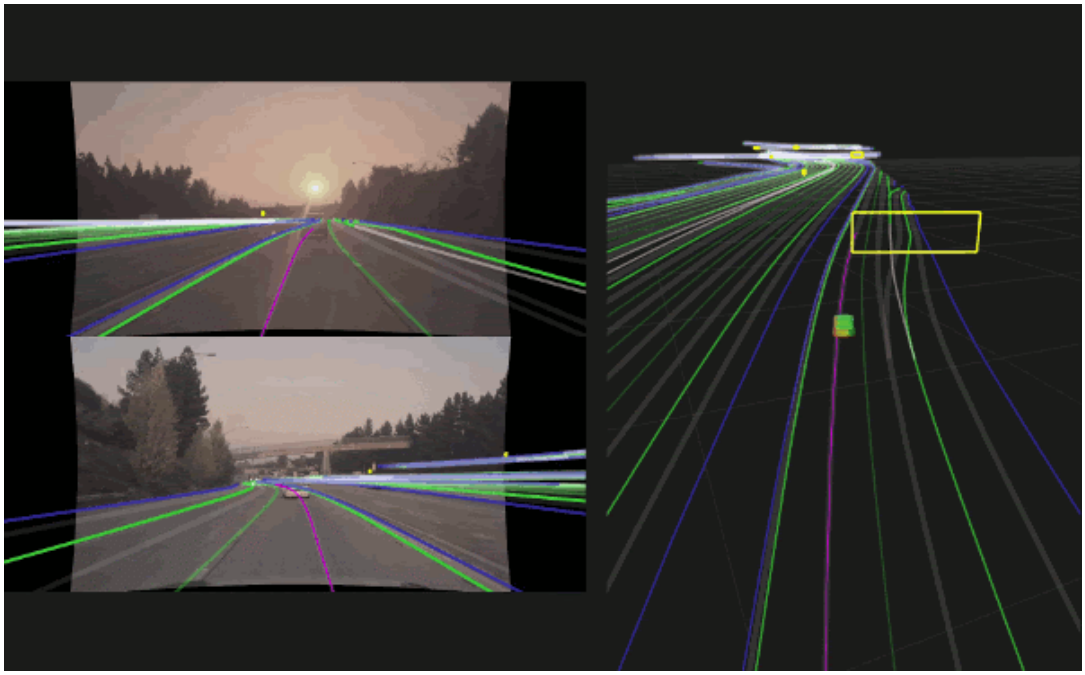

Figure 10. Visual representation of localization in NVIDIA DRIVE AGX (Nvidia Corporation, 2020)

Mapping, this system is a part of the localization process, providing high-definition mapping and GPS location. All the used maps pre-made before using specialized tools. The next process is planning, which considers all the information gathered by software from dispatch, routing, perception, safety, and mapping. It makes a safe path for a vehicle through the road surroundings (General Motors, 2018, 6). Waymo planner is as well able to predict a few next steps (Waymo LLC, 2018, 15). Remote assistance is implemented in most of the modern cars nowadays. This function allows vehicle users to connect with remote operators in case of an emergency. Controls, this technology is responsible for turning data gathered from planning into commands that are sent to vehicle mechanisms through networking. This is mostly just a part of the self-driving process. Dispatch and routing, based on the operations center request, using data obtained from mapping and planning to make the best way for drop-off and pick-up locations. Networking is a system module responsible for transferring a large amount of data between the computer components of the vehicle system and obtaining data from the operations center (General Motors, 2018, 6).

4 TESTING AND VALIDATION OF SELF-DRIVING VEHICLES

4.1 Testing Process Background and Standards

The self-driving cars are modern technology, and it needs to be tested before mass usage in a real-world scenario. Many companies are working on driverless car technology. Waymo, Uber, GM Cruise, Tesla, Baidu, and other companies invest in this technology and produce the equipment for driverless cars.

The testing process is similar to most of the companies. There is a particular document («tests described in ISO and ISTQB standards – ISO 26262»), which describes the whole testing techniques and introduces methods of testing of

self-driving cars for technology developer companies. According to ISO/PAS 21448 SOTIF, the testing process collects four steps: Analysis, Verification, Validation, Field Operation. The SFFAD (Safety First For Automated Driving) publication provides a guideline for improvement of safety by establishing rules for the preparation process. This document designed to assist companies in achieving success in each testing part of the whole process by providing guidelines, tips, and principles. (Wood, 2019, 72.)

4.2 How Companies Testing Self-driving Cars

In this article, three examples of companies testing self-driving vehicles will be provided with a more in-depth explanation of testing technics and validation methods. This is three different companies, with a different approach to testing and different hardware, software combinations. All of the presented companies are allowed to test their vehicles on the public road. Waymo, Argo AO, and General Motors are the companies that provide a lot of relevant data about their testing and validation processes in their safety reports and on their websites.

4.2.1 Argo AI

The first example is the Argo AI. It is a self-driving technology platform company, which develops a production-quality self-driving system. The testing process in this company divided into four parts:

- Development Testing
- Simulation Testing
- Closed Course Testing
- Real-World Testing.

Development Testing. The testing process first stage is hardware and software testing in a lab. Engineers do test radars, cameras, lidar sensors, etc., and the software running on it. Firstly, individual testing, then testing as a unit. (Argo AI LLC, 2020.)

Simulation Testing. This stage includes creating a virtual world to test a variety of scenarios that can happen with a self-driving car in a real-world situation. The environment tests system in different cases, from small (single lane street) to large (entire city) simulations. Engineers put virtual cars running their software into this environment. Also, they can make changes in hardware, software, and re-simulate the system in real-time. (Argo AI LLC, 2020.)

Closed Course Testing. After the previous test has passed, it moves to private track, where Test specialists can safely check its behavior on a real road with the assist of specialized equipment: pedestrians, fake dogs, remote-controlled skateboarders, and baby strollers, and other objects to simulate the situations on the road. This process continues until the positive result. Otherwise, the software returns to the lab for refactoring and improvements. (Argo AI LLC, 2020.)

Real-World Testing. Finally, when software passes all tests, it is time for testing in the real world. The self-driving car with installed equipment goes to the public road. The car drives with abiding of local laws, guidelines. The car interacts with surrounding objects such as cars, pedestrians, cyclists, and others according to local specific regulations. The process starts with gathering data by car. The specialist starts to manually drive around the city to collect the data for the 3D model of streets, where it intended to operate after. Once this part is done, the car can drive in autonomous mode. (Argo AI LLC, 2020.)

4.2.2 Waymo

The second example is Waymo. This company has already been mention in this report before. They publish a report where they also told about their self-driving cars testing methodology. The testing process divided into three subsystems:

- Base vehicle safety testing
- Self-Driving hardware testing
- Self-driving software testing

Base vehicle safety testing. The current self-driving base vehicle for Waymo is the 2017 Chrysler Pacifica Hybrid Minivan. “These cars have been certified by the Fiat Chrysler Automobiles (“FCA”) as compliant with all applicable Federal Motor Vehicle Safety Standards (FMVSS), which standards regulate the safety performance requirements for motor vehicles or items of motor vehicle equipment in the U.S”. Waymo crew integrate the self-driving system in it. (Waymo LLC, 2018, 21.)

Self-Driving hardware testing. Waymo and FCA have technical collaboration and have integrated the Waymo self-driving equipment in the cars. However, while this cooperation, Waymo engineers "has performed thousands of additional tests on top of those completed by FCA”(Waymo LLC, 2018, 21). These tests completed in labs, simulations, private test tracks to ensure every system detail is working correctly. These tests include car equipment testing besides the Waymo hardware testing. The result of this process is confidence in several things: Manual mode, Self-driving mode with driver in a car, and the fully autonomous driving mode, and the car is working safely in every mode after the self-driving system installed. (Waymo LLC, 2018, 21).

Self-driving software testing. The software testing in Waymo is similar to the methodology used in Argo AI and divided into three parts: Simulation testing, Closed-Course testing, Real-World driving. Simulation testing. When the self-driving system is testing in simulation, engineers carefully review any changes or updates to the software before it deployed in the fleet. They define the most complex situations the vehicles have encountered on public roads and turn them around in virtual scenarios for the self-driving software practice and learning. Closed-Course testing. The new software has been installed on multiple cars to allow the most experienced drivers to test the new software on the private test track. Waymo engineers can use different software versions for different vehicles to check new or unique functions in various operational design areas. Real-World driving. Once it is confirmed that the software is working as

expected, the real road test starts. Vehicles with new software will be deployed on public roads. Firstly, it will be a small test - the self-driving vehicles must show it can safely and consistently travel along a predefined route after some time engineers could update directions and destinations. The more miles it travels on public roads, the more opportunities to monitor and evaluate software performance. (Waymo LLC, 2018, 22)

4.2.3 General Motors

The third example is General Motors, according to their safety report, their safety testing is made of multiple phases, analysis, build, simulation, driving. Analyze phase made of the multiple analysis types. The deductive analysis includes a fault tree analysis (FTA), which associates potential risks to their immediate causes. The inductive analysis includes design and process failure mode and effects analysis (DFMEA/PFMEA), which is a bit by bit way to deal with distinguishing every single imaginable risk in a structure. The exploratory analysis includes hazard and operability study (HAZOP), which distinguishes potential dangers by investigating the elements of a complex framework. Implementation into the product development process includes using process hazard analysis at the concept stage to assess potential hazards, software HAZOP, system FTA, and DFMEA during design, system functional interface analysis (SFIA), and DFMEA during requirements definition, and DFMEA during implementation phases. Requirements Traceability Analysis deals with the connections between designed frameworks and the security objectives and attendant requirements. (General Motors, 2020, 17.)

According to General Motors safety report, they aim at avoiding risks where possible, and if it is not possible to avoid, they do try to minimize it. Design requirements are made of two key safety performance thresholds. The first key safety performance threshold: The vehicle can continue working appropriately regardless of whether there is a problem in a critical system. Fail-operational functionality is made to work by the vehicle backup solutions for every single essential system. The redundancy implemented in onboard driving computers, basic systems, critical actuators, critical actuator controllers. For instance, if the vehicle's primary steering actuator breaks, there is another one to assume

control over, decreasing the probability for the vehicle to start a safe-stop maneuver. (General Motors, 2020, 18) The second key safety performance threshold: Qualitative and quantitative evaluation of all critical self-driving functions of the vehicle, it called SOTIF “safety of the intended function”. While this process, the vehicle is being tested in simulations before getting on public roads. If the area where vehicle supposed to drive in self-driving mode has six-way stops, the vehicle will have to practice it in simulations many times and show good results before it eventually will get on the public road. (General Motors, 2020, 18.)

System safety through city testing and proving safe driving through experience, the General Motors vehicles currently on the road tests all equipped with pedals, steering wheel, brake, and accelerator pedals. There is always a safety-driver that is called Autonomous Vehicle Trainer in GM safety report. These drivers could take over the vehicle autopilot at any time. The vehicle is recording the data when the safety-driver takeover event happens. This data is being logged to analyze it and decide if it needs the software update or not. All software tested in simulations on similar situations before getting in an actual vehicle, and to make sure it is better than the previous version. (General Motors, 2020, 18.)

5 PUBLIC PERCEPTIONS OF SELF-DRIVING VEHICLES

5.1 Statistic Research on Public Perceptions of Self-driving Vehicles

Autonomous vehicles (AV) is the field that is getting more and more developed every year. Many big companies are investing in technology development and testing. This makes the field of self-driving cars more popular and known by the public. According to Howard and Dai, “Self-driving vehicles represent a technological leap forward that can offer solutions to current transportation problems and dramatically change how people approach mobility” (Howard & Dai 2017, 2). This technology aimed to improve road safety and increase life

quality, but there is still might be people who are not comfortable with this new technology.

This part of the research will provide a statistic about public opinion for self-driving vehicles. All presented data will represent already existing research data from various surveys in other published works about this topic. According to Brandon Schoettle and Michael Sivak multinational survey that they made in three different countries, with 1533 people participating in this survey. 66% of people in total heard about self-driving vehicles before. The highest percentage of people knowing about self-driving vehicles was in the US, 70.9%. In the U.K. this number was 66%, in Australia, it is the lowest and equal to 61%. Data represented in Figure 11. (Schoettle & Sivak, 2017, 6.)

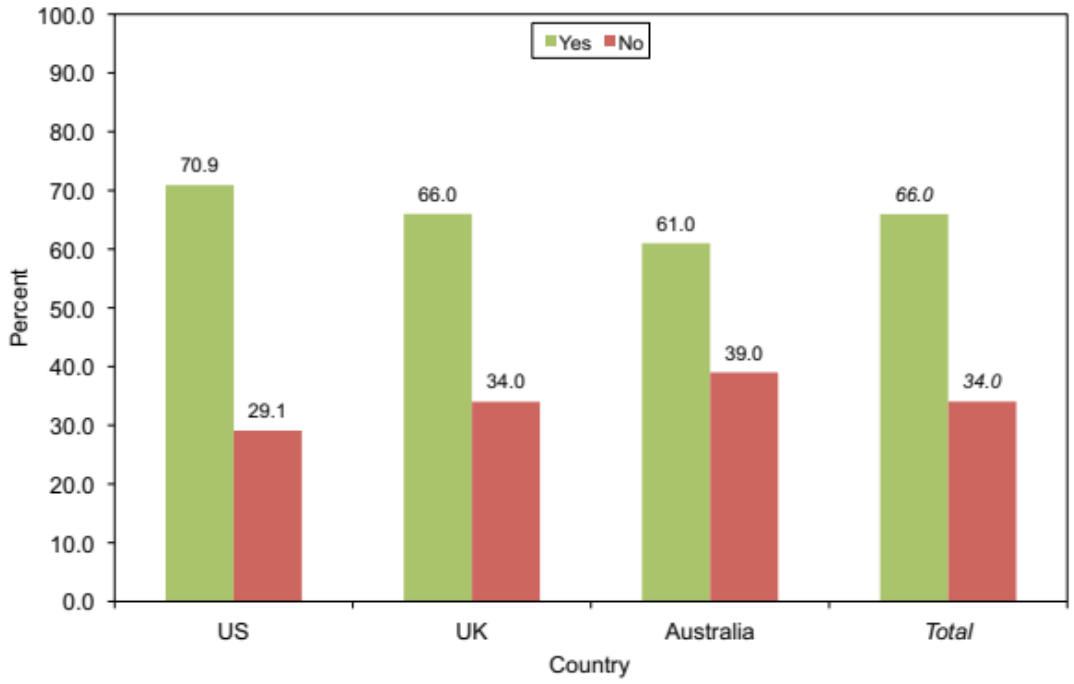

Figure 11. Representation of answers by country and in total on the following question: “Had you ever head of autonomous or self-driving vehicles before participating in this survey?” (Schoettle & Sivak, 2017, 6)

According to their research, 17.4% of people had a very positive opinion regarding self-driving vehicles. Most of the people, 39.4% had a somewhat positive opinion. Also, 29.4% of people had a neutral opinion. The remaining percentage is divided between somewhat negative 10.6% and very negative,

3.2%. (Schoettle & Sivak 2017, 7) This shows that the majority of people are positive about self-driving vehicles, and it represents that most of the people are likely to use self-driving vehicles in the future. These results only prove that all the companies who currently invested in self-driving vehicle technology development, expecting that these people will use their services based on that technology or buy self-driving vehicles for themselves.

The research made by Howard and Dai shows the most and least attractive parts of the self-driving vehicles. It shows that most of the respondents in their survey think that most attractive features are safety, amenities like multitasking while driving, and convenience. Furthermore, the least attractive features were control, liability, and costs. According to the study, many respondents do not like a lack of control in the self-driving vehicle. (Howard & Dai, 2013, 10.)

6 CONCLUSION

Today, the self-driving technology is in the stage of its early development. Even if some companies are already testing Level 4 autonomous vehicles, this technology development still has a long road to pass. People expect this technology to solve the problems with transportation. Optimistic predicts is that in 2030 AVs will be affordable and common on public roads, but as it pointed before in this thesis, predictions not always work. It all depends on how humans will use this technology and how the majority of people will get used to self-driving vehicles on the roads. It is for sure that this technology will be forced to happen sooner or later, due to significant investments made by technological giants like Waymo and General Motors in this technology. Right now, it is a race between technological companies, who will achieve the best results first, will get the most significant share of future yet not explored market.

This thesis research provides an overview and analysis of technology, its current development stage, and top companies working on it. The historical background provided to show the difference between old self-driving vehicles and technologies nowadays. The field of research is significant, so only a few different companies shown as examples. The companies have chosen not

randomly, but because of a different approach for self-driving development, testing, and implementation as a business product in the future.

Self-driving vehicle technology made a big leap forward for a couple of last decades, and it brings significant investments and interests of people. However, most probably, the first customer products in this field will not get a big success on the market due to its high costs. This technology is much more business-to-business oriented, aimed at replacing a taxi and trucks on the roads in the near future. Therefore, self-driving vehicles might affect the economic a lot, replacing human drivers on neural networks, it is not possible to predict if that good or bad, but that is just the fact that most of the human workplaces will be filled with artificial robotics in the future.

This research shows that the field of autonomous vehicles is huge and yet establishing. The current situation in this field is clear. It is still a technology in development, aimed at the future rather than useful nowadays. Laws in most of the countries still limit technology progress, as well as complexity for implementation of this technology is not prepared vehicles. It will take years or decades before the self-driving vehicle technology will become everyday use to people as a smartphone or computer nowadays. Nevertheless, until that, it will be just an improved drive assistant, that could improve safety, but can not work without the driver as been mentioned before. Companies that are working on self-driving vehicles do mind about safety, as well as governments that allow pubic testing of self-driven vehicles on the roads next to typical vehicles.

As the themes for further research, the author would suggest seeing the idea of vehicle sharing. Self-driving vehicles could provide an excellent base for sharing vehicles between people instead of buying them. It is a broad field for research and discussion.

BIBLIOGRAPHY

Argo AI 2020. How do we develop and test self-driving technology?. Accessed 7 May 2020
https://www.argo.ai/how-we-test/.

Adams, T. 2015. Self-driving cars: from 2020 you will become a permanent backseat driver. Accessed 5 March 2020
https://www.theguardian.com/technology/2015/sep/13/self-driving-cars-bmw-google-2020-driving.

CB Information Services 2020. 40+ Corporations Working On Autonomous Vehicles. Accessed 1 December 2019
https://www.cbinsights.com/research/autonomous-driverless-vehicles-corporations-list/.

Fernandez, E. 2020. Who Is Responsible In A Crash With A Self-Driving Car?. Accessed 7 March 2020
https://www.forbes.com/sites/fernandezelizabeth/2020/02/06/who-is-responsible-in-a-crash-with-a-self-driving-car/.

General Motors 2018. Self-driving Safety Report. Accessed 3 March 2020
https://www.gm.com/content/dam/company/docs/us/en/gmcom/gmsafetyreport.pdf.

Gao, P., Kaas H-W., Mohr D. & Wee D. 2016. Disruptive trends that will transform the auto industry. Accessed 4 March 2020
https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/disruptive-trends-that-will-transform-the-auto-industry.

GreyB Services 2020. Top 30 Companies that are working on Autonomous Vehicles. Accessed 5 May 2020
https://www.greyb.com/autonomous-vehicle-companies/#Higher-Safety-And-Possible-Decline-In-Road-Accident.

Howard, D. & Dai, D. 2013. Public Perceptions of Self-driving Cars: The Case of Berkeley, California. Accessed 7 May 2020
https://www.ocf.berkeley.edu/~djhoward/reports/Report%20-%20Public%20Perceptions%20of%20Self%20Driving%20Cars.pdf.

Jeyachandran, S. 2020. Introducing the 5th-generation Waymo Driver: Informed by experience, designed for scale, engineered to tackle more environments. Accessed 26 April 2020
https://blog.waymo.com/2020/03/introducing-5th-generation-waymo-driver.html.

Klyev, L. 2019. Driverless car: reviving algorithms. Yandex Report. Accessed 4 March 2020
https://habr.com/ru/company/yandex/blog/471636/.

Kreindler & Kreindler LLP 2020. When a self-driving car crashes, whose fault is it?. Accessed 12 April 2020 https://www.kreindler.com/Articles/When-a-self-driving-car-crashes-whose-fault-is-it.shtml.

Meola, A. 2016. The public is not ready for self-driving cars. Accessed 12 April 2020 https://www.businessinsider.com/the-public-is-not-ready-for-self-driving-cars-2016-5.

Marr, J., Sheng Y. & Akbarzadeh A. 2020. Drive Labs: How Localization Helps Vehicles Find Their Way. Accessed 7 May 2020 https://news.developer.nvidia.com/drive-labs-how-localization-helps-vehicles-find-their-way/.

Nvidia Corporation 2020. NVIDIA DRIVE LABS Inside look at autonomous vehicle software. Accessed 3 March 2020 https://www.nvidia.com/en-us/self-driving-cars/drive-labs/.

National Highway Traffic Safety Administration 2020. Automated Vehicles for Safety. Accessed 3 March 2020 https://www.nhtsa.gov/technology-innovation/automated-vehicles-safety.

NVIDIA Corporation 2020. Nvidia Drive AGX. Accessed 2 May 2020 https://www.nvidia.com/en-us/self-driving-cars/drive-platform/hardware/.

Singh, S. 2015. Critical reasons for crashes investigated in the National Motor Vehicle Crash Causation Survey. (Traffic Safety Facts Crash•Stats. Report No. DOT HS 812 115). Accessed 25 April 2020 https://crashstats.nhtsa.dot.gov/Api/Public/ViewPublication/812115.

Scott, S. 2019. What's next for Amazon Scout?. Accessed 25 April 2020 https://blog.aboutamazon.com/transportation/whats-next-for-amazon-scout.

Schoettle B. & Sivak M. 2014. A Survey of Public Opinion about Autonomous and Self-driving Vehicles in the U.S., the U.K., and Australia. Accessed 13 May 2020 https://deepblue.lib.umich.edu/bitstream/handle/2027.42/108384/103024.pdf.

Social Tables 2020. 5 Ways Self-Driving Cars Will Forever Disrupt the Future of Hospitality. Accessed 26 April 2020 https://www.socialtables.com/blog/hospitality/self-driving-cars/.

Tarutin, N. 2018. Self-driven vehicles in Logistics: Today and The Future. Accessed 4 December 2019 https://www.theseus.fi/bitstream/handle/10024/141108/Nikita%20Tarutin%20thesis%2011022018.pdf.

Vincent, J. 2019. Amazon has made its own autonomous six-wheeled delivery robot. Accessed April 12 2020. https://www.theverge.com/2019/1/23/18194566/amazon-scout-autonomous-six-wheeled-delivery-robot.

Wagner, I. 2018. Number of vehicles in use worldwide 2006-2015. Accessed 1 December 2019 https://www.statista.com/statistics/281134/number-of-vehicles-in-use-worldwide/.

World Health Organization 2020. Road traffic injuries. Accessed 3 March 2020 https://www.who.int/news-room/fact-sheets/detail/road-traffic-injuries.

Waymo LLC 2017. Waymo's fully self-driving vehicles are here. Accessed 12 April 2020 https://blog.waymo.com/2019/08/waymos-fully-self-driving-vehicles-are.html.

Waymo LLC 2020. Waymo raises first external investment round. Accessed April 12 2020. https://blog.waymo.com/2020/03/waymo-raises-first-external-investment.html.

Waymo LLC 2018. On the Road to Fully Self-Driving. Accessed 12 April 2020 https://storage.googleapis.com/sdc-prod/v1/safety-report/Safety%20Report%202018.pdf.

Wood, M., Robbel, P., Maass M., Tebbens R. D., Meijs, M. and others 2019. Safety First for Automated Driving. Accessed 12 April 2020 https://www.daimler.com/documents/innovation/other/safety-first-for-automated-driving.pdf.

Wiggers, K. 2019. 11 companies propose guiding principles for self-driving vehicles. Accessed 12 April 2020 https://venturebeat.com/2019/07/02/self-driving-car-report-safety-first-for-automated-driving/.

World Health Organization 2020. Global status report on road safety 2018. Accessed 7 May 2020 https://www.who.int/publications-detail/global-status-report-on-road-safety-2018.