DEPARTMENT OF INFORMATICS

TECHNISCHE UNIVERSITÄT MÜNCHEN

Bachelor's Thesis in Informatics

State of the Art, Issues and Trends of Autonomous Driving

Achilleas Tsakpinis

DEPARTMENT OF INFORMATICS

TECHNISCHE UNIVERSITÄT MÜNCHEN

Bachelor's Thesis in Informatics

State of the Art, Issues and Trends of Autonomous Driving

Aktueller Stand, Probleme und Trends des Autonomen Fahrens

Author:	Achilleas Tsakpinis
Supervisor:	Dr. Tobias Neckel
Advisor:	Prof. Thomas Huckle
Submission Date:	15.08.2022

I confirm that this bachelor's thesis in informatics is my own work and I have documented all sources and material used.

Munich, 15.08.2022 Achilleas Tsakpinis

Abstract

In 1939 first attempts were made by General Motors to implement the first self-driving car. With the help of magnetized metal spikes, hidden under the road, the electric car was able to follow the road. With the invention of new sensors and the development of existing sensors, the industry of Autonomous Vehicle (AV)s began to rise. In the last few years, big differences appeared in the ability of AVs, which lead to the definition of automated and autonomous vehicles. The aim of the thesis was, to summarize, analyze and categorize accidents, that have happened so far. With these failures in mind, two different autonomous prototypes are introduced. As applied research method, scientific paper and gray literature including newspaper, articles and websites from the field of autonomous car crashes, autonomous car sensors, law and ethics in autonomous driving and concepts of autonomous cars and their impact on traffic were reviewed. To categorize the accidents, similarities and differences were taken into consideration with the technical background in mind. For the prototypes, the know-how of the leading manufacturers was taken into account as also the technology, that has not been applied in AVs. The result of the accidents-categorization is, that a lot of accidents would not happen with humans. However, the accidents that happen with AVs involve way fewer injured and killed people. The prototypes illustrate, that there are many different approaches when it comes to Autonomous Driving (AD). To gain more safety, a lot of redundancy can be added through different sensors, but it remains open, whether Society of Automotive Engineers (SAE) level 5 can be achieved at all. The main outcome is, that there is still plenty of space for improvements with existing sensor technology but also new inventions have to be made like generic Vehicle-to-Vehicle Communication (V2V)-communication. When it comes to the accidents involving AVs, even more can be avoided with the progress of development in this industry. But despite these developments, the observance of ethical principles and drafting of consistent legislation should not be neglected.

Kurzfassung

1939 unternahm General Motors erstmals Versuche, das erste selbstfahrende Auto zu bauen. Mit Hilfe von magnetischen Metallspitzen, die in der Straße eingebaut waren, war das Elektroauto in der Lage, der Straße zu folgen. Mit der Erfindung neuer und der Weiterentwicklung bestehender Sensoren begann die Industrie der AVs zu wachsen. In den letzten Jahren zeigten sich große Unterschiede in der Leistungsfähigkeit von AVs, was zu der Definition von automatisierten bzw. autonomen Fahrzeugen führte. Das Ziel dieser Arbeit ist es, Unfälle zusammenzufassen, zu analysieren und zu kategorisieren, die bisher geschehen sind. Basierend auf diesen Fehlern, werden zwei verschiedene autonome Prototypen vorgestellt. Als Forschungsmethode wurde Literaturstudium in Form von wissenschaftlichen Papieren und grauer Literatur, einschließlich Zeitungsartikeln und Webseiten aus dem Bereich der autonomen Autounfälle, autonomen Autosensoren, Recht und Ethik beim autonomen Fahren und Konzepte für autonome Autos und ihre Auswirkungen auf den Verkehr analysiert. Um die Unfälle zu kategorisieren, werden Gemeinsamkeiten und Unterschiede in Zusammenhang mit dem technischen Hintergrund in Betracht gezogen. Bei den Prototypen wird das Know-how führender Hersteller sowie Technologien berücksichtigt, die noch nicht in AVs eingesetzt wurden. Das Ergebnis der Unfallkategorisierung ist, dass viele Unfälle nicht passiert wären, wenn ein Mensch gefahren wäre. Jedoch gibt es bei den Unfällen, die mit AVs passieren, weitaus weniger verletzte und getötete Personen. Die Prototypen verdeutlichen, dass es viele verschiedene Ansätze gibt, wenn es um AD geht. Für mehr Sicherheit können eine Reihe von Redundanz durch verschiedene Sensoren hinzugefügt werden, es bleibt aber offen, ob SAE Level 5 überhaupt erreicht werden kann. Das wichtigste Ergebnis der Arbeit ist, dass es noch viel Raum für Verbesserungen mit bestehender Sensorik gibt, aber auch neue Erfindungen gemacht werden müssen, wie z.B. eine generische V2V-Kommunikation. Was Unfälle mit AVs betrifft, werden mit der fortschreitenden Entwicklung der Branche noch mehr Unfälle vermieden werden. Doch trotz dieser Entwicklungen sollten die Einhaltung ethischer Grundsätze und die Ausarbeitung einer konsistenten Gesetzgebung nicht vernachlässigt werden.

Contents

Abstract iii

Kurzfassung iv

1 Introduction 1

2 Background 2
- 2.1 Automated Vehicles 2
- 2.2 Autonomous Vehicles 2
- 2.3 Taxonomy Levels 3

3 Current State of Technology 5
- 3.1 Competitors on the Market 5
- 3.2 Recent Technologies, their Benefits and Challenges 7
  - 3.2.1 Proprioceptive Sensors 7
  - 3.2.2 Exteroceptive Sensors 8
- 3.3 Technology Trends 15
  - 3.3.1 Camera only Approach 15
  - 3.3.2 Quantum Computing in AV 17
- 3.4 Midterm and long-term Goals 18

4 Categorization of Accidents 20
- 4.1 Unreasonable human Behavior/ Interaction between conventional Car and AV 20
- 4.2 Intrinsic limits of AS 22
  - 4.2.1 Stationary Cars/Objects 22
  - 4.2.2 Response to other Road Users 24
- 4.3 Wrong Sensor-data/Misinterpretation of Sensor-data 26
- 4.4 Cyber Attacks 28
- 4.5 Unknown Reasons 28

5 Explanation of Accidents 31
- 5.1 Object Detection and Classification Algorithms 31

5.2 Emergency brakes . . . 32
5.3 Light Detection and Ranging (LiDAR) as potential solution . . . 32

6 Fictional Prototype **33**
6.1 Leading Competitors . . . 33
6.2 Vision-only Prototype . . . 37
6.3 General Prototype . . . 39

7 Legal Background **42**
7.1 Civil Liability . . . 42
7.2 Criminal Liability . . . 43
7.3 Administrative Liability . . . 43
7.4 Situation Awareness . . . 44
7.5 Legal Development in Germany . . . 45
7.5.1 Laws until 2018 . . . 45
7.5.2 Milestone in 2021 . . . 45
7.5.3 Adaptions in 2022 . . . 46

8 Ethical Background **47**
8.1 20 Rules of the "Ethik-Rat" . . . 47
8.2 Surveys . . . 51
8.3 Approaches for ethical Decisions in AVs . . . 52
8.4 Trolley Case . . . 54
8.4.1 Light Trolley Case . . . 54

9 Outlook **56**
9.1 Transferability to other Scenarios and Sectors . . . 56
9.1.1 Autonomous Buses . . . 56
9.1.2 Autonomous Trucks . . . 57
9.2 Change of Traffic . . . 57

List of Figures **60**

List of Tables **62**

Acronyms **63**

Bibliography **65**

1 Introduction

In this thesis, the current state, issues, and trends of autonomous driving will be assessed. In the beginning, there will be some general information about the background of AD and the approach to categorize the autonomy of the systems so you can compare different approaches. Therefore, the six different taxonomy levels will be explained.

After a short introduction of the most important topics, the state of the art will be presented, including also a short overview of the market and some small analysis. In this part of the thesis, the focus is on the different sensors that are used in an AV. The pros and cons will be discussed for each of these sensors, to have a good overview for chapter 6. At the end of this chapter, the mid and long-term goals of this new field of application will be shown.

For advanced information about the sensors and the whole fusion, so that the system works merged with the car, there is already a bachelor's thesis from Michael Grad [40] regarding this. This thesis will give an update on the last 3 years of innovations and changes in this industry.

After that, there will be a closer look at occurred accidents. These accidents will then be analyzed and categorized by their cause. Based on some cases there will be deeper explanations of the behavior of the car.

Before the proposal of a fictional prototype, the current leading competitors will be presented. There will be a comparison between their sensors and used techniques, to then have some inspiration. The prototype will take the leaders of autonomous driving and merge their best approaches with also yet unused techniques. There will be no limits regarding money or effort or computing power/electricity, but of course, this fact will be considered in the comparison between this car and the current systems.

This paper will sum up the legal aspects of autonomous driving in Germany until 2019 but then also complement it with the latest adaptions of the law. Of course, the ethical aspects of autonomous driving will be explained too.

The thesis will end with an outlook for potential industries of other fields of applications where this technology could be useful. Finally, the impact of autonomous cars on traffic will be assessed.

2 Background

2.1 Automated Vehicles

The US department of Transportation defines automated vehicles as following: "Automated vehicles are those in which at least some aspect of a safety-critical control function (e.g., steering, throttle, or braking) occurs without direct driver input. Automated vehicles may be autonomous (i.e., use only vehicle sensors) or may be connected (i.e., use communications systems such as connected vehicle technology, in which cars and roadside infrastructure communicate wirelessly). Connectivity is an important input to realizing the full potential benefits and broad-scale implementation of automated vehicles." Derived from [3].

For some years established car manufacturers like Audi, BMW, Daimler and VW have been implementing such functions. Examples would be an automated emergency brake, lane keeping or adaptive cruise control. It becomes interesting when all these functions must work together without any human supervision and control. This leads us to autonomous vehicles and their different taxonomy levels.

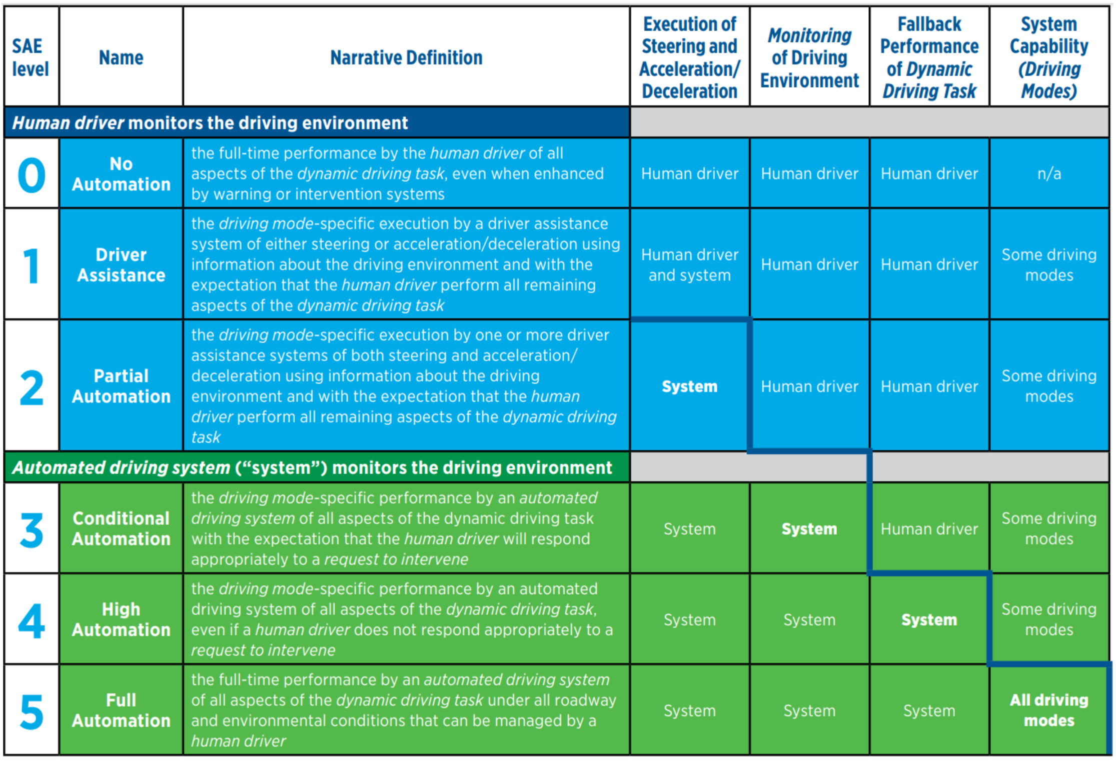
2.2 Autonomous Vehicles

Autonomous vehicles should be able to monitor their driving environment and operate without any human assistance. The autonomous vehicle should deal with every situation itself and does not even require a passenger for supervision. To sum it up it should reach all the destinations that a normal car with an experienced human driver does. Derived from [115].

With this upcoming technology, a lot of new competitors entered the market which are unusual car manufacturers like Google, Uber and Intel but also new startups. As we will see in chapter 9 of this thesis, autonomous driving/vehicles are not just limited to cars but also buses and other means of transport.

2.3 Taxonomy Levels

Information from this section is taken from [52]. The Taxonomy levels were introduced by the SAE International (Society of Automotive Engineers) to classify different autonomous driving skills. The so called SAE J3016 standard defines 6 levels of autonomy reaching from non-autonomous to fully autonomous. The peculiarity is, that it is classified by the amount of driver intervention and attention required but does not consider the vehicle's capabilities. This leads to the advantage that it does not matter how the car is equipped with sensors as long as the whole system works. The classification looks as follows:



SAE level	Name	Narrative Definition	Execution of Steering and Acceleration/ Deceleration	*Monitoring* of Driving Environment	Fallback Performance of *Dynamic Driving Task*	System Capability *(Driving Modes)*
***Human driver* monitors the driving environment**						
0	**No Automation**	the full-time performance by the *human driver* of all aspects of the *dynamic driving task*, even when enhanced by warning or intervention systems	Human driver	Human driver	Human driver	n/a
1	**Driver Assistance**	the *driving mode*-specific execution by a driver assistance system of either steering or acceleration/deceleration using information about the driving environment and with the expectation that the *human driver* perform all remaining aspects of the *dynamic driving task*	Human driver and system	Human driver	Human driver	Some driving modes
2	**Partial Automation**	the *driving mode*-specific execution by one or more driver assistance systems of both steering and acceleration/ deceleration using information about the driving environment and with the expectation that the *human driver* perform all remaining aspects of the *dynamic driving task*	**System**	Human driver	Human driver	Some driving modes
***Automated driving system* ("system") monitors the driving environment**						
3	**Conditional Automation**	the *driving mode*-specific performance by an *automated driving system* of all aspects of the dynamic driving task with the expectation that the *human driver* will respond appropriately to a *request to intervene*	System	**System**	Human driver	Some driving modes
4	**High Automation**	the *driving mode*-specific performance by an automated driving system of all aspects of the *dynamic driving task*, even if a *human driver* does not respond appropriately to a *request to intervene*	System	System	**System**	Some driving modes
5	**Full Automation**	the full-time performance by an *automated driving system* of all aspects of the *dynamic driving task* under all roadway and environmental conditions that can be managed by a *human driver*	System	System	System	**All driving modes**

Table 2.1: The six Taxonomy levels: Level zero to two with continuous monitoring, whereas from three to five the monitoring is handed over to the car step by step, adapted from [50].

In the following section the different levels of the SAE J3016, introduced in table 2.1, will be explained in more detail. Information about this section is taken from [40, 52, 96].

- **Level 0 (No automation):** Most of the vehicles are at this stage today. There is no automation so that the driver takes care of steering, throttle, braking and monitoring the driving environment. But there are assistant systems like blind spot warning, collision warnings, Anti-lock Braking System (ABS) and Electric Stability Control (ESP).
- **Level 1 (Driver Assistance):** The driver has still full responsibility and must monitor the driving environment. The car can take over steering or throttling/braking in some circumstances. Examples of this are Adaptive Cruise Control (ACC) or Lane Keeping Assistant (LK).
- **Level 2 (Partial Assistance):** The driver has still full responsibility and must monitor the driving environment. Level 2 combines steering, braking and throttling, leading to let the car drive on its own with this system for a short time and in special circumstances. Self-parking is also included as automated action in level 2.
- **Level 3 (Condition Assistance):** From level 3 on-wards the car is responsible for monitoring the driving environment in some special situations like on highways. If that is the case the driver can fully rely on the car and take care of other stuff like reading. However, the driver still needs to be there as a potential fallback if there is any problem. But still, the system should know its own boundaries and should give the driver enough time, to react and overtake the control of the car.
- **Level 4 (High Automation):** This level extends the special situations of autonomous driving of level 3. The car is now able to handle complex traffic situations by itself with a variety of driving routes among which it chooses the best one. It is also able to perform fully autonomously in unknown surroundings and if there is any faulty sensor. There is no need for a fallback because the car will go into a so-called safe state if there is any problem like severe weather conditions. This safe state could be a parking lot or parking next to the road without violating any law or endangering pedestrians or other traffic participants.
- **Level 5 (Full Automation):** Level 5 is the highest level and requires just the input of a destination. It can drive on its own with and without passengers and handles every possible task by itself. Additionally, it handles hardware failure and severe weather conditions appropriate.

There are also different approaches like a four-level system from the Bundesanstalt für Straßenwesen (BASt) however, even they took over the SAE J3016 in their law. The difference between both approaches is that level 4 and level 5 are merged.

3 Current State of Technology

With the background of the SAE levels, the market will be further explained in the following. First, there will be an overview of the competitors in the market. Afterwards, the manufacturers are compared and their fleets are analyzed more in detail. With the different technology approaches in mind, there will be a comparison between them. Finally, there will be an outlook on the midterm and long-term goals of the whole industry.

3.1 Competitors on the Market

In a report from [94], this question is addressed in detail. To answer this question, criteria were defined. Important was not just the technology, but also the corporate strategy and the actual execution and implementation of the companies. In detail the report listed following criteria:

- "Vision
- Go-to-Market Strategy
- Partners
- Production Strategy
- Technology
- Sales, Marketing, and Distribution
- Product Capability
- Product Quality and Reliability
- Product Portfolio
- Staying Power."

This leads to following ranking:

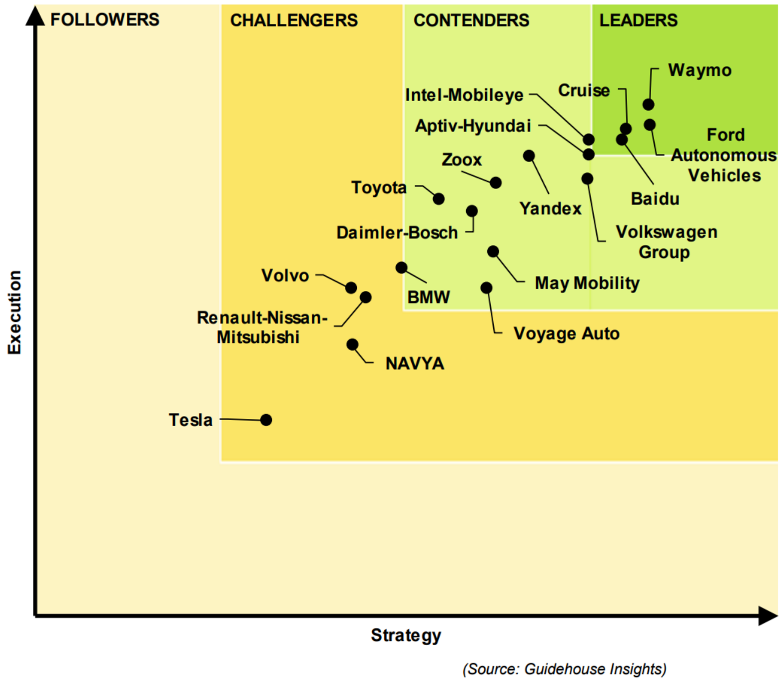


Figure 3.1: Ranking of the market competitors according to the above mentioned criteria [94].

The figure 3.1 is split into four different categories: Followers, challengers, contenders, and leaders. There are some interesting aspects in this ranking.

1. Tesla which is one of the most popular brands out there is at the last position with their so-called Autopilot.
2. Google with their sub-brand Waymo is leading, but has some good competition.
3. More and more competitors without significant experience in car manufacturing are joining in the market.

Tesla has introduced their Autopilot back in 2014. At this time, it was a breakthrough for the consumer market. Their Autopilot is advertised as a Full Self-Driving feature, but the driver still has to supervise the traffic and behavior of the car. This leads to a level 2 in the SAE taxonomy. Since then, a lot of improvements have been done but still, it is not enough for the big step to level 3 without partial supervision.

Google's sub-brand Waymo is leading the market for several years now. It is leading in the number of driven and simulated miles, but also leads the board of number of disengagement rate per 1000 kilometers. Waymo is securing its future by also being one of the leaders in patents for autonomous driving. All these strategic decisions lead to Waymo as market leader.

Due to the market's potential more and more startups are raising and joining the market. These companies do not necessarily build cars but develop the software which is then deployed on an external car. Since big car companies were very hesitant regarding the deployment of autonomous driving, they also started buying these startups to secure them a better position in the competition. In general, three developments are visible on the market. First of all, big car manufacturers implement step-by-step automated features in their cars until the cars are a SAE level 4 or level 5. The second development are new competitors joined the market like Google or other tech companies who implement cars with new designs and sensor strategies with no previous knowledge. The third strategy is based on co-operations between car manufacturers and tech companies or even start-ups to develop fully autonomous cars (Information was taken from [106] and [5]).

3.2 Recent Technologies, their Benefits and Challenges

Information from this section is taken from [98, 122].

Having a closer look at all the sensors that are used in AVs you must distinguish between proprioceptive and exteroceptive sensors. Proprioceptive sensors or so-called internal state sensors, detect the state and measure the internal values of the dynamic system.

3.2.1 Proprioceptive Sensors

- **Gyroscope:**

  Measures with the help of Earth's gravitational force the angular velocity and helps for positioning.

- **Magnetometer:**

  Measures the magnetic field in the environment.

- **Accelerometer:**

  Measures the three-dimensional acceleration force on the sensor.

- **Inertial Measurement Units (IMU):**

  Combines the data of gyroscopes, accelerometers, and magnetometers. It can deliver information about the position of a car, orientation, and gravitational forces. Hence, it is mostly used when there is a weak GPS signal like in bad weather conditions or in tunnels.

- **Encoders:**

  Measures the motion of a wheel and converts it into an electric signal.

- **Real-time kinematics (RTK):**

  Provides location and time data as a reference point for positioning.

- **Positioning sensors (Global Navigation Satellite System (GNSS) receivers):**

  With the help of 5 to up to 15 satellites the position of the car is calculated by triangulation. This is possible because the satellites are sending time signals. With these given time signals the distance between the car and the satellites can be calculated. Information from [4].

These signals are very weak and often get interfered by the earth's atmosphere or buildings. Therefore, a sensor fusion with RTKs and IMUs is needed to provide positional accuracy of up to 1 cm.

For more detailed information, [40] wrote a whole chapter about the localization of an AV.

3.2.2 Exteroceptive Sensors

Information on exteroceptive sensors is taken from [4, 22, 40, 52, 95, 96, 98, 106, 114, 122].

As a next step, the focus will be on the exteroceptive sensors. The also called external state sensors observe and collect data about the surrounding of the AV. In general, there is still a distinction between active and passive sensors. Active sensors are emitting signals like LiDAR is doing with laser bundles whereas passive sensors receive signals like cameras capture light.

LiDAR:

The LiDAR sensor emits infrared or laser bundles. These bundles then reflect in different ways from objects back. Knowing the speed of these bundles, an instrument is receiving them back and can then calculate the distance between the sensor and the object with the help of the time interval and the speed. Because the LiDAR sensor is continuously scanning its environment by turning the sensor 360° at high speed, a 360° map of points is created.

LiDAR sensors can measure different dimensions of the environment. One-dimensional LiDAR sensors can only measure the distance to objects, whereas two-dimensional LiDAR sensors are capable of measuring the distance and the angle of an object. Three-dimensional LiDAR sensors have also the possibility, to measure the height of objects in the environment. The following figure 3.2 illustrates the different LiDAR types.

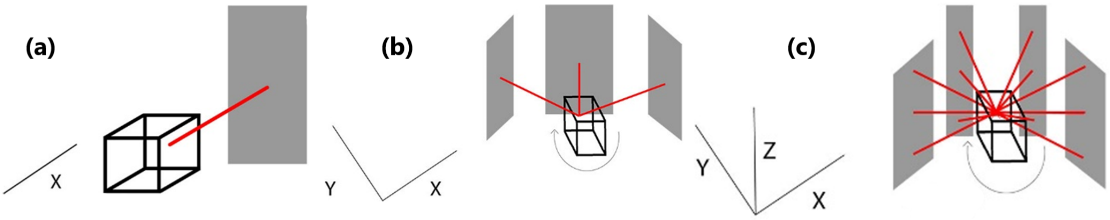


Figure 3.2: LiDAR Dimensions: **(a)** one-dimensional measure, **(b)** two-dimensional measure, **(c)** three-dimensional measure, adapted from [111].

LiDAR comes with its own advantages and disadvantages:

Pro's:

- **Very accurate**
- **Performs during high velocities**
- **High scanning speed**
- **Long distance measurements**
- **Creates a 360-degree map**
- **Easily integrate-able into other sensor data**
- **Operates in daylight and by night**

Con's:

- **Rare earth metals are needed ⇒ Expenses from 10K$ up to Google's 80K$**
- **Snow and fog can be blockers of the laser bundles (degrade by up to 25%)**
- **A lot of data points ⇒ time and resources needed**
- **Can not provide any colored picture**
- **Comparatively big**

Solid-State LiDAR (SSL)

Since a usual LiDAR sensor is spined by an electric motor 360° horizontal, there are a lot of mechanical parts involved too which can lead to a mechanical failure. Furthermore, these mechanical parts are also additional costs. The SSL sensors don't have this risk of failure because they are fixed. Of course, this decision decreases the angle of view, but they can still reach angles up to 120°, at a lower cost and maintenance.

Ultrasonic/Ultrasound sensors:

Additional information about ultrasonic sensors is taken from [4, 22, 114].

Ultrasound sensors work like SSL sensors but are used for many years now. The only difference is as their name already tells is the emitted medium. In this case, ultrasonic sounds are used that are as the light bundles not recognizable by a human being. In general, they are used for low-speed use cases like self-parking and blind-spot detection as near field object detection. The functionality of ultrasound sensors is shown in the following figure 3.3:

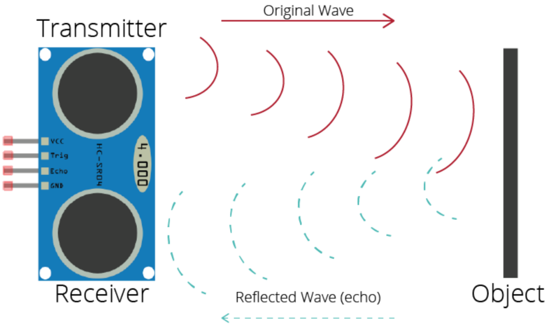


Figure 3.3: Functionality of an ultrasonic sensor [21].

Pro's:

- **Cheap due to production experience**
- **Low up to high resolution imaging depending on the frequencies**
- **Comparatively small size**
- **Operates in daylight and by night**

Con's:

- **Short and slow range measurements**
- **Additional hardware for interpretation is needed**
- **Speed of wave depends on temperature**
- **Can not provide any colored picture**

Radar sensors:

Additional information on ultrasonic sensors is taken from [40, 85, 105].

Radar or so-called Radio Detection and Ranging sensors are working like Ultrasonic sensors and are used for many years now too. The only difference is as their name already tells is the emitted wave. In this case, electromagnetic waves are used that are as the sound waves not recognizable by a human being. However, compared to sound waves, electromagnetic waves are way faster and not that fragile. Tesla is using their radar for ranges up to 500m but in general, they are also used for both low-speed and high-speed use cases.

Pro's:

- **Cheap due to production experience**
- **Short up to long range measurements**
- **Low up to high resolution depending on the frequencies**
- **Comparatively small size**
- **Weather robust**
- **Operates in Daylight and by night**

Con's:

- **Additional hardware for interpretation is needed**
- **Can not provide any colored picture**

Cameras:

Additional information on camera sensors is taken from [40, 95, 98, 122].

Cameras are an important part of AVs, both for the vision-only approach without LiDAR and also for LiDAR as a second data source for object interpretation. In contrast to LiDAR sensors, cameras catch the light reflected by the surroundings on a photosensitive area through a camera lens. Cameras are capable of colored short-range detection but also long-range detection. They are able to detect other road users, different road and traffic signs, signals and constructions. As a next step, they get classified as one of these mentioned and then calculate the distance to them, without the help of a LiDAR sensor. For object detection and interpretation, it is enough to use a monocular camera system, which consists of only one lens. Binocular camera systems are two cameras next two each other taking the same picture from a slightly different position. This difference in the pictures then allows algorithms to generate depth information out of this data.

For more detailed information about the physics of cameras, Michael Grad wrote a very detailed sub-chapter at [40] about it.

Pro's:

- **Cheap due to production experience**
- **Short up to long range measurements**
- **Low up to high resolution**
- **Comparatively small size**
- **Easy integrate-able into other sensor data**
- **Good object interpretation**
- **Colored sensor-data**
- **Well researched image classification algorithms**

Con's:

- **Still leak of quality for good decisions (e.g. color of car like background)**
- **Bad performance at rain, fog, or snow**
- **A lot of data requires time and resources**
- **Bad performance at night**
- **Limited dynamic range can lead to information loss**

Thermal Camera/Infrared Camera (IRC)

Additional information about IRC sensors is taken from [46, 116].

Unlike normal cameras which heavily rely on light, thermal cameras use the heat that is emitted from objects. This gives IRCs the possibility to detect objects like pedestrians animals or cars.

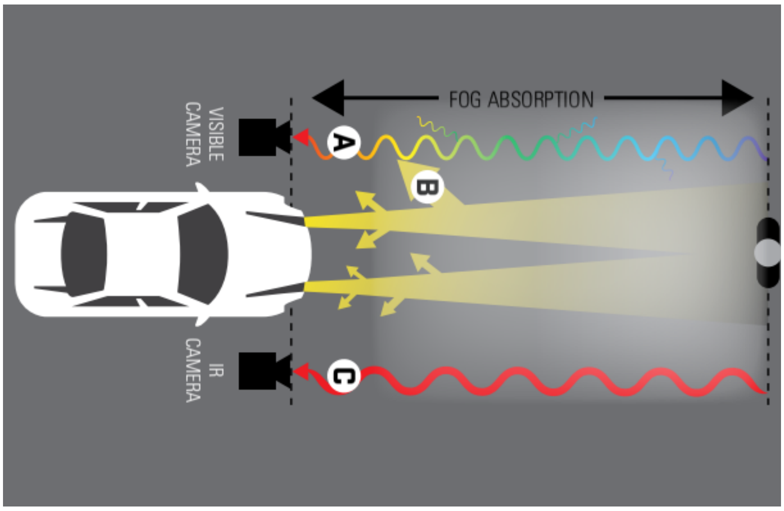


Figure 3.4: Comparison between a visible camera and IR camera [116].

IRCs can detect objects four times further through fog at day and night. The figure 3.4 shows how the light wave is interfered by the fog and light of the car, whereas the infrared wave stays the same. The reason, why IRCs can detect these objects is, that the infrared spectrum has a much wider spectrum compared to the visible spectrum. Thus IRCs are capable of measuring temperature differences up to 0.05°C. With this advantage, IRCs can be a perfect complement to the already existing data. IRCs do not rely on daylight which makes them a perfect sensor operating at day and night-time. Especially when it comes to longer distance (>50 m) information, IRCs outperform low-light cameras with more consistent images. Even though IRCs are not yet used in AVs, they will play a significant role when it comes to SAE 4 and SAE 5. The fact, that half of the pedestrian-related accidents happen during night-time, even though there is way less traffic, proofs, that IRCs can be a crucial sensor to prevent these dangerous pedestrian accidents. The figure 3.5 shows, how IRCs can detect humans in bad vision conditions:

Figure 3.5: Picture of a foggy tunnel taken with thermal long-wave (LWIR), visible RGB, short-wave (SWIR), and near (NIR) camera [116].

Pro's:

- **Does not rely on light**
- **Operates during day and night**
- **Very sensitive to smallest temperature changes**
- **No interference by fog or other waves**
- **Outperforms normal cameras especially at long range**
- **Comparatively small size**
- **Good object interpretation**
- **Weather robust**

Con's:

- **Still expensive but prices are decreasing**
- **Can only be used as a complementary sensor**
- **A lot of data requires time and resources**
- **Can not provide colored picture**

3.3 Technology Trends

As already observed with thermal cameras the development of AVs is not finished yet. Most of the AV developers are stuck at SAE 3 or SAE 4 and still need a lot of work to come close to fully autonomous driving. To achieve this, it is always helpful to introduce new technologies or strategies to achieve a better system.

3.3.1 Camera only Approach

One of the main differences between Tesla and all the other manufacturers is the explicit omission of a LiDAR sensor. Toyota announced to join this camera-only approach for their AVs. This camera-only approach is shown below with a Tesla Model S as an example:

Figure 3.6: A Tesla Model S and its cameras and their angles of view [40].

At the front and back of the car, illustrated in figure 3.6, there is redundancy, because of safety reasons. Otherwise the car is covered with 360° camera view. The main argument for this step are costs and scalability. Woven Planet, a subsidiary of Toyota also justifies this step. For them, it is mandatory to collect a huge amount of diverse data to train their models. Without this amount of data, it would not be possible to develop a safe and robust AV. According to Woven Planet, this is not scale-able with expensive LiDAR sensors. In general, there is now either the bet on a huge fleet with cheap sensors or a small fleet with more expensive ones. Regarding Woven Planet, the trained system would be equal in performance and safety with low-cost cameras in comparison to high-cost sensor data. However, Toyota still works with both approaches. For their Robotaxis, because of safety concerns, LiDAR is still used, whereas in private cars there are low-cost sensors built in to collect additional data.

This decision has several advantages, but also comes with huge challenges. Of course, the main aspect of this decision was the price. Toyota can to reduce the price of the sensors by up to 90%. This has two advantages. First of all, for the customer the prices are not increasing significantly. This is very important so that private customers buy the car and Toyota can collect data from them without investing in anything. Second, cheap sensors mean, Toyota is able, to install even more of them to increase redundancy but also increase the possibility of data collection even more.

For years, car manufacturers have been relying on cameras as sensors. This means it is not a completely new approach, it is just developing an existing technology even further. With the help of already existing knowledge about the technology and high-performance algorithms, this can be a successful path.
Finally this is also a great opportunity for this technology. Through massive investments, there is the possibility of developing even more powerful camera systems with comparably cheap and even more powerful algorithms.
On the other hand, cameras, as already summed up in section 3.2.2, produce a lot of data. This requires high-performance computers to process and analyze this data. This might slightly increase the price, but the data, captured by LiDAR systems is not significantly less so it is comparable.
Of course, cameras are not capable of operating during the night or in bad weather conditions. This causes first a lack of data that is missing for training the models but also does not let the customer operate autonomous driving functions in such conditions. Also, the quality of camera-only data is not that good. To achieve nearly the same performance as a model, trained with multiply-sensor data, a huge amount of data has to be collected.
Information was taken from [65, 107].

3.3.2 Quantum Computing in AV

Even though Quantum Computing (QC) is a very popular research topic, it has not been applied that much to AVs yet. There are some companies like Toyota, Volkswagen, Daimler, BMW and Suppliers like Bosch researching and investing heavily but the applications are more in the area of optimizations regarding for example batteries and simulations for fluid dynamics or material durability and so on.

		Vehicle routing	Heat and mass transfer	Fluid dynamics	Electromechanical systems	Route optimization	Improved battery materials	Material durability	Fuel-cell optimization	Autonomous driving	Predictive maintenance
OEM	Toyota	●				●					
	Volkswagen	●				●	●		●		
	Daimler						●	●	●		
	BMW	●					●		●		
Supplier	Bosch		●	●	●						●

Table 3.1: Fields of applications for QC in the automotive industry [17].

Nevertheless there are applications, QC can be used for near future, as shown in table 3.1. Because of their enormous processing rate, Quantum Computers (QCs) are capable of training models with even more massive data sets in a significantly shorter time than classical computers could ever do it. This would lead to way more accurate models and as a result safer AVs.
It would be possible, that cars send real-time data of sensors to the car manufacturers, where powerful QCs could process the data in real-time and give especially after accidents way faster safety updates.
The second benefit of the enormous computing power is, that the Artificial Intelligence (AI) systems could be even more fine-tuned to be more accurate and also safer.
Additionally, there are applications in traffic management and route optimization of the AVs.
Overall there is still a lot of improvement and research in the field of QC to do until this can be a reliable support. Developers must still manage high error rates which are counterproductive for such a life-critical application. Information about this subsection was taken from [17, 28, 88].

3.4 Midterm and long-term Goals

Information from this section is taken from [5, 20, 27, 44, 48, 61].

All the companies focus heavily on earning datasets from multiple scenarios for different sensor modalities. This especially boosts the models of cars for more safety and performance in all conditions to reach SAE levels 4 and 5. Tesla is already implementing this by having 100.000 beta users for their Self-Driving-Program.

Also, Waymo, a Google subsidiary, is now officially offering fully autonomous SAE level 4 rides to their employees to collect real-world data. This data is useless without processing and safe, reliable and efficient virtual validation. Because of a massive number of conditions like weather, light, road types and traffic, a huge amount of processing power is needed. Possible solutions to overcome the data-processing bottleneck could be cloud systems and clusters. This gives the model the ability to make even faster decisions in different conditions, through which several of moral dilemmas might be avoided.With this information, gained from the simulations, it is then also possible to find a good balance between conservative behavior and safe driving by adjusting the safety parameters based on the car model and environment.

Second, the companies are working intensively on route optimization. This can be a game changer in terms of air pollution reduction. Additionally, up to 60% of fuel can be saved by optimizing the acceleration and braking of the operating car. This is made possible by avoiding traffic jams, particularly in crowded urban traffic. Finally, by setting up a V2V communication, organized platoons with controlled speed can save from 5% up to 20% of fuel.

In general, it is also important for car manufacturers to build up a communication infrastructure. Because there has not been implemented something similar, it would be a great opportunity for the biggest manufacturers, to build up a generic V2V communication. The manufacturers, the environment and other companies would benefit from such a project. Furthermore, a Vehicle-to-Everyone Communication (V2X) communication must be implemented to distribute updates but also to efficiently collect the sensor data, cars are collecting. There would be the possibility to distribute important information about road conditions and so on to the car via V2X.

The biggest non-technical challenge and therefore goal will be, to increase the acceptance of AVs. Whenever there is a big step in technology development, people are skeptical by nature. Car manufacturers must be transparent with their technology and also with accidents and bugs to increase acceptance. This technology is even more challenging, considering that people must give their life in the hands of a driverless car. South Korea took these concerns into account and legally allowed companies to test their AVs only with a control driver. The Driver must take over the steering whenever the car is in safety zones like schools or if the Autonomous System (AS) makes a fatal error.

Worth mentioning is also the development of new technology and software but also the integration of it into existing systems like infrared cameras section 3.2.2.

4 Categorization of Accidents

In October 2021 the National Highway Traffic Safety Administration (NHTSA) introduced a new law. This law forced companies working on vehicles with ASs to report any serious crash one day after getting to know about it. A detailed report about the whole accident must follow within 10 days after the crash. This allows a transparent overview of all the crashes that happened involving ASs. In general, ASs were involved in five more crashes per million miles traveled in comparison to conventional cars. However, the number of crashes involving injuries decreased in comparison to conventional car accidents. In this chapter, there will be a categorization of crashes happened involving ASs [63].

4.1 Unreasonable human Behavior/ Interaction between conventional Car and AV

- **A Waymo AV crashes sideways into a driving bus.**

  The AV thought, the bus would slow down so the AV can fade into the lane of the bus, but the bus did not slow down. The AV crashed sideways into the bus, but no one got injured [47].

- **A Cruise AV gets involved in an accident while cornering at an intersection.**

  A Cruise AV wanted to corner at a four-lane intersection and was located at the second of 4 lanes from left. Another car overtook left and tried to drive straight in the most left lane. The overtaking car crashed into the front left of the cornering AV [118].

- **A Tesla AV warns the passenger because of a potential crash, but the passenger accelerates and crashes.**

  The driver of the Tesla increased speed on a Highway. The Tesla detected a minivan in front and immediately triggered the emergency brake. Because the driver accelerated again the car went into override mode and ignored the emergency brake. This resulted in multiple collisions with the back of the minivan. The Tesla exited via an off-ramp while speeding and crashed into a pickup truck. The Tesla caught fire and six people were injured. The two occupants of the Tesla died afterward as a result of the accident [41, 90].

- **A Tesla AV warns the passenger because of a potential crash, but the driver ignores it and the Tesla crashes into center divider.**

  The driver of the Tesla received several warnings because the driver's hands were not detected. Additionally, there were five seconds and 150 meters where the driver could have recognized the center divider, but he did not react. The driver of the Tesla died. The death could have been avoided because of several reasons. There was enough time to react, but the driver did not pay attention due to a phone game. The center divider was damaged and not yet replaced which killed the driver most likely, as shown in figure 4.2. The car did not recognize the correct lane layout, because of badly painted lane markings and led the driver on the track to the center divider, illustrated in figure 4.1. Another possibility is that the image recognition of the car did not recognize the damaged center divider as a normal center divider [100, 103].

Figure 4.1: Center divider, marked with badly painted lane markings, of the crash [38].

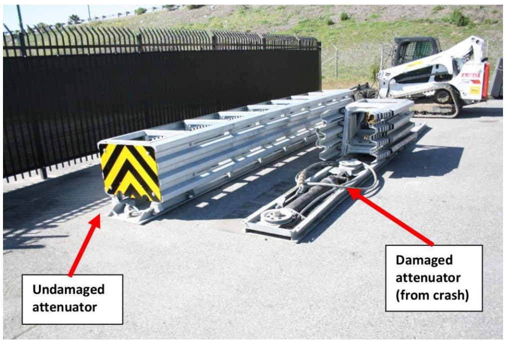


Figure 4.2: New center divider in comparison to a damaged center divider [103].

- **Other cars hit Waymo AVs at slow speed or while decelerating.**

  There were several rear-end collisions reported involving Waymo AVs. Eight of eleven Waymo cars were hit while they did not even drive. Two of them were hit at low speed and the last was hit while decelerating. This behavior could be due to inattention while driving [117].

4.2 Intrinsic limits of AS

4.2.1 Stationary Cars/Objects

- **Tesla AVs crashes into stationary fire truck.**

  In 2018 a Tesla crashed into a stationary fire truck in California. The driver states that the car was driving on Autopilot when the car crashed into the back of the truck. Seconds before the crash was another car in front of the Tesla which suddenly changed lanes because of the fire truck. Despite the stationary fire truck, the Autopilot directly crashed into the truck without braking [47].

  In December 2019 a Tesla crashed into a stationary fire truck in Indiana under similar circumstances. Even though Indiana State Police and NHTSA investigated whether the car was operating in Autopilot, results were never published. According to the firefighters the car did not brake before the crash. One of the two passengers died because of the injuries [54].

- **Tesla AVs crashes into stationary police car.**

  There have been several accidents, in which a Tesla crashes into a stationary police car:
  In May 2018 in Laguna Beach, California, a Tesla crashed into a stationary police car. The Tesla was operating in Autopilot. Nobody got seriously injured [72].
  In December 2019 in Norwalk, Connecticut, a Tesla with Autopilot engaged crashed into a police car. The driver was distracted and did not pay attention to the actions of the Autopilot. Luckily nobody got injured. The police car had turned on flashers and road flares [36].
  In December 2019 in West Bridgewater, Massachusetts, a Tesla with Autopilot engaged crashed into a stationary police car. According to the driver, he "must not have been paying attention" and did not supervise the actions of the Autopilot. Luckily nobody got seriously injured [57, 58].

In July 2020 near Benson, Arizona, a Tesla with Autopilot engaged crashed into a stationary police car while passing it. The driver was distracted due to intoxication and did not pay attention to the actions of the Autopilot. Luckily nobody got seriously injured [74].
In July 2020 Nash County, North Carolina, a Tesla with Autopilot engaged crashed into a stationary police car. The driver was watching a movie and did not pay attention to the actions of the Autopilot. Luckily nobody got seriously injured [74].
In February 2021 in Montgomery County, Texas, a Tesla with Autopilot engaged crashed into a stationary police car. The driver was distracted due to intoxication and did not pay attention to the actions of the Autopilot. Several police officers and a civilian were injured [123].
In March 2021 in Lansing, Michigan, a Tesla with Autopilot engaged crashed into a stationary police car. There is no information about what the driver was doing right before the collision. Luckily nobody got seriously injured. The police car had turned on emergency lights [123].
In July 2021 in San Diego County, California, a Tesla with Autopilot engaged crashed into a stationary police car. The driver was under suspicion of intoxication and thus did not pay attention to the actions of the Autopilot. Luckily nobody got seriously injured. The police car had turned on emergency lights [12, 53].

- **Tesla AV crashes into parked vehicle.**

  In April 2019 in Key Largo, Florida, a Tesla with Autopilot engaged crashed into a parked car. The driver was having a call when his phone fell down. While he was looking for his phone the Autopilot overran a stop sign and a red light before it crashed into a parked car. The driver noticed the situation too late and could start brake just one second before the collision. One person got injured and one died. This is one of the first cases where the driver also survived the crash and thus could support the investigation [11, 97].

- **Tesla AV crashes into an overturned truck.**

  In Mai 2021 in Los Angeles, California, a Tesla with Autopilot engaged crashed into an overturned truck, which was lying on two lanes of the highway. There is no information on whether the driver was distracted right before the collision. Two persons got seriously injured and one died [23, 79].

- **Tesla AV crashes into a road ranger's truck.**

  In Mai 2021 in Miami-Dade County, Florida, a Tesla with Autopilot engaged crashed into a truck. The truck was located on the left express lane in front of another crash, blocking the lane. There is no information on whether the driver was distracted right before the collision. Luckily nobody got seriously injured. The road rangers had put up proper cones, emergency light and the lane closure arrow board activated [6].

- **Tesla AV crashes into a group of people.**

  In April 2018 in Tokyo, Japan, a Tesla with Autopilot engaged crashed into a group of motorcyclists on an expressway. Right before the accident, a vehicle in front of the Tesla changed lanes to avoid the group of people. The Tesla did not change the lane and additionally accelerated. The driver fell asleep right before the collision. One of the people standing in the group of motorcyclists was killed [2].

- **Tesla AV crashes into road sweeper.**

  In January 2016 in Handan, China, a Tesla with Autopilot engaged crashed into a road sweeper on a highway. The vehicle was parked or slowly moving in the left lane, where also the Autopilot was driving. The Tesla approached the service vehicle but did not show any sign of braking. There is no information on whether the driver was distracted right before the collision. The driver got killed because of the accident [19, 113, 119].

4.2.2 Response to other Road Users

- **Car crashing in the back of Pony.ai AV at a traffic light.**

  In November 2021 in Milpitas, California, a car crashed into a stationary AV of Pony.ai in autonomous mode. The AV with a safety driver in it was waiting at a red light to make a right turn. A car approached from behind at high speed but then slowed down rapidly. The safety driver wanted to engage manual driving as the car from behind started rolling forward quickly. There was no chance for the operator to avoid this crash because the driver of the car behind seemed to be distracted and did not pay attention. Such cases show that autonomous cars can not really interact with conventional cars to avoid such collisions due to a lack of communication [78].

- **Car has taken the right of way and crashes into Cruise AV at a junction.**

  In February 2021 in San Francisco, California, a car crashed into a Cruise AV in autonomous mode while the AV was making a right turn with a right of way. The other car was approaching fast from the left disregarded a stop sign and thus crashed into the AV. Humans would have a sense of the situation and maybe would not insist on the right of way when a car is approaching fast a stop sign [76, 118].

- **Waymo AV gets confused with traffic cones.**

Figure 4.3: Waymo AV trying to fade in on a T-junction with cones on one lane [67, 99, 102].

In May 2021 in Chandler, Arizona, a Waymo AV in autonomous mode got confused with traffic cones on the street. The car was attempting to make a right turn while being on a T-junction, as shown in figure 4.3. The right lane, the one the AV tried to reach, was closed with traffic cones. This seemed to be a big challenge for the car because it had to directly fade to the left of the two lanes. After a while of doing nothing, it continued like in the following picture:

Figure 4.4: Waymo AV faded in the main road but went in the by cones closed area of the road [67, 99, 102].

The car started fading in and everything seemed very smooth except for the waiting. After some meters, the AV decided to change lanes back to the right lane, illustrated in figure 4.4. Even though the lane was still closed by cones, the AV decided to drive onto that lane and stopped again [71, 101].

4.3 Wrong Sensor-data/Misinterpretation of Sensor-data

- **Uber AV crashes into a woman pushing a bicycle.**

  In March 2018 in Tempe, Arizona, an Uber AV in autonomous mode struck a pedestrian while she was pushing her bike across a multi-lane street. The safety driver of the car was distracted because she was watching a TV show. National Transportation Safety Board (NTSB) holds the safety driver responsible for having killed the pedestrian, because there was, according to NTSB, enough time to react. The AV's radar and LiDAR detected the pedestrian six seconds before the collision. First, the pedestrian was classified as an unknown object, then a vehicle and lastly a bicycle. Classified as a vehicle and bicycle the AS assumed it was traveling in the same direction next to it. When it was classified as an unknown object the system believed it was static. Only 1.3 seconds before the collision the car tried to initiate an emergency brake, however it was disabled. Interestingly, the AS did not request the driver to take control of the AV. The pedestrian died because of the accident [10, 45].

- **Tesla AV crashes into a turning tractor-semitrailer truck.**

  In May 2016 in Williston, Florida, a Tesla AV in Autopilot crashed into the semitrailer of a truck that was turning onto the highway at an uncontrolled intersection. No brakes were applied as the Tesla approached the semitrailer and thus passed underneath the semitrailer and crashed into a pole. The driver died because of the accident. There is no information on whether the driver was distracted or not. Information was taken from [62].

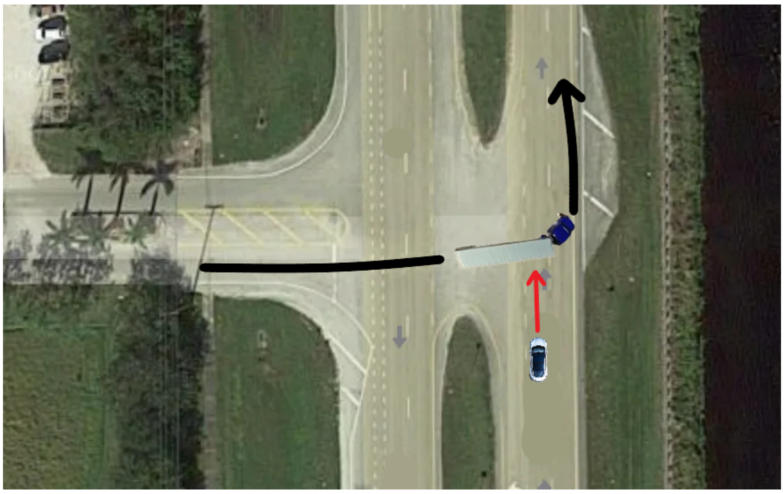


Figure 4.5: Tesla AV approaches semitrailer on highway [62, 112, 126].

In March 2019 in Williston, Florida, a Tesla AV in Autopilot crashed into the tractor-trailer of a truck that was turning onto a divided highway at an uncontrolled intersection, as shown in figure 4.5. No brakes were applied as the Tesla approached the semitrailer and thus passed underneath the semitrailer and ripped off the roof of the AV. The driver died because of the accident. There is no information on whether the driver was distracted or not [47].

These two crashes are very similar in the course of events and also the reasons for the crashes are similar, so they are summed up. Both of the semitrailers were white and on that day it was bright and sunny so cameras might have not detected the semitrailer at all. Second, an emergency brake will be only applied if radar and cameras both agree on it, which was not the case. Additionally, radar might fail too because of the height of the semitrailer. Third and last point is that Mobileye, which developed the computer vision system for Tesla stated, that the system is trained to recognize trailers from behind and not from the side [47, 62].

- **Tesla AV struck a truck driver checking his load.**

  In May 2020 in Arendal, Norway, a Tesla AV in Autopilot struck a truck driver who was standing next to his truck on a highway. The truck driver left his truck, which was parked on the right side of the road but slightly on the lane, to check the safety belts. According to the court, the truck was already visible 350m before impact but neither the Autopilot nor the driver applied the brakes. There is no information on whether the driver was distracted or not. The truck driver died because of the accident [18, 89, 92].

- **Tesla AV struck a car driver changing his tire.**

  In July 2021 in Queens, New York, a Tesla AV in Autopilot struck a car driver who was standing next to his vehicle on a highway. The car driver left his vehicle, which was parked on the left shoulder of an Expressway, to change a flat tire. There is no information on whether the driver was distracted or not. The car driver died because of the accident [60].

4.4 Cyber Attacks

As with all software systems, AS are also vulnerable to cyber-attacks. Although it is a very new topic within AS, it is nevertheless of outmost importance. It is critical for the safety of human beings that there will not be made compromises regarding the Cyber security of a car. It can not just kill the drivers in it but also be a real weapon against pedestrians and other road users. In an article from 2015 the journalist Andy Greenberg is making an experiment with two hackers. At first, they just overtake his infotainment system and non-critical functions of the car. But later on, they also disable transmission which makes the car undriveable. Entry-point is the car that makes itself very vulnerable through its connection to the internet [42].

4.5 Unknown Reasons

- **Tesla AV unexpectedly crossed into oncoming traffic.**

  In January 2019 in Reek, Netherlands, a Tesla AV in Autopilot changed onto the lane of the oncoming cars to overcome traffic. Even though it was a continuous line, the AS changed lines. Regarding the court report, the Tesla crashed with its front into a vehicle’s front. According to the court, the driver was distracted. The other driver involved in the crash died because of the accident [80].

In September 2019 in Osceola County, Florida, a Tesla AV in Autopilot changed onto the lane of oncoming cars to overcome traffic. Regarding the crash report, the Tesla crashed with its front into a pickup-trucks front. There is no information on whether the driver was distracted or not. The car driver died because of the accident [110].

In November 2021 in Brea, California, a Tesla AV in Autopilot did a left turn changing onto a wrong lane. According to the crash report, the driver noticed the mistake and wanted to interfere, but the car did not let him. As a result of this wrong decision, a car crashed into the Tesla. Nobody got seriously injured [56, 64].

- **Pony.ai AV crashes into center-divider.**

  In October 2021 in Fremont, California, a Pony.ai AV in autonomous mode did a right turn to change from Fremont boulevard to Cushing Parkway. While turning into the street the car missed the right lane and crashed into a center divider and a road sign onto the center-divider, as shown in the following figure 4.6.

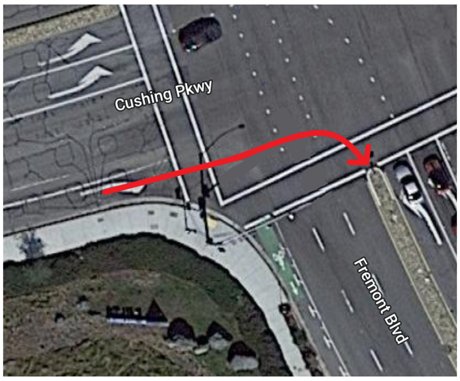


Figure 4.6: Pony.ai AV turns wrong into center-divider [39].

There is no information on whether the driver was distracted or not. Nobody got seriously injured. Reason for this was a not further explained software error [77, 87].

- **Tesla AV crashes into rear-end of a pickup-truck.**

  In August 2019 in Fremont, California, a Tesla AV in Autopilot crashed into the rear-end of a pickup truck which changed onto Tesla's lane. The driver of the pickup truck had already enabled the turning signals of the car and started slowly fading into the lane where the Tesla was diving. The Tesla crashed without any reaction or braking into the rear-end of the truck. There is no information on whether the driver was distracted or not. The car driver's child died because of the accident [8].

5 Explanation of Accidents

In this chapter, the focus will be on the accidents described in section 4.2.1. Usually, there is not one simple explanation that can explain why the AV's behavior is like this, but there are several reasons, resulting in this behavior.

5.1 Object Detection and Classification Algorithms

In general, the task of these algorithms is to detect, whether an object, captured on the camera, is a pedestrian, cyclist, vehicle or something else. This helps then to predict future actions of these traffic participants and because of that the motion planning of the AV. In general, these algorithms are so powerful that operating in everyday life is working reliably. But the performance of these algorithms can be also measured by how they behave in edge cases. And these edge cases play a critical role in object detection [84]. It is impossible to train these models with all possible exceptions because there will be always something new that occurs under certain circumstances [66] and [26]. This leads to the long-tail problem in Machine Learning (ML). It describes, that recognizing something under specific parameters is possible, but recognizing it in every situation under all possible circumstances is nearly impossible due to a long tail of edge cases [120]. An example of that would be the turned-over trucks section 4.2.1 that Tesla ran into. The variety of every situation also plays an important role. Tesla AVs crashed several times into firetrucks section 4.2.1 and police cars section 4.2.1. These vehicles alone can differ in so many ways. For each state, there is of course a unique design for the cars. Depending on the light conditions these cars will have flashlights on which might reflect somehow on the car or somewhere else which makes it another factor. For the algorithm, that analyses pixel for pixel these varieties are hard to understand even though we as humans understand these situations intuitively [66]. Another aspect is the flashlight itself which has different phases of flashing. As a result, the surroundings and the car look different. To at least minimize this issue, it is crucial to have as much training data available as possible to cover as many edge cases as possible. Important for the training-data is that it covers a lot of different scenarios and variations of parameters, like weather, light conditions and so on. Nevertheless, this process must be triggered anew each time for newly designed vehicles or other states [66]. Supporting the whole system by radar and LiDAR can be recommended.

5.2 Emergency brakes

Like in the Uber crash described in section 4.3, emergency brakes were disabled or not triggered. The reason for that are the cheap and unprecise radar sensors built in the AVs. Initially, they were used for ACC to keep the distance from the car in front. Radars can not distinguish between different object classes. This makes a plastic bag or leaf in front of the car to a potential danger just like another car [91]. Tesla went even so far to exclude radar data from their sensor fusion, since their AI combined with cameras outperforms the radar [24]. When it comes to higher velocities, radar data is left out from the data fusion, since false positive brakes during high velocities might statistically be more dangerous [91]. In general, radar is a helpful sensor for AVs when used with the latest technology. This also allows the newest radar technology to detect stationary objects like parked police cars [66]. As support cameras can detect them as a backup but will not be available to perform during nighttime [9].

5.3 LiDAR as potential solution

As already introduced, section 3.2.2, LiDAR, could be a potential solution for this kind of accident. It is still uncertain if neural networks will ever be able to compete with LiDAR in range-detection and depth estimation [24]. Potential support could be binocular camera systems stated in section 3.2.2. Still, LiDAR lacks visual information which again would be a problem when LiDAR should detect harmless objects like plastic bags [84]. Additionally, working with LiDAR 3D-maps would require a huge amount of maintenance and cars would need still to localize themselves during runtime. This is simply not scalable according to Andrej Karpathy, Tesla's chief AI scientist, especially from Tesla's perspective [25].

6 Fictional Prototype

In this chapter, the sensor concepts of the leading manufacturers will be presented. Afterwards, two different prototypes will be presented. The first prototype is designed with the vision-only approach. The second one will contain a mix of every possible sensor for redundancy and safety.

6.1 Leading Competitors

- **Tesla**

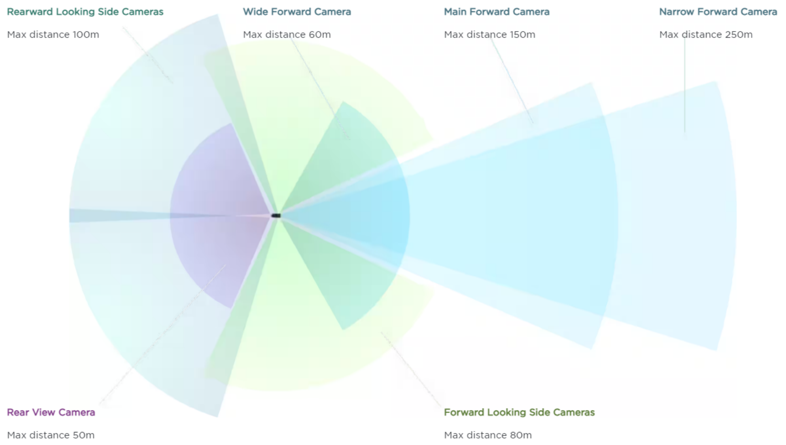


Figure 6.1: Tesla sensor-suite [104].

Tesla is the only manufacturer working with the vision-only approach, as shown in figure 6.1. The car is surrounded by 9 cameras which enable a 360° view. The system is redundant in the sense that there are two camera view ranges. One range covers a short distance from 50 m up to 80 m. The long-range is covered from 100 m up to 250 m in the front. This enables redundancy, especially in the front and back where it is crucial [104].

- **Mercedes**

  Mercedes has built in radar, LiDAR and cameras. In the front, there is a stereo camera combined with a multi-mode radar for mid-range. Long-range data is collected from a long-range radar and a long-range SSL, as described in section 3.2.2. For the back two multi-mode-radars and a camera collecting data [73].

- **Zoox**

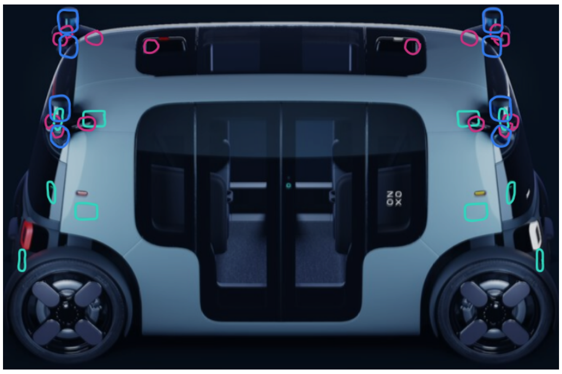


Figure 6.2: Zoox sensor-suite:blue LiDAR, pink cameras and green radar [125].

  Zoox has built in radar, LiDAR and cameras, as illustrated in figure 6.2. In the front, two cameras are mounted on each side combined with radar on each side for mid-range. LiDAR sensors are used for long-range on each side. The back of the car is equally equipped as the front [125].

- **Yandex**

  Yandex has built in radar, LiDAR and cameras. For mid-range, cameras create a 360° view. A rotating LiDAR sensor supports the cameras with depth information in long-range. Additionally, two radars in the front and back and one on each side complete the sensor suite [121].

- **Mobileye**

Figure 6.3: Mobileye sensor-suite [75].

Mobileye has built in radar, mid and long-range LiDARs and cameras, as pictured in figure 6.3. In the front short and long-range SSL are combined with radar and cameras. In the back, the car is equipped with radars, cameras and short-range SSL [75].

- **Cruise**

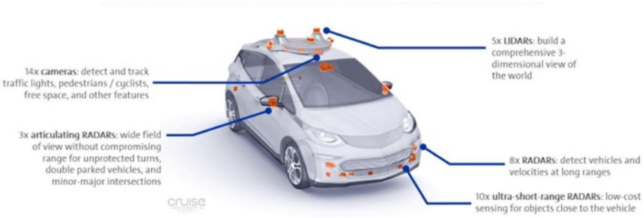


Figure 6.4: Cruise sensor-suite [70].

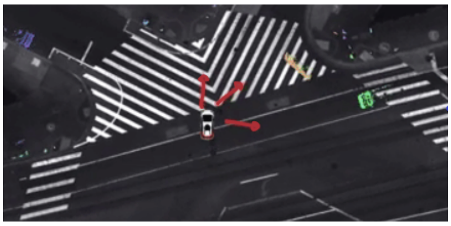


Figure 6.5: Cruise AV doing an unprotected left turn [32].

Cruise has built in radar, mid and long-range LiDARs and cameras, as shown in figure 6.4. Despite the five LiDARs used in the AV more interesting are the articulating radar sensors built in. Especially in case of unprotected turns, they can turn the position of the radar so it always detects approaching cars, as demonstrated in figure 6.5. The turning of the radar position is shown in figure 6.5 [32].

- **Argo AI**

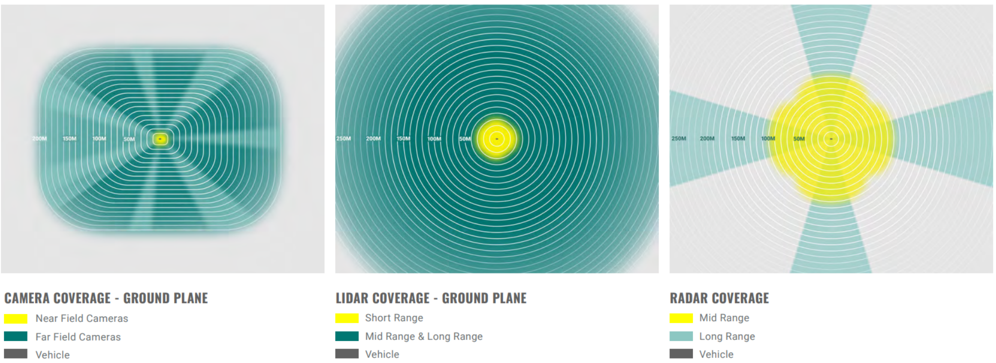


Figure 6.6: Argo AI sensor-suite with the car driving in left direction [1].

Argo AI collaborates with Ford and Volkswagen. Ford's fleet has a rotating LiDAR on top to cover 360° of the environment. At the front and front sideways cameras assist the LiDAR and radar is at the front. For the side-view, cameras are built into the top of the car. For the back, an additional LiDAR, cameras and radar are added. The whole sensor coverage is shown in figure 6.6 [14].

- **Waymo**

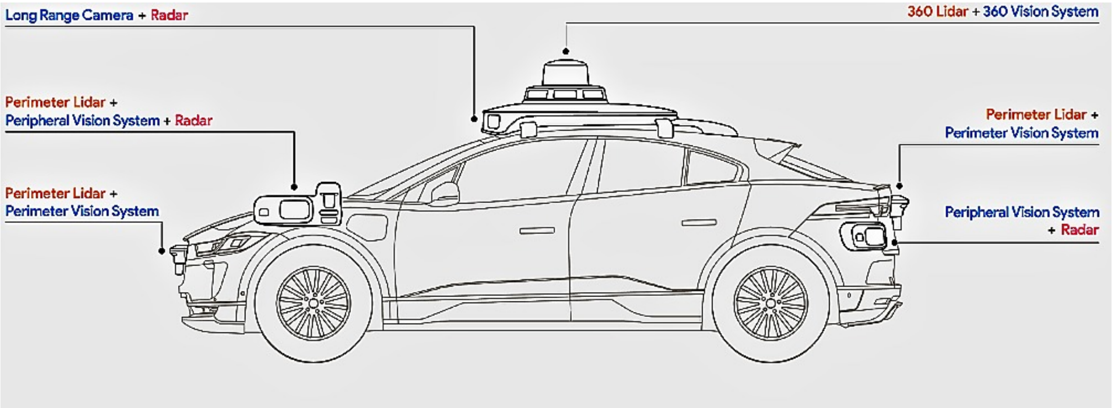


Figure 6.7: Waymo sensor-suite [55].

The market leader Waymo covers all four sites of the car with SSL. Additionally, a LiDAR supervises the environment. Radar and camera systems support the SSL sensors. On top, a long-range camera complements the 360° LiDAR [55].

The car with its sensors is shown in figure 6.7, whereas the sensor coverage is illustrated in figure 6.8:

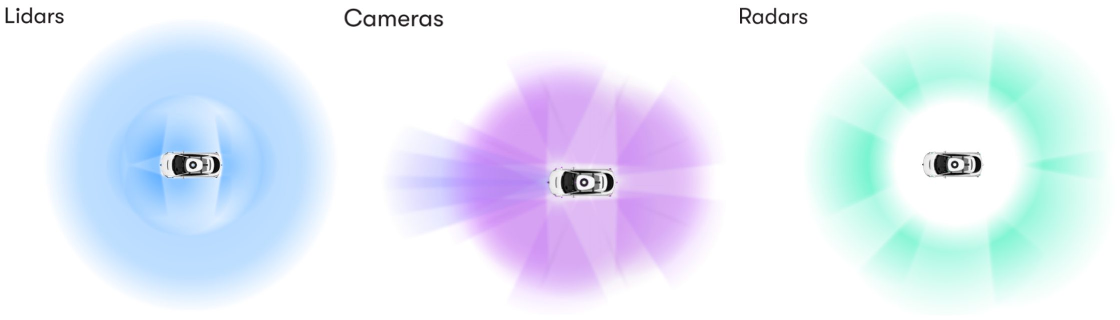


Figure 6.8: Waymo sensor range [55].

6.2 Vision-only Prototype

A vision-only prototype is interesting as it can provide at least SAE level 4 at a low additional cost. Of course, challenges like incorrect object classification and depth estimation would need to be overcome since there is no hardware support for this.

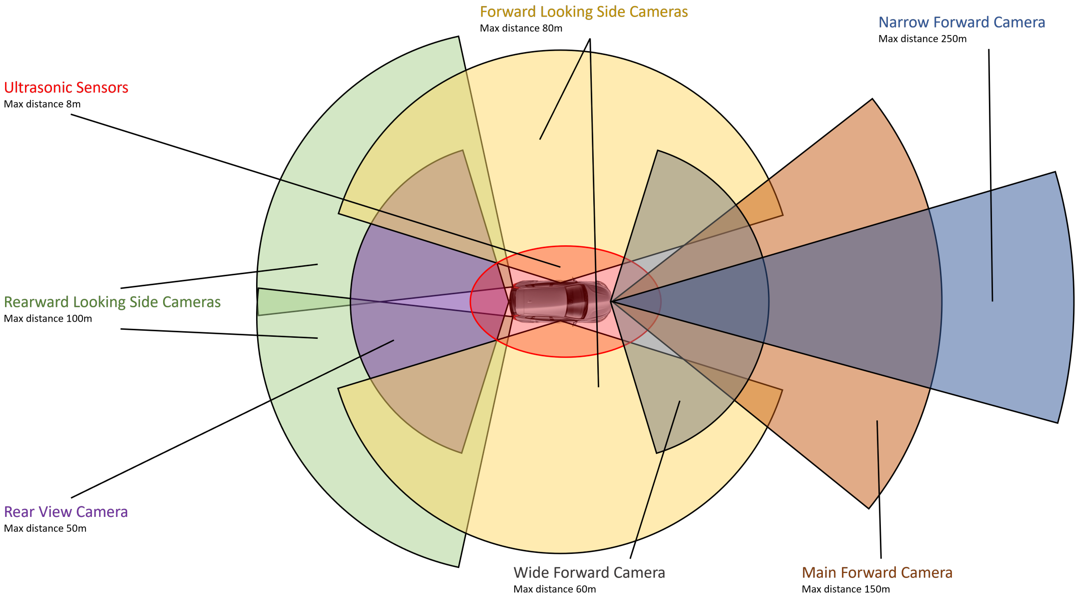


Figure 6.9: Vision-only prototype [104, 109].

The prototype, illustrated in figure 6.9 provides the same coverage as the latest Tesla models do. They differ in the setup of the cameras. Instead of only RGB-cameras at every position, there would be a pair of three cameras combined. The pair would consist of a RGB-camera, a Near-IR-camera and a long-wave-IR-camera. The position of the cameras would be chosen such as triangulation for depth estimation is possible. This would give an output as shown in figure 3.5. When you overlay these pictures and running an object classification algorithm a significantly increased amount of information can be retrieved out of one scene. An overlay of these pictures could look like the following picture:

Figure 6.10: Overlayed picture of Long-wave-IR, Near-IR and RGB-camera [116].

In figure 6.10 the RGB-camera, the LWIR-camera and the NIR-camera were merged. This enables you to see the car on the left. Additionally, the three pedestrians in front of the car appear because of their heat radiation.

Of course, the additional cameras do increase the product price. However, this is still be more cost-effective than a LiDAR sensor. Image processing can also be a bottleneck due to the increased amount of data. This can be counteracted by an overlaying algorithm so that there is only one overlayed more detailed image than four single ones per frame. The combination of the three cameras outperforms the RGB-camera in object detection, vehicle shape and light and road marking detection and road sign recognition [86].

Benefits are the cost-effectiveness of the whole AV. This again helps gain data more easily and thus improves the system even more. Additionally, cameras and software and algorithms are getting closer to competing with LiDAR.

6.3 General Prototype

The following prototype combines the technology of the leading manufacturers. Sensors and sensor coverage is pictured in figure 6.11. Of course, there is a lot of redundancy which leads to a huge amount of costs but this aspect can be kept out of scope in this prototype.

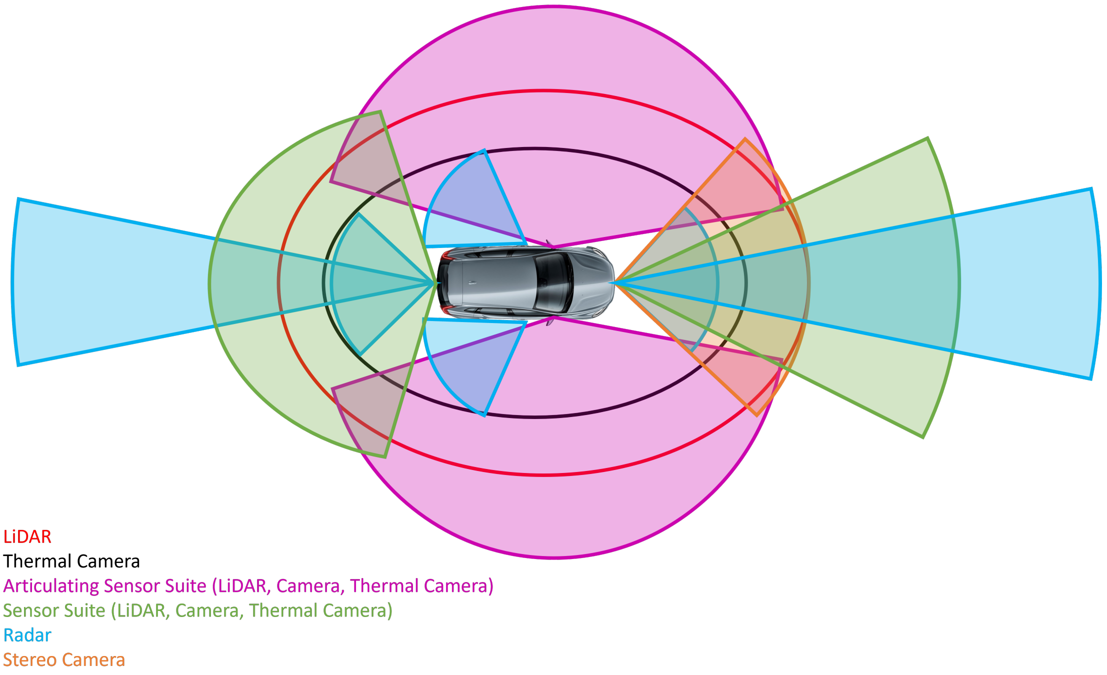
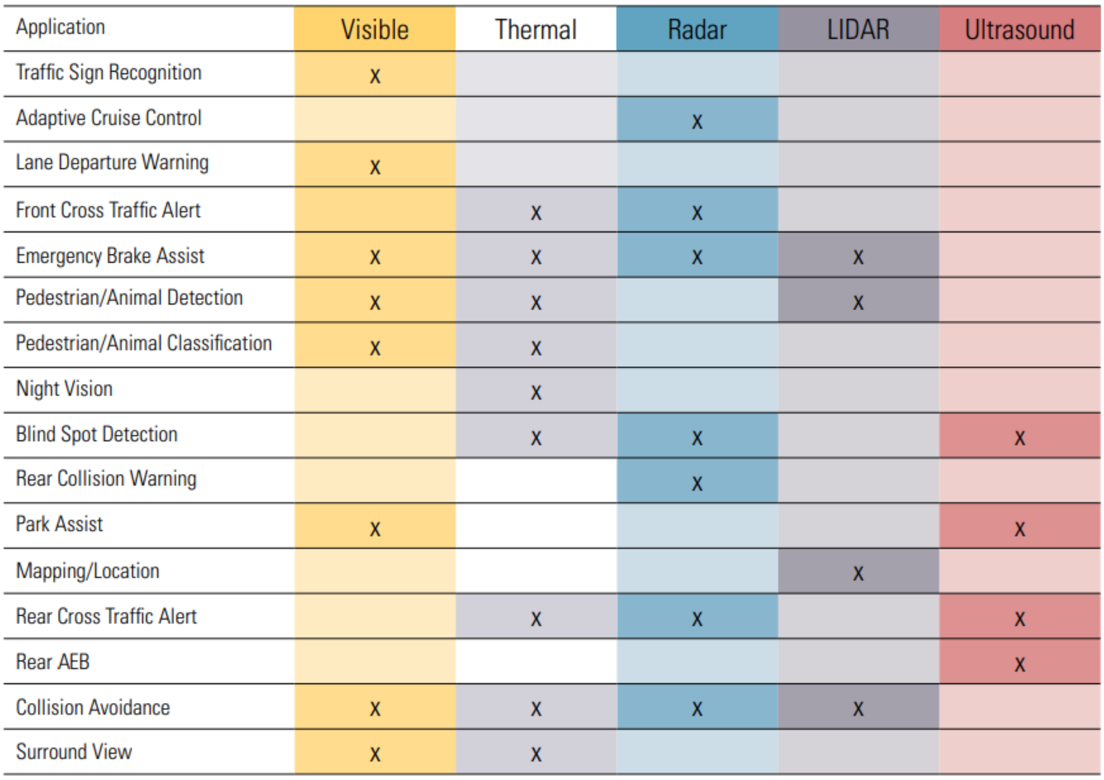


Figure 6.11: General AV prototype [34, 55, 68, 109].

The sensor suite consists of a thermal-camera and a LiDAR which surround the car in short to mid-range 360°. In addition to that short-range radar is applied in front and back and in the blind spots. In front, there is a stereo-camera for mid-range object detection and depth estimation. In addition to that, a long-range radar and a sensor suite is supervising the front. This sensor suite consists of LiDAR, a camera and a thermal-camera. The depth information of the LiDAR is merged with the camera image and the thermal-camera image which support the actual camera. Since the back of the car is not that crucial for mid-range detection a long-range radar and the sensor-suite is sufficient. The sides of the car are additionally equipped with an articulating sensor suite. This sensor suite consists also of LiDAR, a camera and a thermal-camera. Just like the articulating radar from figure 6.4 these sensors support the vehicle while executing unprotected turns. The sensors can move with the turning car and supervise variably.

Because of the redundancy of sensors, the car is able to operate in many different weather and sight conditions since the sensor suites help each other out. Thus, a high level of safety is guaranteed and in addition to a low error possibility. On the other hand, the increased number of sensors produce a huge amount of data that needs to be processed and evaluated at fast speed to fulfill the real-time requirements of this application. Additionally, a lot of sensors, especially moving sensors like the LiDAR or the articulating sensor suite need a lot of maintenance and can therefore easily fail.

Even though the approach of the cars is slightly different, both cars have their right to exist. [34] did a comparison of the most important sensors:



Application	Visible	Thermal	Radar	LIDAR	Ultrasound
Traffic Sign Recognition	x				
Adaptive Cruise Control			x		
Lane Departure Warning	x				
Front Cross Traffic Alert		x	x		
Emergency Brake Assist	x	x	x	x	
Pedestrian/Animal Detection	x	x		x	
Pedestrian/Animal Classification	x	x			
Night Vision		x			
Blind Spot Detection		x	x		x
Rear Collision Warning			x		
Park Assist	x				x
Mapping/Location				x	
Rear Cross Traffic Alert		x	x		x
Rear AEB					x
Collision Avoidance	x	x	x	x	
Surround View	x	x			

Table 6.1: Comparison of the most important sensors [34].

As shown in table 6.1 the combination of RGB-cameras with IR-cameras is a legit approach. The table 6.1 notices that any applications like ACC will not work because of missing depth information. The first prototype overcomes this problem by arranging the sensors in such a way that triangulation is possible but also AI-depth-estimation. LiDAR only adds Mapping and Location possibilities that may be helpful when approaching SAE level 5 for the second prototype. Radar adds data to the fusion which can be generated by software and algorithms in combination with cameras. However, since radar is comparatively cheap, it is also installed in the second prototype for even more redundancy.

7 Legal Background

Information from this section and the three following liability sections was taken from [49, 81].

In this chapter, we will especially focus on the legal background valid in Germany since recently some groundbreaking changes to the law there were made to make the future of ASs possible.

With the introduction of AVs, a lot of changes needed to be conducted to the law. This ranges all over the definition of a car with a steering wheel and pedals for braking and accelerating to the definition of the responsible driver and the liability after an accident. According to the convention of Vienna, the responsible person is always the one who is driving the car. Since ASs take over at least partially the control of the vehicle, the software could be declared as a driver. This would cause huge liability concerns and would not strengthen the trust of the population in ASs. Nevertheless, it would be possible to train ASs in different ethical behaviors and to let the owner decide on the ethical values of the AV. The main benefit would be that the owners are then held responsible for their decision and as a consequence the decision of the car, when a software bug is to be excluded.

In the following sections, the three most important liabilities and core questions will be listed and described for a comprehensive law on autonomous driving.

7.1 Civil Liability

Civil liability deals with the damage to a third party. In general, the occupants of an AV ride will not be responsible for the damage caused by a crash. Comparatively, the same example is a crash in a taxi where the driver is made liable, when it comes to a crash, and not the passengers.

Regarding errors and bugs in the shipped product, the manufacturer has to take full responsibility. However, if the manufacturer did everything possible to address this problem to its owners with an offer to eliminate the defect, and the owner is not taking action, or not in time, this full responsibility might expire. Additionally, the AI and ML techniques that are used in ASs are so complex that it is nearly impossible to reproduce the steps that were made for a specific decision. The training of AI models involves at least a million connections at different stages of learning, and thus the tracking of decisions is almost impossible.

7.2 Criminal Liability

Criminal liability deals with the strict responsibility for a crime but also with the protection against cybercrime and hackers. With the introduction of AVs, some questions need to be answered by law:

- **What are potential crimes in context of AVs?**
- **Who is the responsible person, when a crime is committed and an AV is used?**
- **Does the responsible person change under different circumstances?**
- **What happens if the criminally responsible subject is a legal entity?**
- **Can an AV commit an intentional crime?**

When it comes to an accident in Europe the driver is the liable person. However, if there was no negligence proofed, the manufacturer is taken into account. Vehicle manufacturers are in most of the cases legal entities so it is critical to consider the issue of corporate criminal responsibility. In some countries like Slovakia, the law is still built on the concept of personal guilt. This means that even though the AV is operating on its own, the driver (resp. owner) is made responsible by negligence when it comes to an accident. This raises the question of how much a driver has to pay attention to the AS and which checks should be included? And what checks should be included? Does the driver have to check all the sensors and autonomous technology every time before the start of a journey? This leads to a dilemma. On the one hand, the driver should pay always attention to the AS and in emergencies overtake the control. . On the other hand, the AV should relieve the driver to be able to work on other tasks. The potential benefit for the user is then significantly reduced, however the road safety is kept high. Worth to mention is also the relatively new topic of cybersecurity and cybercrime in the field of ASs. Since the AVs are operating with software, they are susceptible for cyberattacks. The protection of the ASs has two benefits. The protection against cybercrime and secondly the establishment of an appropriate security system following technical regulations and standards.

7.3 Administrative Liability

Administrative liability deals with road traffic law in general and the licensing and registration process. Regarding the administrative aspect and adaptions in regulations, some changes have to be made. Like electric vehicles, AVs could have special license plates. Also insurance requirements and driving license requirements could change. The main questions to address in this field are:

- **Is there a need for specific roads for AVs or should they operate with the traditional traffic?**
- **Should there be special traffic rules for AVs?**
- **Does an operator need a special driving license?**
- **Should this license be on national or international base?**
- **Does a passenger need a license for a ride?**
- **Should there be any minimum age?**
- **Does the passenger need to be sober?**
- **Should AVs be excluded from some regions?**
- **Should AVs report their own traffic violations to the authorities?**
- **Do AVs need an indicator so that externals can recognize it on autonomous driving mode?**

7.4 Situation Awareness

Situation Awareness (SA) is a very important aspect for the legal authorities to consider when it comes to transition times from the AS to human. SA describes, the sequence of actions necessary, through perception and understanding of environmental information, to enable you to respond to a dynamic environment. In the case of ASs, SA describes the level of attention the driver has to pay to the environment even though the AS is driving. Poor SA can lead to accidents and delays the reaction time of the driver significantly. Especially SA should get high attention because of two reasons.

First, AD will dramatically reduce the SA of the driver since this is one of the two main purposes of this technology except of accident reduction. Second, at the stage of SAE level 2 and 3 drivers must be able to overtake the control of the car. This procedure can only run safely if the car gives the driver enough time, to get familiar with the environment and to increase his SA to a safe level. Hancock's Automation Paradox already said: "If you build systems where people are rarely required to respond, they will rarely respond when required". Studies also show, that SA decreases drastically when AS functions increase. This can lead to responding times from 5 up to 9 seconds. Information from this subsection was taken from [49, 81].

7.5 Legal Development in Germany

In the following section, we will have a closer look at the evolution of German law concerning AD.

7.5.1 Laws until 2018

In 2017, Germany adapted the laws to also consider AVs, but did not allow them to be driverless. The following rules, summed up by [40], restrict ASs to minor applications:

- **"Automated driving systems may only be used as intended. A system that is developed to be used on highways only, the manufacturer must make sure, it can not be used elsewhere."**
- **"When an automated driving system has taken over control of the vehicle, the driver may shift his attention to other matters, like operating his phone or watching a movie, however he must stay ready to take over control when asked to do so by the system and when the driver sees need to intervene in order to avoid an accident."**
- **"The driver is still liable for everything the vehicle does when in an automated driving mode. This means that the manufacturer can not be made accountable for the damage that the car caused when driving automatically."**
- **"A ″black box″, similar to those in airplanes, needs to record at all times whether the driver or the autonomous system was controlling the vehicle."**

Another hard restriction was the speed limit of 10 $\mathrm{km\,h^{-1}}$ with a tolerance of 2 $\mathrm{km\,h^{-1}}$. This was stated in the ECE R 79 and makes a real-world autonomous driving scenario impossible. Information from this subsection was taken from [40].

7.5.2 Milestone in 2021

In 2021 a new law was introduced just for AD. AVs are now allowed to operate in defined and preapproved operating areas. Furthermore, there has to be a so-called technical supervisor who can stop the car. However, the supervisor must be a human and in addition to the car, he needs also insurance. If an accident occurs, all accidents must be investigated individually. Potential suspects can be the owner, manufacturer, driver and other participants. Below all the use-cases were summarized that were defined by law:

- **Shuttlebusses**
- **Automatic passenger transport systems for short distances (people movers)**
- **Driverless connections between logistics centers (Hub2Hub transports)**
- **Demand-oriented transport services at off-peak times in rural areas**
- **Dual-mode vehicles, such as in "Automated Valet Parking" (here, the driver can get out directly at the front door and then have the vehicle drive itself into the parking garage by command via smartphone)**

Information from the previous subsubsection was taken from [16, 82, 83].

7.5.3 Adaptions in 2022

This year additional laws were passed with the focus on section 7.3. This includes mainly approval and operation purposes for AVs. These laws are now applicable to ASs up to SAE level 4. Furthermore, an application process has been defined for them:

1. Application for an operating license for the AV
2. Approval for a cartographically delimited operating area
3. Usual road registration

To summarize, a lot of the above liability questions in section 7.1 were addressed, but there is still a lot of legal work to do. Fortunately, the laws have not yet had to be used, but their enforceability, effectiveness and practicability will have to be proven in court. Information from the previous subsubsection was taken from [108].

8 Ethical Background

In this chapter not only some of the most important ethical questions when it comes to ASs will be covered, but also the current state of the ethics commission in Germany.

8.1 20 Rules of the "Ethik-Rat"

Information from the section below was taken from [30, 43]. Even before the first laws were made for AS in 2016, Germany had built an ethics commission to discuss important legal and ethical topics related to AD. In June 2017, 20 ethical rules were introduced by the so-called Ethik-Rat in a final report:

1. "Partially and fully automated traffic systems serve first and foremost to improve the safety of everyone involved in road traffic. In addition, the aim is to increase mobility opportunities and enable other benefits. Technical development obeys the principle of private autonomy in the sense of self-responsible freedom of action.
2. The protection of people takes precedence over all other considerations of utility. The goal is the reduction of damage up to complete prevention. The approval of automated systems is only justifiable if they promise at least a reduction of damage in the sense of a positive risk balance in comparison to human driving performance.
3. The responsibility for the introduction and approval of automated and networked systems in the public transport sector lies with the public authorities. Driving systems therefore require official approval and control. The prevention of accidents is the guiding principle, although technically unavoidable residual risks do not prevent the introduction of automated driving if the risk balance is fundamentally positive.

4. The autonomous decision of the individual is an expression of a society in which the individual, with his or her right to development and need for protection, is at the center. Every state and political regulatory decision therefore serves the free development and protection of the individual. In a free society, the legal design of technology is carried out in such a way that a maximum of personal freedom of decision is balanced in a general order of development with the freedom of others and their security.

5. Automated and networked technology should avoid accidents as much as practically possible. The technology must be designed according to its current state in such a way that critical situations do not arise in the first place, including dilemma situations, i.e. a situation in which an automated vehicle is faced with the "decision" of having to realize one of two evils that cannot be weighed up. In this context, the entire spectrum of technical possibilities - for example, from limiting the scope of application to controllable traffic environments, vehicle sensors and braking performance, signals for persons at risk, to hazard prevention by means of an "intelligent" road infrastructure - should be used and continuously developed. The significant increase in road safety is a development and regulatory goal, starting with the design and programming of vehicles for defensive and anticipatory driving that is gentle on weaker road users ("Vulnerable Road Users").

6. The introduction of more automated driving systems, in particular with the possibility of automated collision avoidance, may be socially and ethically appropriate if it allows existing potential for harm reduction to be exploited. Conversely, a legally imposed obligation to use fully automated traffic systems or to bring about practical inescapability is ethically questionable if this entails submission to technical imperatives (prohibition of degrading the subject to a mere network element).

7. In dangerous situations, which prove unavoidable despite all technical precautions, the protection of human life has the highest priority in a balancing of legal interests. Programming must therefore be designed, within the bounds of what is technically feasible, to accept damage to animals or property in the event of a conflict, if personal injury can be avoided as a result.

8. Genuine dilemmatic decisions, such as the decision of life versus life, depend on the actual concrete situation, including the "unpredictable" behavior of those affected. Therefore, they cannot be standardized unambiguously and can not be programmed ethically without doubt. Technical systems must be designed for accident avoidance, but they cannot be standardized for complex or intuitive accident consequence assessment in such a way that they could replace or anticipate the decision of a responsible vehicle driver capable of moral judgment. While a human driver would be acting unlawfully if he or she killed a human being in a state of emergency in order to save one or more other human beings, he or she would not necessarily be acting culpably. Such judgments of the law, made in retrospect and appreciating special circumstances, cannot easily be transformed into abstract-general ex ante judgments and thus into corresponding programming. For this very reason, it would be desirable for an independent public institution (such as a federal office for accident investigation of automated traffic systems or a federal office for safety in automated and networked traffic) to systematically process experience.

9. In the case of unavoidable accident situations, any qualification according to personal characteristics (age, gender, physical or mental constitution) is strictly prohibited. Offsetting of victims is prohibited. General programming to reduce the number of personal injuries may be justifiable. Those involved in generating mobility risks must not sacrifice bystanders.

10. In automated and connected driving systems, the responsibility reserved for humans shifts from the motorist to the manufacturers and operators of the technical systems and the infrastructural, political and legal decision-making bodies. Legal liability regulations and their concretization in judicial decision-making practice must take sufficient account of this transition.

11. The same principles apply to liability for damage caused by activated automated driving systems as to other product liability. It follows that manufacturers or operators are obliged to continuously optimize their systems and also to monitor and improve systems that have already been delivered, where this is technically possible and reasonable.

12. The public has a right to sufficiently differentiated information about new technologies and their use. For the concrete implementation of the principles developed here, guidelines for the use and programming of automated vehicles should be derived in as transparent a form as possible, communicated to the public, and reviewed by a technically suitable, independent body.

13. It is not possible today to estimate whether it will be possible and practical in the future to fully network and centrally control all motor vehicles in the context of a digital transport infrastructure in the same way as in rail and air transport. Complete networking and central control of all vehicles in the context of a digital transport infrastructure is ethically questionable if and to the extent that it cannot safely rule out the risks of total monitoring of road users and manipulation of vehicle control.

14. Automated driving is only justifiable to the extent that conceivable attacks, in particular manipulation of the IT system or even intrinsic system weaknesses, do not lead to such damage as to cause lasting damage to confidence in road traffic.

15. Permitted business models that make use of the data generated by automated and connected driving, which may be significant or insignificant for vehicle control, are limited by the autonomy and data sovereignty of road users. Vehicle owners or vehicle users basically decide on the disclosure and use of their accruing vehicle data. The voluntary nature of such data disclosure presupposes the existence of serious alternatives and practicability. A normative force of the factual, such as prevails in the case of data access by the operators of search engines or social networks, should be counteracted at an early stage.

16. It must be clearly distinguishable whether a driverless system is used or a driver retains responsibility with the possibility of "overruling". In the case of non-driverless systems, the human/machine interface must be designed in such a way that it is clearly regulated and identifiable at all times which responsibilities lie on which side, in particular on which side control lies. The distribution of responsibilities (and thus of accountability), for example with regard to timing and access regulations, should be documented and stored. This applies above all to handover processes between humans and technology. International standardization of handover processes and documentation (logging) should be sought in order to ensure compatibility of logging or documentation obligations in view of the cross-border spread of automotive and digital technologies.

17. Software and technology of highly automated vehicles must be designed in such a way that the need for an abrupt transfer of control to the driver ("emergency") is practically excluded. In order to enable efficient, reliable and safe communication between humans and machines and to avoid excessive demands, the systems must adapt more closely to the communication behavior of humans and not, conversely, demand increased adaptation efforts from humans.

18. Learning systems and systems that are self-learning in vehicle operation, as well as their connection to central scenario databases, may be ethically permissible if and to the extent that they achieve safety gains. Self-learning systems may only be used if they meet the safety requirements for vehicle control-relevant functions and do not undermine the rules established here. It seems sensible to hand over relevant scenarios to a central scenario catalog of a neutral body in order to create corresponding generally valid specifications, including any acceptance tests.

19. In emergency situations, the vehicle must reach a "safe state" autonomously, i.e. without human assistance. Standardization, especially of the definition of the safe state or also of the handover routines, is desirable.

20. The proper use of automated systems should already be part of general digital education. The proper use of automated driving systems should be taught and tested in an appropriate manner during driver training."

    Ethical rules were taken from [29].

8.2 Surveys

Information from this section was taken from [81].
In the following section results of different surveys concerning ASs will be presented:

- There have been several surveys to evaluate human behavior in different scenarios compared to the ethical guidelines. One of them is made by the MIT and is called the Moral Machine. The goal was to get the opinion of as many people from as many different countries as possible. This resulted in 40 million decisions over 233 countries with interesting outcomes. In general, people from neighboring countries had very similar opinions but there could be a main differentiation between East, South and West. Even more interesting is the fact that there were still some unwritten rules that everyone has obeyed. Humans are more important than animals, saving more lives and also younger ones. It also showed that people will not get treated equally because women, young and rich had a higher chance of surviving than men, old people and poor.
  On the one hand, protecting human life over everything is exactly what the German ethical rules specify. Additionally, it is stated in item 8 that it would not be legal to kill one life to rescue more lives but it is not a guilty action. On the other hand, people are still deciding based on age and gender what violates item 9.

- Another survey addressed the question of whether one would rather save passenger lives including his own or pedestrians. Again people decided to minimize the number of victims, however, there was a trend to rescue the passengers' lives, especially when there were family members in it.
- In 2015 and 2016 there was a survey asking people about the behavior, the AS should have. There was a strong preference for a utilitarian algorithm that is sparing more lives instead of protecting the passengers. However, people would rather buy an AV with a non-utilitarian algorithm instead.
- When people were asked which pre-specified car behavior they prefer over utilitarian, self-focused, random or law-based, the majority goes for the law-based or random approach. The conclusion here is that the passengers do see the protection of their own life as the priority.
- In a simulator test people would have to choose between killing a pedestrian or swerving and make a random crash with different probabilities. The outcome showed, children will be saved more often, there is no differentiation between strangers and friends and people most likely sacrifice their own life to rescue others. Only 16% of the people chose to save their lives instead of others.

In general, the ethical discussion is still a really important discussion that has not come to an end. From the people's perspective, there is no sample solution for the behavior of ASs. There are some selfish approaches but also the utilitarian approach had a lot of consent. Still, people were not sure if they would purchase a car that, when it comes to the situation, sacrifices the passengers' lives to save more people.

8.3 Approaches for ethical Decisions in AVs

[81] summarized in his paper *"Public acceptance and perception of autonomous vehicles: a comprehensive review"* different approaches for ethical decisions in AVs. These approaches will be summarized in the following section.

- Rational approach
  - Deontological rule

    The ethical decision is determined by a set of rules, the system is following. The main advantage of this approach is that a computer is built to follow rules, so that it is easily implementable and executable. However, in a complex environment, it is impossible to have a complete set of rules. Moreover, it is really challenging, to define these complex human ethics as a set of rules.

  - Consequentialisms

    The ethical decision is determined through an optimization problem by maximizing the overall utility and minimizing the collision costs. The main advantage is here that the optimization problem is well defined and therefore easily solvable. However, it is really complex to define cost functions and evaluate in such an environment them especially when it involves human lives.

- Artificial intelligent approach

  The ethical decision is determined by an AI. This AI is trained by monitoring human behavior and through rewards, for making a set of ethical acceptable actions. The main advantage is that people can not actively interfere in the rules and training. However, the training of the AI would require a huge amount of critical situations. Additionally, the AI would always act selfishly due to the training data because drivers always try to prevent damage for there self first. This would not increase overall safety at all. Lastly, AI is difficult for humans to comprehend.

- Hybrid approach

  The ethical decision is determined by a combination of AI and rational decision-making. In general, the rational approach should be applied first. If the rational approach does not cover this situation, AI should focus on this situation. First, through its redundancy, it is ensured that the system's AI is not learning any unintended ethical rules because of the training set. Additionally, it is guaranteed that the vehicle is acting rationally in boundary situations. However, this system would require complex software which is not available yet.

8.4 Trolley Case

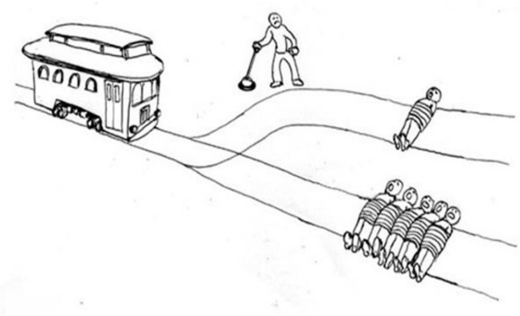


Figure 8.1: Trolley Case illustrated with a train [15].

Information from the trolley case and the light-trolley case is taken from [37, 69]. In figure 8.1 a controversial issue of AD is described. This experiment is firstly published by Philippa Foot in 1967. This scenario aims to draw attention to the question of whether one should kill a single person or five persons, if somebody only has these two choices. The German ethical rules give a small direction but no recommendation for action. There it is stated that protecting five lives over one would not be legal but also not an act of guilt.

8.4.1 Light Trolley Case

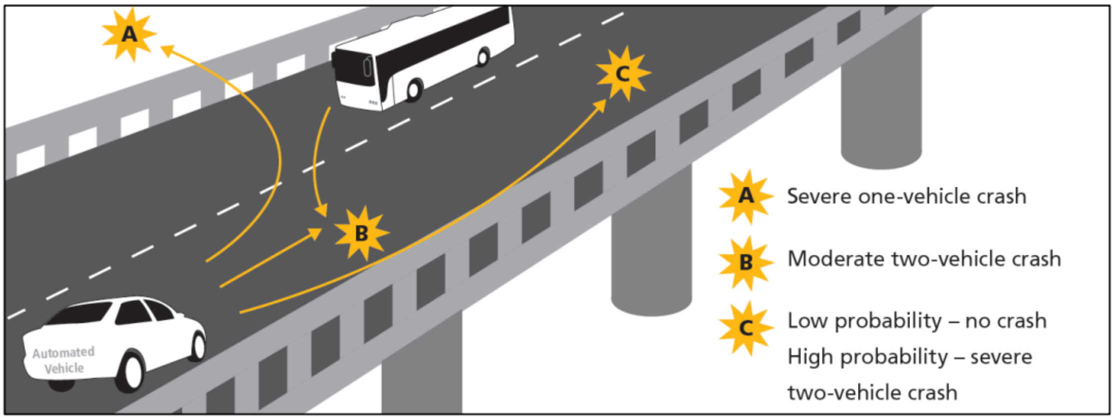


Figure 8.2: Light Trolley Case with the three alternatives [37].

Because the trolley case is a really specific, stylized and a binary situation, that would be highly unrealistic in extreme real-life traffic, there was defined the light trolley case, illustrated in figure 8.2. In this scenario, there is a bridge with a lane for each side of the traffic. An AV is driving in its lane and a bus is coming from the other side of the road in its own lane. Suddenly the bus switches to the AVs lane. The AV can change lanes and crash into the side of the bridge causing a one-vehicle severe crash. Both can brake which would resolve in a moderate two-vehicle crash. But the AV can also try to accelerate. With a low probability, it is fast enough, or the bus corrects back towards its own lane, to pass the bus before the bus is on the AVs lane, otherwise, there will happen a severe two-vehicle crash with both their fronts. Solving this dilemma with a cost function as suggested in section 8.3 would have different outcomes depending on the number of passengers in the bus and in the car, but also depending on the construction of the bus and the nature of the bridge's wall.

9 Outlook

In the last chapter is an overview of other areas AS can be used in. As last topic, the impact of AVs on traffic will be assessed.

9.1 Transferability to other Scenarios and Sectors

Transferability of knowledge is a very important aspect. The higher the rate, the cheaper ASs can be offered on the market. As a result, people are buying more of these systems, which lets the prices of sensors drop because of investments into cheaper production.

9.1.1 Autonomous Buses

- In the UK in the Summer of 2022 the first autonomous bus will carry passengers. Test drives started in April and later on in summer passengers will be able to use the vehicle. Five buses will operate in different regions of Scotland. A bus will offer rides for up to 36 persons and a safety driver, which does not require to intervene in normal situations [93].
- In Málaga, Spain, in 2021 the first autonomous bus was introduced to carry passengers. Six times a day the bus will transport people over an eight-kilometer trip. The bus will offer rides for up to 60 persons and a safety driver, which does not require to intervene in normal situations [33].
- In Toulouse, France, since March 2021 an autonomous bus is driving test runs. Later that year the bus was allowed to transport people. The bus will offer rides for up to 12 persons and without a safety driver. The bus will run on a fixed 600m route, but with remote supervision [7].

9.1.2 Autonomous Trucks

Autonomous trucks are a relatively new topic in AD, but one of the most promising. Since trucks are operating most of the time on highways the initial situation of trucks is a bit easier than that of cars. A lot fewer exceptions do occur on highways and no pedestrians and bikes are traffic participants. In addition, because of poor wages and hard working conditions, it is harder to hire truck drivers. Einride, a Swedish startup, is working on such a solution. They are offering a driver-less truck with remote supervision. In 2019 they already transported goods in Europe. After their expedition to the US, they got their operating permit for Tennessee. For urban operation, the technology is not sufficiently mature yet [13].

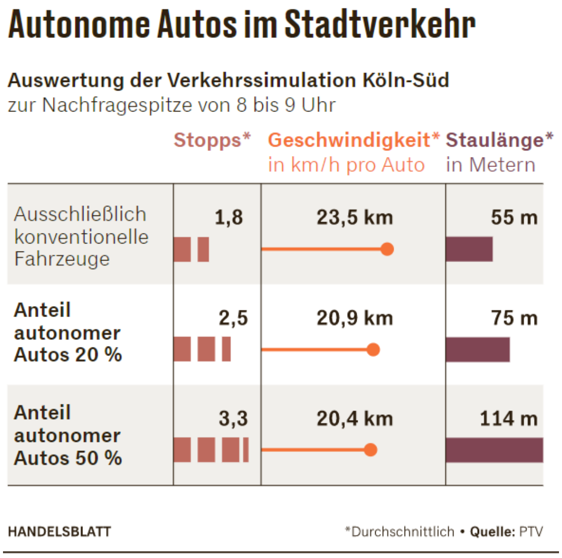
9.2 Change of Traffic

With the introduction of AVs, not only benefits come up. The software company PTV ran simulations on traffic with a certain percentage of AVs included in the traffic. With only 20% of AVs involved in traffic, significantly more traffic jams can be observed. In addition, the average velocity drops drastically from $23{,}5\,\mathrm{km\,h^{-1}}$ down to $20{,}9\,\mathrm{km\,h^{-1}}$. However, increasing this percentage to 50%, traffic jams double in their occurrence [51].

There are three main reasons for this phenomenon. First, people are different and so is the behavior of drivers. There is an appearance, called the accordion effect. It describes the behavior of drivers when a red light switches to green. Due to inattention, people overlook, that the cars in the front start to drive. This causes a gap between the started car and the one who missed it. Because most of the drivers have a small delay, the gaps are getting bigger and fewer cars can pass the green phase [51].

Second, the aggressive behavior of most of the drivers is not traffic flow promoting. To prove this an experiment was made. In the first round, 20 human drivers drove in a circle. Because people tend to overreact, a lot of braking and accelerating could be observed resulting in Stop&Go traffic. After putting one AV into traffic, the situation calmed down since AVs are trained to drive proactive and defensive [59].

The last point is more a general fact than an explanation. A simulation of the southern part of cologne was made. Again with just conventional cars, 20% AVs and 50% AVs. This resulted in the following table:



Autonome Autos im Stadtverkehr

Auswertung der Verkehrssimulation Köln-Süd
zur Nachfragespitze von 8 bis 9 Uhr

	Stopps*	Geschwindigkeit* in km/h pro Auto	Staulänge* in Metern
Ausschließlich konventionelle Fahrzeuge	1,8	23,5 km	55 m
Anteil autonomer Autos 20 %	2,5	20,9 km	75 m
Anteil autonomer Autos 50 %	3,3	20,4 km	114 m

HANDELSBLATT

*Durchschnittlich • **Quelle:** PTV

Table 9.1: Traffic simulation of the southern part of cologne [51].

As stated in table 9.1, average stops, average velocity per car in $\mathrm{km\,h^{-1}}$ and traffic jam length in meter, from left to right, were measured. The number of stops almost doubled and the length of traffic jams more as doubled. The average velocity dropped by 3,1 $\mathrm{km\,h^{-1}}$[51]. The cause of the first two observations can be explained by the proactive and defensive driving behavior of AVs. The drop in the average velocity has also to do with speed regulations. Human drivers can decide, whether they follow the speed limit or drive faster. AVs can not act against the law [35]. The average speed in cologne also underlines that explanation. Human drivers drive on average 58 $\mathrm{km\,h^{-1}}$, whereas AVs drive 49 $\mathrm{km\,h^{-1}}$ [51]. A possible solution for regulating the traffic load until more AVs are on the road could be additional lanes only for AVs. This would allow human drivers to continue as regular and not being slowed down by the AVs. However, most cities do not have extra space for an additional lane. In a scenario where an existing lane would be taken the traffic would be loaded again because of reduced space [51]. A digital twin of the street infrastructure could help out, by regulating the traffic light phases. This would require a lot of sensor supervision and infrastructure that is not available at the moment and is expensive [51]. A promising approach includes an AI that communicates with the traffic lights to get to know the green phases. With this information, the speed of the traveling car would be adjusted to pass all traffic lights at green light. This approach reduces consumption and emissions and increases the average speed. With a number of just 25% of AVs [124] states, there is a "substantial" benefit. [124] simulated an intersection, where all these cars followed this algorithm. Compared to human drivers, fuel consumption sunk by 18% and CO2 emissions by 25%, whereas travel time was boosted by 20%.

Another challenge, that has to be overcome is the communication between AVs and humans but also between AVs. It would be desirable, that the leading AV manufacturers implement a generic vehicle-to-vehicle communication that is brand-independent. Additionally, it is crucial that AVs can understand human gesture-communication while driving, but also AVs can answer them [31].

Despite of all the challenges, there are also many advantages. According to an article [51], in a simulation was observed that if the number of AVs is significantly higher than 50% and AVs are connected to calculate optimal velocity and distances, the traffic situation will improve drastically. As already mentioned, platooning, the ability to form a huge line of cars that drive behind each other to minimize fuel consumption, will be possible [35]. This will be possible because of the faster reaction time of computer systems based on the communication between the cars. Because of this ability, the speed limit could also be increased [35]. If people switch from private cars to robo-taxis or car-pools, fewer cars will be on the street. This would relax the traffic, but also create more car-free spaces for people.

List of Figures

3.1 Ranking of the market competitors according to the above mentioned criteria [94]. 6
3.2 LiDAR Dimensions: **(a)** one-dimensional measure, **(b)** two-dimensional measure, **(c)** three-dimensional measure, adapted from [111]. 9
3.3 Functionality of an ultrasonic sensor [21]. 11
3.4 Comparison between a visible camera and IR camera [116]. 14
3.5 Picture of a foggy tunnel taken with thermal long-wave (LWIR), visible RGB, short-wave (SWIR), and near (NIR) camera [116]. 14
3.6 A Tesla Model S and its cameras and their angles of view [40]. 16

4.1 Center divider, marked with badly painted lane markings, of the crash [38]. 21
4.2 New center divider in comparison to a damaged center divider [103]. . 21
4.3 Waymo AV trying to fade in on a T-junction with cones on one lane [67, 99, 102]. 25
4.4 Waymo AV faded in the main road but went in the by cones closed area of the road [67, 99, 102]. 26
4.5 Tesla AV approaches semitrailer on highway [62, 112, 126]. 27
4.6 Pony.ai AV turns wrong into center-divider [39]. 29

6.1 Tesla sensor-suite [104]. 33
6.2 Zoox sensor-suite:blue LiDAR, pink cameras and green radar [125]. . . 34
6.3 Mobileye sensor-suite [75]. 35
6.4 Cruise sensor-suite [70]. 35
6.5 Cruise AV doing an unprotected left turn [32]. 35
6.6 Argo AI sensor-suite with the car driving in left direction [1]. 36
6.7 Waymo sensor-suite [55]. 36
6.8 Waymo sensor range [55]. 37
6.9 Vision-only prototype [104, 109]. 37
6.10 Overlayed picture of Long-wave-IR, Near-IR and RGB-camera [116]. . . 38
6.11 General AV prototype [34, 55, 68, 109]. 39

8.1 Trolley Case illustrated with a train [15]. 54

8.2 Light Trolley Case with the three alternatives [37]. 54

List of Tables

2.1 The six Taxonomy levels: Level zero to two with continuous monitoring, whereas from three to five the monitoring is handed over to the car step by step, adapted from [50]. 3

3.1 Fields of applications for QC in the automotive industry [17]. 18

6.1 Comparison of the most important sensors [34]. 40

9.1 Traffic simulation of the southern part of cologne [51]. 58

Acronyms

ABS Anti-lock Braking System.

ACC Adaptive Cruise Control.

AD Autonomous Driving.

AI Artificial Intelligence.

AS Autonomous System.

AV Autonomous Vehicle.

BASt Bundesanstalt für Straßenwesen.

ESP Electric Stability Control.

GNSS Global Navigation Satellite System.

GPS Global Positioning System.

IMU Inertial Measurement Units.

IRC Infrared Camera.

LiDAR Light Detection and Ranging.

LK Lane Keeping Assistant.

ML Machine Learning.

NHTSA National Highway Traffic Safety Administration.

NTSB National Transportation Safety Board.

QC Quantum Computing.

QCs	Quantum Computers.
RTK	Real-time kinematics.
SA	Situation Awareness.
SAE	Society of Automotive Engineers.
SSL	Solid-State LiDAR.
V2V	Vehicle-to-Vehicle Communication.
V2X	Vehicle-to-Everyone Communication.

Bibliography

[1] A. AI. “Safety Report.” In: (Apr. 2021). URL: `https://www.argo.ai/wp-content/uploads/2021/04/ArgoSafetyReport.pdf` (visited on 06/24/2022).

[2] B. ANDERSON. “Tesla Autopilot Blamed On Fatal Japanese Model X Crash.” In: (Apr. 2020). URL: `https://www.carscoops.com/2020/04/tesla-autopilot-blamed-on-fatal-japanese-model-x-crash/` (visited on 06/14/2022).

[3] O. of the Assistant Secretary for Research and T. (OST-R). “Automated Vehicle Research.” In: (). URL: `https://www.its.dot.gov/automated_vehicle/index.htm#:~:text=Automated%20vehicles%20are%20those%20in,occurs%20without%20direct%20driver%20input` (visited on 04/27/2022).

[4] “Autonomous Cars 101: What Sensors Are Used in Autonomous Vehicles?” In: (). URL: `https://levelfivesupplies.com/sensors-used-in-autonomous-vehicles/` (visited on 04/29/2022).

[5] I. Barabás1*, A. Todoruț1, N. Cordoș1, and A. Molea1. “Current challenges in autonomous driving.” In: (). URL: `https://iopscience.iop.org/article/10.1088/1757-899X/252/1/012096/pdf` (visited on 05/06/2022).

[6] A. Batchelor. “3 injured after Tesla collides with road ranger truck on I-95.” In: (May 2021). URL: `https://www.local10.com/news/local/2021/05/19/3-injured-after-tesla-collides-with-road-ranger-truck-on-i-95/` (visited on 06/14/2022).

[7] T. Bateman. “France approves fully autonomous bus for driving on public roads in a European first.” In: (Dec. 2021). URL: `https://www.euronews.com/next/2021/12/01/france-approves-fully-autonomous-bus-for-driving-on-public-roads-in-a-european-first` (visited on 06/28/2022).

[8] P. BELFIORE. “Family of boy, 15, who was thrown from a Ford Explorer and died when Tesla Model 3 traveling at 60mph on autopilot crashed into the car sues the electric car giant.” In: (June 2021). URL: `https://www.dailymail.co.uk/news/article-9758873/Family-boy-15-killed-Tesla-autopilot-crash-sues-electric-car-giant.html` (visited on 06/22/2022).

[9] C. Bergenhem, R. Johansson, A. Soderberg, J. Nilsson, J. Tryggvesson, M. Torngren, and S. Ursing. "How to Reach Complete Safety Requirement Refinement for Autonomous Vehicles." In: ed. by M. Roy. Sept. 2015. URL: `httpshal.archives-ouvertes.frhal-01190734`.

[10] N. T. S. Board. "Collision Between Vehicle Controlled by Developmental Automated Driving System and Pedestrian Tempe, Arizona." In: (Nov. 2019). URL: `https://www.ntsb.gov/investigations/accidentreports/reports/har1903.pdf` (visited on 06/15/2022).

[11] N. E. Boudette. "'It happened so fast': Inside a fatal Tesla Autopilot accident." In: (Aug. 2021). URL: `https://www.moneycontrol.com/news/business/it-happened-so-fast-inside-a-fatal-tesla-autopilot-accident-7353831.html` (visited on 06/14/2022).

[12] C. Bravo. "Tesla Crash With CHP Vehicle in San Diego Part of Investigation Into Autopilot Feature." In: (Aug. 2021). URL: `https://www.nbcsandiego.com/news/local/tesla-crash-with-chp-vehicle-in-san-diego-part-of-investigation-into-autopilot-feature/2694531/` (visited on 06/13/2022).

[13] J. Brien. "„Revolution hat begonnen": Einride darf autonome E-Lkw fahren lassen." In: (June 2022). URL: `https://t3n.de/news/revolution-einride-autonome-e-lkw-1481428/` (visited on 06/28/2022).

[14] D. B. BROWNING. "New Eyes, New Ears, New Brains: Inside the Next Generation Argo AI Self-Driving System." In: (Jan. 2021). URL: `https://groundtruthautonomy.com/self-driving/new-eyes-new-ears-new-brains-inside-the-next-generation-argo-ai-self-driving-system/` (visited on 06/24/2022).

[15] A. Bühler. "Autonomes Fahren - Dilemma vorprogrammiert." In: (). URL: `https://www.br.de/puls/themen/netz/philosophische-memes-memes-kolumne-100.html` (visited on 06/05/2022).

[16] D. Bundesregierung. "Autonomes Fahren in die Praxis holen." In: (). URL: `https://www.bundesregierung.de/breg-de/suche/faq-autonomes-fahren-1852070` (visited on 06/03/2022).

[17] O. Burkacky, N. Mohr, and L. Pautasso. "Will quantum computing drive the automotive future?" In: (). URL: `https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/will-quantum-computing-drive-the-automotive-future` (visited on 05/05/2022).

[18] R.-I. CAPAR. “Tesla driver charged with negligent homicide of truck driver he hit while using auto-steering on E18.” In: (Dec. 2020). URL: `https://norwaytoday.info/news/tesla-driver-charged-with-negligent-homicide-of-truck-driver-he-hit-while-using-auto-steering-on-e18/` (visited on 06/15/2022).

[19] CGTN. *Shocking footage: Fatal Tesla crash in China triggers suspicion of auto-drive*. Sept. 2016. URL: `https://www.youtube.com/watch?v=CgLE_ZLLaxw` (visited on 06/14/2022).

[20] “Closed-loop engineering for autonomous vehicles.” In: (). URL: `https://www.plm.automation.siemens.com/global/en/webinar/autonomous-vehicle-technology/95666?gclid=Cj0KCQjwuMuRBhCJARIsAHXdnqOMQGVooBKzT1Vy0sPc8tz23lk4g9NlE_Zf6UzAtPxrEmUx5n1NCKwaAgS6EALw_wcB&stc=dedi100034&ef_id=Cj0KCQjwuMuRBhCJARIsAHXdnqOM` `Zf6UzAtPxrEmUx5n1NCKwaAgS6EALw_wcB%3AG%3As&s_kwcid=AL%21463%213%21530795022675%21p%21%21g%21%21self+driving+car+technology&gclsrc=aw.ds&_ref=Z2NsaWQ9Q2owS0NRand1TXVSQmhDSkFSSXNBSFhkbnFPTVFHVm9vQkt6VDFWeU9zUGM4dHoyM` `3D%3D` (visited on 05/16/2022).

[21] “Complete Guide for Ultrasonic Sensor HC-SR04 with Arduino.” In: (). URL: `https://randomnerdtutorials.com/complete-guide-for-ultrasonic-sensor-hc-sr04/` (visited on 05/03/2022).

[22] J. Condliffe. “Tesla announces new sensors and puts brakes on autopilot.” In: (). URL: `https://www.technologyreview.com/2016/10/20/156529/tesla-announces-new-sensors-and-puts-the-brakes-on-autopilot/` (visited on 05/03/2022).

[23] S. DAZIO and T. KRISHER. “Officials: Tesla Autopilot probed in fatal California crash.” In: (May 2021). URL: `https://apnews.com/article/california-business-technology-204e5600ec902d0bfda10feca74a9ed0` (visited on 06/14/2022).

[24] B. Dickson. “Tesla AI chief explains why self-driving cars don’t need lidar.” In: (June 2021). URL: `https://bdtechtalks.com/2021/06/28/tesla-computer-vision-autonomous-driving/` (visited on 06/22/2022).

[25] B. Dickson. “Tesla’s AI chief: Self-driving cars don’t need LiDAR.” In: (May 2021). URL: `https://thenextweb.com/news/tesla-ai-chief-explains-self-driving-cars-dont-need-lidar-syndication` (visited on 06/22/2022).

[26] B. Dickson. “Why deep learning won’t give us level 5 self-driving cars.” In: (July 2020). URL: `https://bdtechtalks.com/2020/07/29/self-driving-tesla-car-deep-learning/` (visited on 06/22/2022).

[27] A. Donath. "Waymo schickt fahrerlose Autos durch San Francisco." In: (). URL: `https://www.golem.de/news/autonomes-fahren-waymo-schickt-fahrerlose-autos-durch-san-francisco-2203-164280.amp.html` (visited on 05/06/2022).

[28] L. Eliot. "Here's How Quantum Computer Supremacy Will Impact Self-Driving Cars." In: (). URL: `https://www.forbes.com/sites/lanceeliot/2019/11/14/heres-how-quantum-supremacy-will-impact-self-driving-cars/?sh=4384e08c72f3` (visited on 05/05/2022).

[29] Ethik-Kommission. "Automatisiertes und Vernetztes Fahren." In: *2017* (). URL: `https://www.bmvi.de/SharedDocs/DE/Publikationen/DG/bericht-der-ethik-kommission.html` (visited on 07/20/2022).

[30] Factory. "20 ethische Regeln für autonomes Fahren." In: (). URL: `https://factorynet.at/artikel/20-ethische-regeln-fuer-autonomes-fahren/` (visited on 06/05/2022).

[31] B. Färber. *Communication and Communication Problems Between Autonomous Vehicles and Human Drivers*. Ed. by J. Christian, L. Barbara, W. H. M. Markus, and Gerdes. Springer Berlin Heidelberg, 2016, pp. 125–144. ISBN: 978-3-662-48847-8. DOI: `10.1007/978-3-662-48847-8_7`. URL: `https://doi.org/10.1007/978-3-662-48847-8_7`.

[32] J. Fischer. "The Decision Behind Using Articulating Sensors on Cruise AVs." In: (July 2020). URL: `https://medium.com/cruise/cruise-embedded-systems-articulating-radars-7cae24642930` (visited on 06/23/2022).

[33] S. Fleming. "Europe's first full-sized self-driving urban electric bus has arrived." In: (Mar. 2021). URL: `https://www.weforum.org/agenda/2021/03/europe-first-autonomous-electric-buses-spain/` (visited on 06/28/2022).

[34] Flir. "WHY ADAS AND AUTONOMOUS VEHICLES NEED THERMAL INFRARED CAMERAS." In: (Dec. 2018). URL: `https://www.flir.com/globalassets/email-assets/pdf/flir_thermal_for_adas_and_av.pdf?source=content_type%3Areact%7Cfirst_level_url%3Aarticle%7Csection%3Amain_content%7Cbutton%3Abody_link#:~:text=Thermal%2C%20or%20longwave%20infrared%20(LWIR,and%20safe%20ADAS%20and%20AV.` (visited on 06/27/2022).

[35] A. Forrest and M. Konca. "Autonomous cars and society." In: *Worcester Polytechnic Institute* 15 (2007), p. 23. URL: `https://web.wpi.edu/Pubs/E-project/Available/E-project-043007-205701/unrestricted/IQPOVP06B1.pdf` (visited on 06/29/2022).

[36] B. Gilbert. "Tesla on Autopilot crashes into parked police car." In: (Dec. 2019). URL: https://www.businessinsider.com/tesla-autopilot-crashes-into-police-car-2019-12 (visited on 06/13/2022).

[37] N. J. Goodall. "Ethical Decision Making during Automated Vehicle Crashes." In: *Transportation Research Record: Journal of the Transportation Research Board* 2424 (1 Jan. 2014), pp. 58–65. DOI: 10.3141/2424-07. URL: https://doi.org/10.3141%2F2424-07.

[38] Google. *Center Divider Mountain View*. Nov. 2017. URL: https://www.google.com/maps/@37.4105526,-122.0747806,3a,75y,127.68h,90.01t/data=!3m7!1e1!3m5!1sacKIfW6A1Znw6opJ6GXEaA!2e0!6s%2F%2Fgeo2.ggpht.com%2Fcbk%3Fpanoid%3DacKIfW6A1Znw6opJ6GXEaA%26output%3Dthumbnail%26cb_client%3Dmaps_sv.tactile.gps%26thumb%3D2%26w%3D203%26h%3D100%26yaw%3D217.50317%26pitch%3D0%26thumbfov%3D100!7i16384!8i8192 (visited on 06/10/2022).

[39] Google. *Maps Picture Pony.ai Center Divider*. 2022. URL: https://www.google.com/maps/place/Cushing+Pkwy,+Fremont,+CA+94538,+USA/@37.4904357,-121.9487552,56m/data=!3m1!1e3!4m5!3m4!1s0x808fc70ea8af57b9:0x3571215169356e92!8m2!3d37.4931709!4d-121.9670257 (visited on 06/19/2022).

[40] M. Grad. "Challenges in Developing Software for Autonomous Driving." URL: http://mediatum.ub.tum.de/doc/1485683/1485683.pdf (visited on 05/03/2022).

[41] J. GREEN. "Saratoga: Man killed in fiery crash identified." In: (Aug. 2020). URL: https://www.mercurynews.com/2020/08/13/saratoga-man-killed-in-fiery-freeway-crash-identified/ (visited on 06/09/2022).

[42] A. GREENBERG. "Hackers Remotely Kill a Jeep on the Highway—With Me in It." In: (July 2015). URL: https://www.wired.com/2015/07/hackers-remotely-kill-jeep-highway/ (visited on 06/19/2022).

[43] M. B. Group. "Automated and Autonomous Driving. Legal Framework." In: (). URL: https://group.mercedes-benz.com/innovation/case/autonomous/legal-framework.html (visited on 06/05/2022).

[44] T. Hahn. "Maschine mit Mensch." In: (). URL: https://www.sueddeutsche.de/panorama/seoul-suedkorea-taxi-selbstfahrende-autos-verkehr-autonomes-fahren-1.5558811 (visited on 05/06/2022).

[45] M. HARRIS. "NTSB Investigation Into Deadly Uber Self-Driving Car Crash Reveals Lax Attitude Toward Safety." In: (Nov. 2019). URL: https://spectrum.ieee.org/ntsb-investigation-into-deadly-uber-selfdriving-car-crash-reveals-lax-attitude-toward-safety (visited on 06/15/2022).

[46] E. Y. Huangfu and B. Miethig. "How thermal imaging can improve autonomous driving sensory systems." In: (). URL: `https://www.laserfocusworld.com/detectors-imaging/article/14201281/how-thermal-imaging-can-improve-autonomous-driving-sensory-systems` (visited on 05/02/2022).

[47] T. Huckle and T. Neckel. *Bits and Bugs: A Scientific and Historical Review on Software Failures in Computational Science*. SIAM, 2019. ISBN: 1611975557. URL: `https://opac-ub-tum-de.eaccess.ub.tum.de/TouchPoint/perma.do?q=+1035%3D%22BV045551496%22+IN+%5B2%5D&v=tum&l=de` (visited on 06/09/2022).

[48] R. Hussain and S. Zeadally. "Autonomous Cars: Research Results, Issues, and Future Challenges." In: (). URL: `https://ieeexplore.ieee.org/abstract/document/8457076` (visited on 05/06/2022).

[49] V. Ilková and A. Ilka. "Legal aspects of autonomous vehicles — An overview." In: 2017, pp. 428–433. DOI: `10.1109/PC.2017.7976252`.

[50] S. INTERNATIONAL. "AUTOMATED DRIVING." In: (). URL: `https://web.archive.org/web/20170903105244/https://www.sae.org/misc/pdfs/automated_driving.pdf` (visited on 05/03/2022).

[51] T. Jahn. "Mehr Staus durch selbstfahrende Autos: So wollen Verkehrsforscher das Problem lösen." In: (Apr. 2022). URL: `https://www.handelsblatt.com/technik/forschung-innovation/insight-innovation-mehr-staus-durch-selbstfahrende-autos-so-wollen-verkehrsforscher-das-problem-loesen/28254208.html` (visited on 06/29/2022).

[52] O. Ján, K. Eduard, V. Peter, and Š. Željko. "How Do Autonomous Cars Work?" In: (). URL: `https://www.sciencedirect.com/science/article/pii/S2352146520300995` (visited on 04/27/2022).

[53] A. Jarin. "Tesla Crashes Into CHP Car on SR-56." In: (July 2021). URL: `https://www.nbcsandiego.com/news/local/tesla-crashes-into-chp-car-on-sr-56/2652742/` (visited on 06/13/2022).

[54] J. JERNAGAN. "Fatal Tesla crash into fire truck was one year ago today." In: (Dec. 2020). URL: `https://www.bannergraphic.com/story/2856765.html` (visited on 06/13/2022).

[55] S. Jeyachandran. "Introducing the 5th-generation Waymo Driver: Informed by experience, designed for scale, engineered to tackle more environments." In: (Mar. 2020). URL: `https://blog.waymo.com/2020/03/introducing-5th-generation-waymo-driver.html` (visited on 06/24/2022).

[56] D. John. "First Tesla FSD Beta crash reported to NHTSA, but some questionable allegations are made." In: (Nov. 2021). URL: `https://driveteslacanada.ca/model-y/first-tesla-fsd-beta-crash-reported-nhtsa-questionable-allegations/` (visited on 06/19/2022).

[57] R. Kath. "Federal Government Investigating Tesla Crash in Massachusetts." In: (Nov. 2020). URL: `https://www.nbcboston.com/investigations/federal-government-investigating-tesla-crash-in-massachusetts/2229521/` (visited on 06/13/2022).

[58] R. Kath. "Police: Tesla That Hit Mass. State Trooper's Vehicle Was In Autopilot." In: (June 2020). URL: `https://www.nbcboston.com/investigations/police-tesla-that-hit-mass-state-troopers-vehicle-was-in-autopilot/2151164/` (visited on 06/13/2022).

[59] B. Knellwolf. "Führen autonome Autos zu mehr Verkehr?" In: (July 2019). URL: `https://www.tagblatt.ch/leben/autonome-autos-gibt-es-mehr-verkehr-und-stau-ld.1134237` (visited on 06/29/2022).

[60] T. KRISHER. "Feds probe NY Tesla crash that killed man changing flat tire." In: (Sept. 2021). URL: `https://www.courthousenews.com/feds-probe-ny-tesla-crash-that-killed-man-changing-flat-tire/` (visited on 06/19/2022).

[61] F. Lambert. "Tesla has now more than 100,000 people in its Full Self-Driving Beta program – is an accelerated rate of improvement coming?" In: (). URL: `https://electrek.co/2022/04/20/tesla-number-people-full-self-driving-beta-program-an-accelerated-rate-improvement-coming/` (visited on 05/06/2022).

[62] F. Lambert. "Tesla Model 3 driver again dies in crash with trailer, Autopilot not yet ruled out." In: (Mar. 2019). URL: `https://electrek.co/2019/03/01/tesla-driver-crash-truck-trailer-autopilot/` (visited on 06/15/2022).

[63] G. I. Law. "Autonomous Vehicle Statistics." In: (June 2021). URL: `https://www.gerberinjurylaw.com/blog/2021/june/autonomous-vehicle-statistics/#:~:text=Overall%2C%20autonomous%20vehicles%20(AVs),ones%20involving%20injury%20were%20minor` (visited on 06/09/2022).

[64] A. Lemonde. "Tesla Model Y Crash in California Could be the First One to Involve FSD Beta." In: (Sept. 2021). URL: `https://motorillustrated.com/tesla-model-y-crash-in-california-could-be-the-first-one-to-involve-fsd-beta/89249/` (visited on 06/19/2022).

[65] "Like Tesla, Toyota develops self-driving tech with low-cost cameras." In: (). URL: `https://www.reuters.com/business/autos-transportation/toyota-joins-tesla-developing-self-driving-tech-with-low-cost-cameras-2022-04-06/` (visited on 04/29/2022).

[66] A. MAK. "Why Teslas Keep Striking Parked Firetrucks and Police Cars." In: (Aug. 2021). URL: `https://slate.com/technology/2021/08/teslas-allegedly-hitting-emergency-vehicles-why-it-could-be-happening.html` (visited on 06/22/2022).

[67] G. Maps. *Maps Source Waymo fail*. 2022. URL: `https://www.google.com/maps/@33.3939219,-111.72266,75m/data=!3m1!1e3` (visited on 06/15/2022).

[68] A. MARSHALL. "Puny Humans Still See the World Better Than Self-Driving Cars." In: (Aug. 2017). URL: `https://www.wired.com/story/self-driving-cars-perception-humans/` (visited on 06/27/2022).

[69] A. Martinho, N. Herber, M. Kroesen, and C. Chorus. "Ethical issues in focus by the autonomous vehicles industry." In: *Transport Reviews* 41 (5 2021), pp. 556–577. DOI: `10.1080/01441647.2020.1862355`. URL: `https://doi.org/10.1080/01441647.2020.1862355`.

[70] S. MCEACHERN. "Why Cruise Uses Rotating Radar Assemblies On Its Self-Driving Prototypes." In: (July 2020). URL: `https://gmauthority.com/blog/2020/07/why-cruise-uses-rotating-radar-assemblies-on-its-self-driving-prototypes/` (visited on 06/23/2022).

[71] M. McFarland. "Traffic cones confused a Waymo self-driving car. Then things got worse." In: (May 2021). URL: `https://edition.cnn.com/2021/05/17/tech/waymo-arizona-confused/index.html` (visited on 06/14/2022).

[72] B. MEJIA. "Tesla in Autopilot mode crashes into parked Laguna Beach police cruiser." In: (May 2018). URL: `https://www.latimes.com/local/lanow/la-me-ln-tesla-collision-20180529-story.html` (visited on 06/13/2022).

[73] Mercedes. "Introducing DRIVE PILOT: An Automated Driving System for the Highway." In: (Feb. 2019). URL: `https://group.mercedes-benz.com/documents/innovation/other/2019-02-20-vssa-mercedes-benz-drive-pilot-a.pdf` (visited on 06/23/2022).

[74] A. MINKLER. "Tesla on autopilot crashes into DPS patrol car on I-10." In: (July 2020). URL: `https://eu.azcentral.com/story/news/local/arizona-breaking/2020/07/14/tesla-autopilot-hits-dps-patrol-car-10-near-benson/5439368002/` (visited on 06/13/2022).

[75] Mobileye. "Mobileye Sensor Suite." In: (). URL: https://www.mobileye.com/blog/mobileye-drive-self-driving-system/ (visited on 06/23/2022).

[76] D. D. of Motor Vehicles. *cruiseUnderscore022521*. Feb. 2021. URL: https://www.dmv.ca.gov/portal/file/cruise_022521-pdf (visited on 06/14/2022).

[77] D. D. of Motor Vehicles. "pony-aiUnderscore102821." In: (Oct. 2021). URL: https://www.dmv.ca.gov/portal/file/pony-ai_102821-pdf/ (visited on 06/19/2022).

[78] D. D. of Motor Vehicles. *ponyUnderscoreaiUS021121*. Nov. 2021. URL: https://www.dmv.ca.gov/portal/file/pony-ai_021121-pdf/ (visited on 06/14/2022).

[79] D. NGUYEN. "Tesla driver in fatal California crash had posted videos of himself in vehicle." In: (May 2021). URL: https://www.latimes.com/california/story/2021-05-16/tesla-driver-in-fatal-california-crash-had-post-videos-of-himself-in-vehicle (visited on 06/14/2022).

[80] B. Ostbrabant. "Zoekresultaat - inzien documentECLI:NL:RBOBR:2019:5057." In: (Sept. 2019). URL: https://uitspraken.rechtspraak.nl/inziendocument?id=ECLI:NL:RBOBR:2019:5057 (visited on 06/19/2022).

[81] K. Othman. "Public acceptance and perception of autonomous vehicles: a comprehensive review." In: *AI and Ethics* 1 (3 2021), pp. 355–387. ISSN: 2730-5961. DOI: 10.1007/s43681-021-00041-8. URL: https://doi.org/10.1007/s43681-021-00041-8.

[82] T. Paulsen. "Gesetz zum autonomen Fahren: Diese Regeln gelten." In: (). URL: https://www.adac.de/rund-ums-fahrzeug/ausstattung-technik-zubehoer/autonomes-fahren/recht/gesetz-zum-autonomen-fahren/#:~:text=Im%20Mai%202021%20haben%20Bundestag,festgelegten%20und%20vorab%20genehmigten%20Betriebsbereichen (visited on 06/03/2022).

[83] D. Petereit. "Bundesrat winkt Erleichterungen für autonomes Fahren durch." In: (). URL: https://t3n.de/news/bundesrat-autonomes-fahren-1474313/ (visited on 06/03/2022).

[84] F. Petit. "It won't work without LiDAR!" In: (June 2020). URL: https://www.blickfeld.com/blog/autonomous-driving-without-lidar-wont-work/ (visited on 06/22/2022).

[85] P. Pickering. "Radar and Ultrasonic Sensors Strengthen ADAS Object Detection." In: (). URL: https://www.electronicdesign.com/markets/automotive/article/21805470/radar-and-ultrasonic-sensors-strengthen-adas-object-detection (visited on 06/04/2022).

[86] N. Pinchon, M. I. Khedher, O. Cassignol, A. Nicolas, F. Bernardin, P. Leduc, J.-P. Tarel, R. Brémond, E. Bercier, and G. Julien. "All-weather vision for automotive safety: which spectral band?" In: June 2016. URL: `https://www.researchgate.net/publication/309291304_All-weather_vision_for_automotive_safety_which_spectral_band` (visited on 06/26/2022).

[87] A. PRESS. "US investigating Fremont-based autonomous vehicle company's crash report." In: (Mar. 2022). URL: `https://www.mercurynews.com/2022/03/30/us-investigating-autonomous-vehicle-companys-crash-report/` (visited on 06/19/2022).

[88] "Quantum Computing: A Key to Autonomous Vehicle Industry Success." In: (). URL: `https://www.futurebridge.com/industry/perspectives-mobility/quantum-computing-a-key-to-autonomous-vehicle-industry-success/` (visited on 05/05/2022).

[89] P. RAAUM. "90 dagers fengsel for grov uaktsomhet med autostyring." In: (Dec. 2020). URL: `https://www.motor.no/autopilot-e18-tesla/90-dagers-fengsel-for-grov-uaktsomhet-med-autostyring/188977` (visited on 06/15/2022).

[90] REUTERS. "Fatal Tesla crash in Saratoga: Driver overrode Autopilot's braking, the NTSB says." In: (Nov. 2021). URL: `https://www.mercurynews.com/2021/11/16/u-s-ntsb-closes-probe-into-fatal-tesla-2020-california-crash/` (visited on 06/09/2022).

[91] A. Review. "Why Do Teslas Crash into Firetrucks and Other Emergency Vehicles?" In: (). URL: `https://www.autopilotreview.com/model-s-fire-truck/` (visited on 06/22/2022).

[92] G. RØED. "Tesla på auto-styring da mann ble meid ned." In: (Dec. 2020). URL: `https://www.motor.no/autopilot-nyheter-tesla/tesla-pa-auto-styring-da-mann-ble-meid-ned/188623` (visited on 06/15/2022).

[93] R. Russell. "UK's first self-driving bus takes to the road for tests in Scotland." In: (Apr. 2022). URL: `https://news.sky.com/story/uks-first-self-driving-bus-takes-to-the-road-for-tests-in-scotland-12598505` (visited on 06/28/2022).

[94] A. Sam. *Executive Summary: Guidehouse Insights Leaderboard: Automated Driving Vehicles Assessment of Strategy and Execution for 18 Companies Developing Automated Driving Systems Published 1Q 2020 Sam Abuelsamid Principal Research Analyst Eric Woods.*

[95] K. Sandra. "3 types of autonomous vehicle sensors in self-driving cars." In: (). URL: `https://www.itransition.com/blog/autonomous-vehicle-sensors` (visited on 04/27/2022).

[96] R. Schesswendter. "Autonomes Fahren: Das bedeuten Level 0 bis 5." In: (). URL: `https://t3n.de/news/level-0-bis-5-automes-fahren-aktueller-stand-1466454/amp/` (visited on 04/28/2022).

[97] K. Seamons. "There Was Something Different About This Fatal Tesla Crash." In: (Aug. 2021). URL: `https://www.newser.com/story/309951/there-was-something-different-about-this-fatal-tesla-crash.html` (visited on 06/14/2022).

[98] "Sensor Technology in Autonomous Vehicles." In: (). URL: `https://encyclopedia.pub/entry/8356` (visited on 04/29/2022).

[99] shutterstock. "Traffic cones." In: (). URL: `https://www.shutterstock.com/de/image-illustration/3d-rendering-traffic-cones-top-view-750289585` (visited on 06/15/2022).

[100] G. staff and agencies. "Tesla car that crashed and killed driver was running on Autopilot, firm says." In: (Mar. 2018). URL: `https://www.theguardian.com/technology/2018/mar/31/tesla-car-crash-autopilot-mountain-view` (visited on 06/10/2022).

[101] J. Studios. *Waymo Self Driving Taxi Goes Rogue: Blocks Traffic, Evades Capture JJRicks Rides With Waymo Hashtag54*. 2021. URL: `https://www.youtube.com/watch?v=zdKCQKBvH-A` (visited on 06/14/2022).

[102] P. Sun, H. Kretzschmar, X. Dotiwalla, A. Chouard, V. Patnaik, P. Tsui, J. Guo, Y. Zhou, Y. Chai, B. Caine, V. Vasudevan, W. Han, J. Ngiam, H. Zhao, A. Timofeev, S. Ettinger, M. Krivokon, A. Gao, A. Joshi, Y. Zhang, J. Shlens, Z. Chen, and D. Anguelov. "Waymo Car Grafik." In: (). URL: `https://openaccess.thecvf.com/content_CVPR_2020/papers/Sun_Scalability_in_Perception_for_Autonomous_Driving_Waymo_Open_Dataset_CVPR_2020_paper.pdf` (visited on 06/15/2022).

[103] B. Templeton. "NTSB Releases Report On 2018 Fatal Silicon Valley Tesla Autopilot Crash." In: (Feb. 2020). URL: `https://www.forbes.com/sites/bradtempleton/2020/02/13/ntsb-releases-report-on-2018-fatal-silicon-valley-tesla-autopilot-crash/?sh=5798fe4b42a8` (visited on 06/10/2022).

[104] Tesla. "Advanced Sensor Coverage." In: (). URL: `https://www.tesla.com/autopilot` (visited on 06/23/2022).

[105] G. Tischler. “80 GHz radar vs. ultrasonic: Non-contact Level Measurement Technology Comparison.” In: (). URL: https://www.vega.com/en-us/company/blog/2019/80-ghz-radar-vs-ultrasonic (visited on 06/04/2022).

[106] “Top 30 Self Driving Technology and Car Companies.” In: (). URL: https://www.greyb.com/autonomous-vehicle-companies/ (visited on 04/28/2022).

[107] “Toyota-Tesla join hands for camera-only self driving tech.” In: (). URL: https://www.cartoq.com/toyota-tesla-join-hands-for-camera-only-self-driving-tech/amp/ (visited on 04/29/2022).

[108] “VDA: Deutschland sichert sich Pole Position.” In: (). URL: https://industrie.de/top/rechtsverordnung-autonome-fahren-vda-deutschland/ (visited on 06/03/2022).

[109] Volvo. “Prototype car.” In: (). URL: https://www.media.volvocars.com/ch/de-ch/media/photos/175954/volvo-v40-t4-momentum-studio-birds-eye-view1 (visited on 06/27/2022).

[110] B. Volz. “Family calls for investigation after Tesla driver dies in Osceola crash.” In: (Sept. 2019). URL: https://www.clickorlando.com/news/2019/09/26/family-calls-for-investigation-after-tesla-driver-dies-in-osceola-crash/ (visited on 06/19/2022).

[111] “Was ist die LiDAR Technologie?” In: (). URL: https://www.generationrobots.com/blog/de/was-ist-die-lidar-technologie (visited on 05/03/2022).

[112] D. Weecks. *Trailer Backing Tutorial by Swift Academy*. 2017. URL: https://www.youtube.com/watch?v=O8IOOwRHzUQ (visited on 06/15/2022).

[113] X. WEI. “Tesla Admits Autopilot Feature Led to Fatal China Crash in 2016.” In: (Feb. 2018). URL: https://www.yicaiglobal.com/news/tesla-admits-autopilot-feature-led-to-fatal-china-crash-in-2016 (visited on 06/14/2022).

[114] Z. Wendt and J. S. Cook. “Saved by the Sensor: Vehicle Awareness in the Self-Driving Age.” In: (). URL: https://www.machinedesign.com/mechanical-motion-systems/article/21836344/saved-by-the-sensor-vehicle-awareness-in-the-selfdriving-age (visited on 05/01/2022).

[115] “What is an Autonomous Car?” In: (). URL: https://www.synopsys.com/automotive/what-is-autonomous-car.html (visited on 04/27/2022).

[116] “Why ADAS and Autonomous Vehicles Need Thermal Infrared Cameras.” In: (). URL: https://www.flir.com/discover/oem/automotive/why-adas-and-autonomous-vehicles-need-thermal-infrared-cameras/ (visited on 06/27/2022).

[117] K. Wiggers. "Waymo's driverless cars were involved in 18 accidents over 20 months." In: (Oct. 2020). URL: `https://venturebeat.com/2020/10/30/waymos-driverless-cars-were-involved-in-18-accidents-over-20-month/` (visited on 06/10/2022).

[118] B. Wodecki. "Human Error Causes 99 Percent of Autonomous Vehicle Accidents: Study." In: (Oct. 2021). URL: `https://www.iotworldtoday.com/2021/10/20/blame-the-humans-idtechex-finds-99-percent-of-autonomous-vehicle-accidents-caused-by-human-error/` (visited on 06/09/2022).

[119] M. Xue. "Tesla confirms 'Autopilot' engaged in fatal crash in China." In: (Feb. 2018). URL: `http://chinaplus.cri.cn/news/china/9/20180228/96198.html` (visited on 06/14/2022).

[120] A. Yahya. "The Long-Tail Problem in AI, and How Autonomous Markets Can Solve It." In: (July 2020). URL: `https://a16z.com/2020/07/24/long-tail-problem-in-a-i/` (visited on 06/22/2022).

[121] Yandex. "Yandex Sensor Suite." In: (). URL: `https://sdg.yandex.com/` (visited on 06/23/2022).

[122] D. J. Yeong, G. Velasco-Hernandez, J. Barry, and J. Walsh. "Sensor and Sensor Fusion Technology in Autonomous Vehicles: A Review." In: (). URL: `https://www.mdpi.com/1424-8220/21/6/2140/htm` (visited on 04/29/2022).

[123] B. Zamora-Nipper. "Several officers, 1 civilian injured after suspected intoxicated driver strikes patrol vehicle." In: (Feb. 2021). URL: `https://www.click2houston.com/news/local/2021/02/27/several-officers-1-civilian-injured-after-suspected-intoxicated-driver-strikes-patrol-vehicle/` (visited on 06/13/2022).

[124] A. Zewe. "Artificial intelligence to help autonomous vehicles avoid idling at red lights." In: (May 2022). URL: `https://techxplore.com/news/2022-05-artificial-intelligence-autonomous-vehicles-idling.amp` (visited on 06/29/2022).

[125] Zoox. "Zoox Sensor Suite." In: (). URL: `https://zoox.com/autonomy/` (visited on 06/23/2022).

[126] ZZAP. *Bird's eye view.* Aug. 2019. URL: `https://twitter.com/zzapcars/status/1163591245219762177` (visited on 06/15/2022).