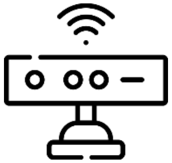
Waymo, 360° Experience
https://www.youtube.com/watch?v=B8R148hFxPw

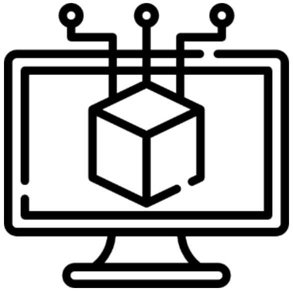
Institute of Automotive Technology
Faculty for Mechanical Engineering
Technical University of Munich

Autonomous Driving Software Engineering

Prof. Dr.-Ing. Markus Lienkamp / Prof. Dr.-Ing. Boris Lohmann

Phillip Karle, M. Sc.





Lecture Overview

Lecture – 90min	Practice – 45min
1 Introduction: Autonomous Driving Karle	**1 Practice** Karle
2 Perception I: Mapping Sauerbeck	**2 Practice** Sauerbeck
3 Perception II: Localization Sauerbeck	**3 Practice** Sauerbeck
4 Perception III: Detection Huch	**4 Practice** Huch
5 Prediction Karle	**5 Practice** Karle
6 Planning I: Global Planning Trauth	**6 Practice** Trauth
7 Planning II: Local Planning Ögretmen	**7 Practice** Ögretmen
8 Control Wischnewski	**8 Practice** Wischnewski
9 Safety Assessment Stahl	**9 Practice** Stahl
10 Teleoperated Driving Feiler	**10 Practice** Feiler
11 End-to-End Betz	**11 Practice** Betz
12 From Driver to Passenger Fank	**12 Practice** Karle

Objectives for Lecture 1: Introduction

Depth of understanding

After the lecture you are able to…

Remember | Understand | Apply | Analyze | Evaluate | Develop

… explain the levels of driving automation (SAE-level)

... recollect the milestones of autonomous driving

… know the different layers of a software architecture

… identify common sensors for detection and localization and know their properties

… understand the current open challenges (technical, social, legal) to enable autonomous driving on public roads

… setup up your system and apply the virtual environment of python for the homework

Introduction
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Agenda

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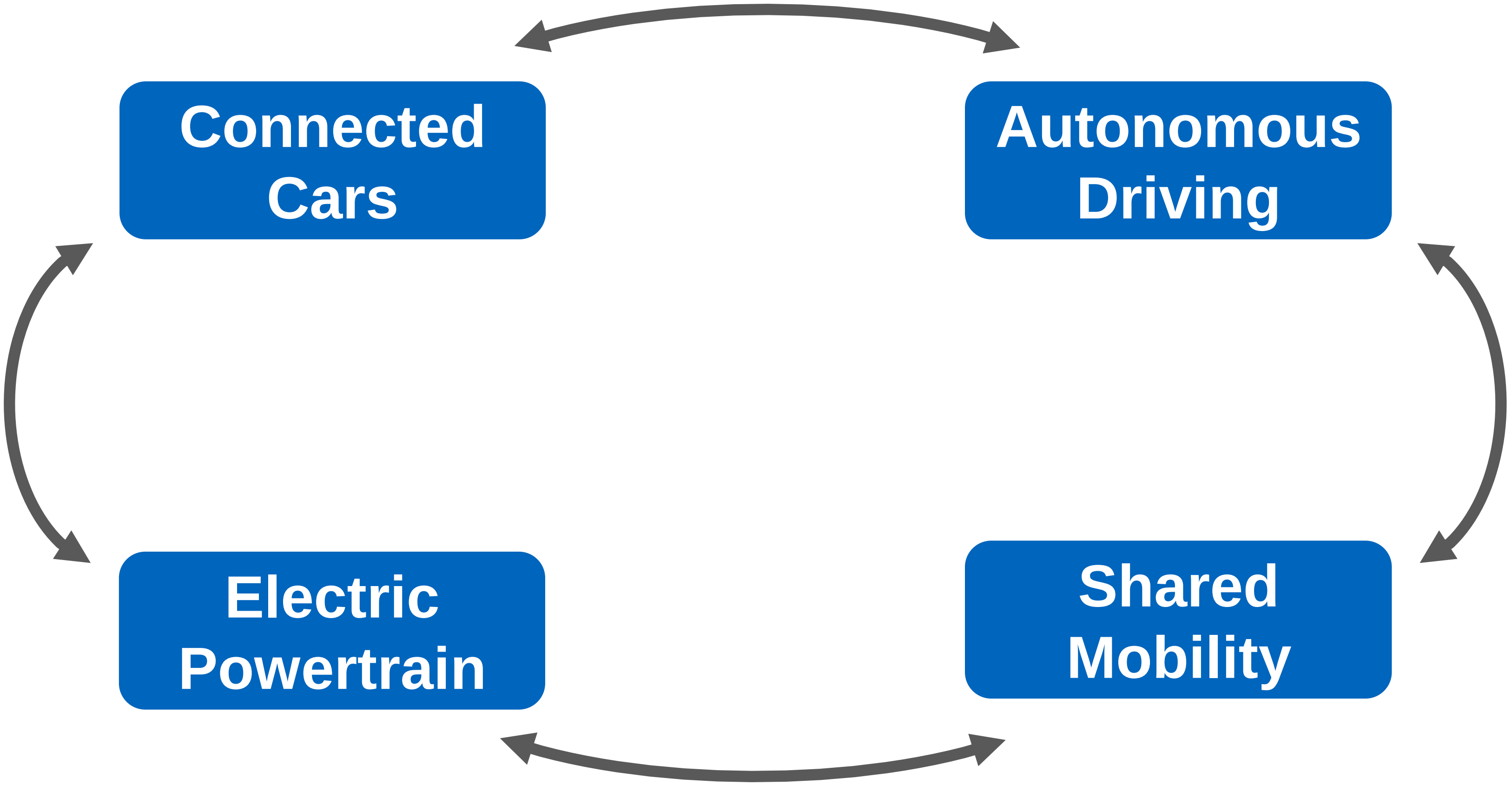
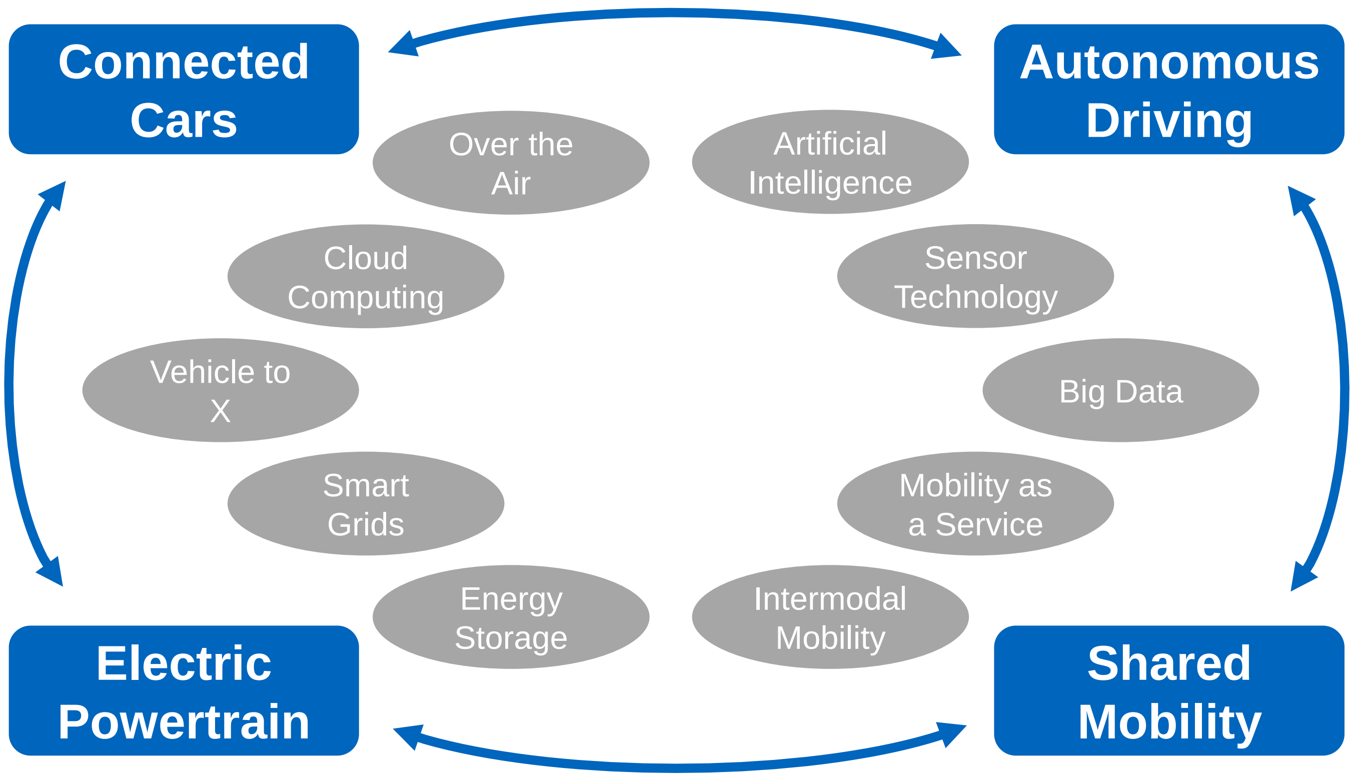
Megatrends in Automotive Industry: CASE

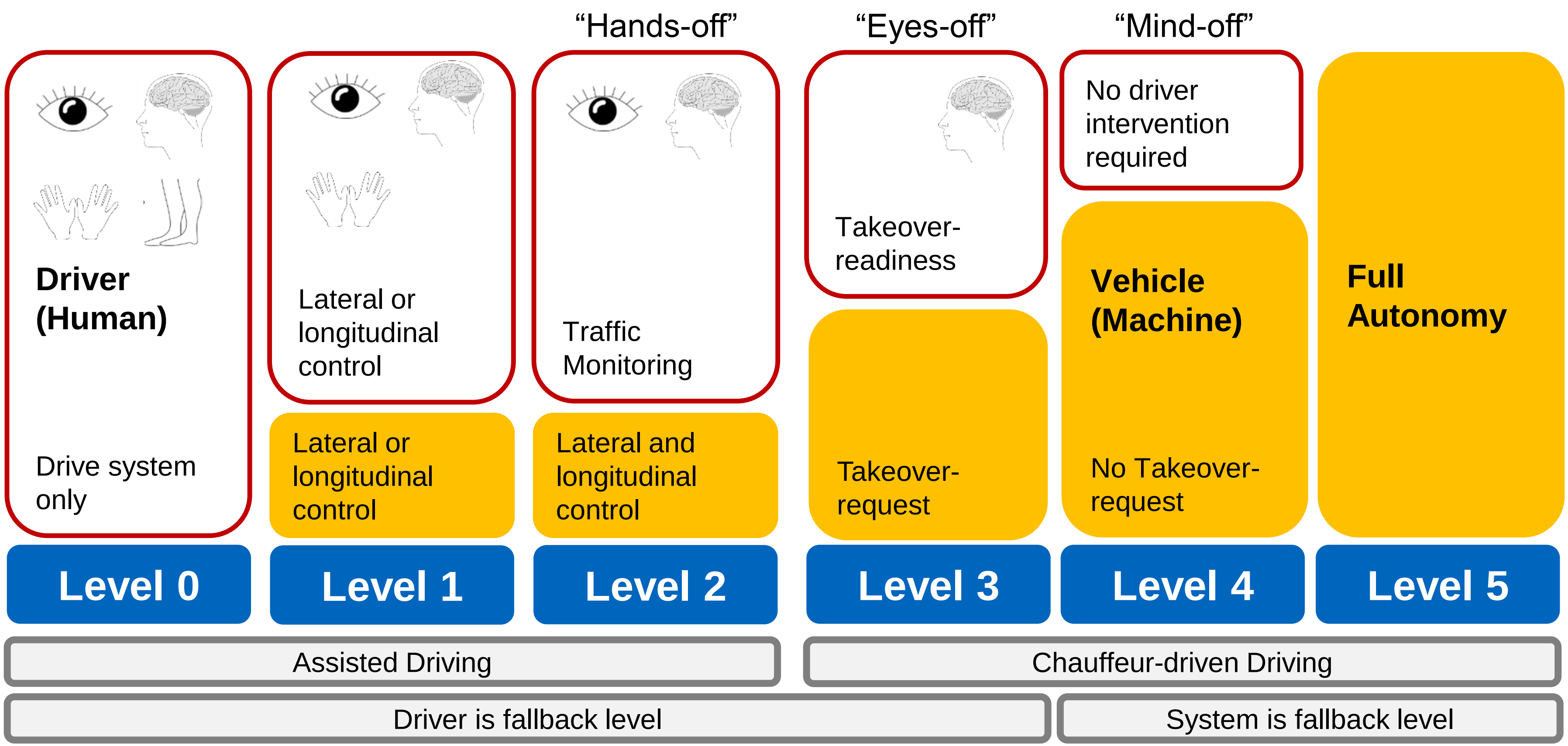


Additional Slides

Some key technologies of these four mega trends are shown below. Also, note, that theses trends influence each other. An example is the usage of self-driving robotaxis for concepts of shared / smart mobility.



Levels of Vehicle Autonomy – SAE[1] / BASt[2]



[1] SAE International (former Society of Automotive Engineers)
[2] Bundesanstalt für Straßenwesen

Additional Slides

	Level 0	Level 1	Level 2	Level 3	Level 4	Level 5
BASt[1]	Driver only	Assisted	Partially automated	Highly Automated	Fully Automated	
SAE[2]	No Automation	Driver Assistance	Partial Automation	Conditional Automation	High Automation	Full Automation

[1] Report „Rechtsfolgen zunehmender Fahrzeugautomatisierung", 2012, Bundesanstalt für Straßenwesen (BASt)

[2] Norm SAE J3016, SAE International (former Society of Automotive Engineers)

Level 0.

No Automation: the driver performs all driving tasks, Example: Blind Spot Warning, LDW

Level 1.

Driver Assistance: vehicle is guided by driver, but some driving-assist features may be included in the vehicle. Example: LKA or ACC

Level 2.

Partial Automation: vehicle has combined automated functions, like acceleration and steering, but the driver must maintain control of all driving tasks and monitor the environment at all times. Example: LKA and ACC

Level 3.

Conditional Automation: vehicle can run autonomously, but the driver must be ready to take control of the vehicle at all times with notice. Example: Traffic Jam Pilot

Level 4.

High Automation: vehicle is capable of performing all driving functions under certain conditions, but the driver has the option to take control of vehicle. Example: Local driverless taxi, Autonomous Racing

Level 5.

Full Automation: vehicle is capable of performing all driving functions under all conditions, but the driver may have the option to control the vehicle. Example: Full Autonomous Car

Highway Pilot

Concept

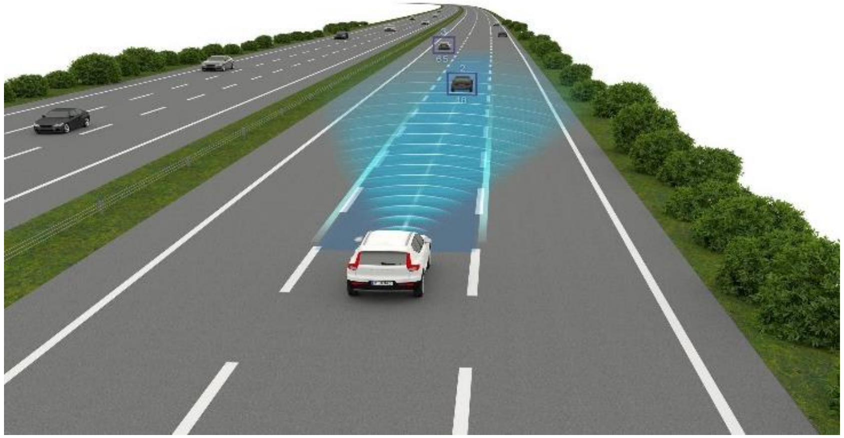
- Highly automated freeway travel by algorithm (Level 3-4)
- Traffic Jam Pilot up to 60 km/h

Reduced mental stress

Driver does not have to monitor constantly or is even released completely from the driving task.

Increased productivity

Travel time can be used to work or to rest. Connected car becomes a car office.



https://www.dezeen.com/2014/02/21/driverless-car-concept-vehicle-xchange-by-rinspeed/
https://www.autoweek.com/news/technology/a1831286/five-levels-driving-autonomy-autoweek-explains/

Robotaxis

Concept

- Autonomous car cruise 24-7
- Passengers are picked up on demand and dropped at destination
- No need of stations nor depots
- Relief city-centers of private cars

Makeover of townscape

- Parking areas become obsolete
- Reduction of total car volume to $^{1}/_{3}$

Downside: Empty runs

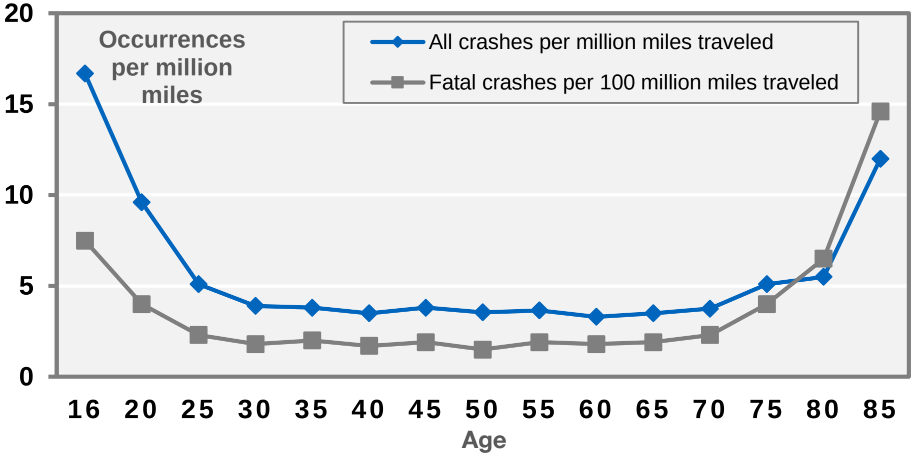
https://www.sueddeutsche.de/auto/verkehrsanalyse-muenchen-ist-wieder-deutschlands-stau-hauptstadt-1.4832763
https://www.continental.com/de/produkte-und-innovationen/innovationen/unsere-vision-fuer-morgen/robo-taxi-214388

Motivation – Access to Mobility

Facilitate access to mobility

Minors, elderly and people with disabilities get access to individual mobility.

Ensure safety for all ages

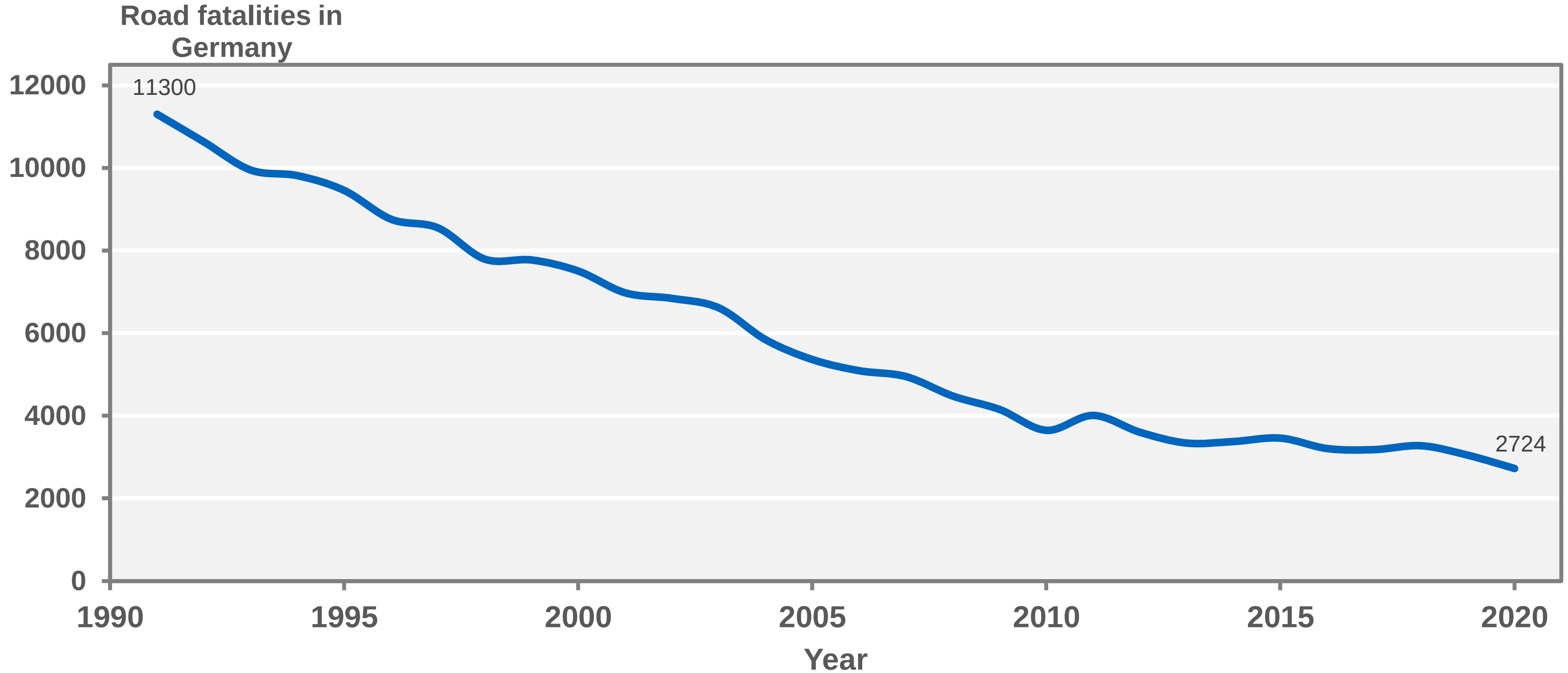


https://www.cnbc.com/2018/06/13/alphabet-waymo-testing-early-riders-interview-with-saswat-panigrahi.html
http://archive.boston.com/lifestyle/health/blog/inpractice/2012/02/driving_while_old.html

Motivation – Vision Zero, 2050

Zero road fatalities in 2050

- More than 90% off all accidents are human failure
- Disruptive technologies required to further reduce road fatalities



Clustering of Competences

High complexity

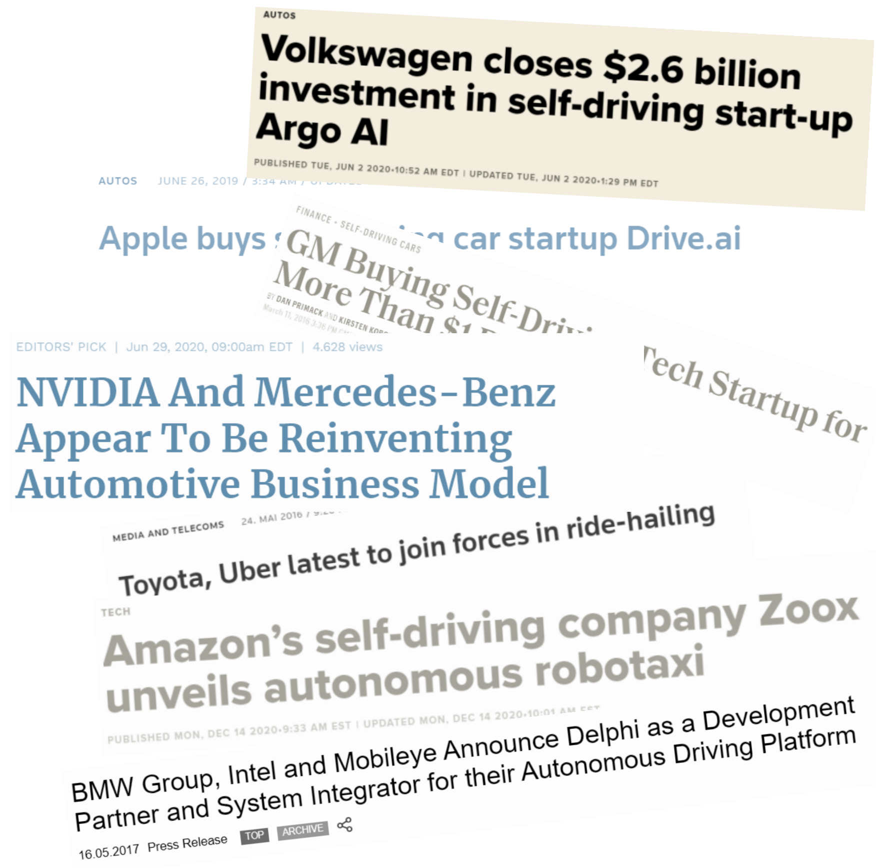
Software algorithms as well as car manufacturing are sophisticated and require experience

Reduced cost

Huge investments in R&D[1] and cost saving from industrialization

Shared risk

Risk of technical decisions and potential risk from liability and warranty claims



[1] Research and Development

Additional Slides

Exemplary Clusters of Competences between OEM – Supplier – Mobility Provider and Tech Firm in the field of autonomous driving

OEM Competences: • System Integration • Component Drivetrain Chassis • HMI • Costumer Support	**Supplier** Competences: • Components of drivetrain, chassis • Control Units • BUS-Systems	**Mobility Provider** Competences: • Mobility as a Service (Sharing etc.)	**Tech Firm** Competences: • Know-How in AI • Software-Development • Software-Support (Over-the-Air) • Data Mining
Daimler	Bosch, Continental, …	Share Now	Nvidia, …
VW		MOIA	Argo AI, …
BMW		Share Now	Mobileye, Intel, …
…			

Additional Slides

Autonomous driving is one of the most complex development challenges in the automotive industry. The broad range of required skills and capabilities barely exists in-house at any traditional OEM, supplier or tech player. The latter are well positioned then it comes to software development and agile working principles to achieve shorter development cycles and time to market, but lack the experience with industrialization and scaling a real hardware business like building cars. On the other side, OEMs and traditional automotive suppliers often struggle with the transformation towards a new agile product and software development system with significantly short cycle times for E/E and software-related functions. Cross-industry partnerships are an (inevitable) prerequisite to mitigate these complex challenges and to close own technology blind spots. Many of the major stakeholders engaged in the development of partnerships. In addition to the lack of technological or process expertise, there are several other reasons to join forces. Reduced development costs and risk sharing between partners are further important drivers for the emergence of those cooperation. Lastly, from a topline perspective, a larger addressable customer base and associated revenue potentials have to be mentioned.

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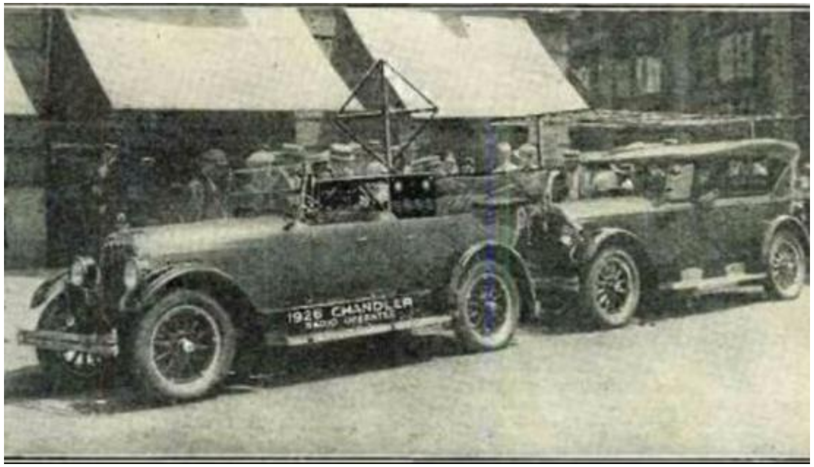
Milestones of Autonomous Driving

First driverless car in public road traffic

The American Wonder

Francis P. Houdina, 1925, New York City

Radio-operated automobile on 5th Avenue



First software concept for modern autonomous driving

John McCarthy, pioneer of AI, 1969

Essay „Computer Controlled Cars“

Specification of software pipeline

“Our system requires a computer in the car equipped with television camera input that uses the same visual input available to the human driver. […] The user enters the destination with a keyboard.”
John McCarthy, 1969

Kröger, 2016 - Automated Driving in Its Social, Historical and Cultural Contexts
John McCarthy, 1969 – Computer Controlled Cars (http://jmc.stanford.edu/commentary/progress/cars.pdf)

Additional Slides

The first attempt of a driverless vehicle in public traffic was realized by Francis P. Houdina, a former U.S. Army electrical engineer, in New York City in 1925. A modified Chandler sedan, later called the American Wonder, received radio signals via an antenna that controlled its speed and direction. The car's operator sat in a vehicle directly behind. However, the journey ended with a crash into another car with a bunch of photographers. From the today's viewpoint, it was no real autonomous driving, but more teleoperated driving.

In 1969, John McCarthy, one of the founding fathers of artificial intelligence, wrote an essay titled "Computer-Controlled Cars" about the software and functional architecture of autonomous vehicles, similar to modern AVs. McCarthy referred to an "automatic chauffeur" capable of navigating a public road via a "television camera input that uses the same visual input available to the human driver." He wrote that users should be able to enter a destination using a keyboard, which would then prompt the car to immediately drive them there. Additional commands would allow users to change the destination, stop at a restroom or restaurant, slow down, or speed up in the case of an emergency. No such vehicle was built, but McCarthy's essay laid out the mission for other researchers to work toward.

Reference:

https://www.digitaltrends.com/cars/history-of-self-driving-cars-milestones/

Milestones of Autonomous Driving

First autonomous vehicle based on artificial intelligence

Prof. Dickmanns, Uni BW, 1986 – 1994

Camera-based steering using automatic image processing (4D-Approach)

> 1000km, Three-Lane Highway, 130 km/h

Public attendance to autonomous driving

DARPA[1] Grand Challenge, 2004 / 2005
DARPA Urban Challenge, 2007

First long distance competition for driverless cars in rural and urban areas

[1] Defense Advanced Research Projects Agency

Additional Slides

Prof. Ernst Dickmanns from the University of the Federal Armed Forces in Munich (UniBW) developed for the first time visually guided autonomous cars with digital processors onboard. In 1984, his team conceptualized the first vehicle that used dynamical models for visual autonomous guidance: The VaMoRs (Versuchsfahrzeug für autonome Mobilität und Rechnersehen) was a 5-ton van (Mercedes 508 D), that was able to carry the big sized computers and cameras of this time. In summer 1987, the VaMoRs drove autonomously – only with the help of cameras, without radar and GPS – 20 km with a speed up to 96 km/h (60 mph). The technology was based on a spatiotemporal dynamic model called 4-D approach, which added to the three dimensions of space the category of time and integrated a feedback of prediction errors.

The concept of vision-based autonomous driving gained momentum with the EUREKA-PROgraMme for a European Traffic of Highest Efficiency and Unprecedented Safety (PROMETHEUS) of the European Union (1987–1994).

In the context of the PROMETHEUS-Project, the team of Dickmanns developed with Mercedes Benz two S-Class (W 140) robotic vehicles: VaMP (UniBw Munich) and VITA-2 (DBAG). During the final event in October 1994 in France, the twin-robot vehicles drove more than 1000 km autonomously on three-lane highways around Paris, in the middle of heavy traffic and with speeds up to 130 km/h. The system was based on real time evaluation of image sequences caught by four cameras (320 x 240 pixels). Steering, throttle and brakes were controlled automatically through computer commands. The next year, Dickmanns' team piloted a Mercedes S-Class from Munich to Denmark, a trip of more than 1,600 kilometers at a maximum speed of 180 km/h with, as Dickmanns notes, "about 95% of the distance…traveled fully automatically."

Reference:

M. Maurer, B. Lenz, H. Winner, und J. C. Gerdes, *Autonomous Driving: Technical, Legal and Social Aspects*. s.l.: Springer, 2016.

Additional Slides

Announced on 30 July 2002, the first DARPA (Defense Advanced Research Projects Agency) Grand Challenge held in Mojave Desert in the United States, mandated by the US Congress, had $1 Million of prize aimed to unman one-third of Armed Forces' ground combat vehicles by 2015. It was an autonomous robotic ground vehicle competition with 150 miles of length. However, none of the vehicles travelled the whole length, the Red Team of Carnegie Mellon University travelled farthest completing 11.9 km. Hence, no team could claim the prize as they could barely reach 5% of the total distance.

The same year in June 2004, DARPA announced second grand challenge with 150 miles (212 km) off-road course with $2 million prize, double than the previous one. With lessons learned and improved vehicles, 23 final participants performed in October 2005. It was a challenging run that included three tunnels, more than 100 turns and navigating a steep pass with sharp drop-offs. The Stanford Racing Team won $2 million prize with the winning time 6 hours and 53 minutes followed by the Red Team of Carnegie Mellon University. Total five teams completed the competition.

The Urban Challenge, the third installment in the series of the competition launched by Defense, was announced in May 2006 and was held on November 3, 2007, at the Former George AFB Victorville, California. Building on the success of the 2004 and 2005 Grand Challenges, this event aimed to build a vehicle which is capable of driving without a human driver in traffic, maneuvering complex situations like parking, passing, and negotiating intersections. This event was unique and truly groundbreaking as the first time autonomous vehicles have interacted with both, highly automated and conventional cars, in the traffic of an urban environment.

The competition was tougher this time with 60 miles (97 km) of urban course. It was won by “Boss” of Tartan Racing of Carnegie Mellon University with the average speed of 22.5 km/h with a complex urban environment and driving time limited to a total of six hours.

Reference:

https://automotiveindianews.com/milestones-development-autonomous-driving/

Milestones of Autonomous Driving

First self-parking series vehicle

VW Park Assist, 2006

Parallel parking assistance

System determines optimal steering motion

Bertha-Benz Ride

Pforzheim – Mannheim, 2013

Intelligent drive system with close-to-production sensors

https://www.volkswagen-newsroom.com/de/volkswagen-news-international-ces-asia-3159
https://media.daimler.com/marsMediaSite/en/instance/ko/Pioneering-achievement-Autonomous-long-distance-drive-in-rural-and-Mercedes-Benz-S-Class-INTELLIGENT-DRIVE-drives-autonomously-in-the-tracks-of-Bertha-Benz.xhtml?oid=9904223

Milestones of Autonomous Driving

Tesla Autopilot

Tesla Models S, 2015

Highway Pilot (Level 2) based on radar and camera perception

Adaptive Cruise Control and Lane Change on Freeway

Autonomous car fatality

Tesla Model X crashes unbraked into safety barrier with 70 miles per hour

Driver was playing on his smartphone in autopilot mode

https://fortune.com/2015/12/17/tesla-mobileye/
https://www.youtube.com/watch?v=jdPIdNS2LUk&feature=emb_logo
https://www.theguardian.com/technology/2020/feb/25/tesla-driver-autopilot-crash

Milestones of Autonomous Driving

First public autonomous taxi fleet

Waymo, 2020

Robotaxis in a 50-mi^2-area in Phoenix suburbs without safety driver

20 million miles of testing

First autonomous head-to-head race

Indy Autonomous Challenge

Indianapolis Motor Speedway,

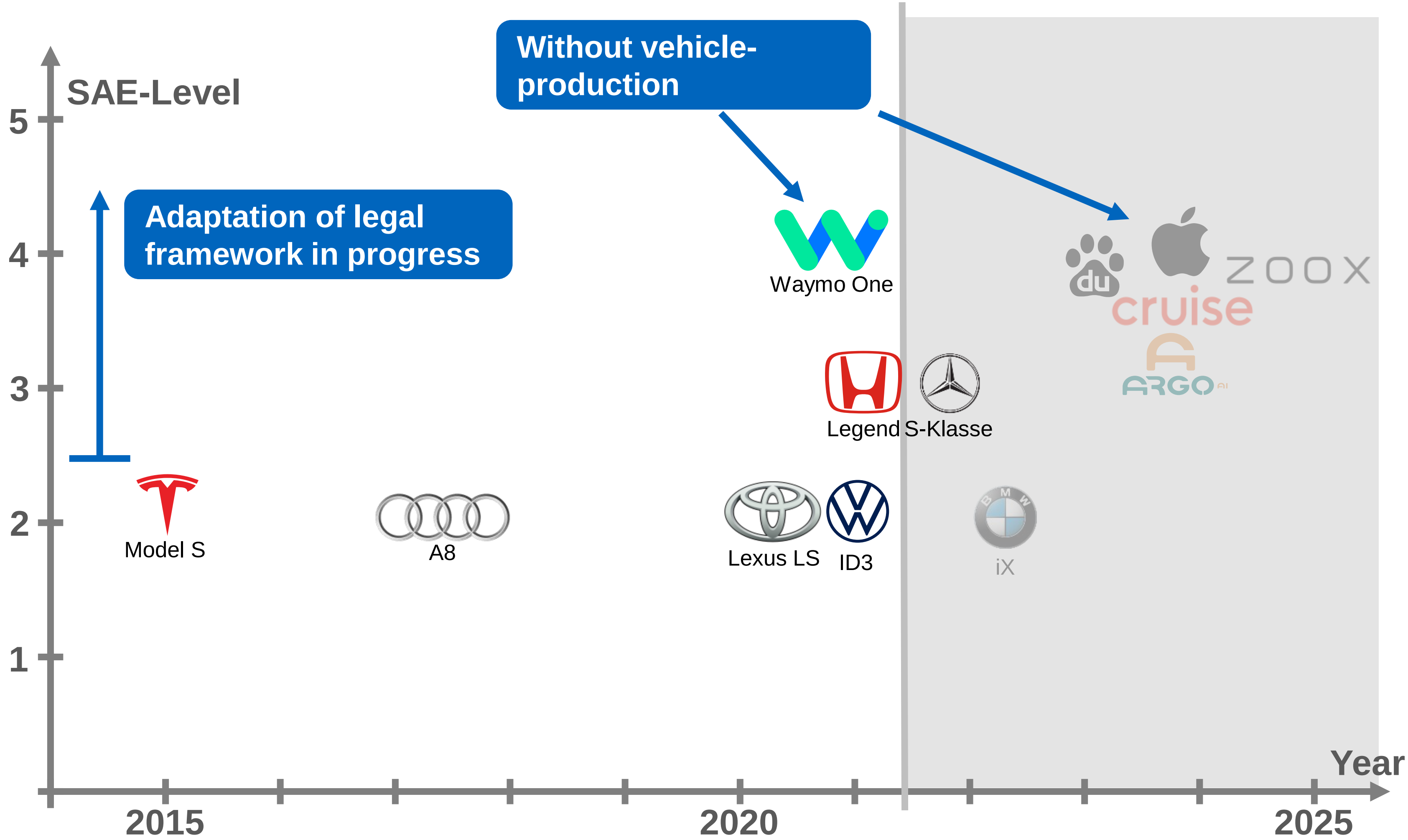
October 23rd, 2021

Inspired by the DARPA Challenges

Wheel-to-wheel racing with up to 300 km/h

https://www.auto-motor-und-sport.de/tech-zukunft/mobilitaetsservices/waymo-autonomes-fahren-operator/
https://www.mw.tum.de/ftm/forschungsfelder/intelligente-fahrzeugsysteme/indy-autonomous-challenge/
https://www.indyautonomouschallenge.com/challenge

Status Quo



SAE-Level
5
4
3
2
1
Without vehicle-production
Adaptation of legal framework in progress
Waymo One
Legend
S-Klasse
Model S
A8
Lexus LS
ID3
iX
ZOOX
cruise
ARGO
Year
2015
2020
2025

Additional Slides

Today, Level 2 systems are not only standard in premium vehicles, but are also used in lower vehicles classes. Common systems are Lane Keeping Assistance (LKA) and Adaptive Cruise Control (ACC) on highways. The driver is allowed to take off his hands for short times, but has to supervise the car in every situation. For Level 3 and Level 4 systems an adaptation of legal framework is necessary in many countries. Furthermore, these systems result in higher costs for the costumer and increasing cases of liability for the OEM. Therefore, the unofficial Level 2+ emerged, which exceed the functionality of typical Level 2 model, but still requires the supervision of the human driver. OEMs use this level to point out the enhanced robustness of their level 2 systems or refer to advanced functionalities such as Lance Change Assistant or Cloud Based Services.
The progression from level 3 to level 4 is not a steady one. Classic rule-based ADAS function reach their limits with level 3 requirements. Linear “if then” conditions need to consider every possible use case or combination of use cases in any given traffic situation, which is virtually impossible in urban environments (level 4 and 5). Apart from confined spaces such as highways traffic situations are highly dynamic and complex. For this reason, self-learning systems based on artificial intelligence (AI) that mimic human decision-making processes are critical for meeting the demand for complex scene interpretation, behavior prediction and trajectory planning. AI is becoming a key technology in all areas along the automotive value chain is paramount for the success of level 4+ AD systems.

The Tesla Autopilot, which was introduced with the Model S in 2015, was the first level 2 system. The Audi A8 is capable to drive with level 3 up to 60 km/h, but due to legal aspects the system was not offered for costumers. BMW announced a level 3 system for the iX, but took the announcement back because of technical and legal aspects. Honda received the type designation for level 3 in Japan and plans to introduce the “Traffic Jam Pilot” in the Honda Legend in the first half of 2021. Mercedes-Benz developed a level 3, which already is in the certification process through the KBA. Waymo started a level 4 robotaxi in the greater area of Phoenix, Arizona, but it has to be mentioned that e.g. local weather conditions, lower the algorithmic requirements. Many tech companies such as Zoox (amazon), Apple and Baidu already test or develop autonomous vehicle software, but as of today it is unclear which level of autonomy and when the vehicle will be offered to public.

References:

https://www.autonews.com/cars-concepts/audi-quits-bid-give-a8-level-3-autonomy

https://europe.autonews.com/automakers/lexus-prepares-introduce-level-2-autonomy

https://jesmb.de/4449/

https://global.honda/newsroom/news/2020/4201111eng.html

https://www.automobilwoche.de/article/20201009/AGENTURMELDUNGEN/310089895/ohne-sicherheitsfahrer-waymo-oeffnet-robotaxi-dienst-fuer-mehr-nutzer

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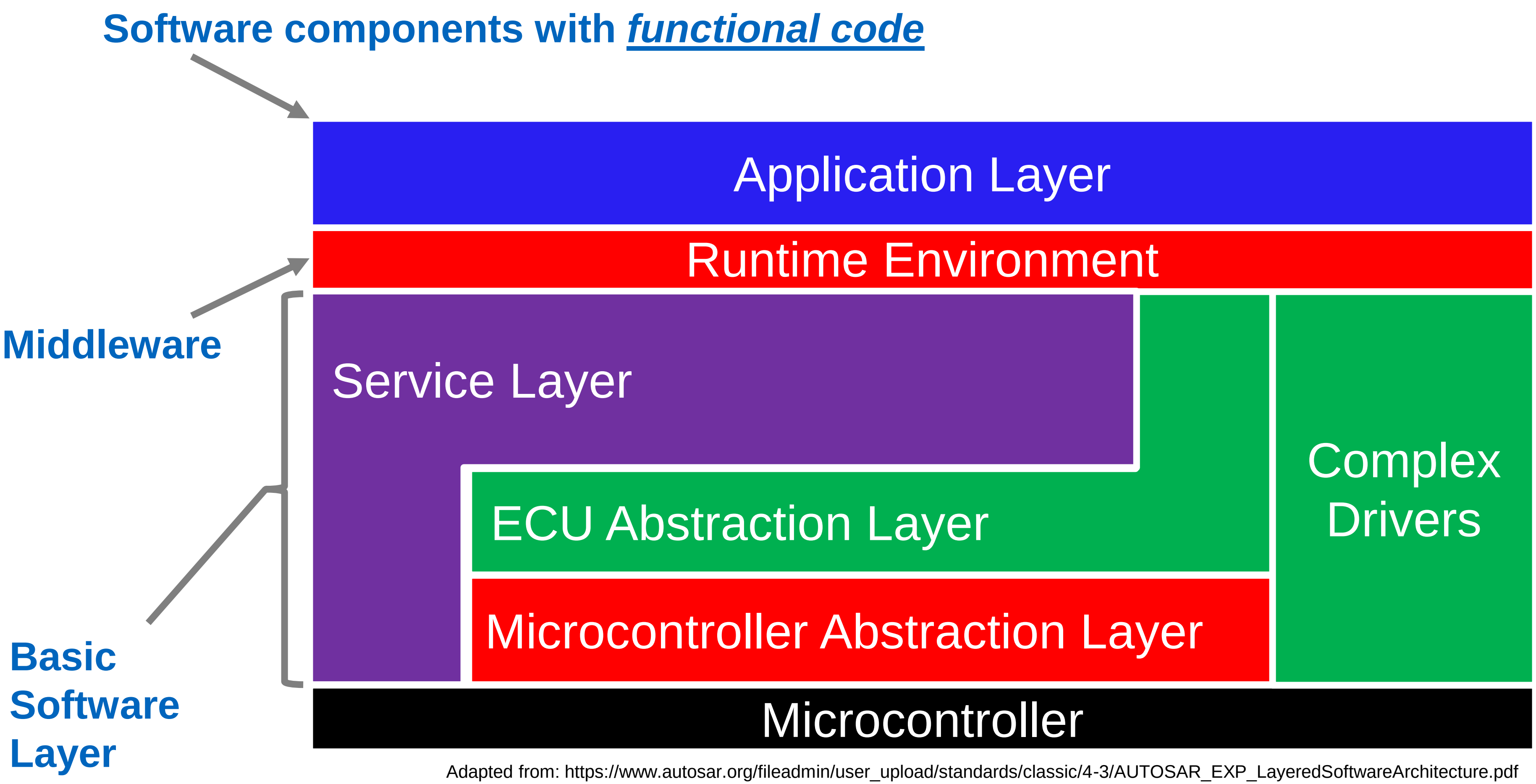
Layered Software Architecture



Adapted from: https://www.autosar.org/fileadmin/user_upload/standards/classic/4-3/AUTOSAR_EXP_LayeredSoftwareArchitecture.pdf

Additional Slides

The AUTOSAR or Automotive Open System Architecture was developed in 2003 to create a common standardized software architecture for designing automotive electronic control units (ECUs). The AUTOSAR architecture is based on a 3-layered architecture model, developed jointly by the stakeholders of the automotive industry including – the automobile manufacturers, the suppliers, and the tool developers.

Basic Software (BSW):

The basic software can be defined as standardized software module offering various services necessary to run the functional part of the upper software layer. This layer consists of the ECU specific modules along with the generic AUTOSAR modules.

Runtime Environment (RTE):
The real-time environment ensures communication between the software components depending on the assignment of the software components to the ECUs. If two software components that communicate with each other are located on one and the same ECU, the RTE establishes the communication link directly between the software components. If the software components are located on different ECUs, the connection to the other software component is established via the basic software and the vehicle bus. So, the RTE layer manages the inter- and intra-ECU communication between application layer components as well as between the Basic Software and the application layer. So, the RTE acts as a middleware between the AUTOSAR application layer and the lower layers by managing the inter- and intra-ECU communication between application layer components as well as between the Basic Software and the application layer.

Application Layer:
In this layer are the software components with their functional code. The development of the functional code takes place here independently of the vehicle bus and the hardware used. An exception build the software components for sensors and actuators, which depend of the sensor and actuator concept.

In this lecture we are located on the application layer

Perception

X = Lectures

Perception I: Mapping & Localization

Methods of State Estimation

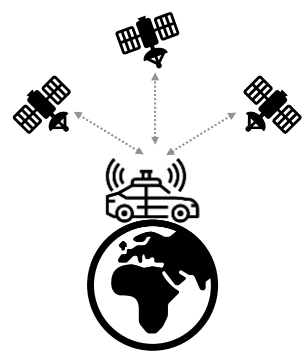
An overview of different filter methods and the application for tracking is given.

Sensor fusion for mapping

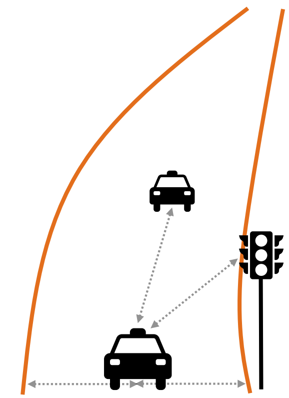
By means of multiplication and addition of distribution probabilities, inputs from multiple sensors can be fused.

Map representations

Depending on the target algorithm, different map representations are preferable.



Global Position



Relative Position

IMU
Wheel Encoders

→ **Vehicle Ego State**

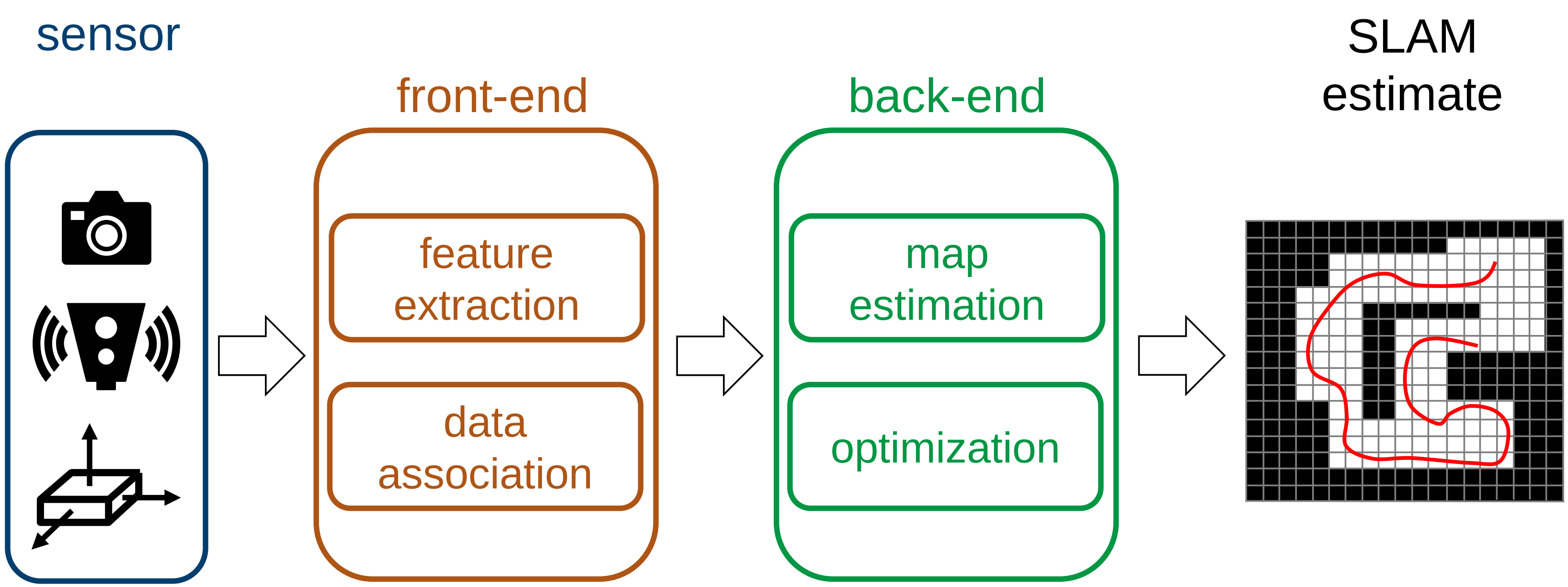
Camera
LiDAR
Radar
GPS (distance to satellites)

→ **Perceive Environment**

Perception II: Mapping & Localization

SLAM

Simultaneous Localization and Mapping is the central concept to solve the dual problem of ego-localization and map generation. The most common SLAM algorithms build upon a Kalman Filter, a Particle Filter and a graph-based approach.

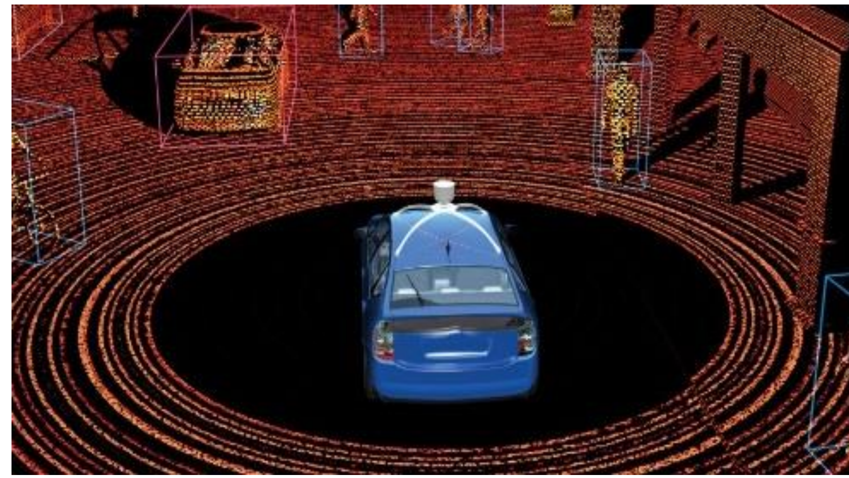


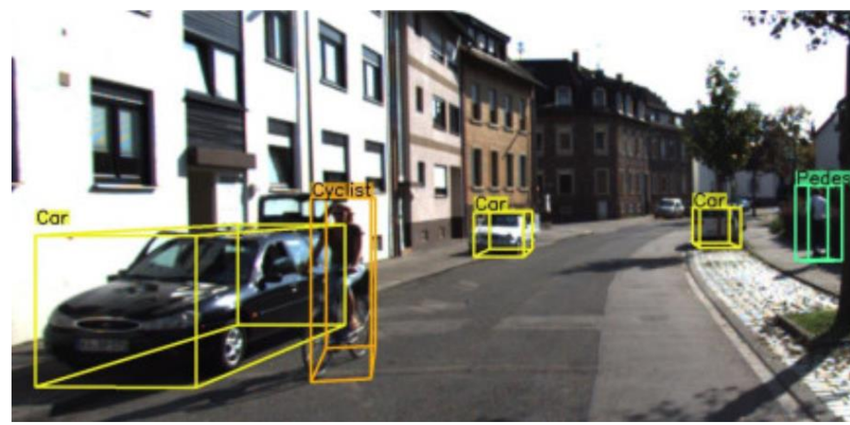
Perception III: Detection

Detection tasks
Based on environmental sensors the three main tasks are road, traffic light and sign and object detection.

Sensor-dependent algorithms
The state of the art of algorithms for camera, LiDAR, and RADAR detection are presented, all of which are based on deep learning algorithms.

Sensor fusion
Methods to fuse multiple sensor to enhance the overall detection performance are presented.





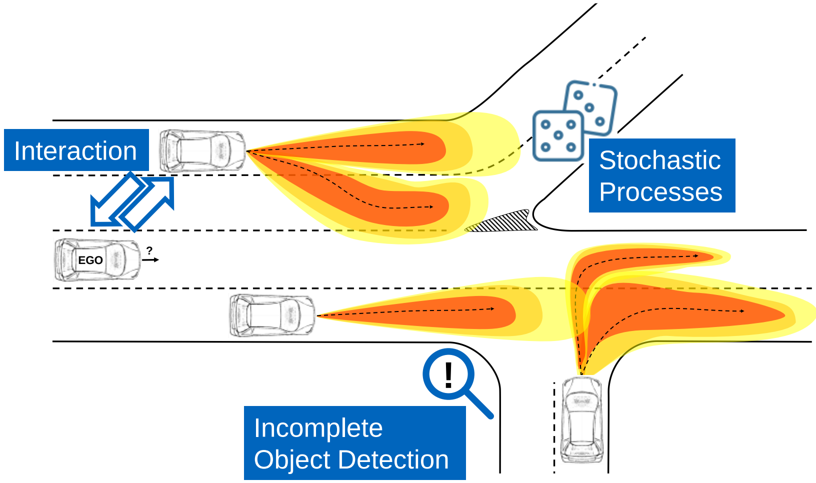
Lecture Overview

X = Lectures

Prediction

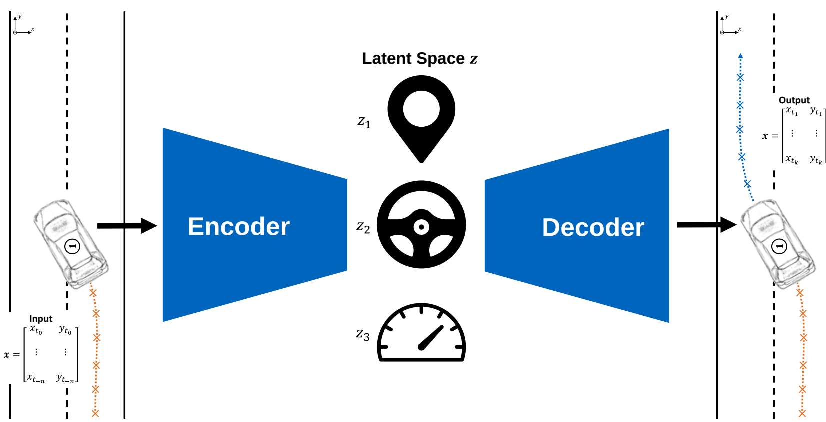
Intention estimation

Motion prediction estimates the intention and future positions of dynamic objects and quantifies the associated uncertainty.

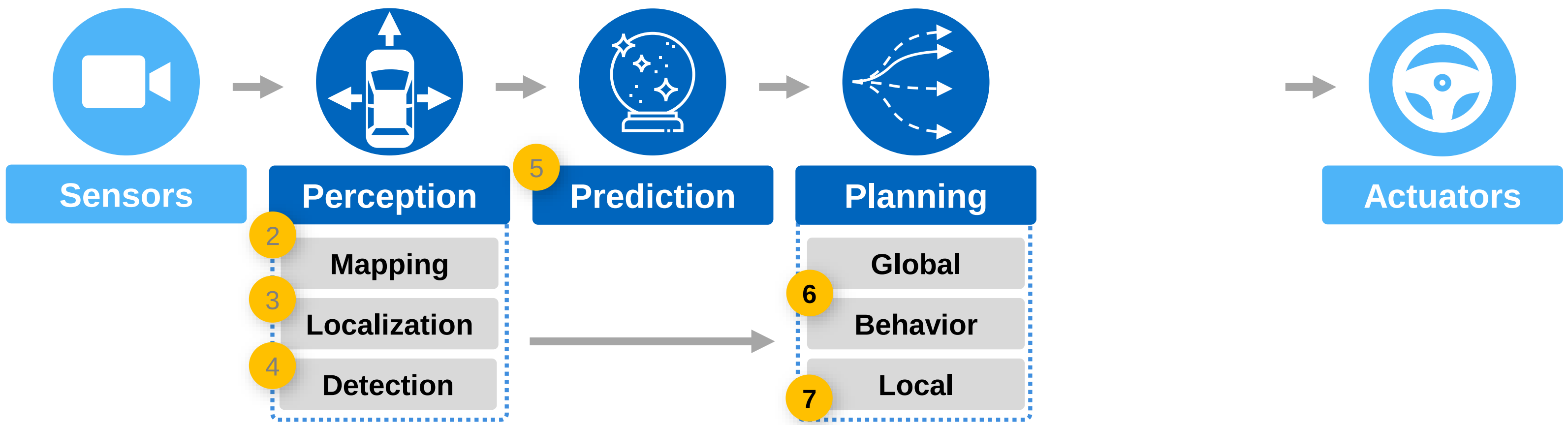


Prediction methods

Prediction algorithms can be divided into physics-based, pattern-based and planning-based approaches. The focus of the lecture lies on the Encoder-decoder architecture, which is a pattern-based method.



Lecture Overview



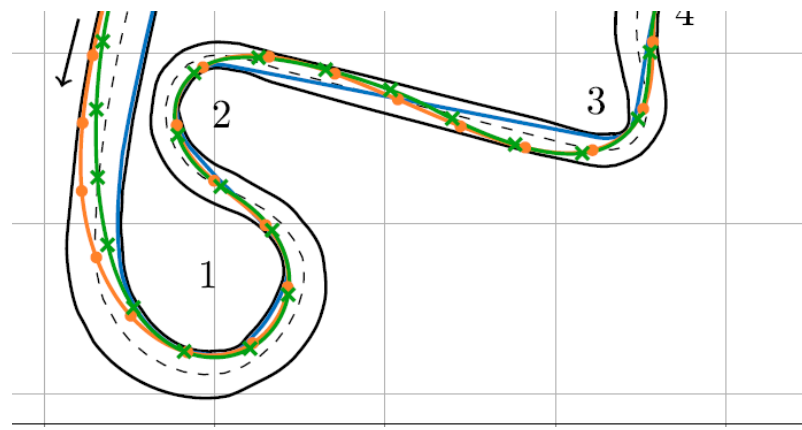
X = Lectures

Planning I: Global Planning

Navigation Task
In hierarchical planning approaches, global planning contains the navigation task, i.e. the route to go from A to B.

Behavioral Planning
The idea of a state machine to switch between discrete behavior models enables situation-dependent planning.

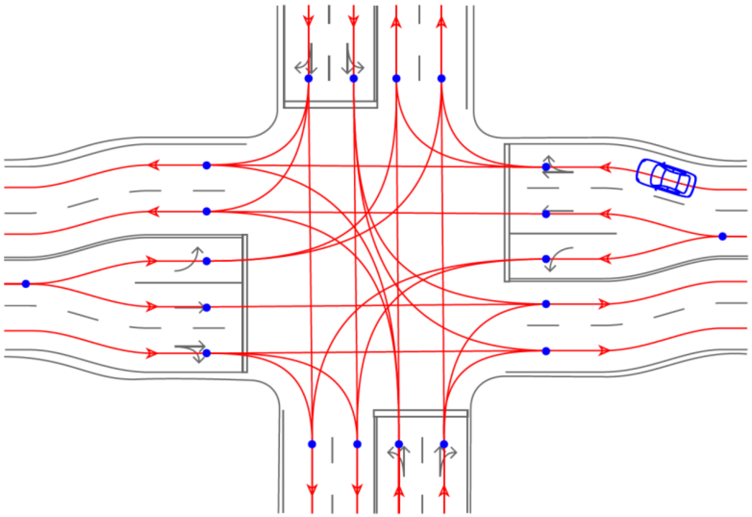
Excursus: Global optimal race line
For Grand Prix racing, a global optimal race line can be calculated with different optimization criteria.



Planning II: Local Planning

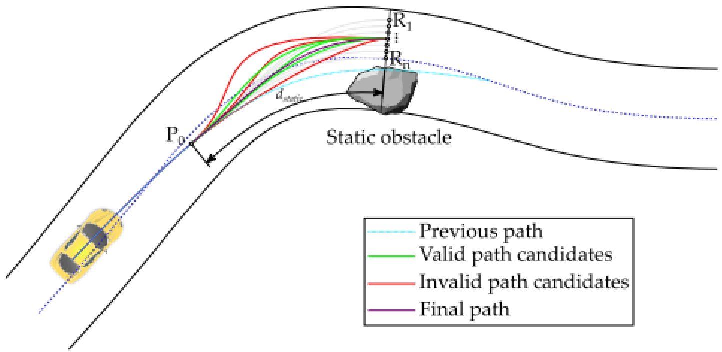
Sensor-based planning

With the input of the global route, the local planning module determines a kinematically feasible, collision-free trajectory.

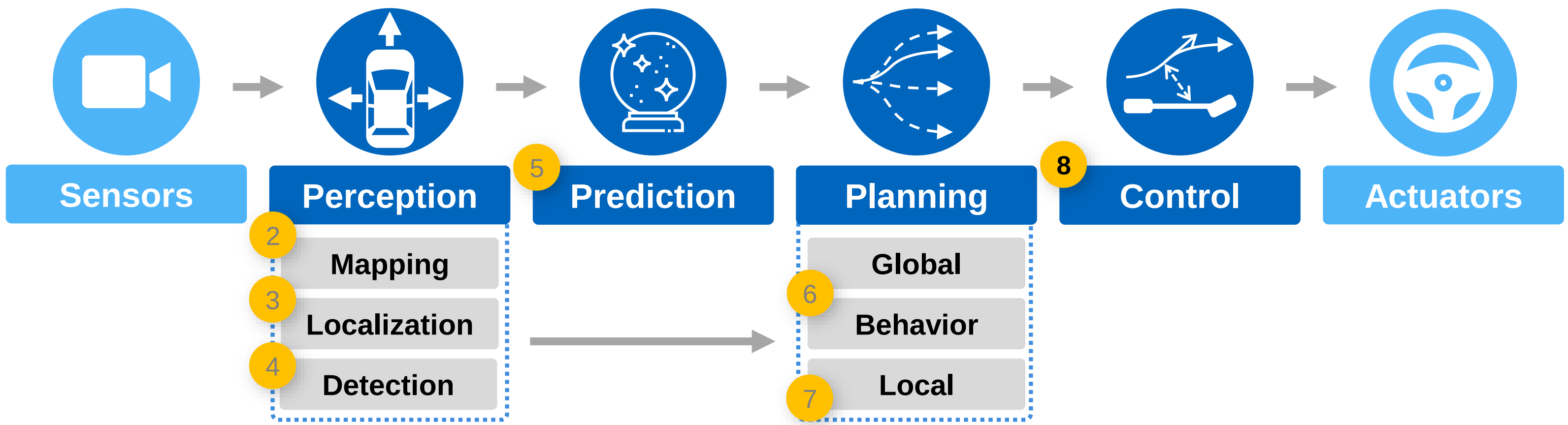


Methods for local planning

The state of the art offers the three categories of variational, incremental and graph-based methods, which are introduced in this lecture.



Lecture Overview



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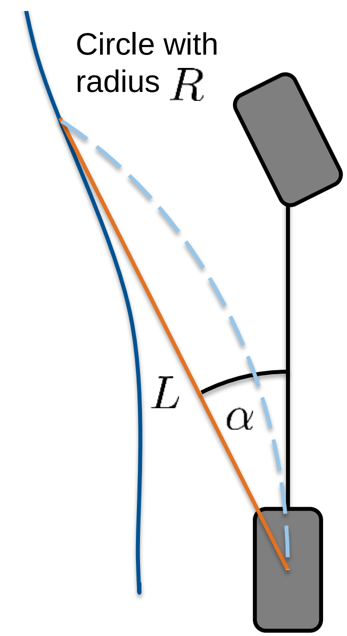
Motion Control

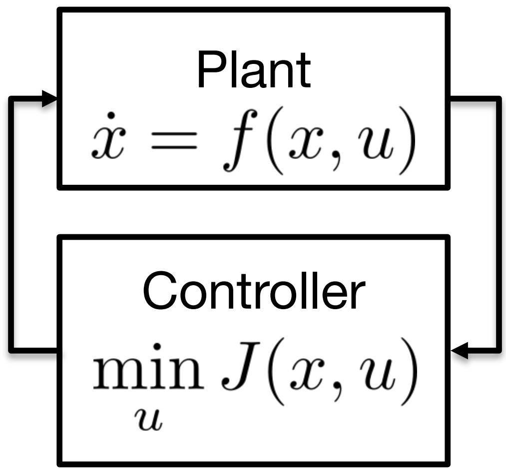
Control Task

Based on a planned trajectory the motion control module determines the required command signals to process this trajectory into vehicle motion and to handle external disturbances.

Methods for motion control

Model-free control methods (PID, geometric) and model-based methods (state-space control, model predictive control) are the most common types of motion controller for road traffic and racing.





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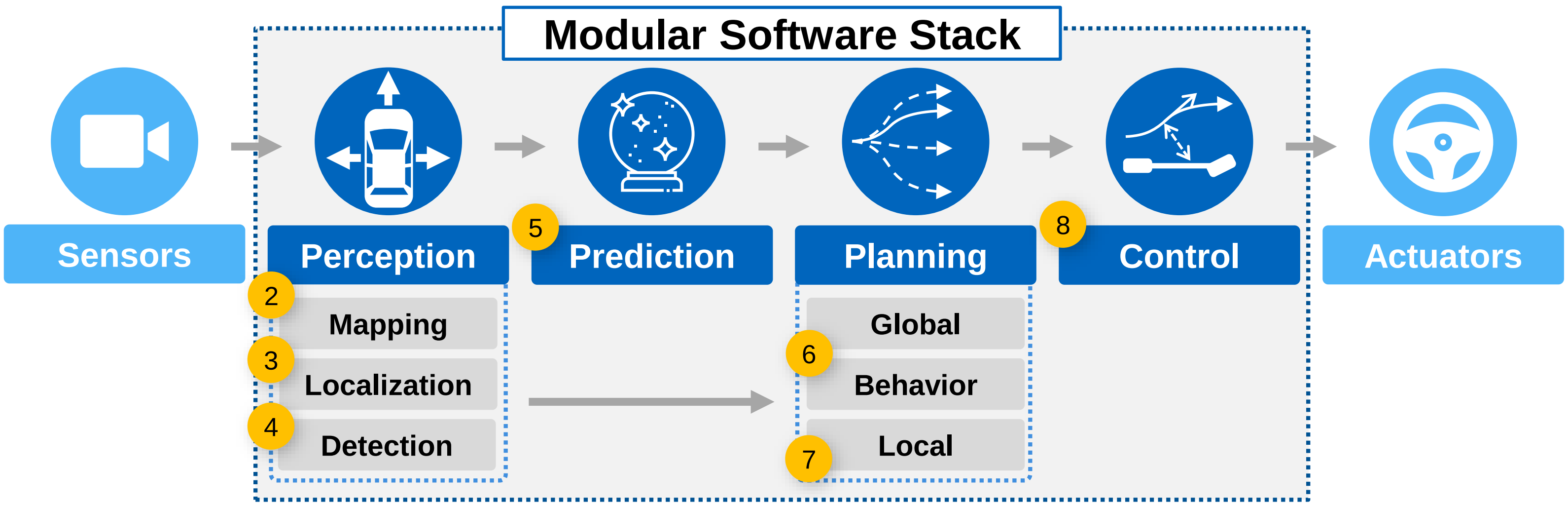

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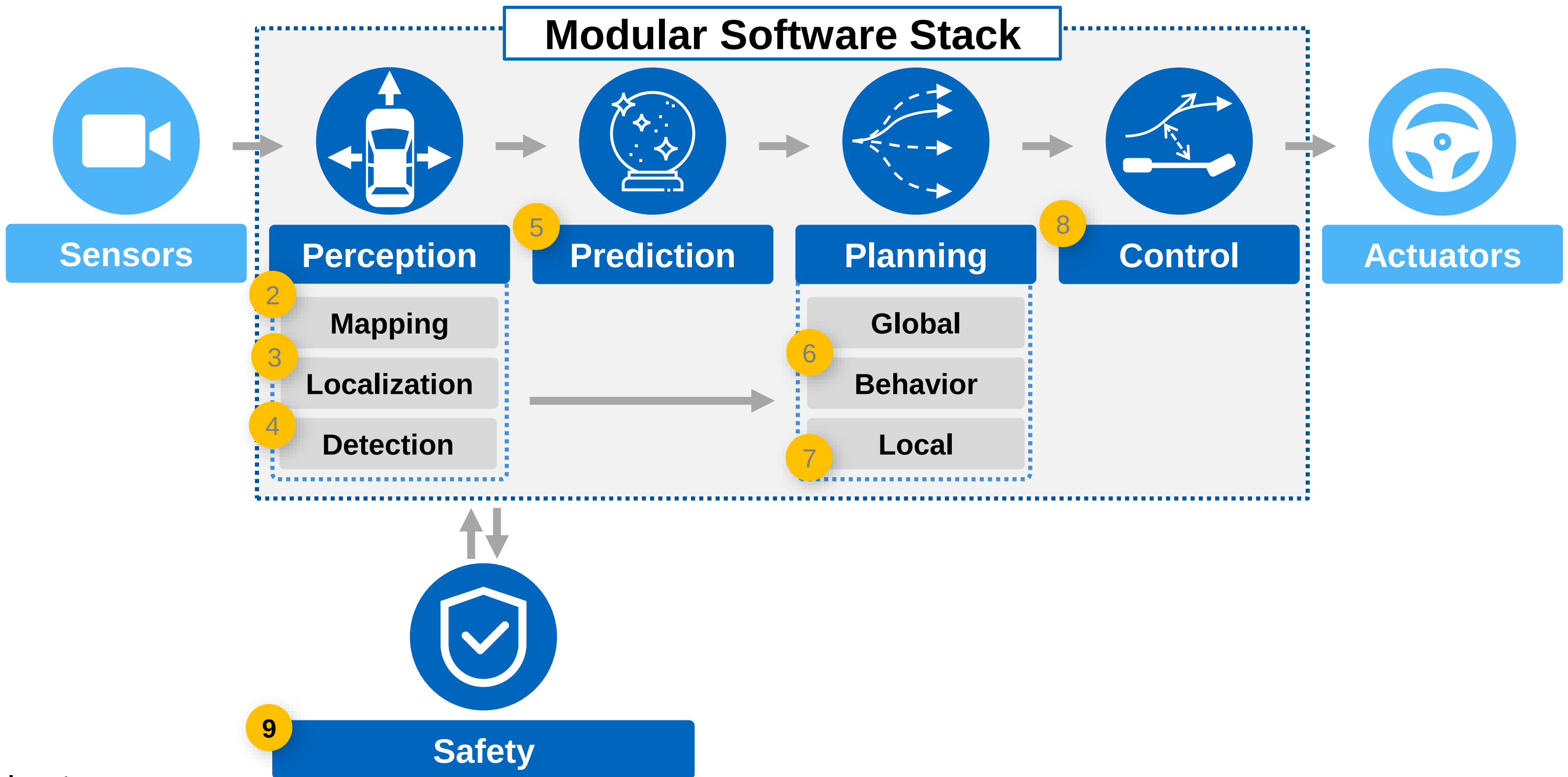
Lecture Overview



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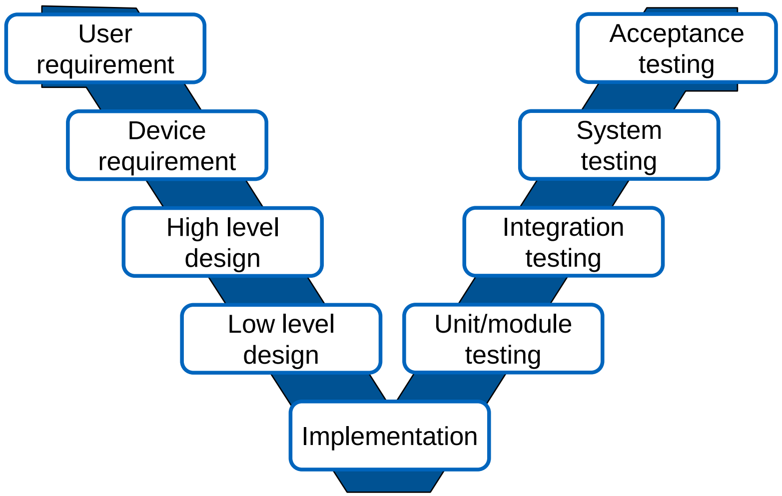
Safety Assessment

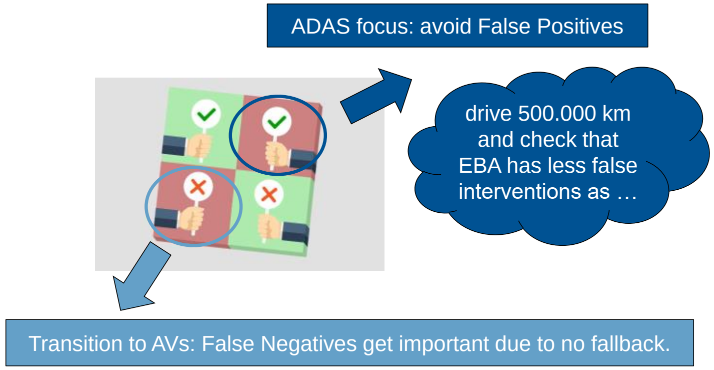


Automotive safety and security

The three main types of safety and security in the automotive domain and their respective standards are introduced: Functional safety, safety of the intended functionality, cybersecurity.

Safeguarding approaches

Real-world testing, scenario-based testing and stepwise introduction are some of the most promising approaches targeting the safeguarding and approval challenge.



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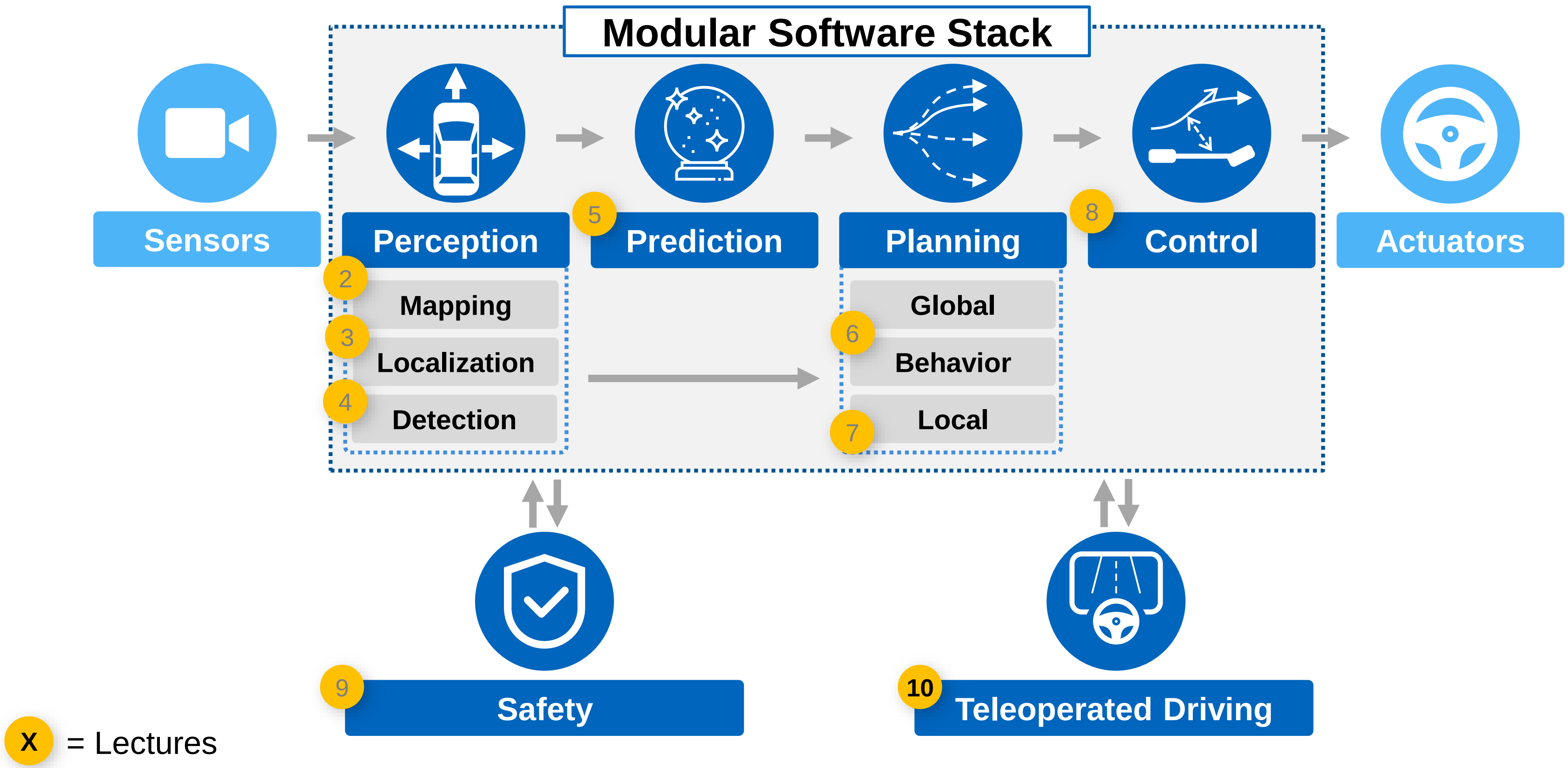


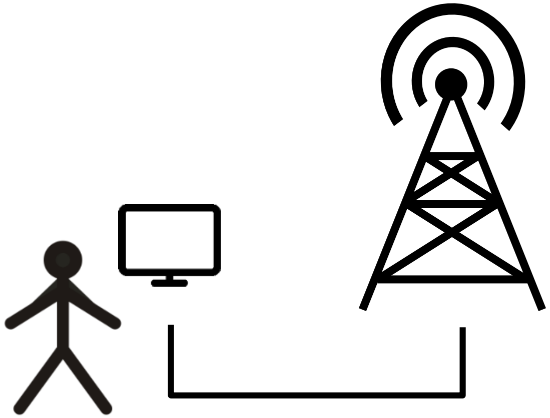
Teleoperated Driving

Remote Control

Remote control of the automated vehicle in traffic situation, which are too complex or lie outside the operation design domain (ODD), is the task of Teleoperated Driving.

Sensor and Actuator Latency

While the latency mainly influences the controllability and safety of the vehicle, the upload-bandwidth affects the amount of transmit-table sensor data. Hence, the network is a central aspect for this task.



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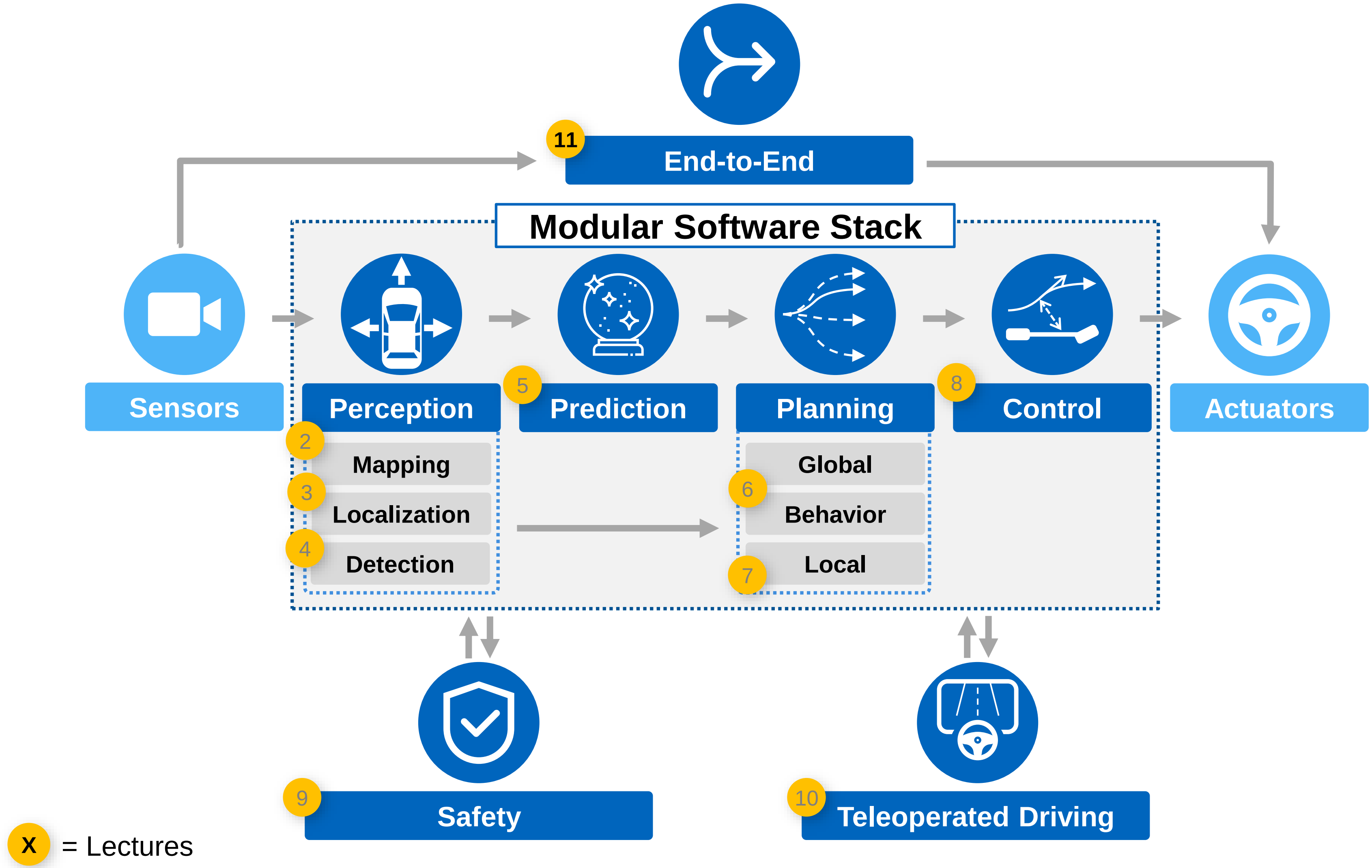
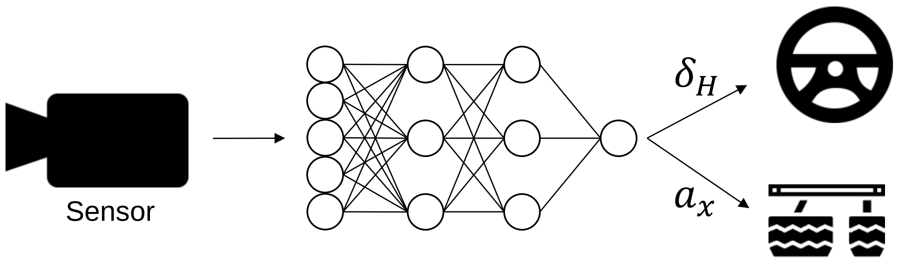


End-to-End (E2E) and Combined Modules

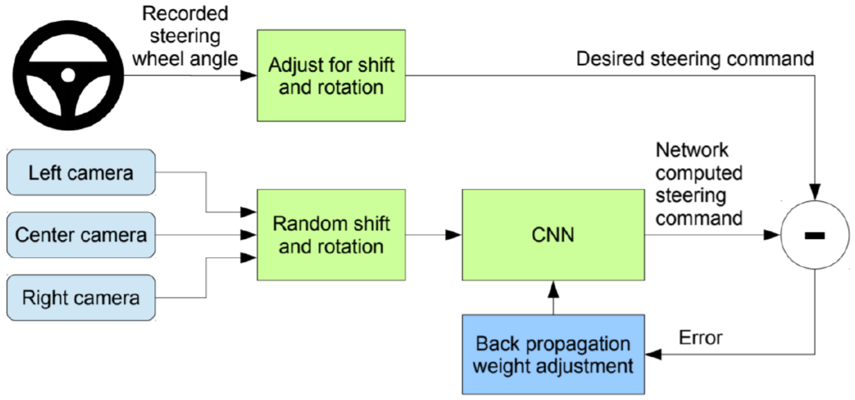
Integral Software Approach

In contrast to the modular approach, E2E aims to combine multiple modules with mapping raw sensor data to steering wheel commands as the highest abstraction level.

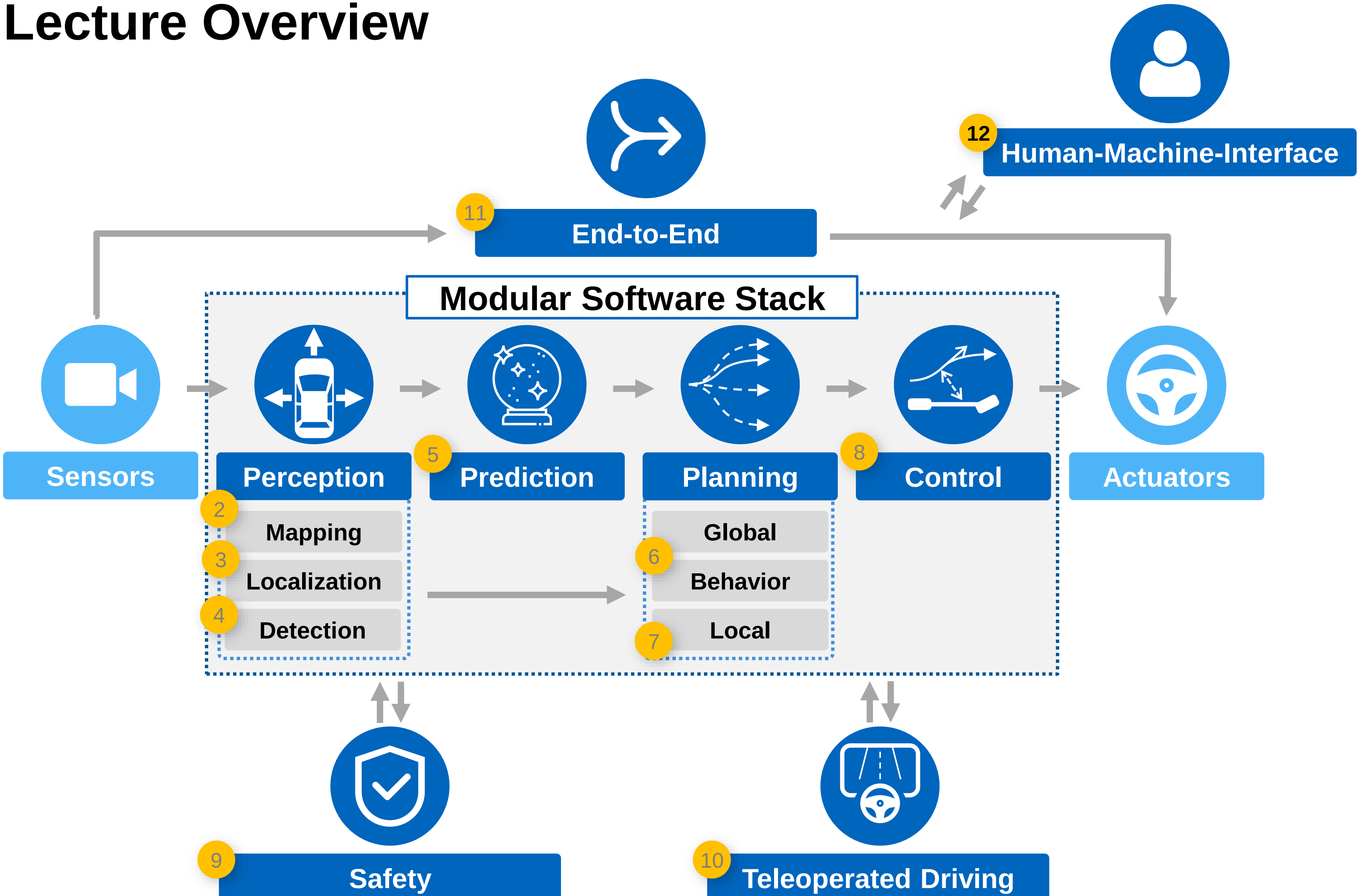


Imitational Learning

Behavior Cloning and (inverse) reinforcement learning are methods to realize integral software approaches.



Lecture Overview



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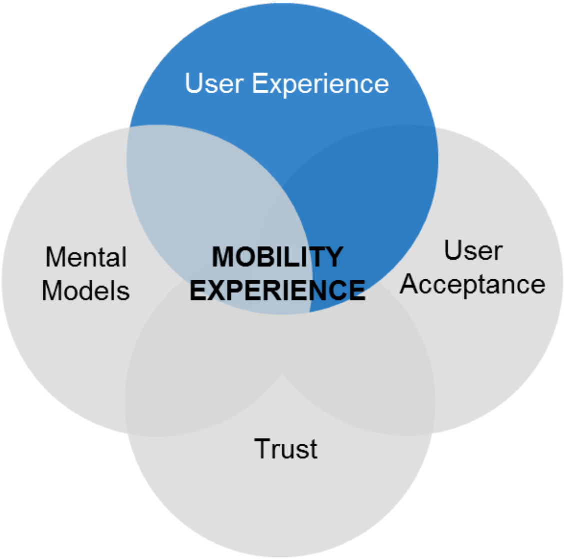
From Driver to Passenger



Human Factors

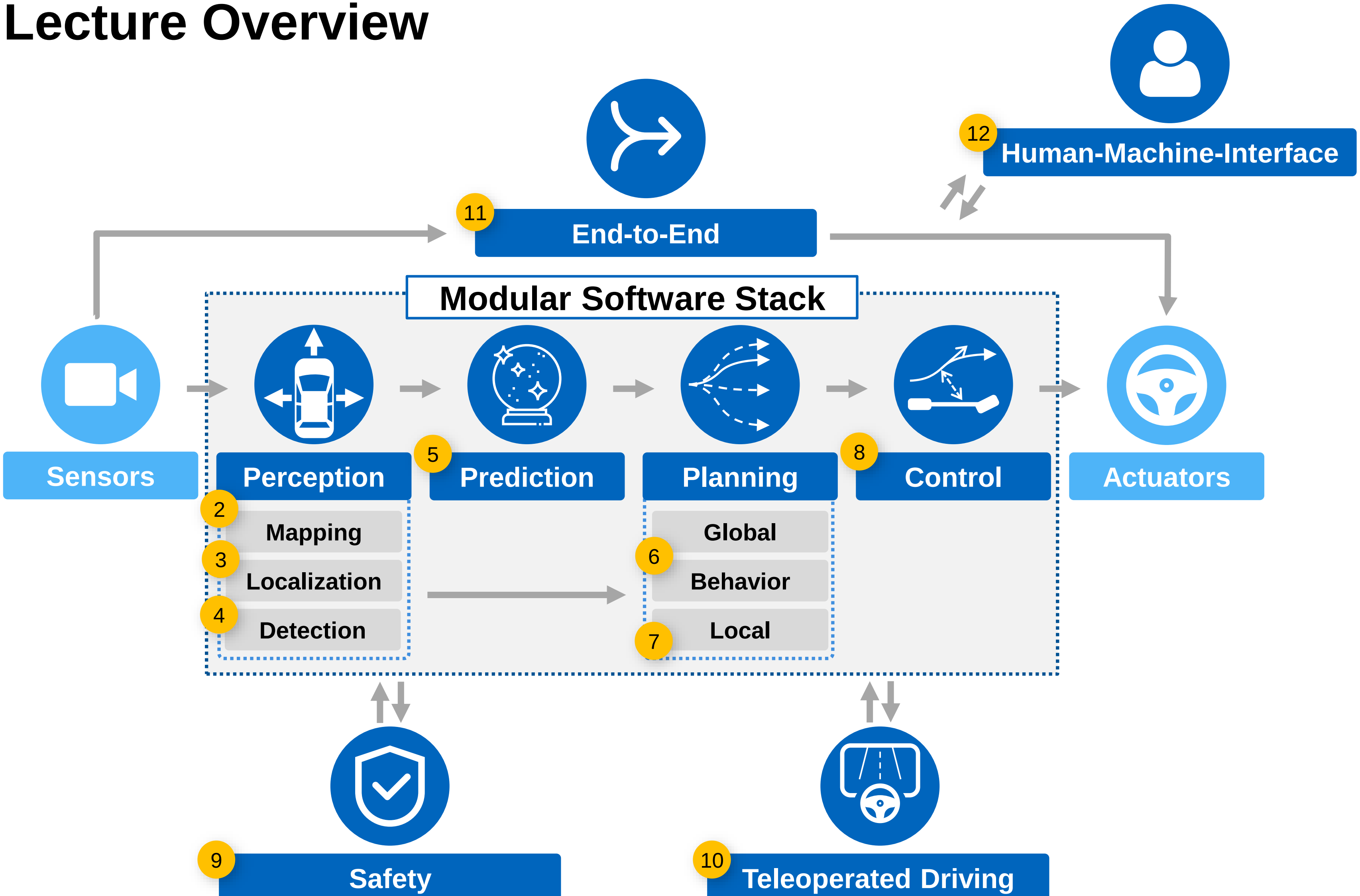
The shift from driver to passenger requires a re-definition of HMI[1] within as well as between vehicle and environment to ensure safety, comfort and confidence during autonomous rides.

Customer Needs

New costumer needs occur, which are a crucial aspect to reach the acceptance for the new technology on the consumer market.

[1] Human-Machine-Interface

Lecture Overview



X = Lectures

Introduction
Prof. Dr. Markus Lienkamp / Prof. Dr. Boris Lohmann

Phillip Karle, M. Sc.

Agenda

1. Autonomous Driving – A Megatrend
2. Milestones of Autonomous Driving
3. Lecture Overview
4. **Basics of Sensors and Actuators**
5. Challenges of Autonomous Driving
6. Summary

Sensor Types

Vehicle status sensor

- Measurement of components‘ states for safe operation
- Examples: Tire pressure sensors, temperature sensors

https://www.bosch-mobility-solutions.com/en/

Sensor Types

Vehicle status sensor

- Measurement of components‘ states for safe operation
- Examples: Tire pressure sensors, temperature sensors

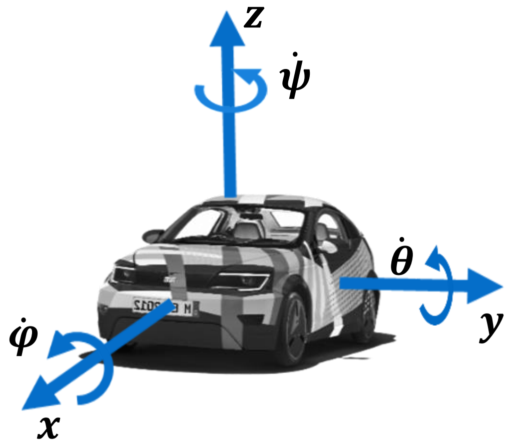
Vehicle dynamic sensors

- Measurement of dynamic vehicle state (position, speed, yaw rate)

https://www.bosch-mobility-solutions.com/en/
https://www.car-bock.de/ABS-sensor-FA-VW-Golf4-left
https://vrtracker.xyz/handling-imu-drift/

Inertial Measurement Unit (IMU)

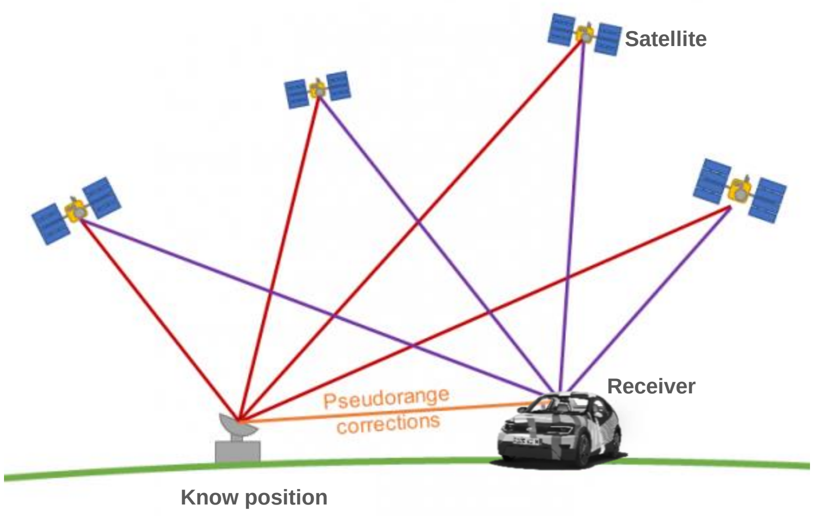
- 6 Degree of Freedom (DOF)
- 3-axis linear accelerometer (x, y, z)
  - Measurement based on capacitive change of micromechanical structures due to mechanical forces ($F = m\,a$)
- 3-axis rate gyroscope (φ, θ, ψ)
  - Measurement based on Coriolis principle: inertia force of oscillations in a rotating system
- High accuracy and high sampling rate
- “Sensor Drift”: Accumulating position error



https://www.bosch-mobility-solutions.com/

Global Navigation Satellite System (GNSS)

- Networks: GPS, GLONASS, Galileo
- GNSS receivers work by receiving signals sent from satellites in orbit
- Time-of-Flight to calculate distance
- Relative position to three satellites (atomic clock) by trilateration
- Additional satellites to improve accuracy
- Differential GPS:
  - Additional geo-referenced signals
  - Correction of time-of-flight position calculation



Sensor Types

Vehicle status sensor

- Measurement of components‘ states for safe operation
- Examples: Tire pressure sensors, temperature sensors

Vehicle dynamic sensors

- Measurement of dynamic vehicle state

Perception sensors

- Detection of semantic information for ADAS[1] and autonomous driving

[1] Advanced Driver Assistance Systems

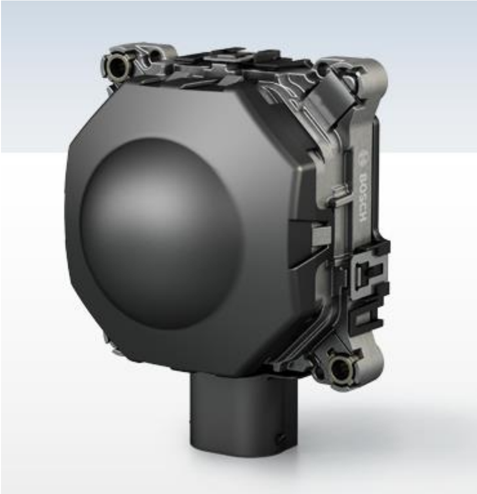
https://www.japanautomotivedaily.com/2017/05/25/ricoh-denso-develop-worlds-smallest-adas-stereo-camera/
https://velodynelidar.com/products/ultra-puck/
https://www.continental-automotive.com/en-gl/Passenger-Cars/Autonomous-Mobility/Enablers/Radars

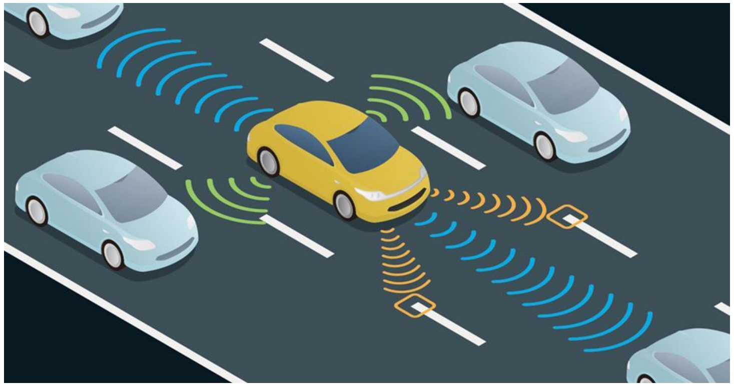
Radar

- Acronym for „Radio Detection and Ranging“
- Radar sensors send out radio waves that detect objects and gauge their distance and speed in relation to the vehicle in real time:
  - Distance: Time-of-flight
  - Speed: Doppler effect
- Types
  - short-range: blind spot monitoring
  - long-range: distance control

\+ High robustness (weather)

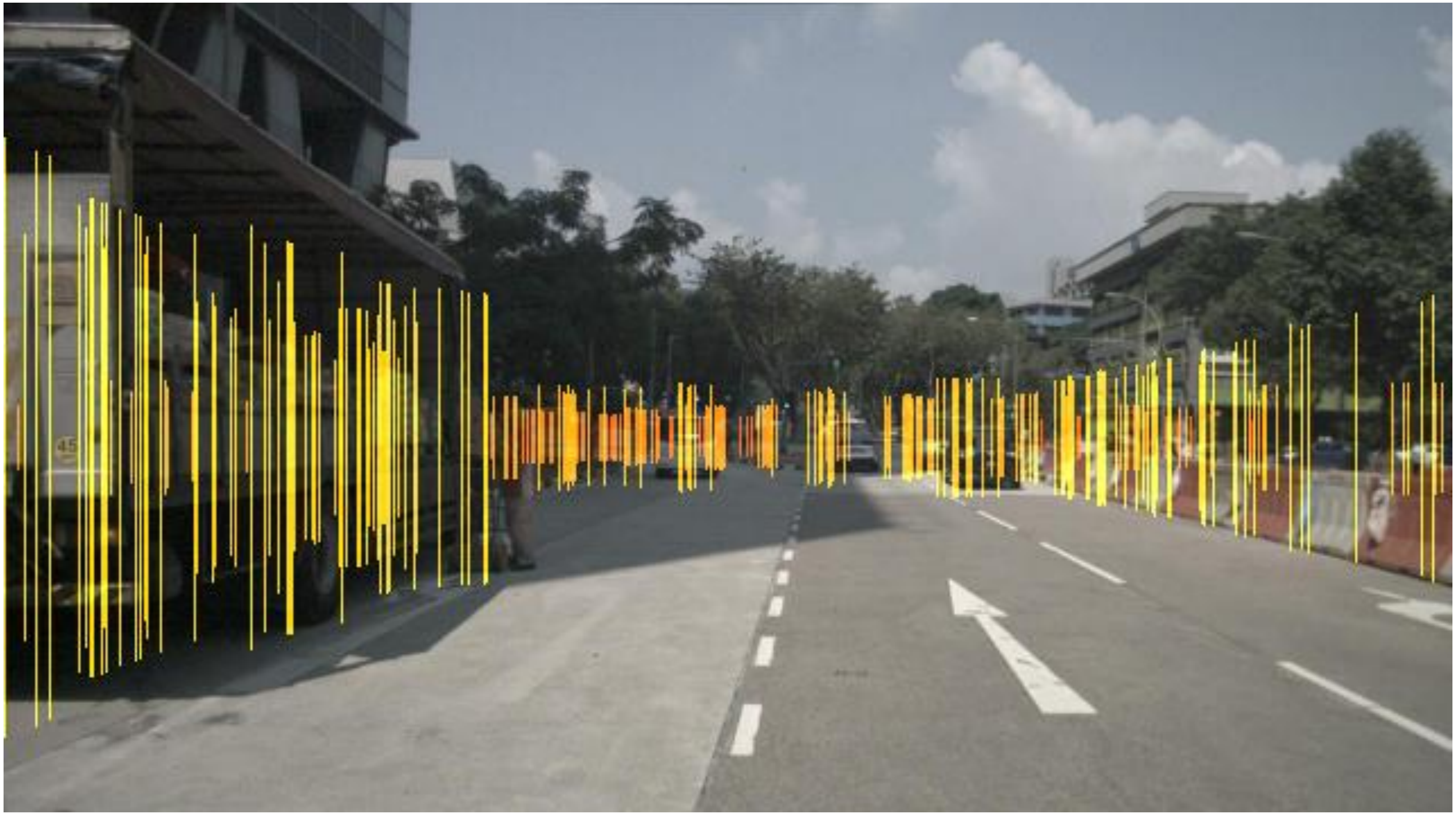
\- No vertical resolution nor 3D image





https://www.bosch-mobility-solutions.com/en/products-and-services/passenger-cars-and-light-commercial-vehicles/driver-assistance-systems/automatic-emergency-braking/long-range-radar-sensor/
https://industrytechnologyreports.home.blog/2020/02/14/automotive-radar-market-2/

Radar – Environment Representation



Nobis, Geisslinger, et al. - Deep Learning-based Radar and Camera Sensor Fusion Architecture for Object Detection, 2019

Additional Slides

Radar - Specifications

- short-range (24 GHz): blind spot monitoring
- long-range (77 GHz): distance control
- Distance measurement: 0,5 – 250 m
- Field of view:
  - Horizontal: 20° for Long-Range (<250m) and 60° - 120° for Mid-Range (<60m)
  - Vertical: No vertical resolution
- Resolution:
  - Distance: ~ 0.3m
  - Relative velocity: ~ 0.1 m/s
  - Azimuth angle: ~ 1°

Benefits

High robustness against weather (rain) and ambient light

Accurate measurement of distance and velocity (Direct speed measurement)

Cheap

Most used sensor for detection today (ACC, Collision avoidance system)

Drawbacks

No measurement of lateral velocity nor object size or type

Low resolution

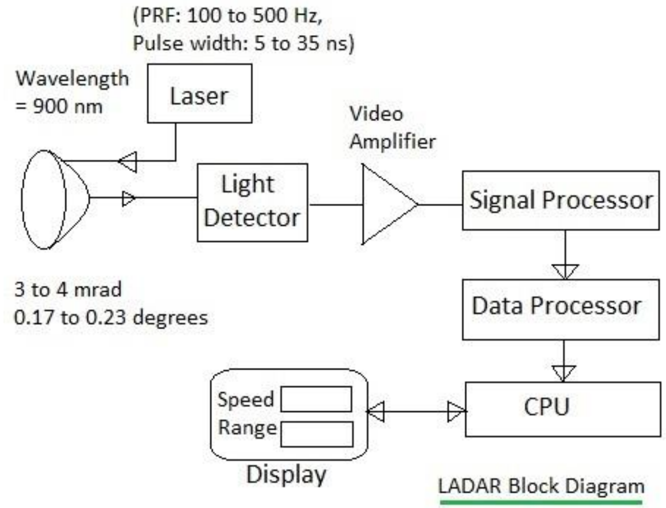
Only for moving objects

No contrast/color

LiDAR

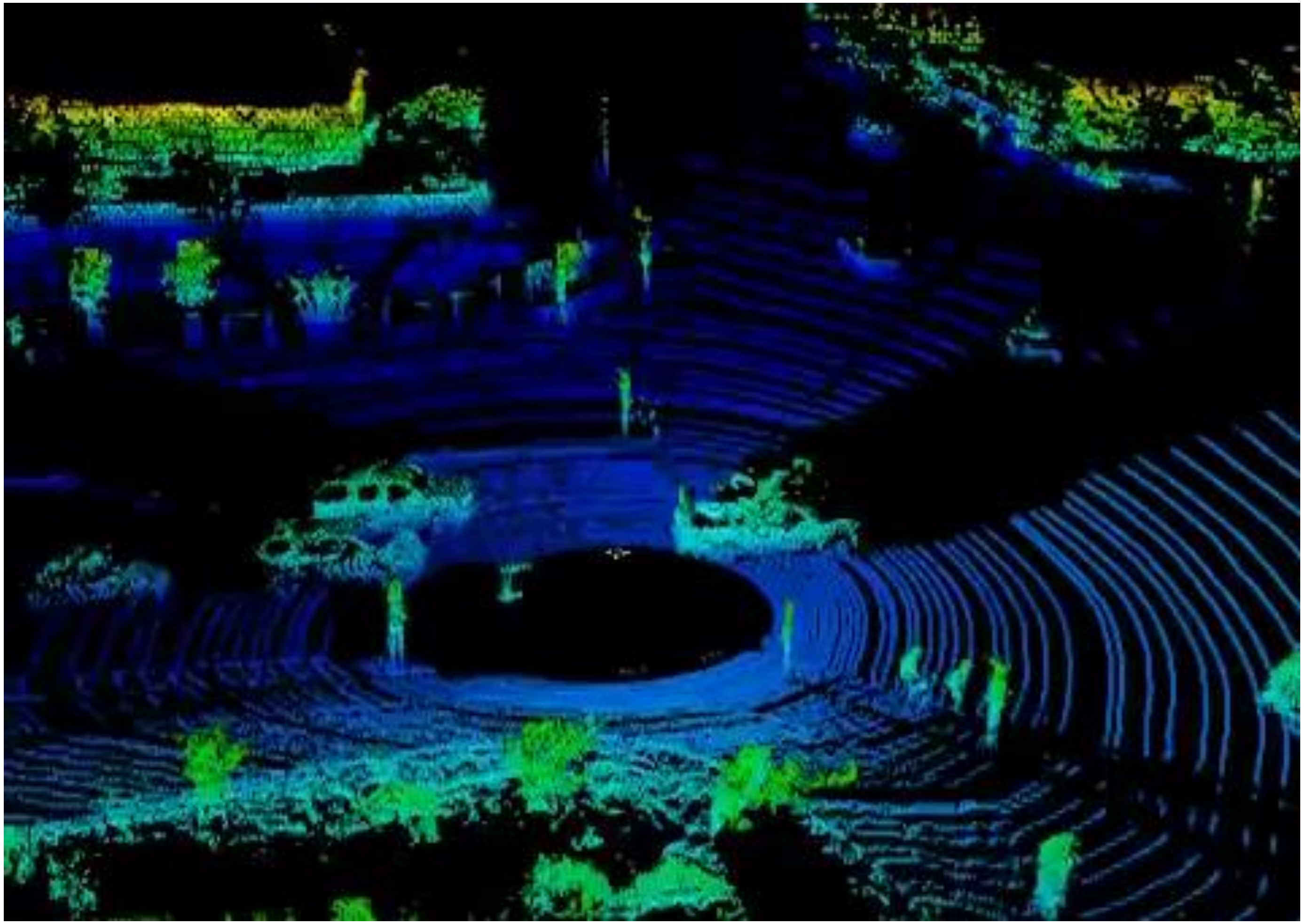
- Acronym for „light detection and ranging“
- Similar to radar systems, with the difference being that they use infrared light instead of radio waves.
  - Distance: Time-of-flight of narrow light pulse echoes.
  - Speed: Difference between pulses for speed estimation

+ 3D image generation of environment
- High costs



https://www.rfwireless-world.com/Terminology/Advantages-and-Disadvantages-of-LiDAR.html
https://www.nhregister.com/technology/businessinsider/article/Lyft-wants-to-bring-self-driving-cars-to-Boston-11199145.php

LiDAR – Visualization



Velodyne HDL-64E. 120m range. 360° Horizontal FOV,
27° Vertical FOV, 0.1° angular resolution
https://velodynelidar.com/products/hdl-64e/

Additional Slides

LiDAR - Specifications

- Distance measurement: 1 – 200 m (Short Range: <30m)
- Field of view:
  - Horizontal: 30° for Long-Range and up to 360° for Short-Range
  - Vertical: 30°
- Resolution:
  - Distance: ~ 0.02 m
  - Relative velocity (via tracking): ~ 0.3 m/s
  - Horizontal angle: ~ 0.1°
  - Vertical angle: ~ 0.8°

Benefits

Measurement objects size (width, height) and lateral velocity

3D image generation of detected objects and mapping the surroundings

Accurate depth information

Higher resolution than radar

Drawbacks

Struggles in detection of black vehicle

High costs

High data rate

No contrast/color information

Weak performance in rain

Further Information: Comparison of LiDAR vs Radar

https://archer-soft.com/blog/lidar-vs-radar-pros-and-cons-autonomous-driving

Camera

- Idea: see and interpret the objects in the road just like human drivers do with their eyes.
  → traffic is based on visual input
- Mono-, Stereo-, Fisheye-camera
- No direct measurement of position and velocity
  → Algorithms for 4D-motion streams & stereo cameras required

\+ 3D Detection of various features: object types, road lanes, traffic signs etc.

\- Conditions of illumination

https://www.continental-automotive.com/de-DE/Passenger-Cars/Autonomous-Mobility/Enablers/Cameras/Stereo-Camera

Camera – Depth estimation

A stereo depth map encodes the actual depth of every pixel. Red represents points that are close and green denotes those that are far away. Only a few pixels (e.g. at the left image border or at left edges of objects) are without a depth measurement. Typically, this is due to left-to-right occlusion or failed depth consistency checks.

Camera – Object Detection

Google's TensorFlow implementation of Faster RCNN.
Modified from: https://github.com/CharlesShang/TFFRCNN
https://www.youtube.com/watch?v=PgnsapPGaaw

Additional Slides

Camera - Specifications

- Distance measurement: 1 – 200 m (Short Range: <30m)
- Field of view:

  Horizontal: 30° - 45°, Fish-eye: 360°
- Resolution:
  - No direct measurement, Depends on image resolution and algorithm

Benefits

Imitation of human perception of road traffic, road traffic relies on visual perception

Detection of road lanes, traffic sign and object classification possible (Roads are designed for human eyes)

Price: mass product from consumer electronics

High resolution

Small (Package)

Drawbacks

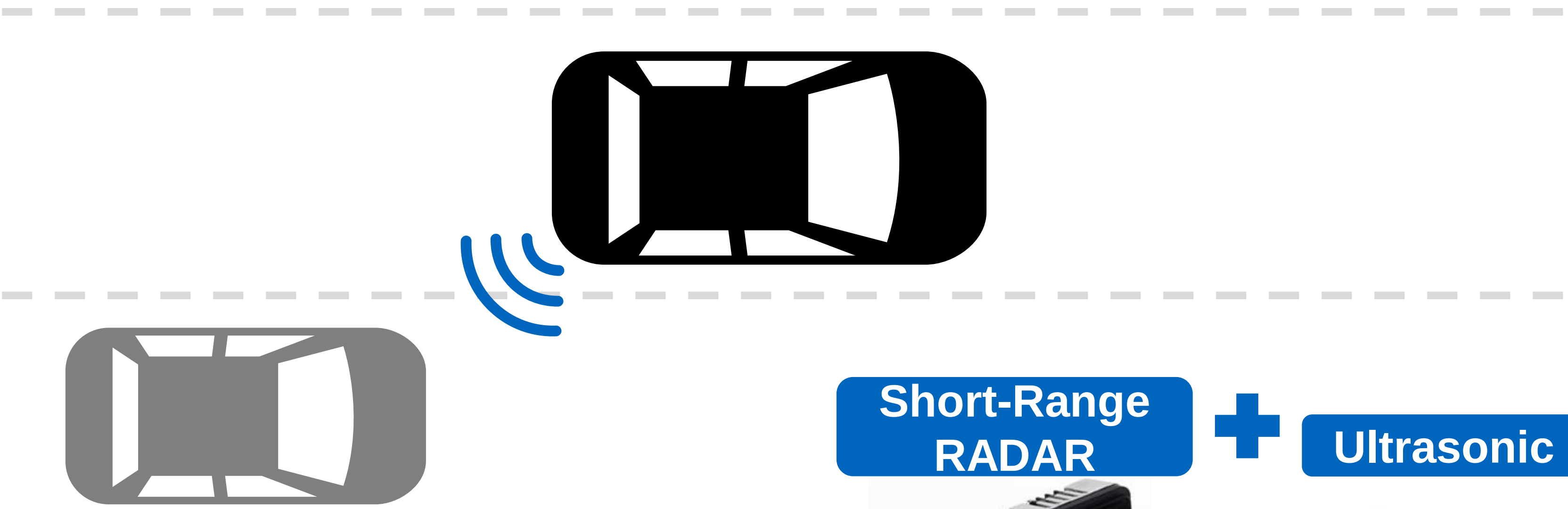
No direct measurement of position and velocity

Data processing of images is complex → .. But major improvements through Deep Neural Networks

Comparison

	RADAR	LiDAR	Camera
Range	++	o	+
Resolution	-	+	++
Field of view	-	++	+
Velocity	++	o	-
3D-Perception	-	++	o
Object features	-	o	++
Robustness (weather)	++	o	-
Cost	+	--	++
Package	+	--	+

Level 0 – Blind Spot Warning



Short-Range RADAR + **Ultrasonic**

Additional Slides

Blind Spot Warning:

Two ultrasonic sensors on each side of the vehicle serve as electronic eyes and monitor the space in the adjacent lane, allowing the system to cover the dangerous blind spot. If another vehicle is situated in the monitored area, the driver is alerted to the potential danger by means of a warning sign in the side mirror. If the driver fails to spot or ignores this warning and activates the turn signal to change lanes, the system can also trigger an audible warning. The system recognizes stationary objects on or alongside the road, such as guardrails, masts or parked vehicles, as well as the driver's own overtaking maneuvers – and does not trigger the warning in this case.

Reference:

https://www.bosch-mobility-solutions.com/en/products-and-services/passenger-cars-and-light-commercial-vehicles/driver-assistance-systems/blind-spot-detection/

Level 1 – Adaptive Cruise Control (ACC)

Long-Range RADAR + **Ultrasonic**

Additional Slides

ACC:

A radar sensor is usually at the core of the adaptive cruise control (ACC). Installed at the front of the vehicle, the system permanently monitors the road ahead. As long as the road ahead is clear, ACC maintains the speed set by the driver. If the system spots a slower vehicle within its detection range, it gently reduces speed by releasing the accelerator or actively engaging the brake control system. If the vehicle ahead speeds up or changes lanes, the ACC automatically accelerates to the driver’s desired speed.

Standard ACC can be activated from speeds of around 30 km/h (20 mph) upwards and supports the driver, primarily on cross-country journeys or on freeways. The ACC stop & go variant is also active at speeds below 30 km/h (20 mph). It can maintain the set distance to the preceding vehicle even at very low speeds and can decelerate to a complete standstill. If the vehicle has automatic transmission, and the traffic hold-up is only brief, ACC stop & go can set the vehicle in motion once again. When the vehicle remains stopped longer, the driver needs only to reactivate the system, for example by briefly stepping on the gas pedal to return to ACC mode. In this way, ACC stop & go supports the driver even in heavy traffic and traffic jams.

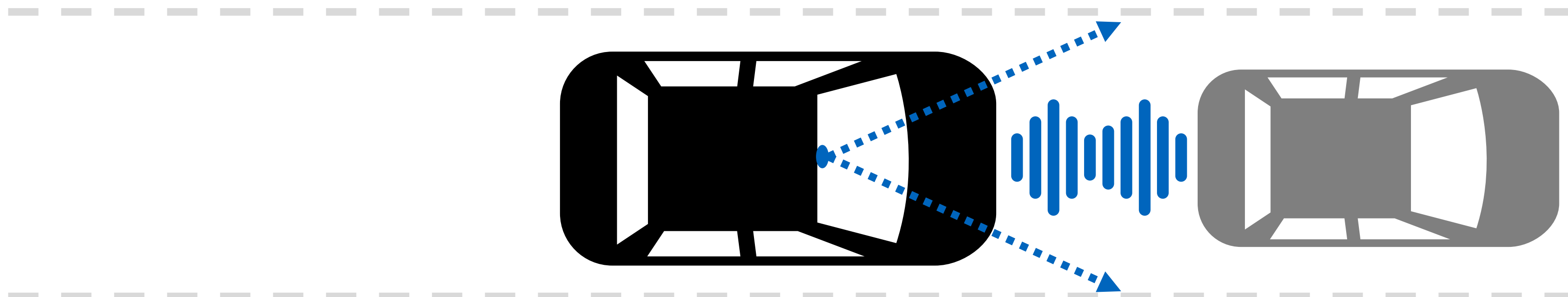
Since ACC is a comfort and convenience system, brake interventions and vehicle acceleration only take place within defined limits. Even with ACC switched on, it remains the driver’s responsibility to monitor the speed and distance from the vehicle in front.

To increase comfort and safety of this function, a multi purpose camera can be installed in addition to the radar sensor. By this, for instance, ACC can, thanks to the lateral measuring accuracy of the multi purpose camera, detect a vehicle entering the driver’s own lane – either planned or unplanned – much earlier, enabling the system to respond more dynamically. For a better and more robust understanding of the scene, data of the radar sensor and the camera can be merged.

Reference:

https://www.bosch-mobility-solutions.com/en/products-and-services/passenger-cars-and-light-commercial-vehicles/driver-assistance-systems/adaptive-cruise-control/

Level 2 – ACC and Lane Keep Assist (LKA)



Mono-Camera + Long-Range RADAR + Ultrasonic

Additional Slides

LKA:

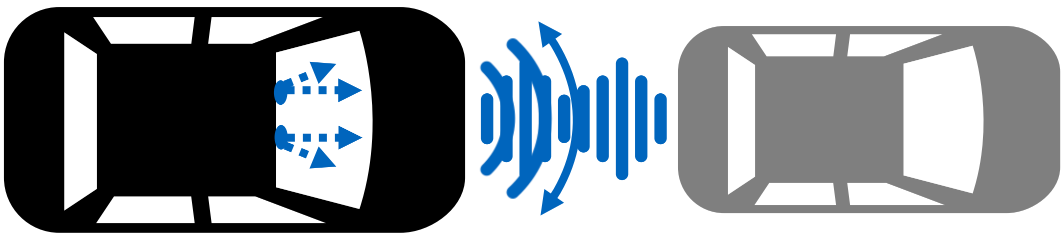
Lane keeping assist uses a video camera to detect the lane markings ahead of the vehicle and to monitor the vehicle's position in its lane. If the vehicle’s distance to the lane markings falls below a defined minimum, the system steps in. In vehicles with electric power steering, it gently, but noticeably countersteers in order to keep the vehicle in the lane. In vehicles without electric power steering, it achieves the same effect by utilizing the electronic stability program (ESP) to brake individual wheels.

Drivers can override the function at all times, so they retain control of the vehicle. If they activate the turn signal in order to intentionally change lanes or turn, the system does not intervene.

Reference:

https://www.bosch-mobility-solutions.com/en/products-and-services/passenger-cars-and-light-commercial-vehicles/driver-assistance-systems/lane-keeping-assist/

Level 3 – 5



LiDAR + Stereo-Camera + Long-Range RADAR + Ultrasonic

Additional Slides

Level 3 – 5, Detection Tasks:

Traffic Sign Recognition, Lane Detection, Pedestrian Detection, Object Detection: Yaw, Pose etc.

Sensor also at the rear of the vehicle

More Details of the introduced sensors are given in the lecture „Advanced Driver Assistant Systems in Vehicles”, also offered by the Institute of Automotive Technology, TUM.

https://www.mw.tum.de/en/ftm/teaching/courses/advanced-driver-assistant-systems-in-vehicles/

References

https://www.bosch-mobility-solutions.com/en/products-and-services/passenger-cars-and-light-commercial-vehicles/driving-safety-systems/electronic-stability-program/inertial-sensor/

https://www.car-bock.de/ABS-sensor-FA-VW-Golf4-left

https://vrtracker.xyz/handling-imu-drift/

https://www.flaticon.com/

https://jumbonews.co.uk/news/1850510/global-automotive-ultrasonic-radar-market-2020-industry-scenariodevelopment-analysis-strategies-growth-factors-and-forecast-to-2025/

https://www.japanautomotivedaily.com/2017/05/25/ricoh-denso-develop-worlds-smallest-adas-stereo-camera/

https://velodynelidar.com/products/ultra-puck/

https://www.continental-automotive.com/en-gl/Passenger-Cars/Autonomous-Mobility/Enablers/Radars

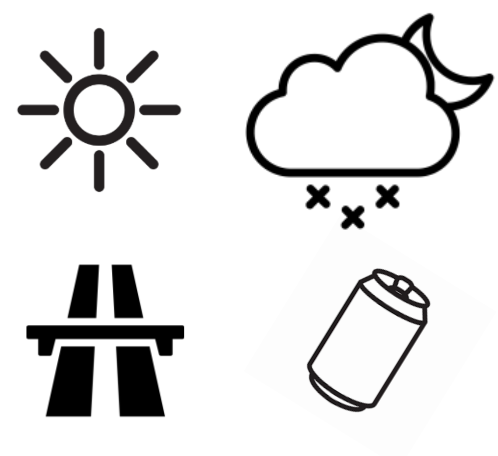
Challenges of Detection

Main sensors for semantic perception

- RADAR
- LiDAR
- Camera

Challenges

- Conditions of illumination
- Weather conditions
- Static obstacles
- Reflection



Sensors – Safety Concepts

Diversity

- Definition: *Implementation of components with physical or technical distinct operating principles.*
- Every sensor has its benefits.
- Different types of sensors are applied to enhance robustness against weather conditions and to obtain more information.

→ Common concept for perception sensors

Redundancy

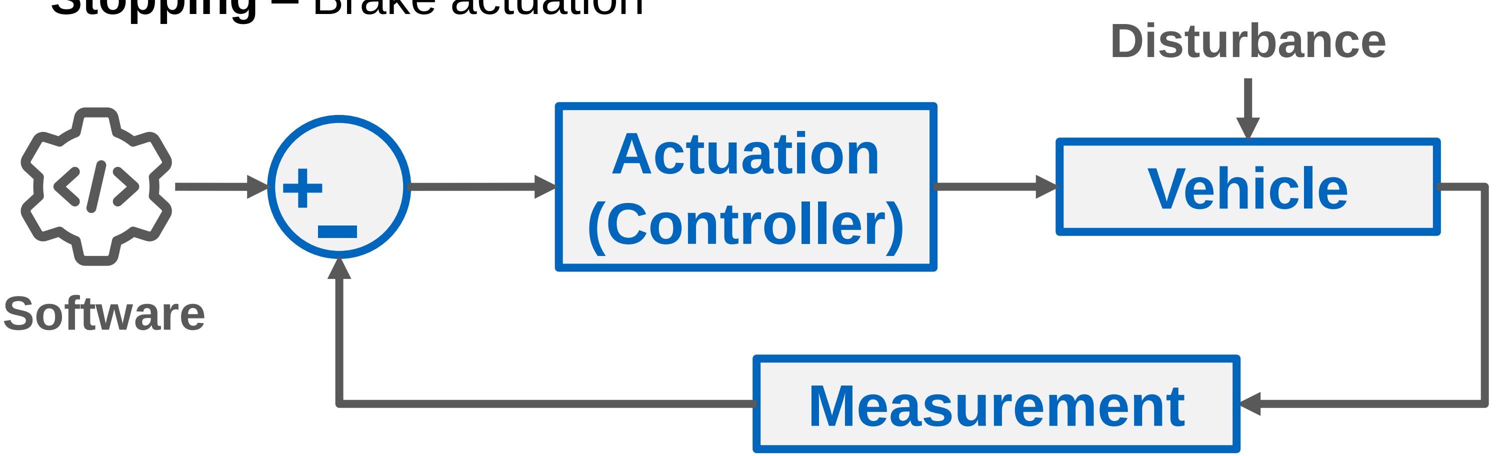
- Definition: *The duplication of critical components or functions of a system.*
- Faulty detection should be minimized.
- Overlapping sensors of the same or different type to verify measurements.

Actuators for Autonomous Driving

Task: Transform desired lateral and longitudinal control variables into actuator commands such that the desired motion is realized.

The operation of an autonomous vehicle requires actuation of 3 major controls

- **Acceleration** – Throttle actuation
- **Steering** – Steering actuation
- **Stopping** – Brake actuation



Additional Slides

Most vehicles on the road today already have all of the actuators needed to control the vehicle for automation. Up to Level 4, these actuators are selectable by human input or by control input from software. Hence, they are designed for manual driving as well and already part of ADAS-systems. The most common systems are electronic motors. These group of actuators are called “X-by-Wire”, when there is no mechanical connection between control input and component. However, to ensure reliability, systems like electric power steering systems still have a mechanical connection in contrast to pure “Steer-by-Wire”-systems.

Throttle actuation is achieved in most modern vehicles via electronic control between the pedal and the drive train (Drive-by-Wire). Electric assisted power steering has become the norm, already displacing hydraulically driven power steering systems throughout the industry. Finally, brake actuation is achieved by way of electronic stability control, which is required by law in the European Union since 2014 on all new passenger vehicles, <3,500 kg.

Reference:

https://www.robsonforensic.com/articles/autonomous-vehicles-sensors-expert/

Actuators – Constraint: Safety

Fail safe

Property: *Causing a device to revert to a safe condition in the event of a breakdown or malfunction.*

Reliability

Same reliability as conventional systems with human driver.

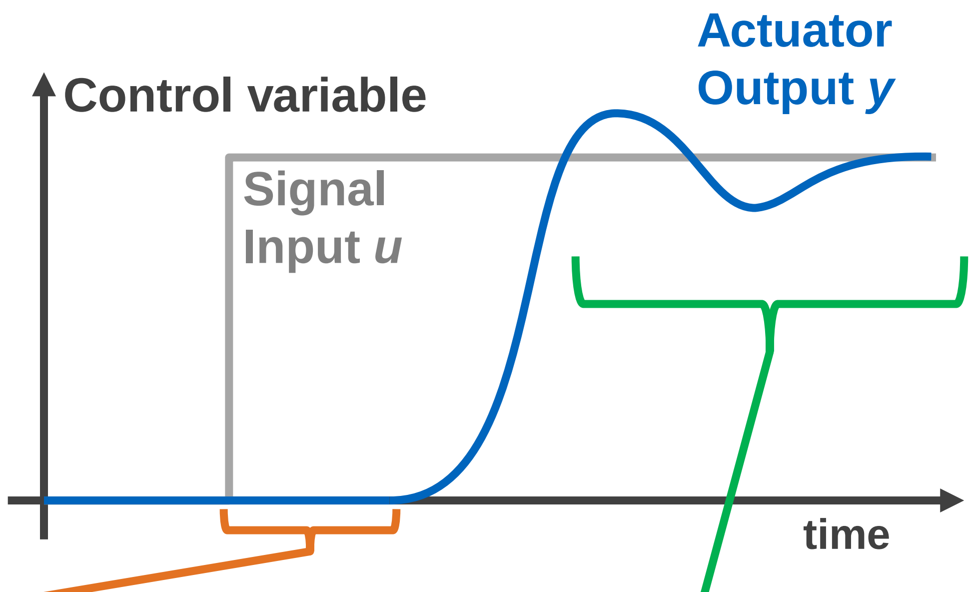
Concepts

Redundancy

Diversity

Example: Electromechanical Power Steering

Actuators – Constraint: Control



Dead times

- Computation time
- Dead time of motors
- Transmission delay (Bus)
- Backlash between components
- Sampling frequency

Responsiveness

- Moment of inertia
- Actuator dynamic
- Actuator friction

Behavior: Low-pass Filter

Introduction
Prof. Dr. Markus Lienkamp / Prof. Dr. Boris Lohmann

Phillip Karle, M. Sc.

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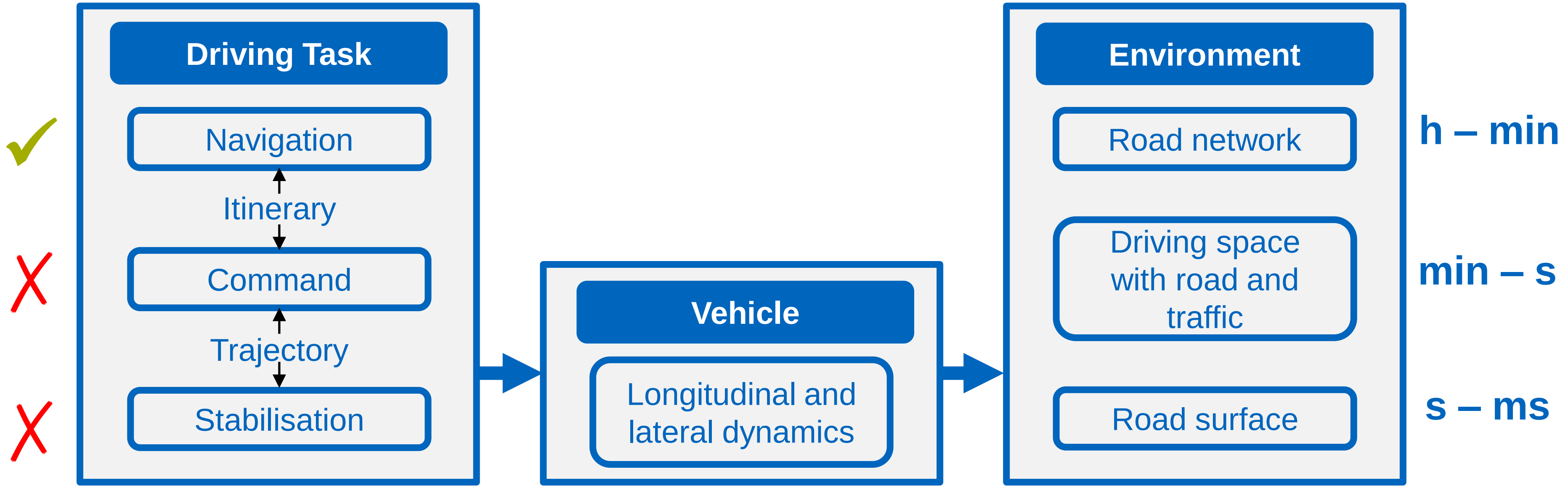
4. Basics of Sensors and Actuators
5. **Challenges of Autonomous Driving**
6. Summary

Levels of Driving



Adapted from: Donges, E.: Aspekte der Aktiven Sicherheit bei der Führung von Personenkraftwagen. Automobil-Industrie 27, 183–190 (1982)

Complexity of Road Traffic

Complex Environment

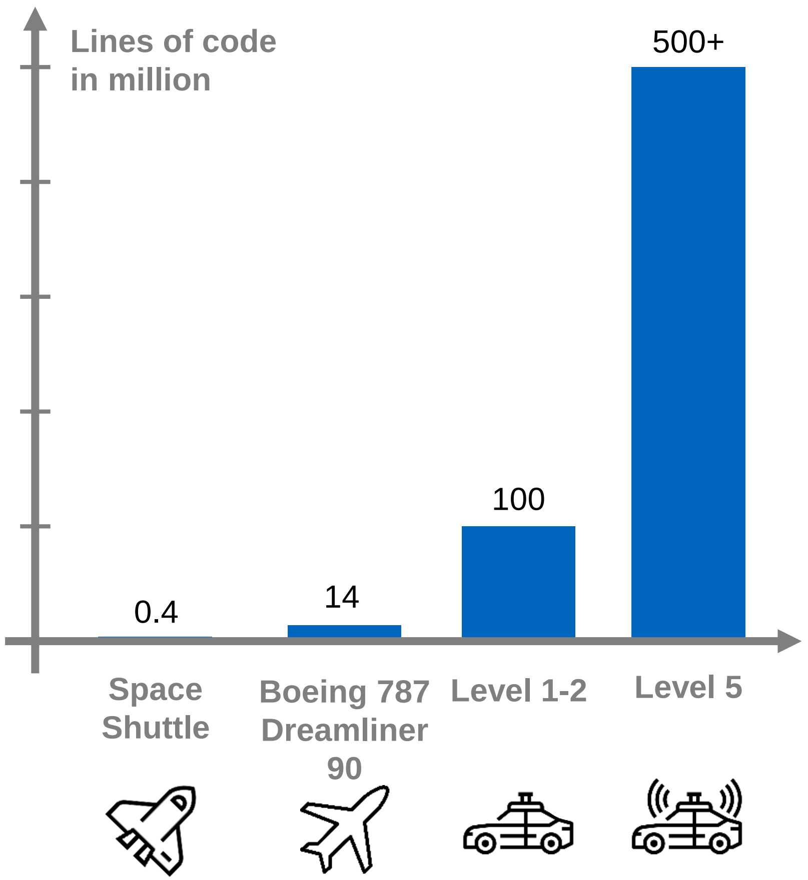
Individual road geometry, road-works and traffic rules

Stochastic Behavior

The intentions of other traffic participants are unknown and non-deterministic

Unlimited ODD[1]

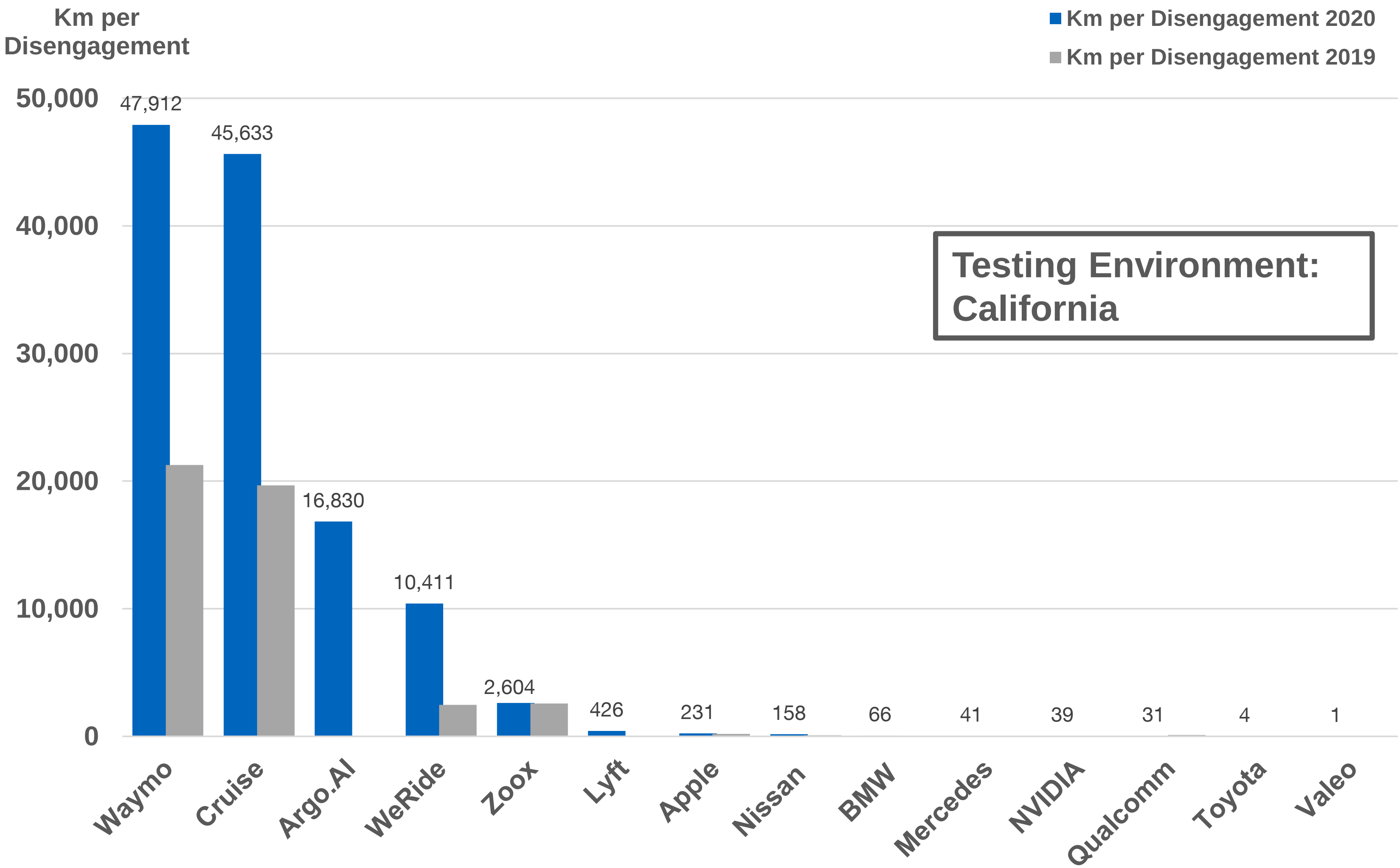
In Level 5, the number of possible scenarios is unlimited



[1] Operation Design Domain

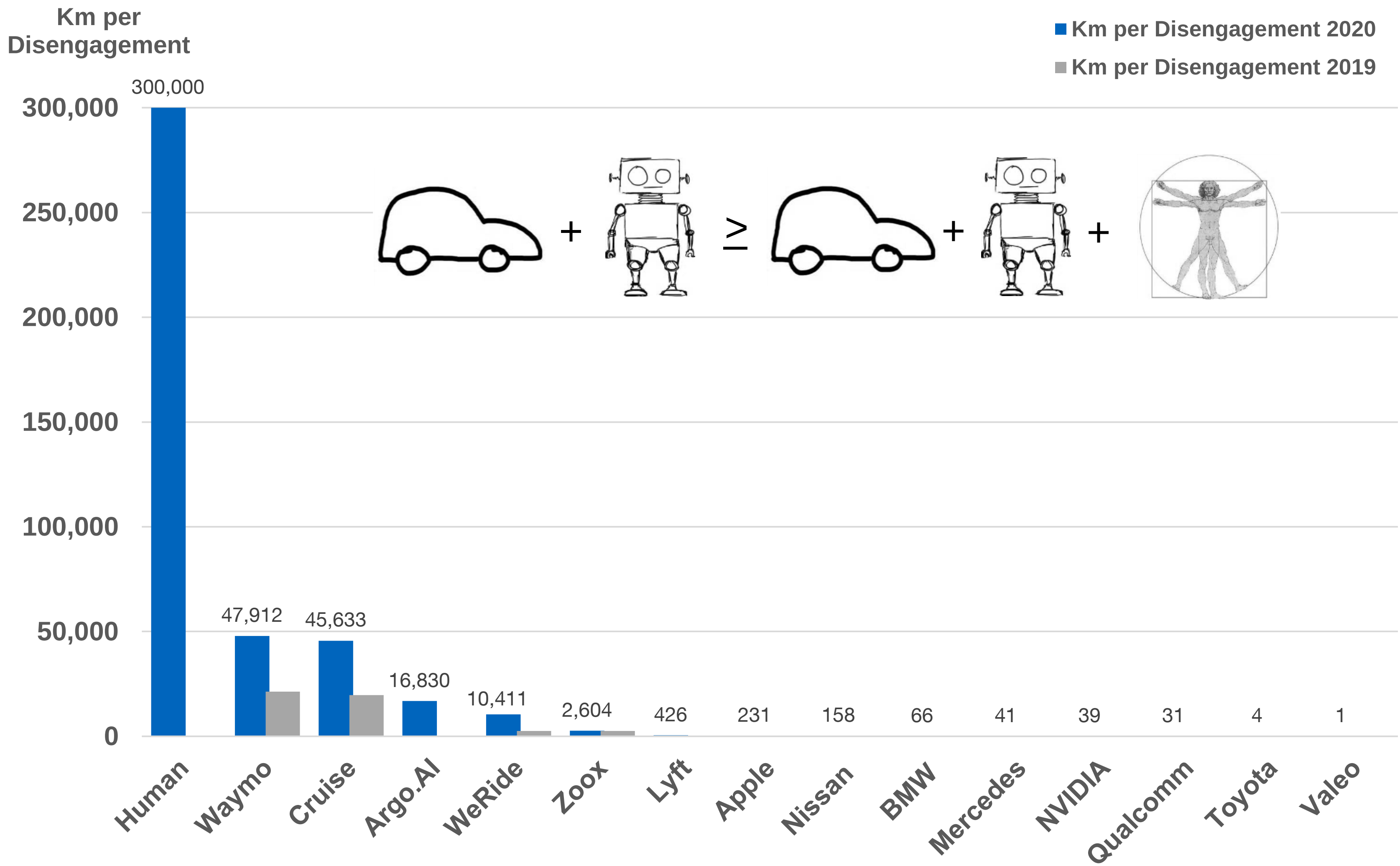
Deloitte research 2018, FEV 2018, Wired 2018, NXP 2017, MIT 2016

Benchmark in passenger safety



https://www.dmv.ca.gov/portal/vehicle-industry-services/autonomous-vehicles/disengagement-reports/

Benchmark in passenger safety



https://www.dmv.ca.gov/portal/vehicle-industry-services/autonomous-vehicles/disengagement-reports/

Additional Slides

Disengagement Report California DMV, 2020

Manufacturer	Miles	Km	Disengagements	Miles per Disengagement	Km per Disengagement
Waymo	628,839	1,006,142	21	29,944.69	47,911.50
Cruise	770,049	1,232,079	27	28,520.34	45,632.55
AutoX	40,734	65,174	2	20,367.00	32,587.20
Pony.AI	225,496	360,794	21	10,737.90	17,180.65
Argo.AI	21,037	33,659	2	10,518.59	16,829.74
WeRide	13,014	20,822	2	6,507.00	10,411.20
DiDi	10,401	16,642	2	5,200.75	8,321.19
Nuro	55,370	88,592	11	5,033.62	8,053.79
Deeproute.AI	10,018	16,029	3	3,339.33	5,342.93
Zoox	102,521	164,034	63	1,627.32	2,603.71
QCraft	7,582	12,131	16	473.88	758.20
Aurora	12,208	19,532	37	329.93	527.90
Lyft	32,731	52,370	123	266.11	425.77
Gatik.AI	2,352	3,763	11	213.82	342.11
Apple	18,805	30,088	130	144.66	231.45
Nissan	395	631	4	98.63	157.80
BMW	122	195	3	40.67	65.07
Aimotive	2,987	4,779	113	26.43	42.29
Mercedes	29,984	47,974	1,167	25.69	41.11
NVIDIA	3,033	4,853	125	24.26	38.82
Qualcomm	1,727	2,763	90	19.19	30.70
SF Motors	875	1,400	61	14.34	22.94
Atlas R.	47	76	10	4.74	7.58
EasyMile	424	678	128	3.31	5.30
Toyota	2,875	4,600	1,215	2.37	3.79
Telenav	4	6	2	2.00	3.20
Udelv	66	106	49	1.35	2.16
Ridecell	148	236	189	0.78	1.25
Valeo	49	78	99	0.49	0.79
TOTAL	**1,955,208**	**3,128,333**	**3,695**	**529.15**	**846.64**

https://www.dmv.ca.gov/portal/vehicle-industry-services/autonomous-vehicles/disengagement-reports/

Friction Estimation

Weather & road conditions

Tire-road friction is influenced by the weather and resulting road conditions, which is an important safety aspect and has to be considered in motion control.

Degradation of components

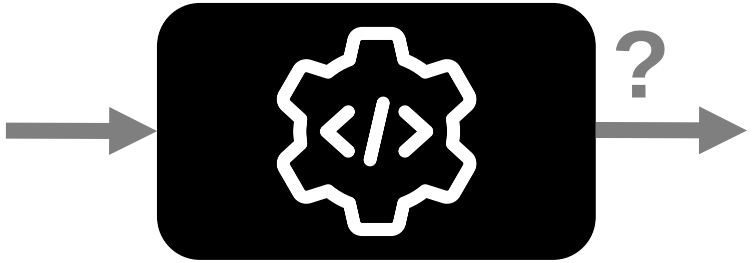
Tires and components reduce in performance over lifetime, which is another reason for a decreasing friction value.

https://www.abs-autoservice.de/presse-aktuelles/maengel-bereifung-und-bremsen-sind-haeufig-ursache-fuer-unfaelle-mit-personenschaeden/

Validation

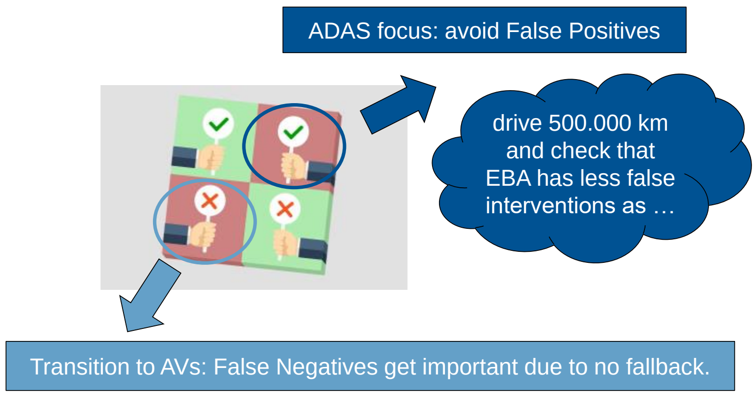
Explainbale AI

- AI-algorithms cause unhedgeable risks
- Explainbality of AI is a major trend, which targets this issue



Safety Assessment

No deterministic approaches to test every possible traffic scenario, which a Level 4-5 systems have to handle



Additional Slides

Why is it impossible to validate a system only by test drives?

- Km per Accident, 2015, „Autobahn, D“: 660 * 10^6 km
- Factor 10 for 5 % risk

→ 6.6 * 10^9km required to validate one software release

- Average driven kilometer per test vehicle per year: 66,000km per year per vehicle

- So, 100,000 test vehicles would be required per year for a single OEM to validate one software release.
Additionally, 2-3 test drivers per vehicle required. Total Costs: ~ 10^9 €

.. And this war just one software release and would be required after every software update

Additional Slides

Cyber Security

To ensure a comprehensive cybersecurity environment a multi-layered approach is required that leverages existing cybersecurity frameworks and encourages industry to adopt best practices that improve the security posture of their vehicles.

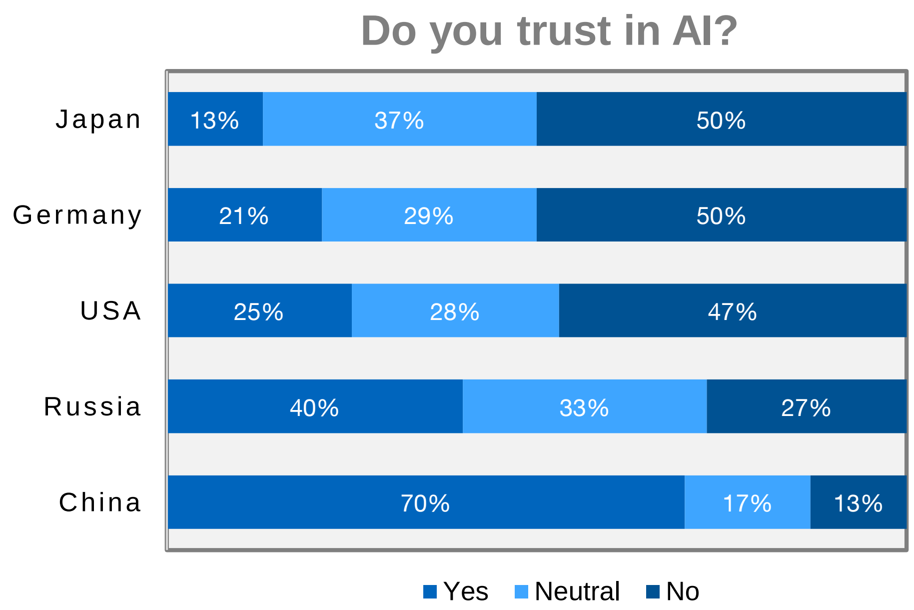
- A risk-based prioritized identification and protection process for critical vehicle systems
- Timely detection and rapid response to potential vehicle cybersecurity incidents.
- Architectures, methods, and measures that design-in cybersecurity and cyber resiliency, facilitating rapid recovery from incidents when they occur.
- Methods for effective intelligence and information sharing across the industry to facilitate quick adoption of industry-wide lessons learned.
- Creation of standards that articulate best practices.

From: https://cyberstartupobservatory.com/cybersecurity-connected-autonomous-vehicles/

Social Acceptance

Trust in AI and machines

Big parts of an autonomous driving software rely on AI, which lacks in explainability.



Control of actions

Most humans like to have a certain level of control on their actions.
→ change of mindset for autonomous driving

https://www.statista.com/aboutus/our-research-commitment

Costumer Value

Motion Sickness

A high level of motion comfort is required to enable reading, sleeping or working during vehicle ride, besides a respective road surface.

Driving Pleasure

Driving pleasure of manual driving counteracts the request of highly automated passenger cars

https://www.health.harvard.edu/diseases-and-conditions/coping-with-motion-sickness
https://www.bmw-m.com/de/topics/magazine-article-pool/m-donuts-zum-donut-day.html

Legal Aspects

Regulatory law – StVO[1], StVG[2]

- Vienna convention (1968) was long time the base of national traffic laws
- February 10th, 2021: Adaptation of German law regarding applications of autonomous driving

Vienna Convention, Art. 8, § 5:
“Every driver shall at all times be able to control his vehicle or to guide his animals.”

Liability law

- Currently, three-pillar liability system between drivers, owners and manufacturers
- New division of liability for Level 4-5

[1] Straßenverkehrs-Ordnung
[2] Straßenverkehrs-Gesetz

Additional Slides

February 10th, 2021

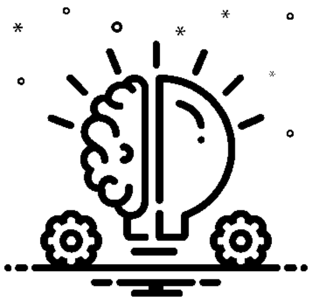
https://www.bundesregierung.de/breg-de/aktuelles/faq-autonomes-fahren-1852070

System is allowed to drive, but a person in the vehicle is required for observation. The use-case is not limited to specific scenarios, but the location of the application is limited. Exemplary application could be: Shuttle-Transports, People-Mover, Hub2Hub-Traffic, Traffic Offers in rural areas, Automated Valet Parking (e.g. via Smartphone)

Ethical Aspects

Rational algorithm

- Algorithm acts rational and follows the programmed logic
- How should the algorithm be programmed for situations of inevitable accidents?



Ethical dilemma

Opposing imperatives of:

- No weighting of human life acceptable
- Imperative of damage minimization

Business Model

OEM[1] Costs – Development

The development costs that the companies have to invest as front-loading are huge.

OEM[1] Costs – Verification & Technical Reserves

Verification and validation costs will increase significantly. Furthermore, technical reserves are necessary.

Get Insurance companies on board

In Level 4-5 the system is the fallback-level. New concepts for vehicle insurance are necessary.

[1] Original Equipment Manufacturer

Unstructured Environment

Consider scenarios outside existing traffic rules

Ethical and algorithmic challenges arise when traffic participants disobey traffic rules.
→ Mixed traffic

Expanding coverage outside of well-mapped/flat areas

Driving in unstructured environment without road marking and map infor-mation.

https://www.ticketsnipers.com/ticket/cvc-21456-pedestrian-crosswalk-violation
https://medium.com/rahuls-personal-blog/the-great-indian-road-traffic-4a1a5571661e

Our Approach

Unstructured Environment

Limited ODD[1] – Level 4
Vehicle application
Evaluation of applicability
Validation of edge cases

Structured Environment

Unlimited ODD[1] – Level 5
Addition of road rules
Extension of generic algorithms

[1] Operation Design Domain

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Summary – What did we learn today

Mega Trends – CASE

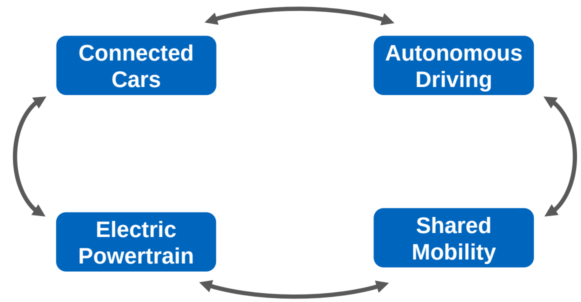
Autonomous Driving is one of the big megatrends in automotive industry. It is a disruptive technology and game-changer for further mobility.

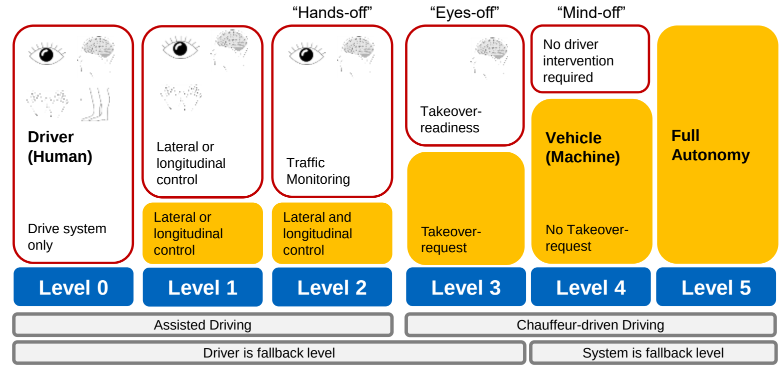
Levels of Vehicle Autonomy

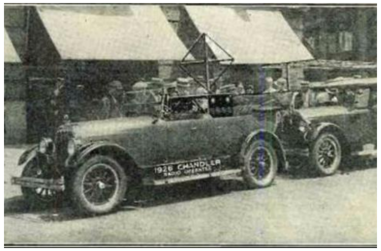
Highway Pilot and Robotaxis are two important concepts on the evolutionary road to full autonomy.

Milestones

A brief overview of the history of driverless cars and the status quo is given.



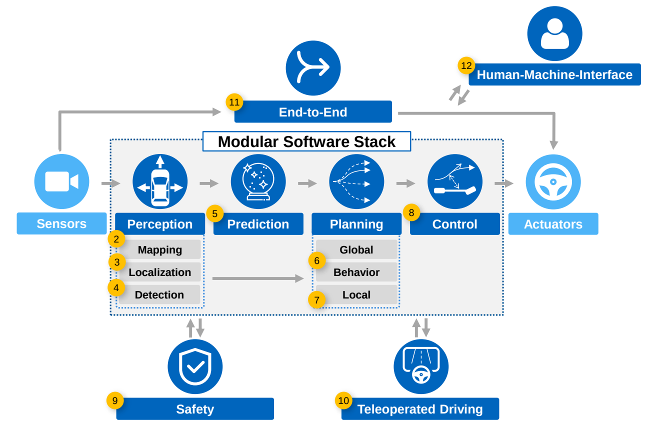




Summary – What did we learn today

Lecture Overview

Within this lecture, the full software for autonomous driving is presented in theory and practice.

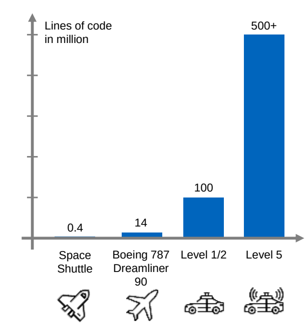


Sensors and Actuators

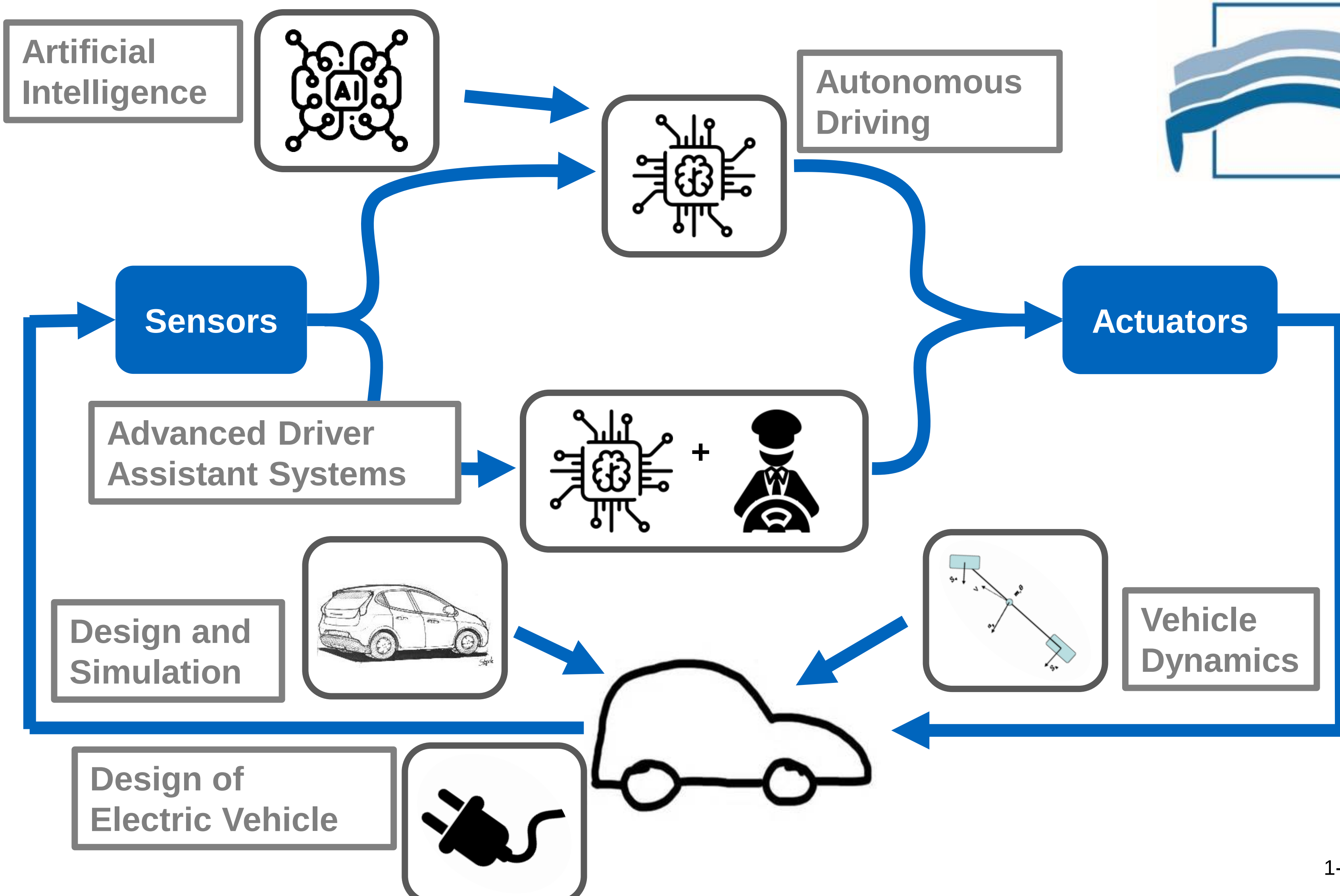
Related hardware for autonomous driving are introduced to get a more comprehensive understanding.

Open Challenges

Major challenges to realize autonomous driving are not only technical, but cover also social, ethical, legal and safety aspects.



Lectures at the Institute of Automotive Technology



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J. Betz et al., “A Software Architecture for the Dynamic Path Planning of an Autonomous Racecar at the Limits of Handling,” in 2019 IEEE International Conference on Connected Vehicles and Expo (ICCVE), 2019, pp. 1–8.

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M. Maurer, B. Lenz, H. Winner, and J. C. Gerdes, Autonomous Driving: Technical, Legal and Social Aspects. s.l.: Springer, 2016.

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A. Faisal, T. Yigitcanlar, M. Kamruzzaman, and G. Currie, “Understanding autonomous vehicles: A systematic literature review on capability, impact, planning and policy,” JTLU, vol. 12, no. 1, 2019, doi: 10.5198/jtlu.2019.1405.