Introduction to Automotive Electronics Systems

Guest-lecture at the Department of Electrical Power Engineering
Brno University of Technology

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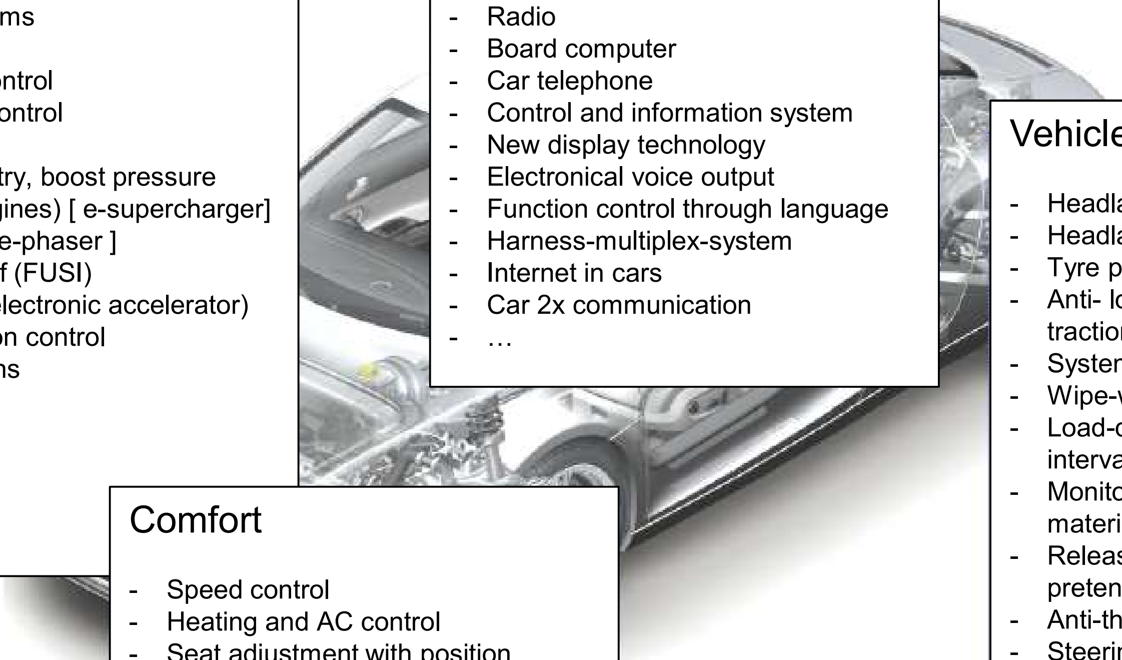
- Research topics: future mobility, sustainable transport, alternative powertrains, electric propulsion, new vehicle technologies, mechatronics systems and virtual product development
- PhD at the Institute of Internal Combustion Engines and Thermodynamics in 2005, habilitation at the Institute of Automotive Engineering in 2011, Associate Professor since 2016
- International periods / lectures at Universities in the USA (Tampa, FL), China (Shanghai, Zhenjiang), Thailand (Bangkok), Saudi-Arabia (Riyadh), Slovenia (Maribor) and Innsbruck
- Program Coordinator of the Double Degree Program Mechanical Engineering in co-operation with the Tongji University, Shanghai, China
- Scientific head of life-long learning training programs in the automotive industry.

1. Introduction

The Car as a Mechatronics System

The most popular mechatronics system is the car. It consists of a multitude of mechatronics subsystems for engine & drive train management, communication, safety and comfort.



Engine / propulsion systems

- Electronic ignition systems
- Fuel injection systems
- Electronic idle speed control
- Air/fuel ratio (lambda) control
- Start / stop automatism
- Variable turbine geometry, boost pressure control (for charged engines) [e-supercharger]
- Variable valve control [e-phaser]
- Electronic engine cut-off (FUSI)
- Engine power control (electronic accelerator)
- Exhaust gas recirculation control
- Automated transmissions
- All-wheel drive
- Electric drive systems
- Hybrid drive systems
- Battery systems
- …

Communication

- Radio
- Board computer
- Car telephone
- Control and information system
- New display technology
- Electronical voice output
- Function control through language
- Harness-multiplex-system
- Internet in cars
- Car 2x communication
- …

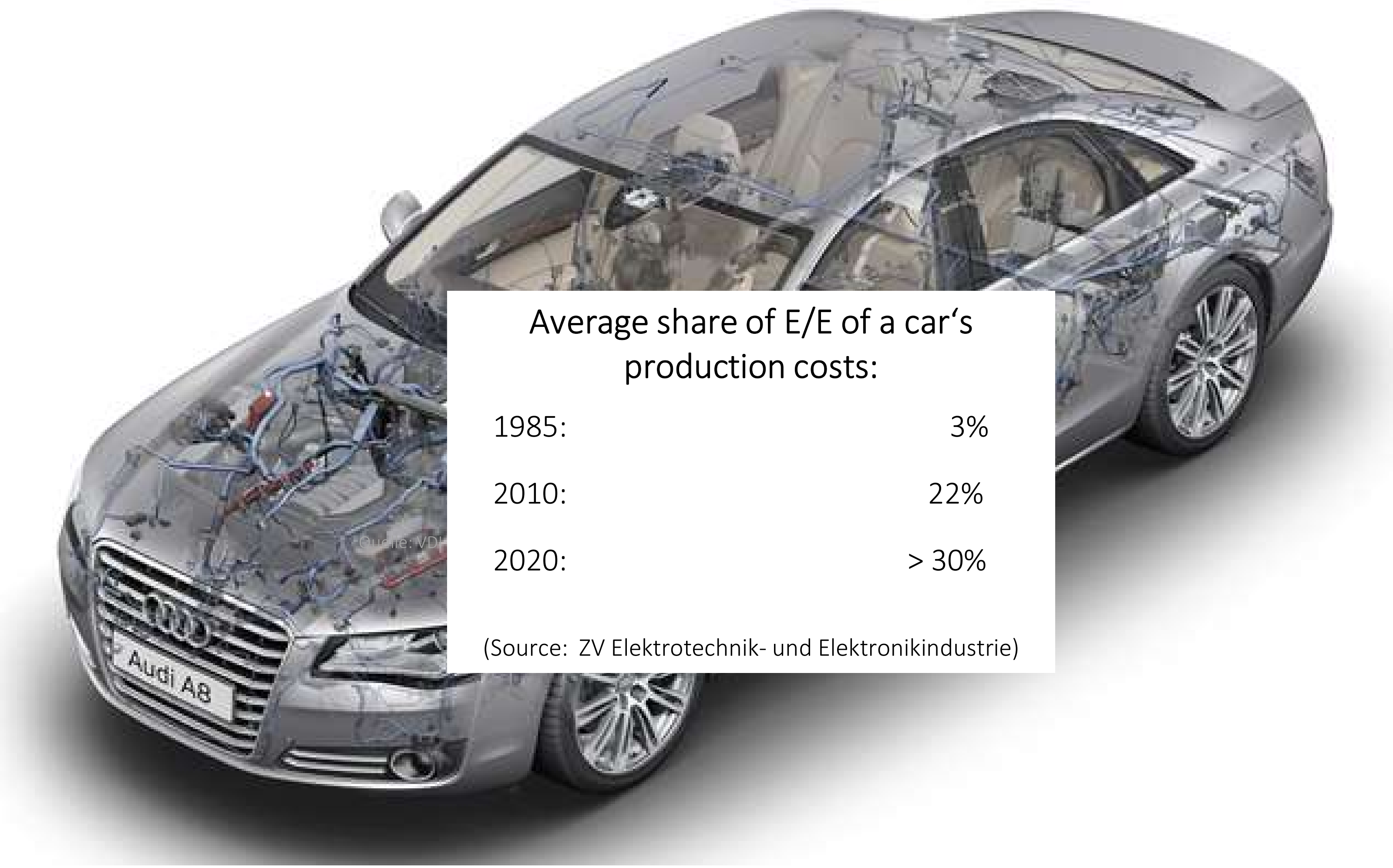
Comfort

- Speed control
- Heating and AC control
- Seat adjustment with position memory
- Central lock
- Chassis control
- Automated driving functions
- …

Vehicle safety

- Headlamps adjustment and cleaning
- Headlamps with gas discharge lamp
- Tyre pressure monitoring
- Anti- lock braking system (ABS), traction- control- system (ASR)
- System diagnosis
- Wipe-wash-control
- Load-dependent maintenance interval report
- Monitoring system for operating material and wear parts
- Release system for airbag, belt pretensioner, roll bar
- Anti-theft system
- Steering system for front and rear axle
- Adaptive cruise control (ACC)
- Lane assist
- Brake assist
- Automated driving functions
- …

The Car as a Mechatronics System



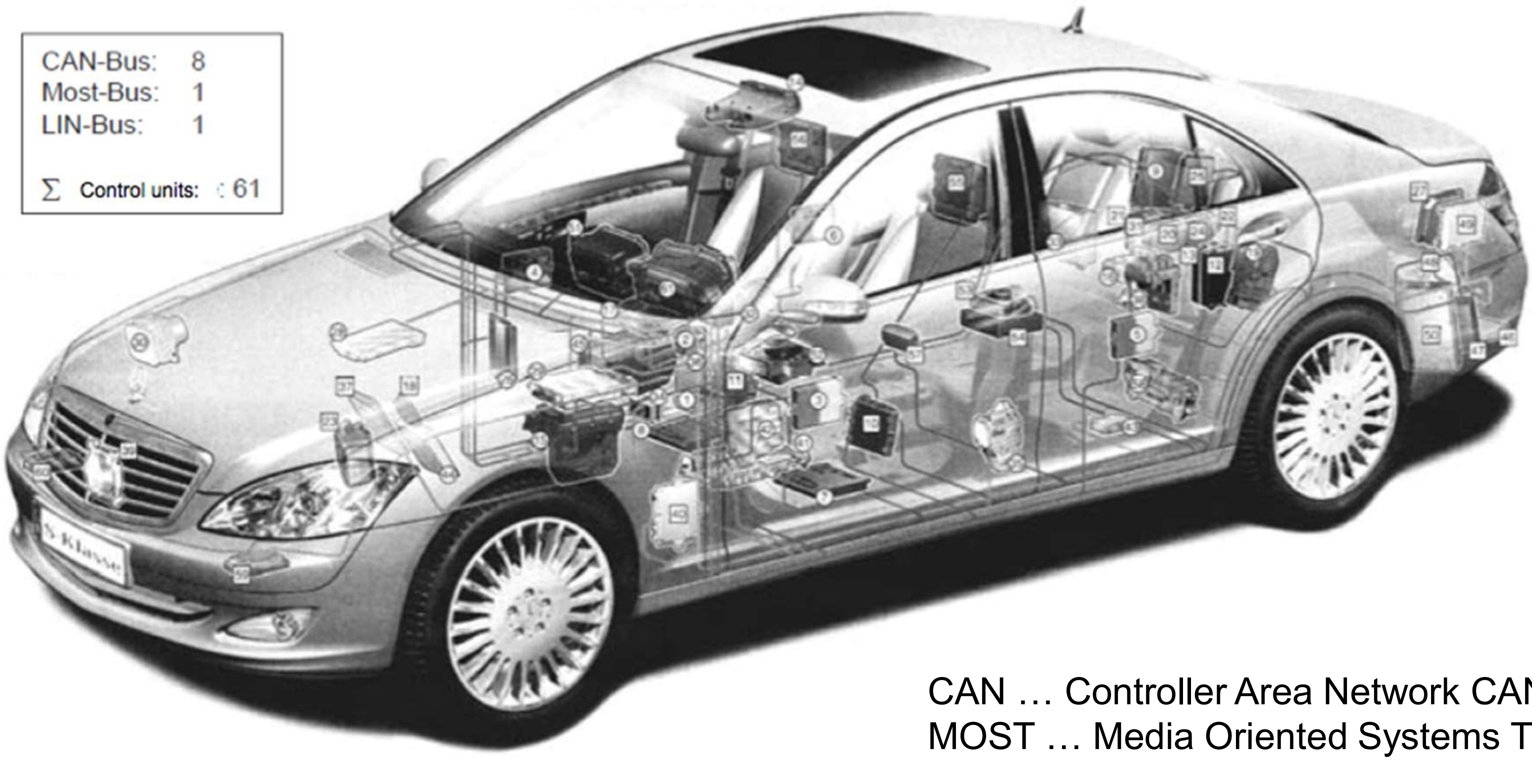
Average share of E/E of a car‘s production costs:

1985:	3%
2010:	22%
2020:	> 30%

(Source: ZV Elektrotechnik- und Elektronikindustrie)

The Car as a Mechatronics System

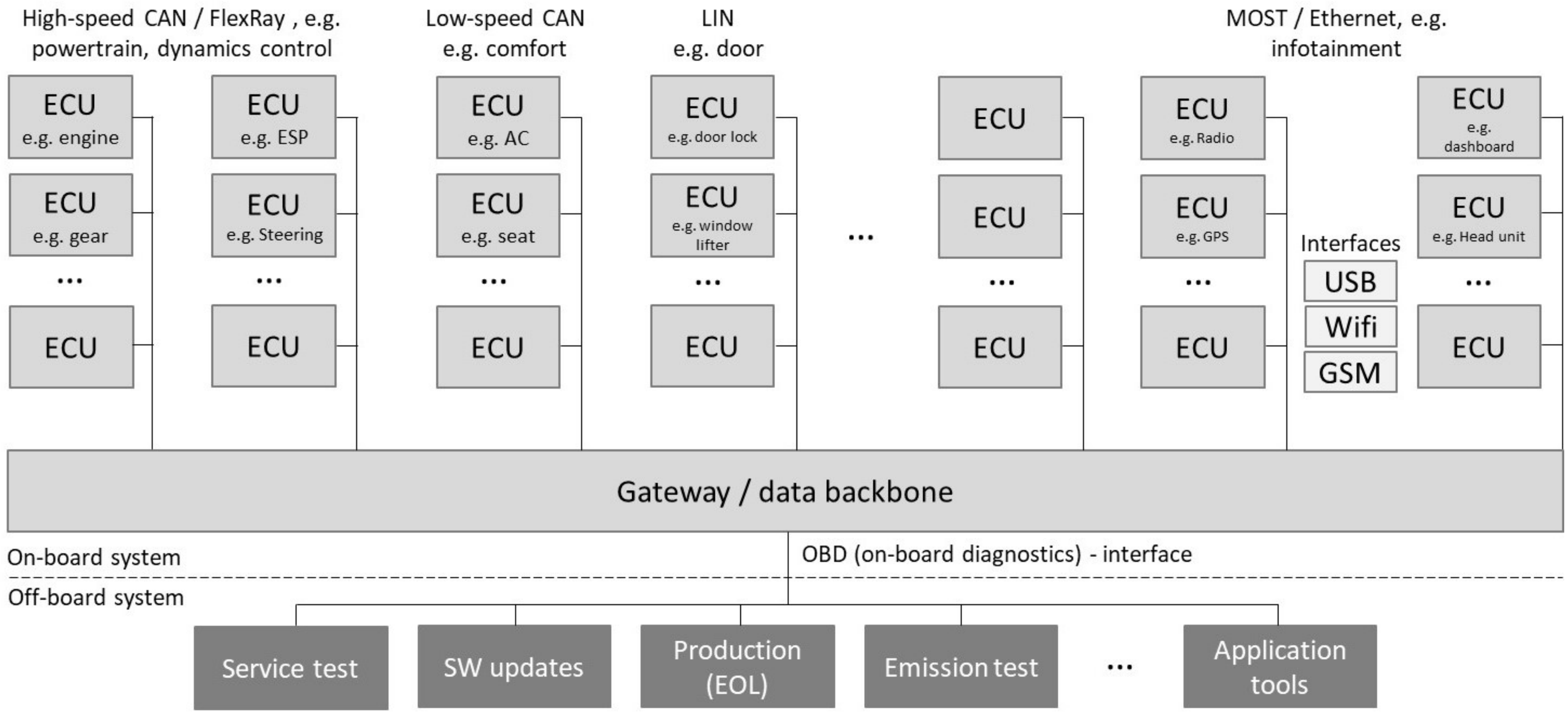
Control unit linkage of a upper class vehicle (MB W221, 2005)



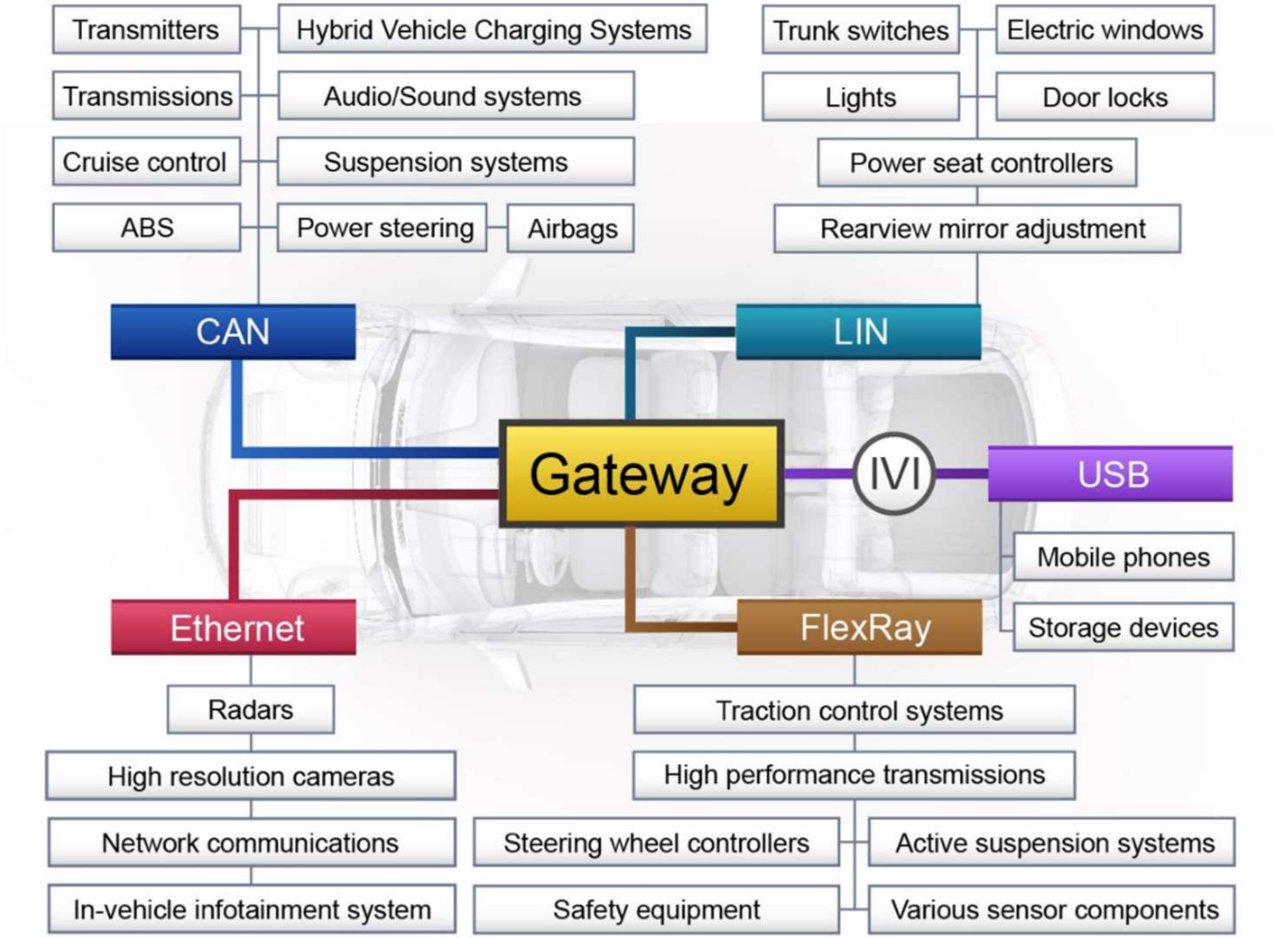
CAN … Controller Area Network CAN
MOST … Media Oriented Systems Transport
LIN … Local Interconnect Network
FlexRay … Flexible Data Rate
Ethernet … Automotive Ethernet

Source: Trautmann

Bus Systems of a Modern Vehicle



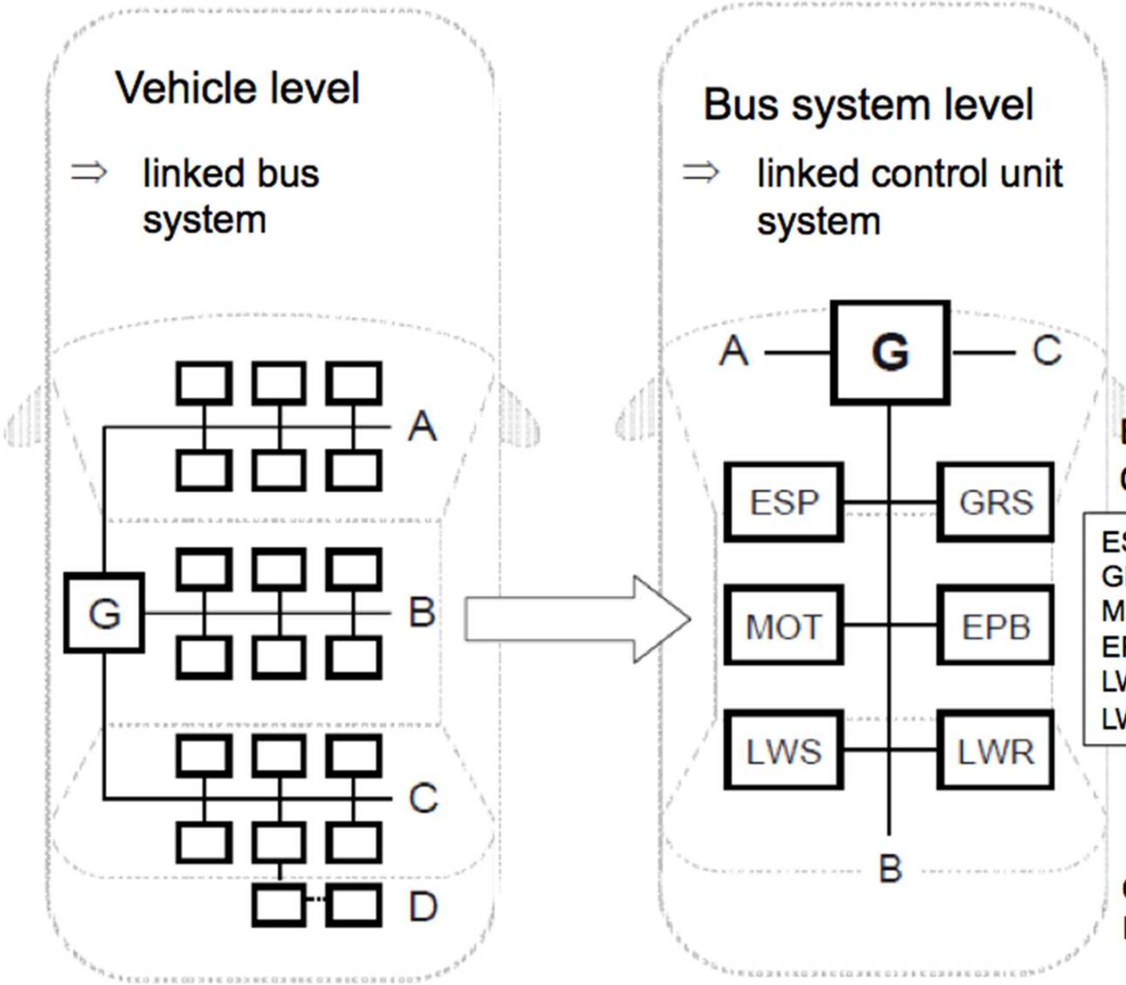
Typical Application of Different Bus Systems



Source: Amine Elibrahimi

Controller System Levels

Bus Systems



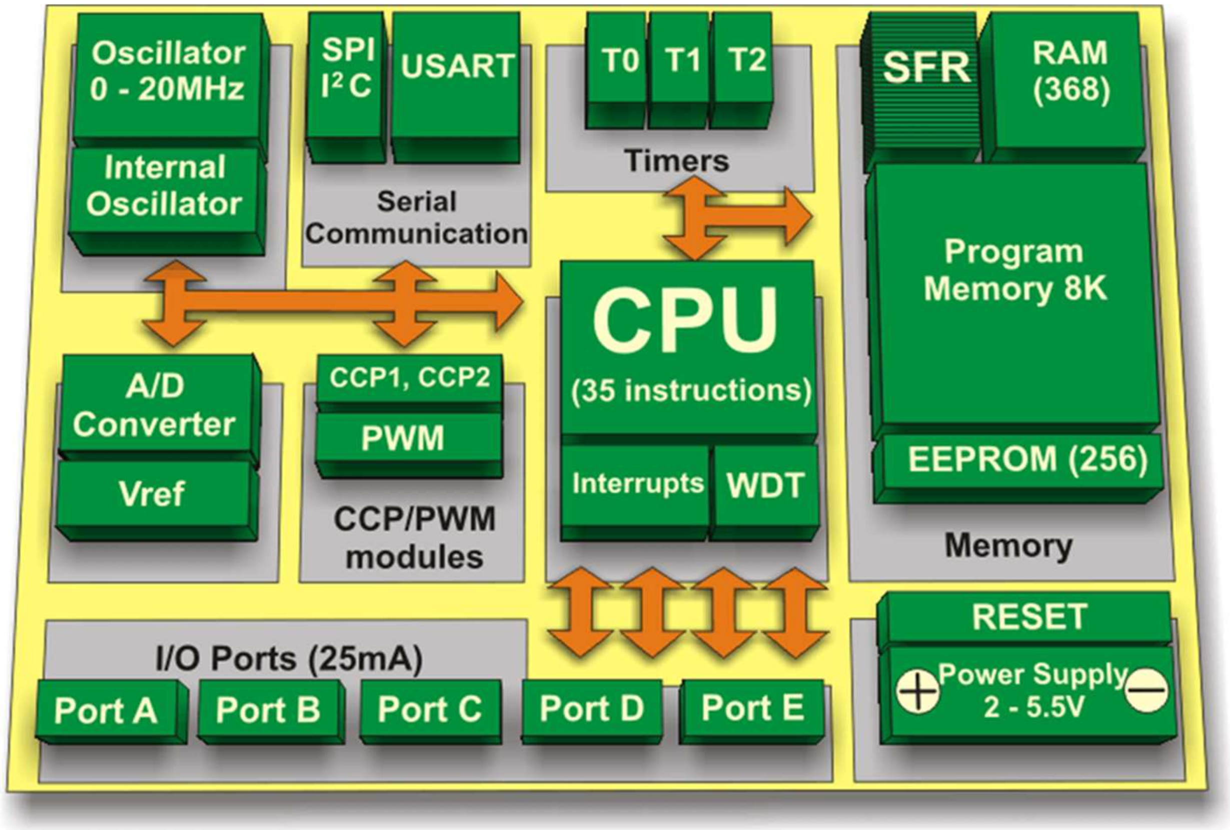
A ... CAN-Bus Infotainment
B ... CAN-Bus Drive
C... CAN-Bus Comfort
D... Subordinate Bus system, e.g. LIN

Exemplified indicated control for CAN-Bus B

ESP – electronical stability program
GRS – yaw rate sensor
MOT – engine control
EPB – electronic parking brake
LWS – steering angle sensor
LWR – headlamp levelling

CAN ... Controller Area Network
LIN ... Local Interconnect Network (serial bus systems)

Block Diagram of a Simple Microcontroller



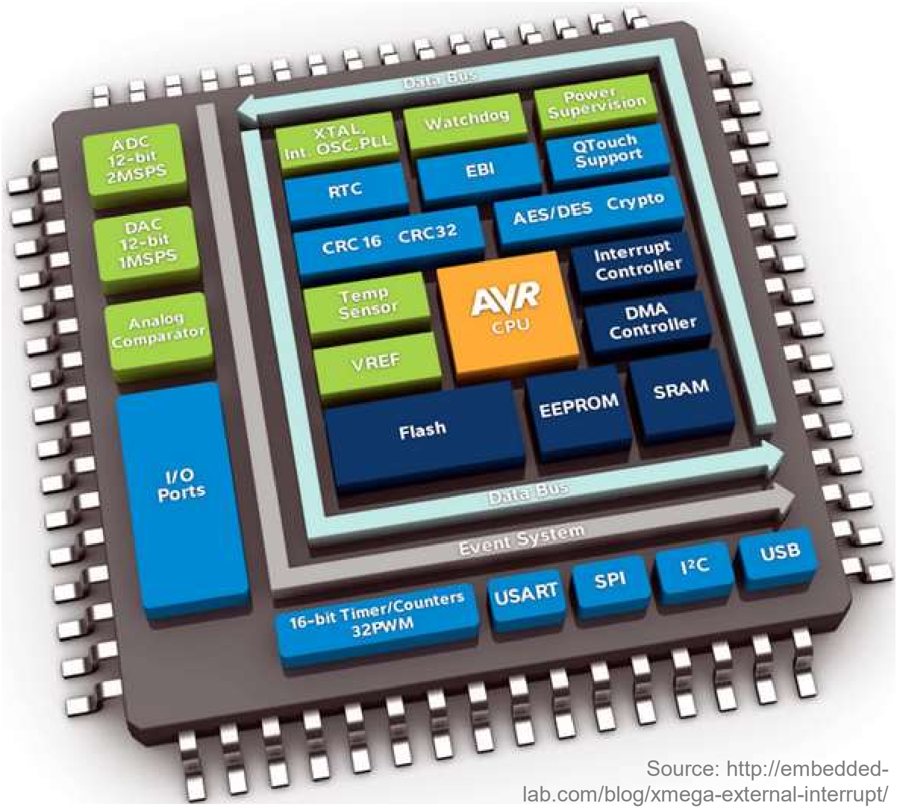
Microcontroller PIC16F887
block diagram with main components

SPI … bus interface
USART. com interface
CPU … relatively low number of functions (Δ to PC)
PWM … pulse width modulation for fan control
Vref … input interface for temperature sensor
A/D … converter for sensors, actuators
WDT … CPU watchdog timer
SFR … Special function register (addressable memory)
CCP … CPU control panel (data communication)

Typical Microcontroller (µC) Architecture

Is a small computer (SoC) on a **single integrated circuit** containing a processor core, memory, and programmable input/output peripherals

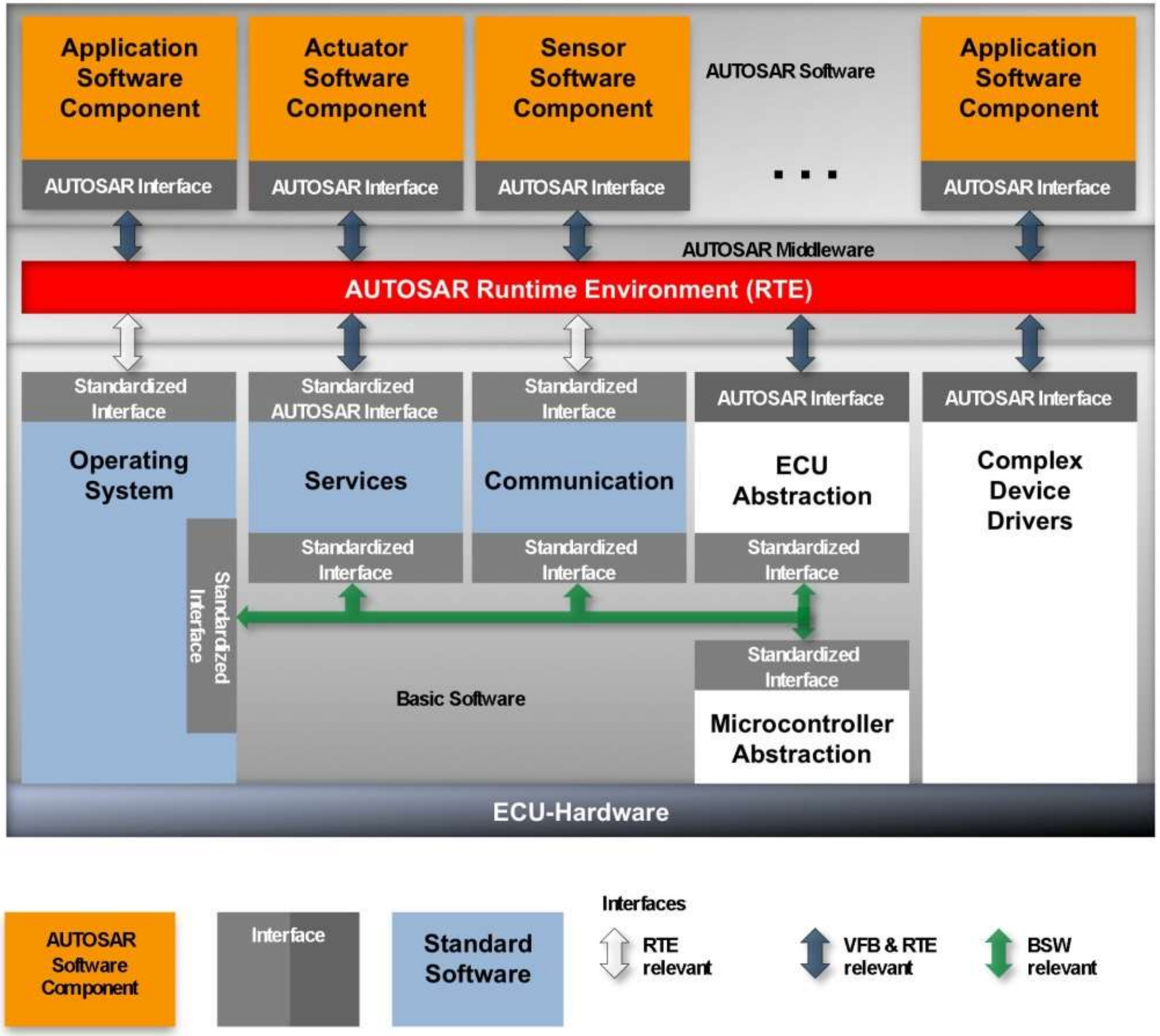
- Microcontrollers are designed for **embedded applications** (microprocessors are used in personal computers)
- e.g. automobile engine control systems, implantable medical devices, remote controls, office machines, appliances, power tools, toys…
- Depending on the **architecture**: 4 Bit-, 8 Bit-, 16 Bit- & 32 Bit-microcontroller



Source: http://embedded-lab.com/blog/xmega-external-interrupt/

Microcontroller block diagram showing the main components

Example: Automotive Software Platform AUTOSAR



AUTomotive Open System Architecture

Trend: Transition of Controller Architectures

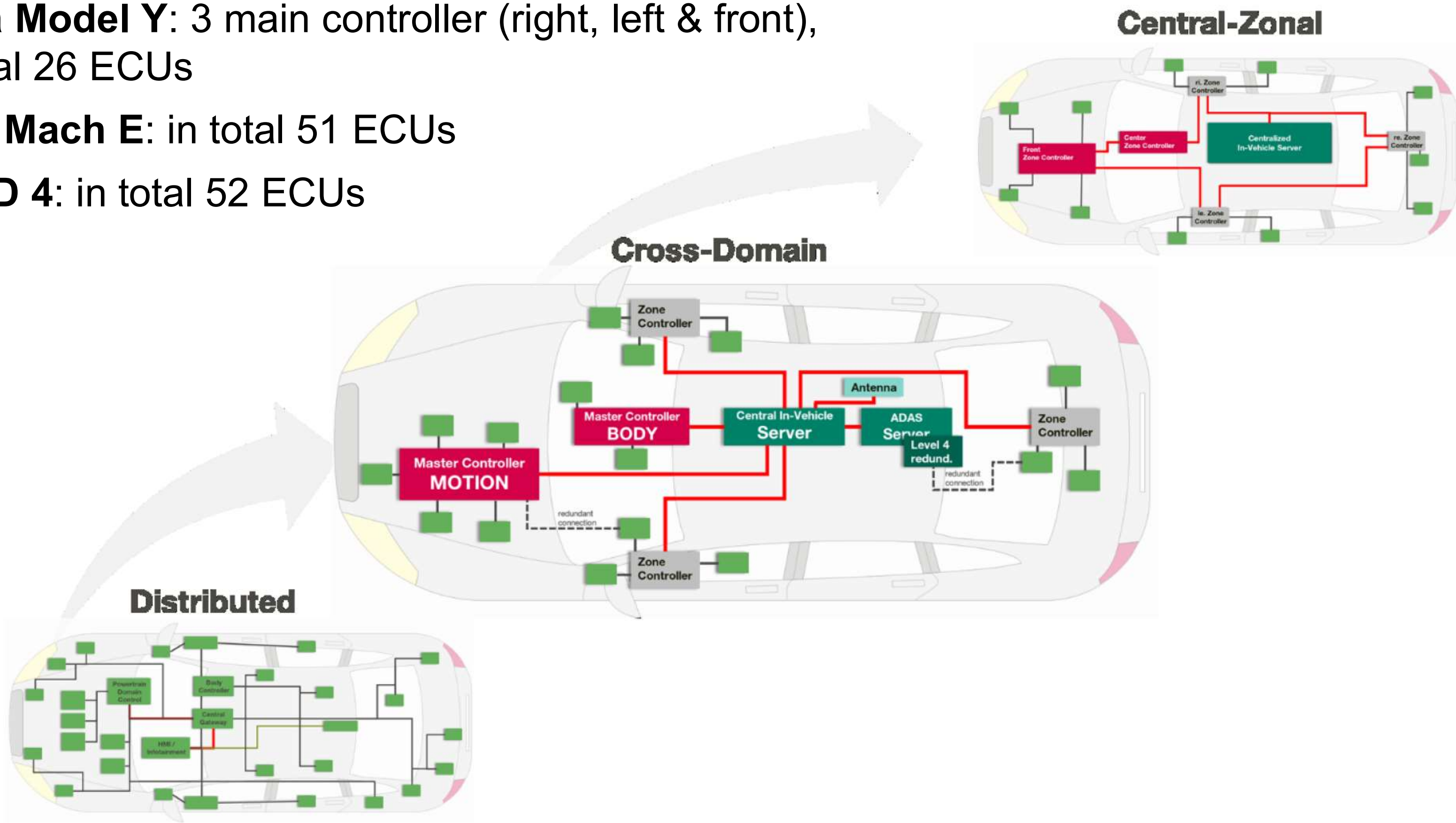
… from distributed to cross-domain and central zonal architectures

In serial production of electric cars, e.g.:

Tesla Model Y: 3 main controller (right, left & front), in total 26 ECUs

Ford Mach E: in total 51 ECUs

VW ID 4: in total 52 ECUs

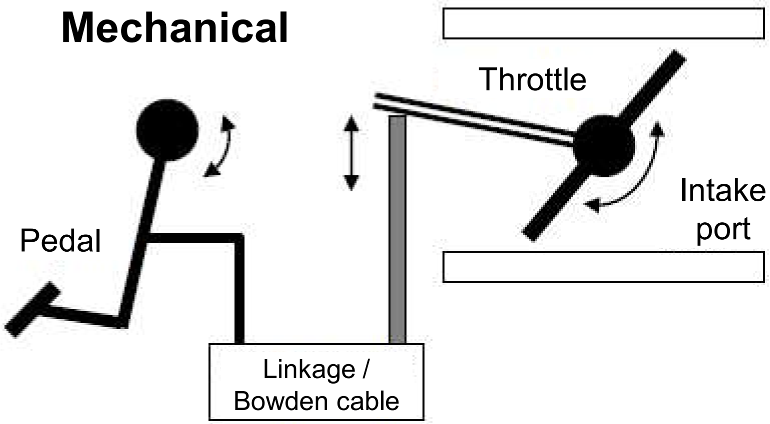


Source: R. Mader et.al, Vitesco Technologies

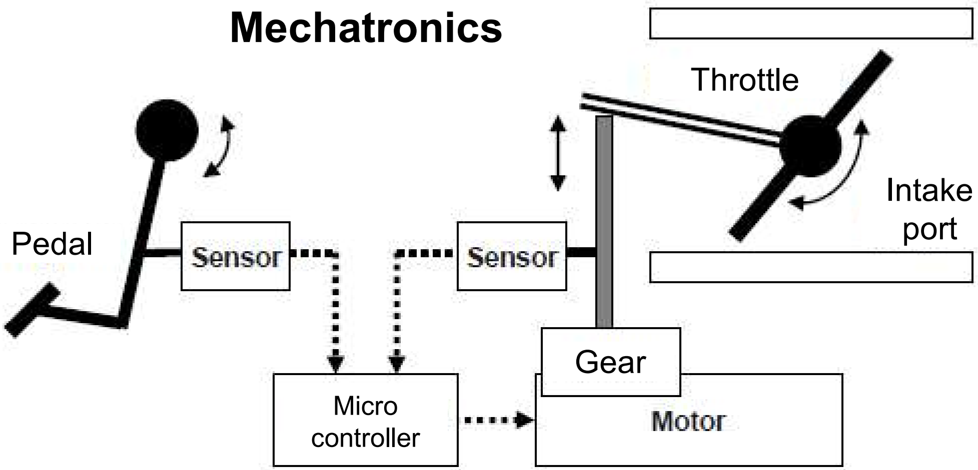
2. Automotive Mechatronics Systems

Example: Mechanical vs. Mechatronic throttle

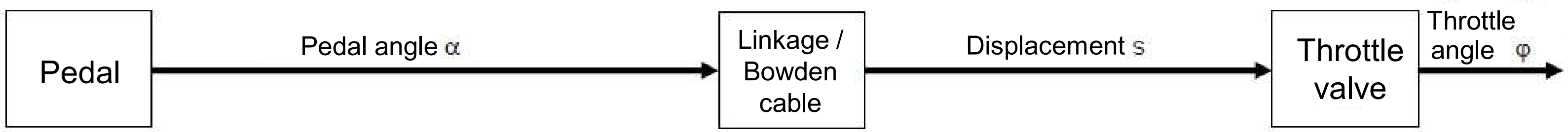
Mechanical



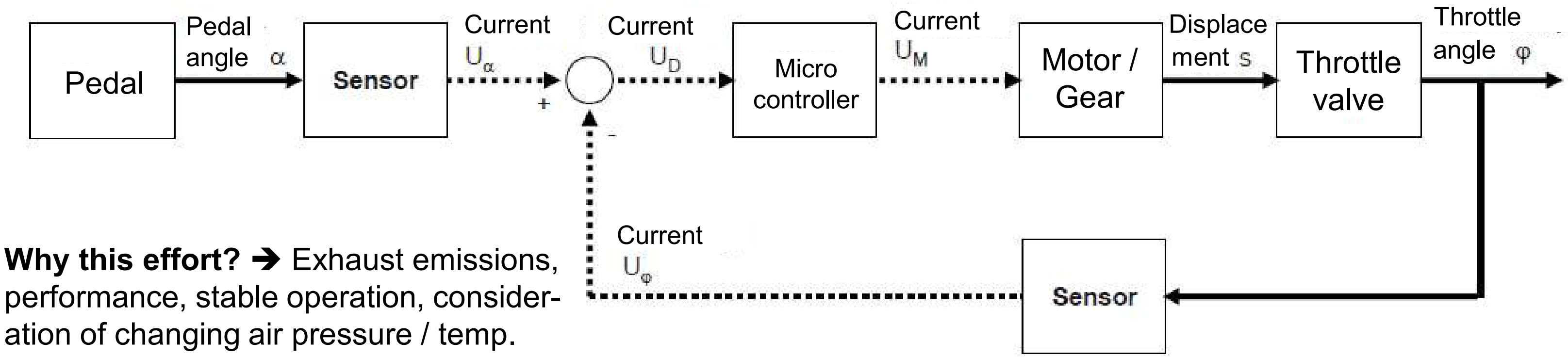
Mechatronics



Mechanical



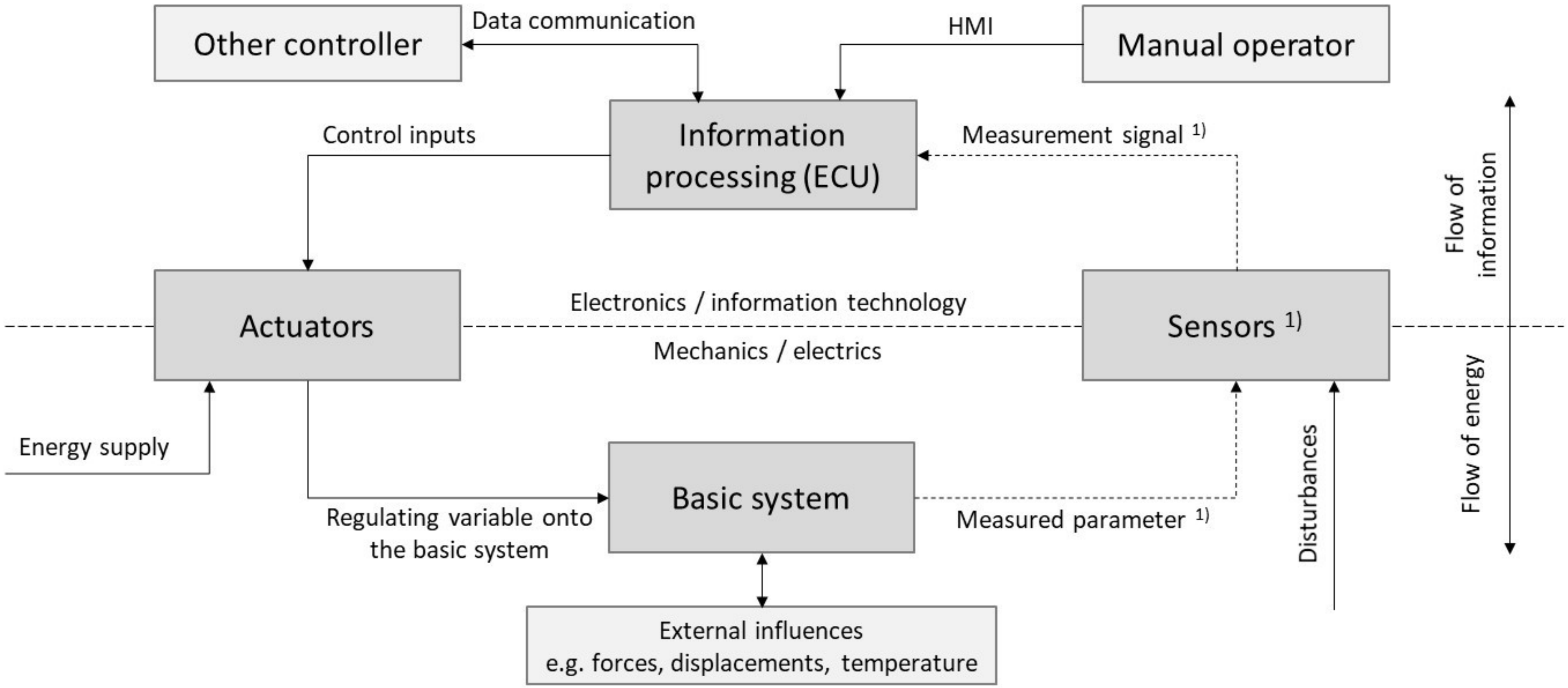
Mechatronics



Why this effort? ➔ Exhaust emissions, performance, stable operation, consideration of changing air pressure / temp. cold start, fail safe (redundant systems)

Source: Trautmann

Components of Mechatronics Systems – Overview



[1] Feedback loop in case of closed-loop control

Embedded Systems

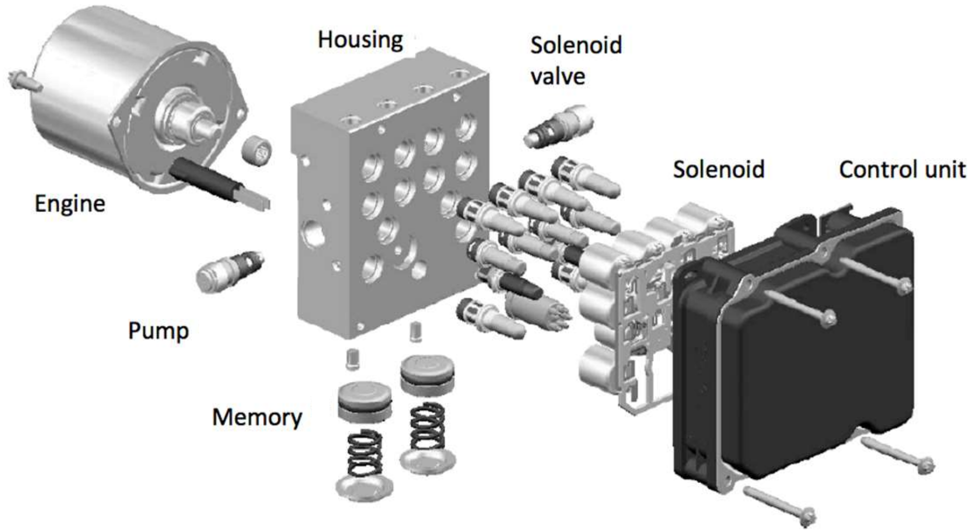
- In embedded systems the control unit (“computer”) is an integral part
- This way, they include control unit, electrical parts (sensors, actuators) as well as mechanical parts (e.g. gears)
- Embedded systems are special-purpose systems, designed to perform one or a few dedicated functions (often in real-time computing and / or as part of distributed systems)
- Can be optimized by reducing the size and costs of the product or increasing the reliability and performance

Example: Electric throttle actuator incl. ECU and mechanical linear transmission.

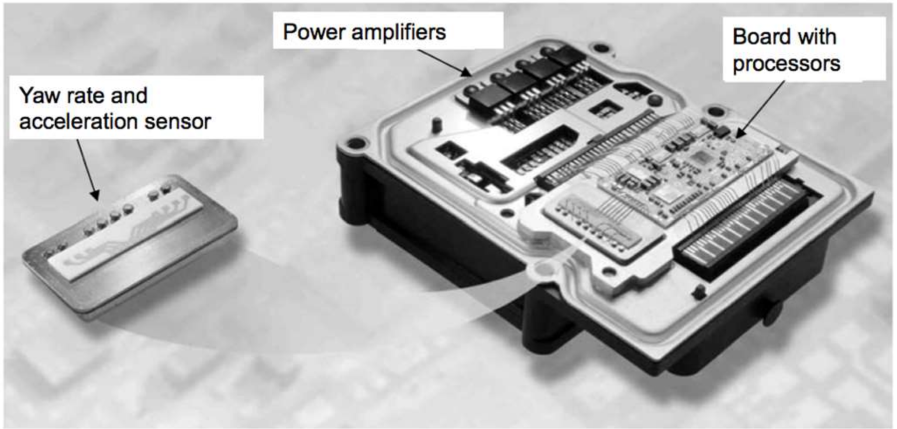
Source: Thomson Linear

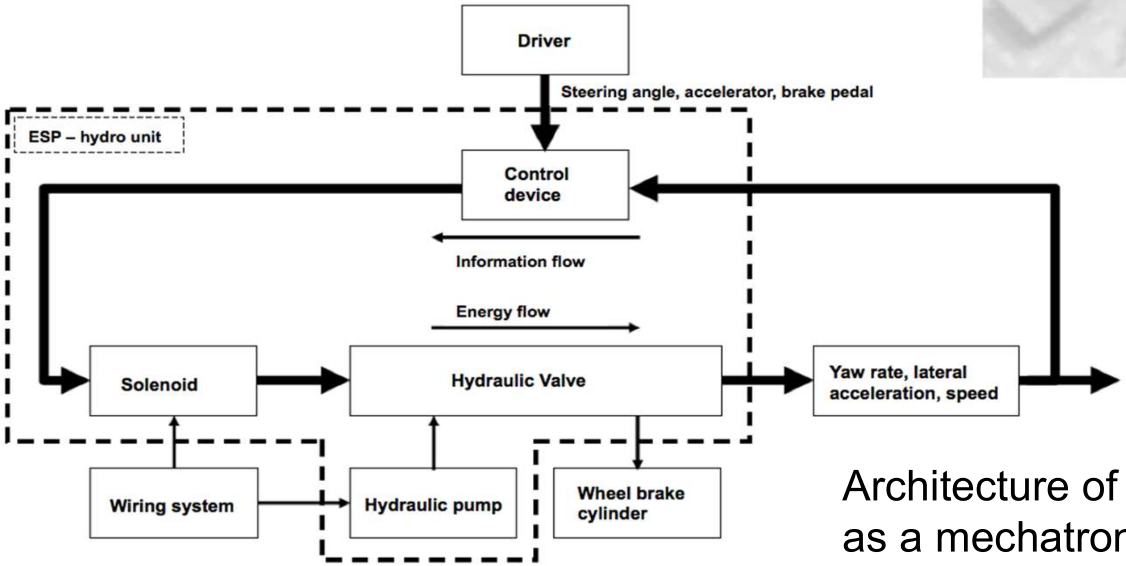
Examples of Automotive Mechatronics Systems:

Electronic Stability Program ESP



ESP unit with integrated sensor module („embedded system“)



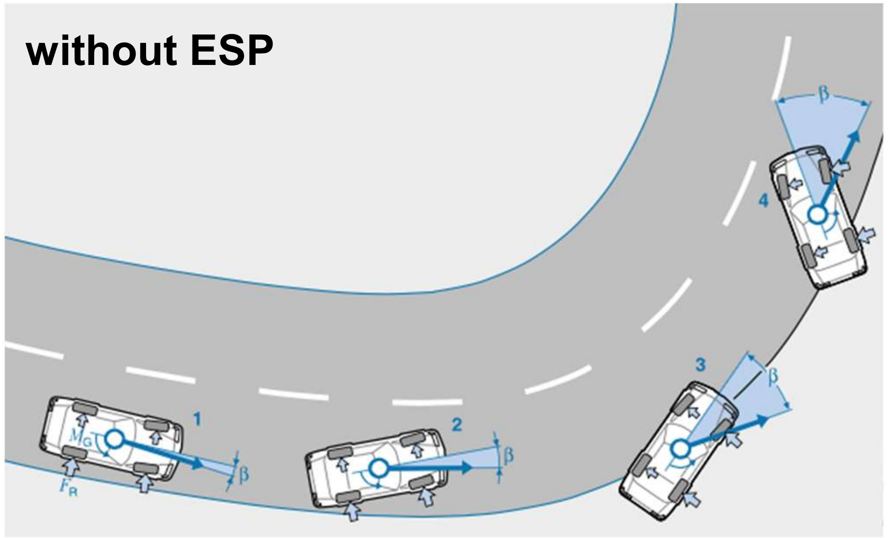


Architecture of ESP as a mechatronical system

Source: Bosch

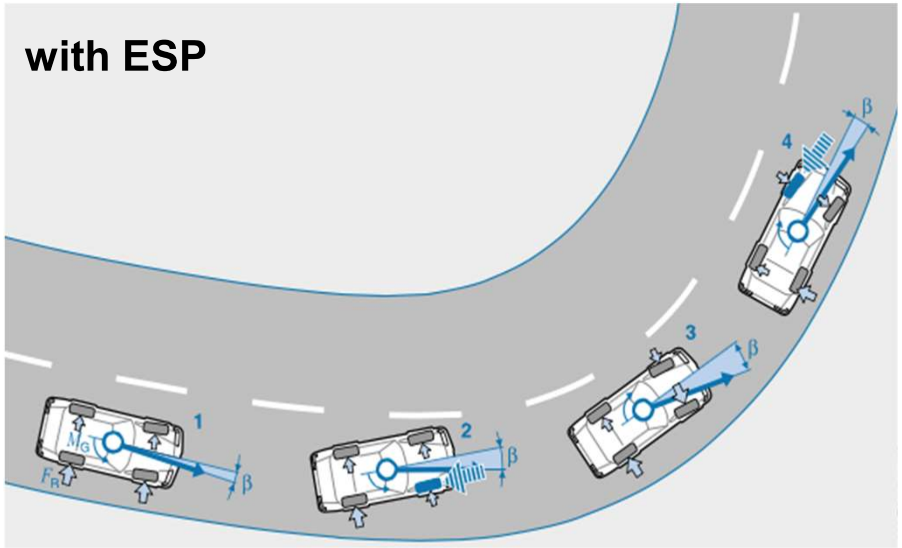
Examples of Automotive Mechatronics Systems:

Electronic Stability Program ESP



1. driver is steering, side force rises
2. threat of instability due to large sideslip angle
3. countersteering, car goes out of control
4. car is no longer under control

M_G … yaw moment
F_R … wheel forces
β … direction deviation of the vehicle longitudinal axis (sideslip angle)



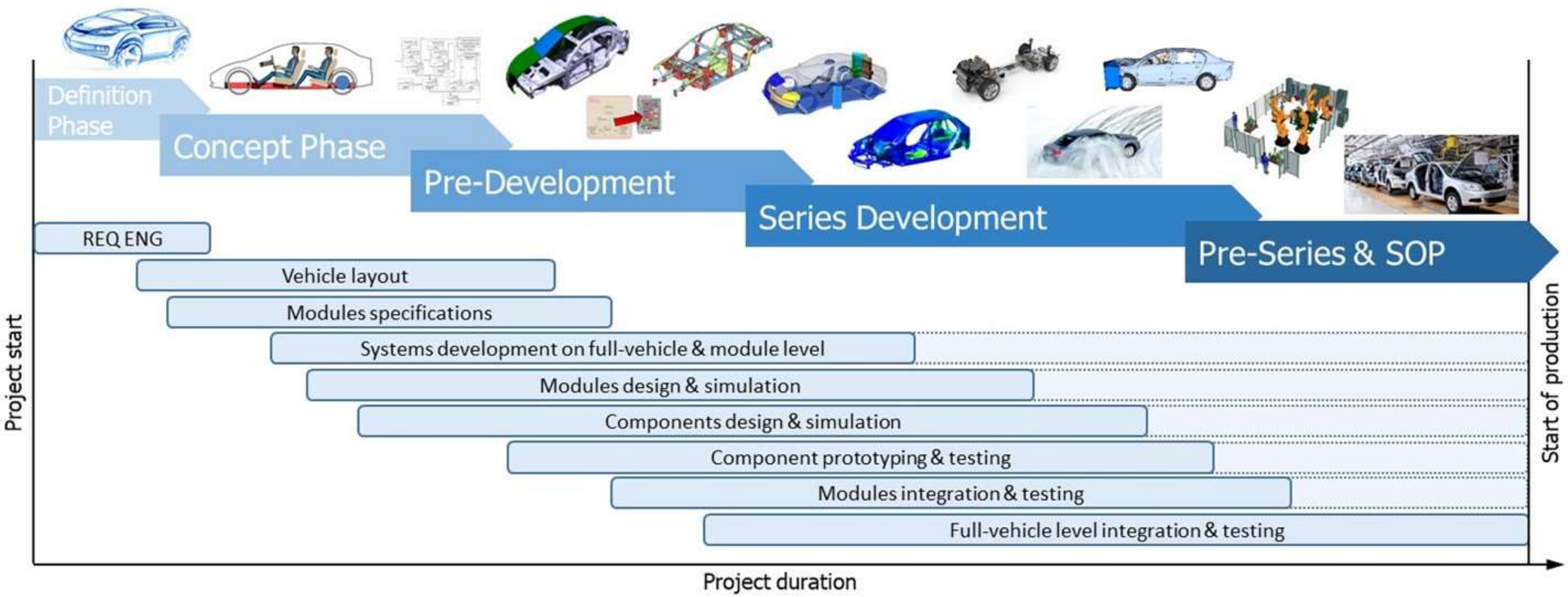
1. driver is steering, side force rises
2. threat of instability, ESP intervention front right
3. car stays under control
4. threat of instability, ESP intervention, front left, complete stabilization

M_G … yaw moment
F_R … wheel forces
β … direction deviation of the vehicle longitudinal axis (sideslip angle)
🡐 … brake force activated

Source: Reif

3. Development Processes

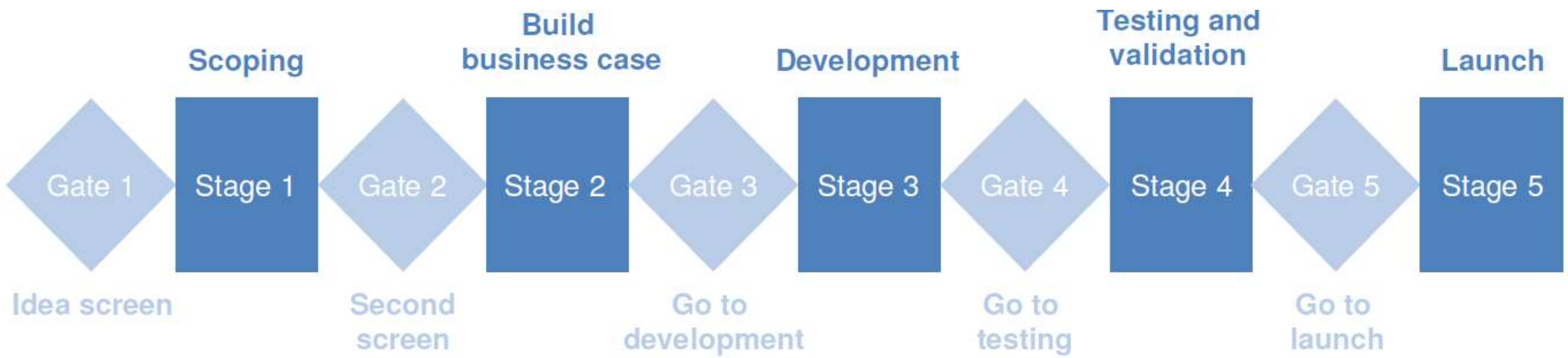
Exemplary Complete Vehicle Development Process



Reduced project times lead to increasingly overlapping of project phases

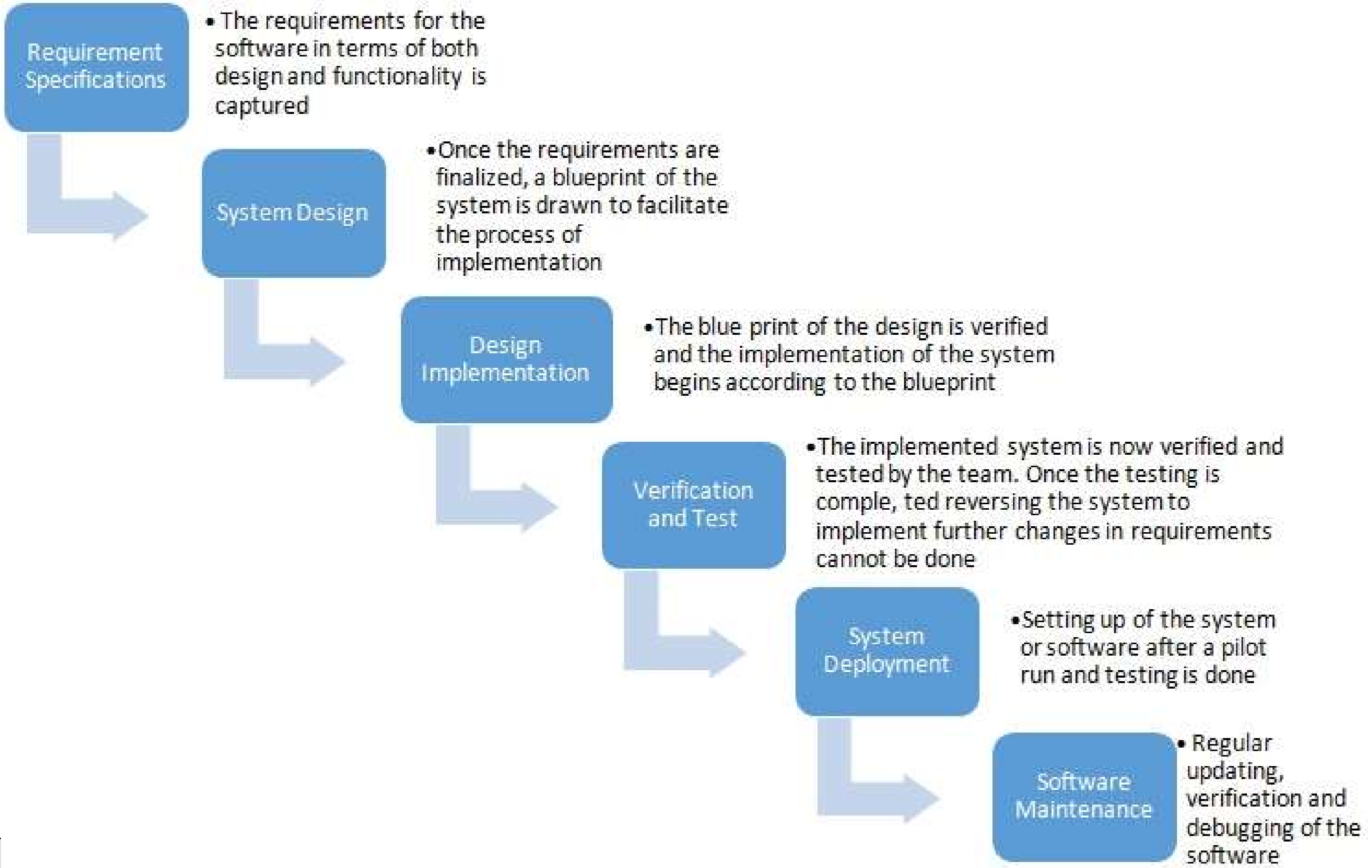
Stage-Gate-Process

- Aim: to provide correct information with the appropriate level of detail to support decisions and the development process.
- Main idea: to break the complex approach down to smaller tasks and introduce gates for decision-making.
- Initial focus (examples)
  - Detection of possible challenges as early as possible.
  - Stronger focus and setting of priorities in early phases.
  - Simplifies parallel process execution in specific stages to reduce development time.



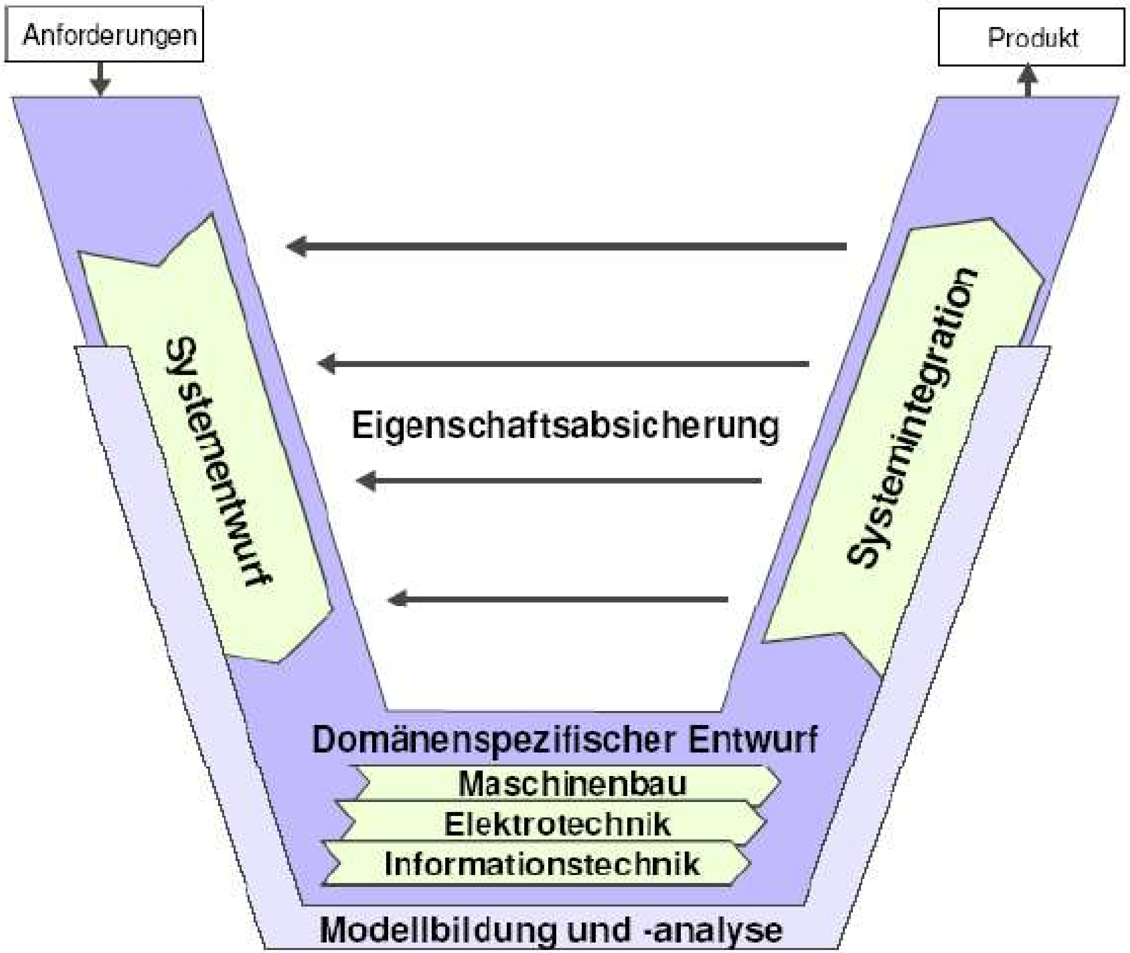
Waterfall Model

- Initially, sequential (non-iterative) design process, used in software development processes.
- Process is separated in phases.
- Each phase result forms the input of the next phase.
- Progress is seen as flowing steadily downwards (like a waterfall).



Development Process according to the V-Model

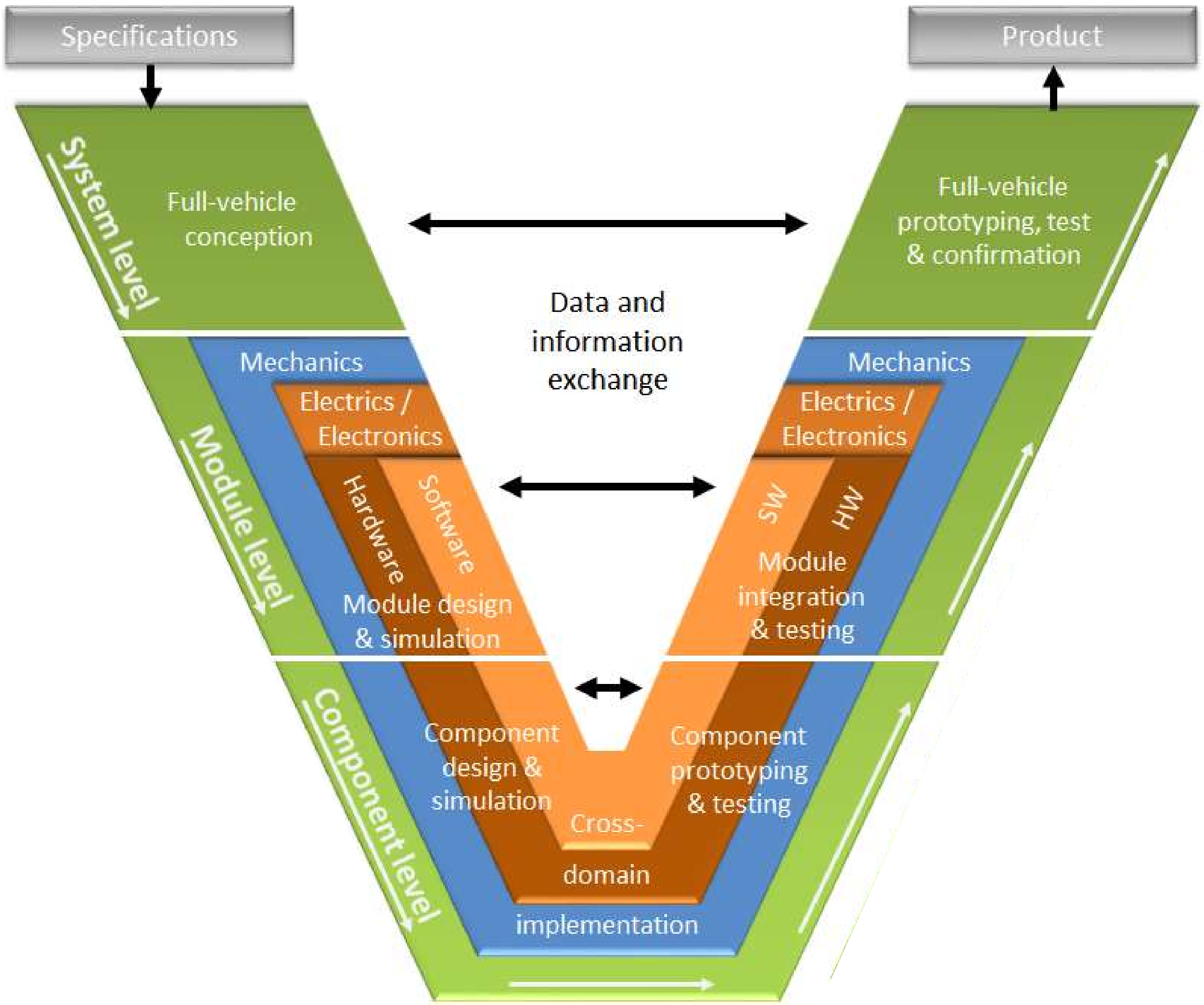
The V-model as a macro cycle according to VDI 2206:
Methodology of development for mechatronics systems



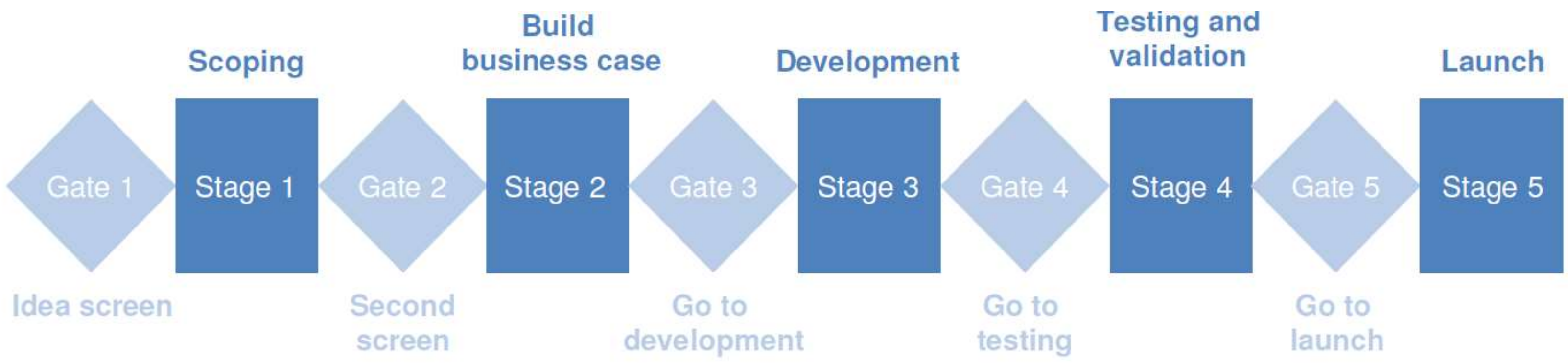
Challenges:

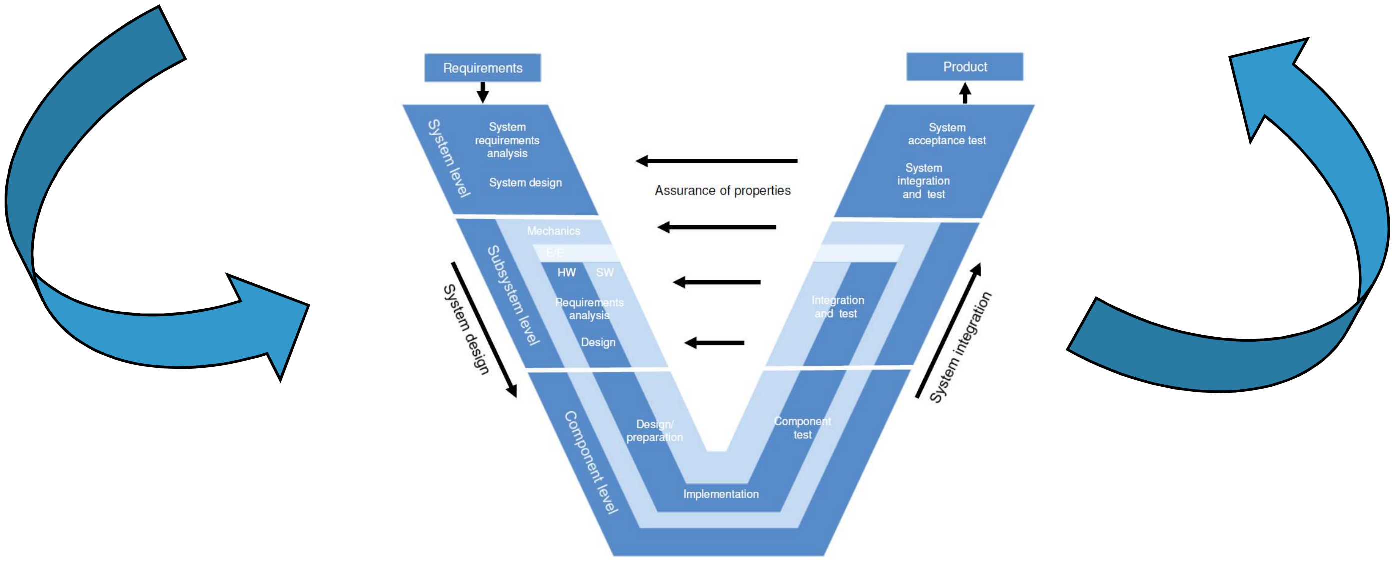
- ➔ Requirements specification
- ➔ Requirements management
- ➔ Communication
- ➔ Data management
- ➔ Data availability
- ➔ Interfaces
- ➔ Documentation
- ➔ Project target realization & confirmation

Mechatronics System Development according to the V-Model



Challenge:
Integration of the V-Model into Stage-Gate-Processes





4. Automated / autonomous driving

Automated driving:

- **Traffic safety**
- **Comfort**
- **Ecological motivations**
- **Mobility for all**
- **Economical motivations**

Source: Eichberger, Bosch

Automated Driving

Development is driven by tech-companies and some car manufacturers

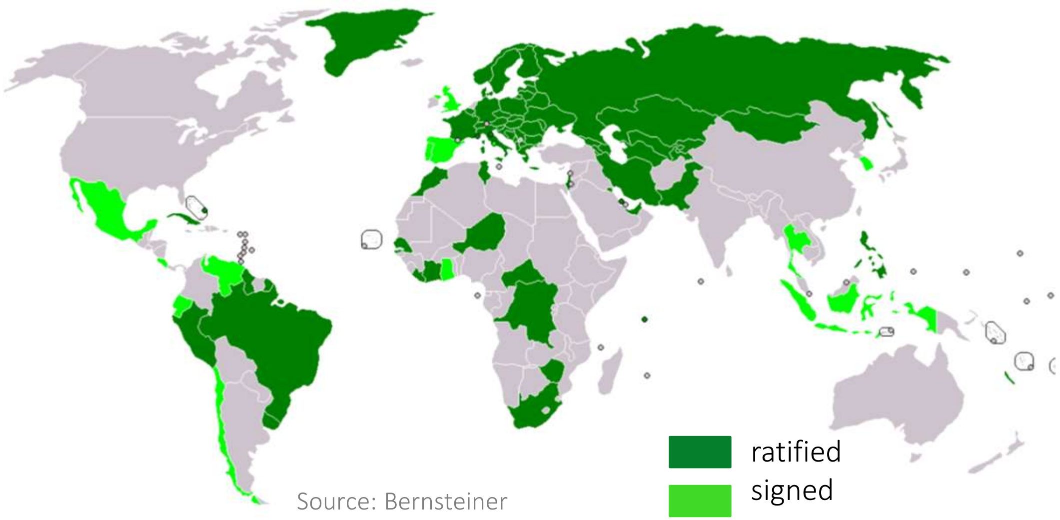
Expectations:

- Big business by increasing comfort, offering new services and having access to customer data
- Increase of safety (very likely) and reduction of traffic (to be discussed)

Challenges:

- Complex task, high technological effort
- Unclear legislative boundary conditions
- Issues in terms of responsibility and ethics questions

Vienna Convention: Driver‘s responsibility

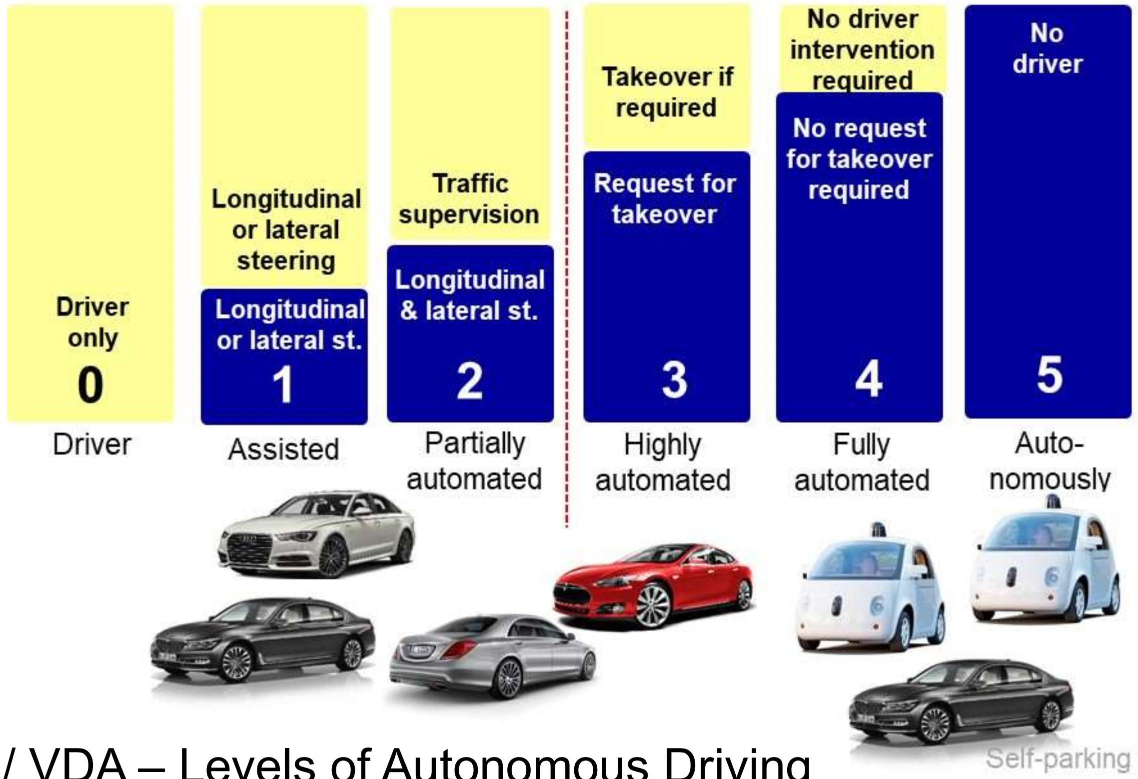


Source: Bernsteiner

Automotive Sensor Systems for Advances Driver Assistance Systems (ADAS)

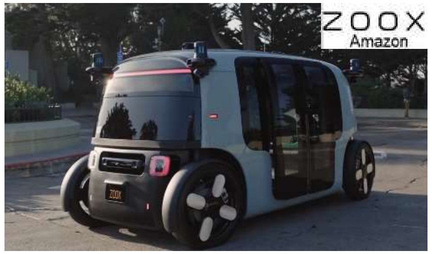
Automotive sensor market doubled within the past 10 years.

Automotive development trends require new sensor technologies, e.g. for advanced propulsion technologies and automated driving.

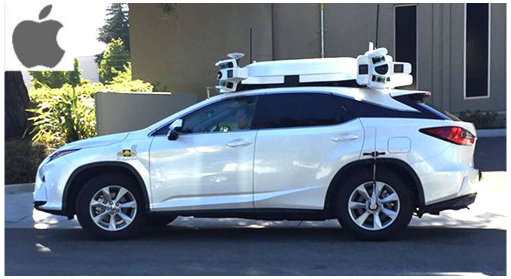


SAE / VDA – Levels of Autonomous Driving

Tech-Companies that Invest in Autonomous Driving, e.g.:



Canoo / Hyundai



… and of course car manufacturers

Tesla: “Autopilot”
in Series => ca. Level 3

New Vehicle Concepts

Example: Zoox

Source: Zoox

… and some Youtube-links:

https://youtu.be/ksyiIqf3HMU
https://youtu.be/B8R148hFxPw
https://youtu.be/g5SeVxYAZzk
https://youtu.be/3r7PEI0tMSk

Autonomous Delivery & Logistics - New Services

Starship Tech

Nuro

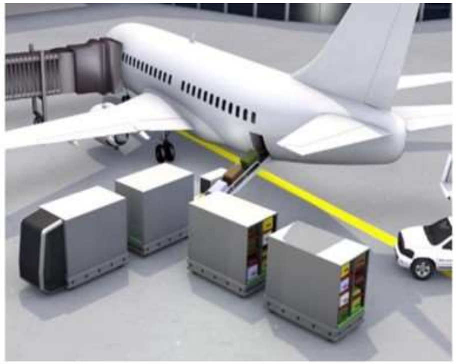
Amazon delivery

PostBot

Drones

Amazon warehouse logistics robots

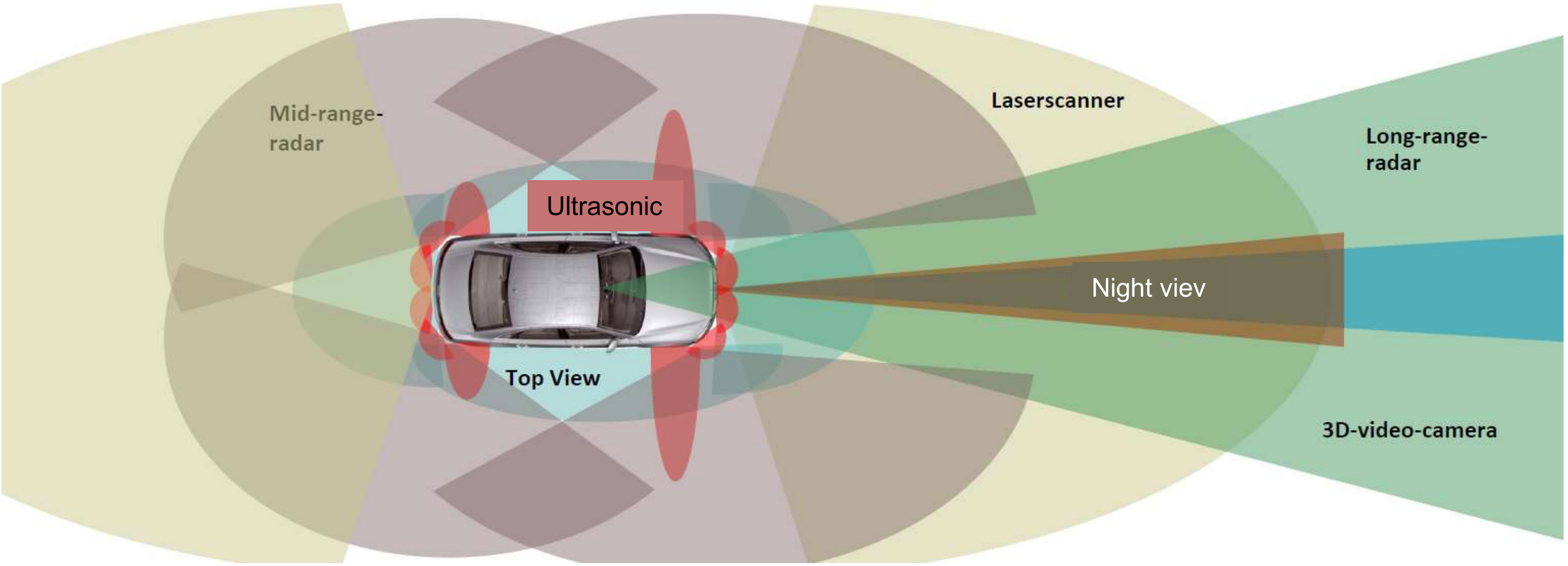
Production logistics robots



Autonomous airport cargo concept

Sources: amazon, KUKA, HET engineering, starship, forbes, wired, theverge, spiegel, dpdhl, amazon, diepresse, engadget, nuro

Sensors for ADAS

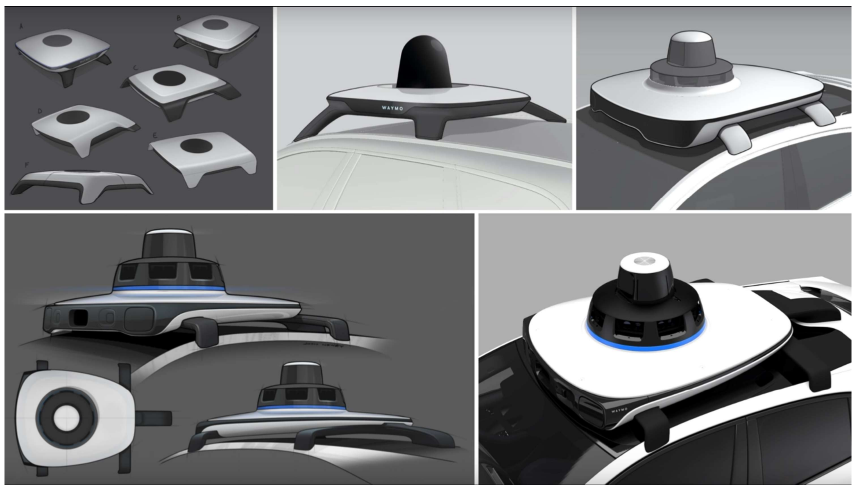


Source: VW, T. Form

- Vision systems
  - *Long Range- & Midrange-Radar, Laser scanner, 3D Video-Camera, Topview-Cameras, Ultrasonic sensors, Infrared (Night view) …*
- On-Board Sensors
  - *e.g. ESP: Lateral acceleration sensors, Wheel speed, Yaw rate, Steering angle, Brake system pressure sensor; … , Ambient temperature, Air pressure, Rain sensor, ...*
- Further sensors / Information sources
  - *Digital maps & GPS, Car2Car, Car2Infrastructure, Car2Home, …*

Waymo Driver Technology

Base vehicle	Ready for the Waymo Driver	Custom-built HW and compute	Waymo Driver application
Base vehicle	**Waymo Driver-ready vehicle**	**The Waymo Driver**	**Final vehicle with the Waymo Driver**
I-PACE (Model Year 2021) Manufactured and sold by Jaguar Land Rover (JLR)	Waymo custom I-PACE configuration built and delivered by JLR	Collections of custom modules that collectively make up the Waymo Driver	Final configuration of the custom vehicle with the Waymo Driver

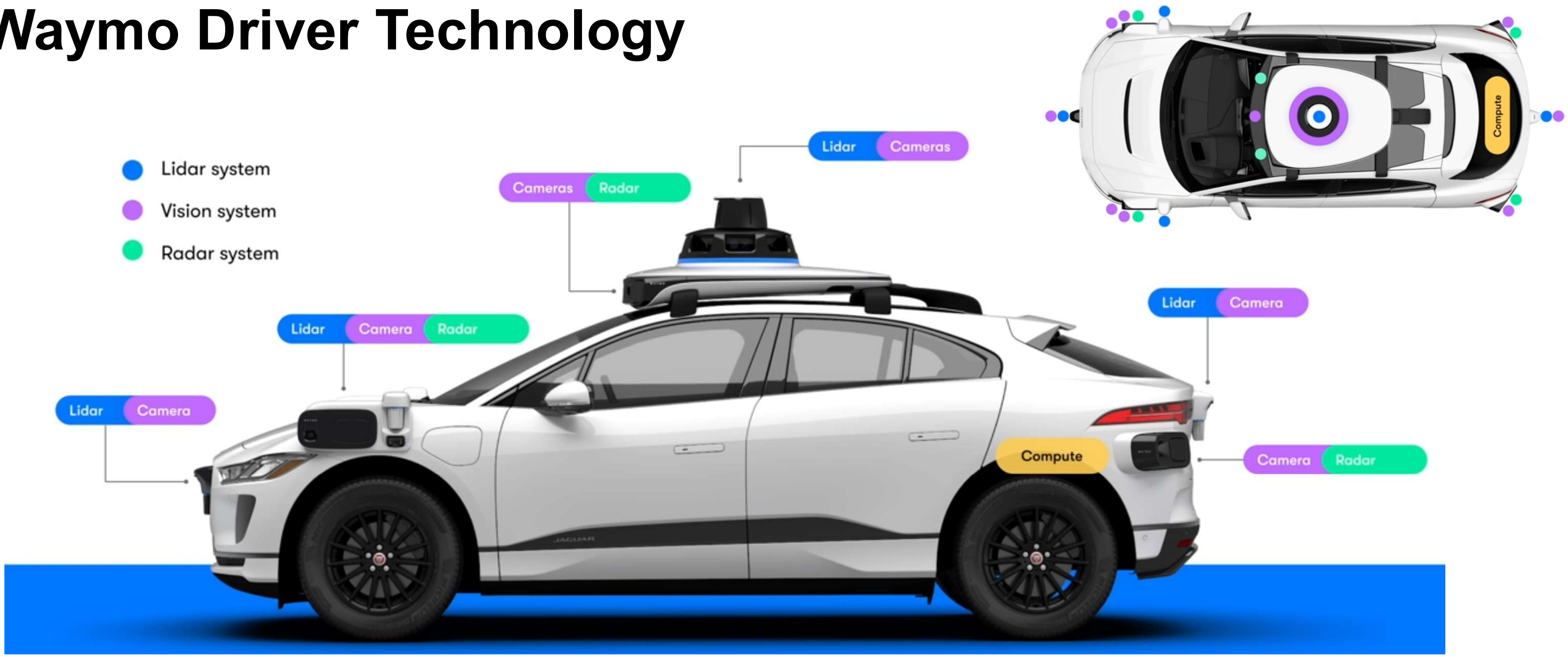


The Waymo Driver

Waymo Driver components

Source: Waymo

Waymo Driver Technology



- 360° Lidar: max. 300m range, day & night applicability
- Perimeter Lidar: objects close to the vehicle
- 29 cameras: high resolution images, overlapping fields, equipped **with cleaning systems and heaters**
- 360° long range cameras > 500m range
- Perimeter cameras ... near field
- Radar: high resolution radars at 6 spots around the car. Complements the cameras and Lidars in bad weather conditions

Source: Waymo

Waymo Driver Technology

Some detail views on the components

Roof unit:
360° Lidar
360° cameras
Long range cameras
2 Radars

Both side units:
Radar, perimeter Lidar, cameras

Front unit: Perimeter Lidar, cameras

Rear side units:
Radar, perimeter Lidar, cameras

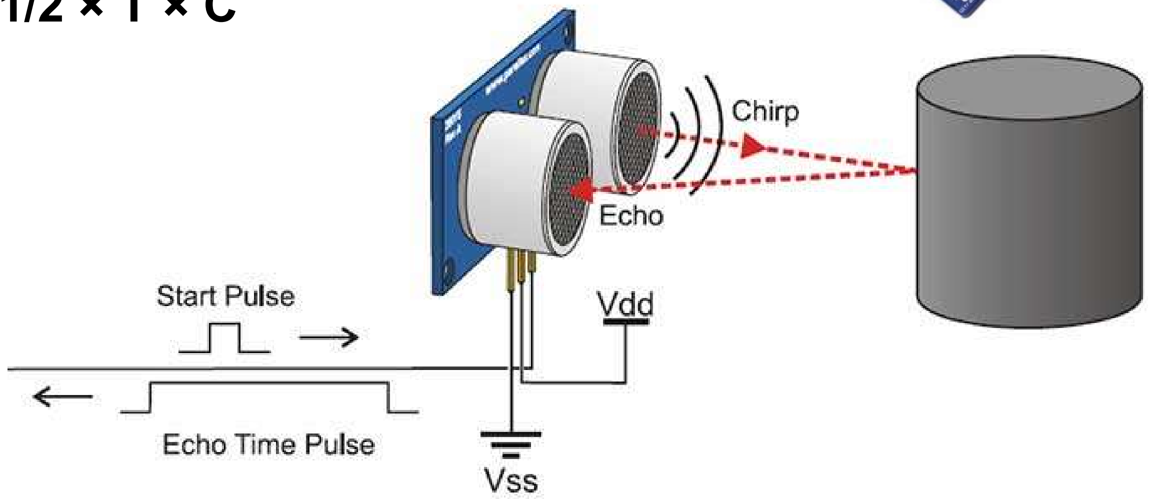
Source: Waymo

Ultrasonic Sensors

- Sound waves with frequencies higher than the upper audible limit of human hearing (about 20 kHz).
- Ultrasonic Module sends out a cycle burst of ultrasound (e.g. at 40 kHz via Transmitter).
- Sound wave in medium with sonic velocity.
- Ultrasonic Module records echo (via Reciever) and **measures time between sending and receiving signal**.
- The distance can be calculated with:

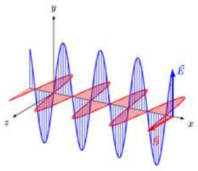
$$\mathbf{L = 1/2 \times T \times C}$$

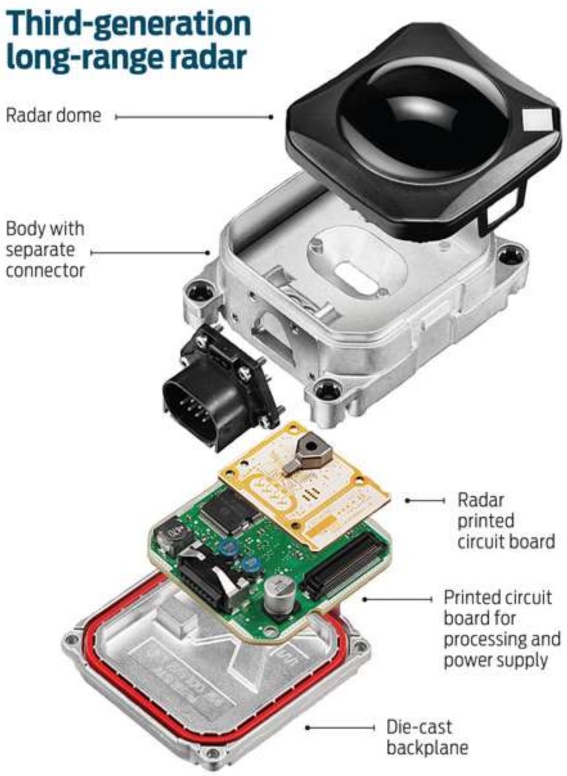
L…distance
T…time between the emission and reception
C…the sonic speed,



RAdio Detecting and Ranging (RADAR)

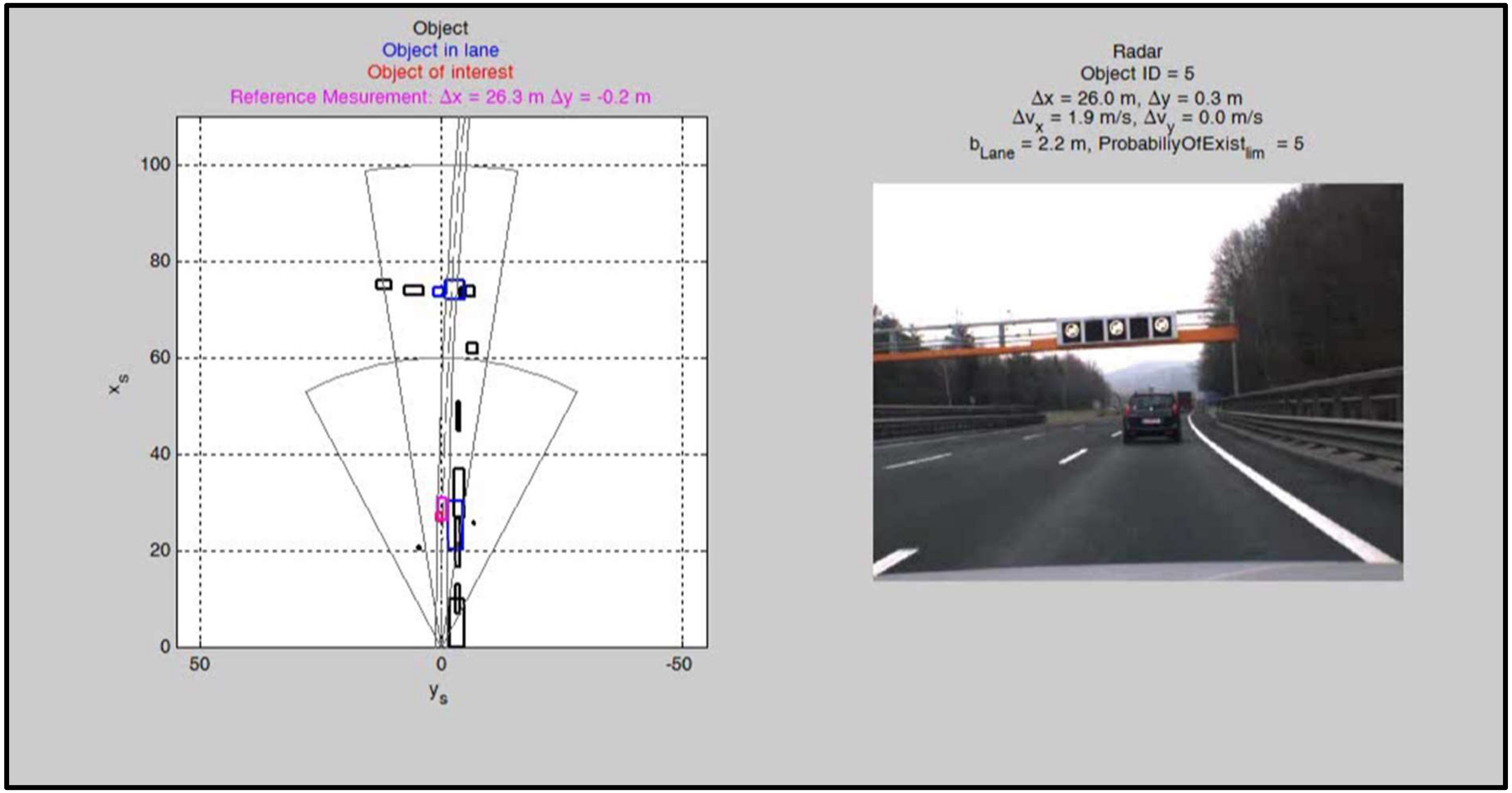
- Radio frequency: 30 Hz → 300 GHz
- Frequency Modulated Continuous Wave (FMCW).
- Radio-frequency (rf) energy is transmitted to and reflected from the reflecting object.
- A small portion of the reflected energy returns to the radar set. This returned energy is called an ECHO, just as it is in sound terminology. Radar sets use the echo to determine the direction and distance of the reflecting object.
- Applicable e.g. for collision avoidance.
- In today's vehicle safety systems, radars are used in conjunction with cameras, ultrasound and other sensors to obtain information about a vehicle's surroundings.
- Using high-level processing technology to facilitate the fusion of this sensor data can lead to improved object identification and decision-making.





Sensors for ADAS

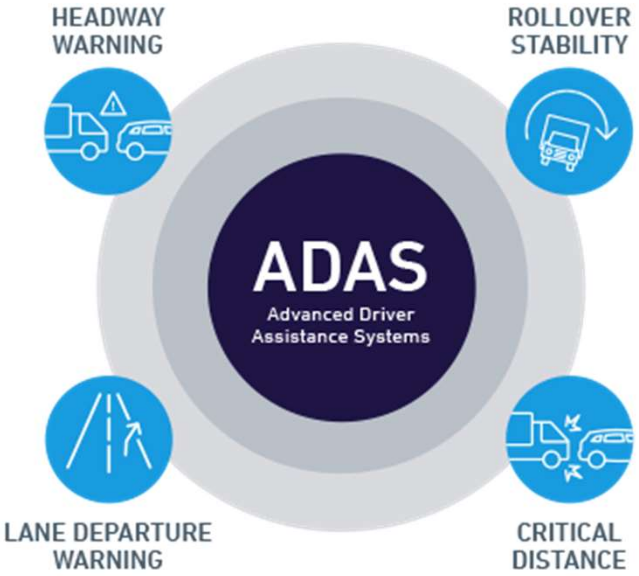
What does a RADAR sensor see?



Source: Bernsteiner

Automotive Cameras

- Cameras are the most precise mechanism available to capture accurate data at high resolution.
- Collect the highest amount of information in relation to e.g. radar, lidar, or ultrasonic
  - Distance, colors, shape, …
- Many of ADAS (Advanced Driver Assistance Systems) applications can be implemented by using a **vision system** with forward, rear, and side mounted cameras for pedestrian detection, traffic-sign recognition, blind spots, and lane-detect systems.



Sensors for ADAS

Published by Tesla
…unclear boundary conditions…

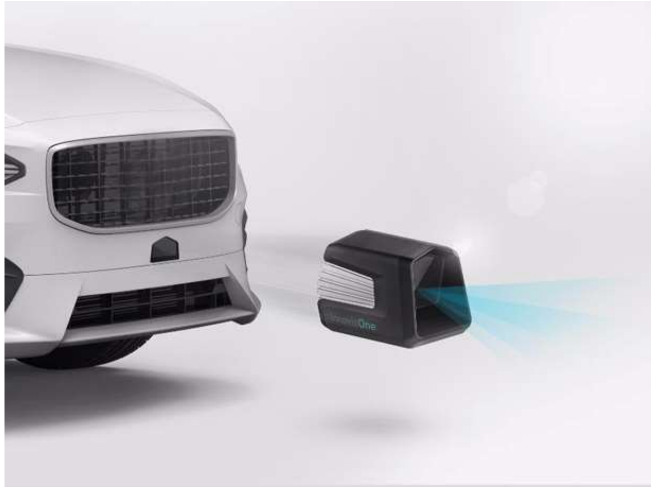
What does a camera – based sensor system see?

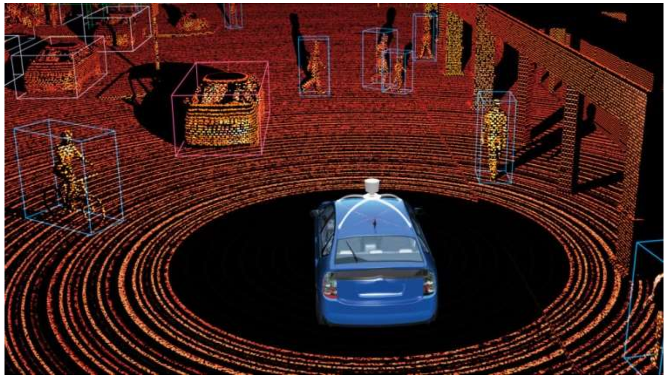
… here is another video (Tesla FSD Beta 10.4, status 11-2021): https://www.youtube.com/watch?v=65gvtEQqTCw

Source: Tesla

LIDAR

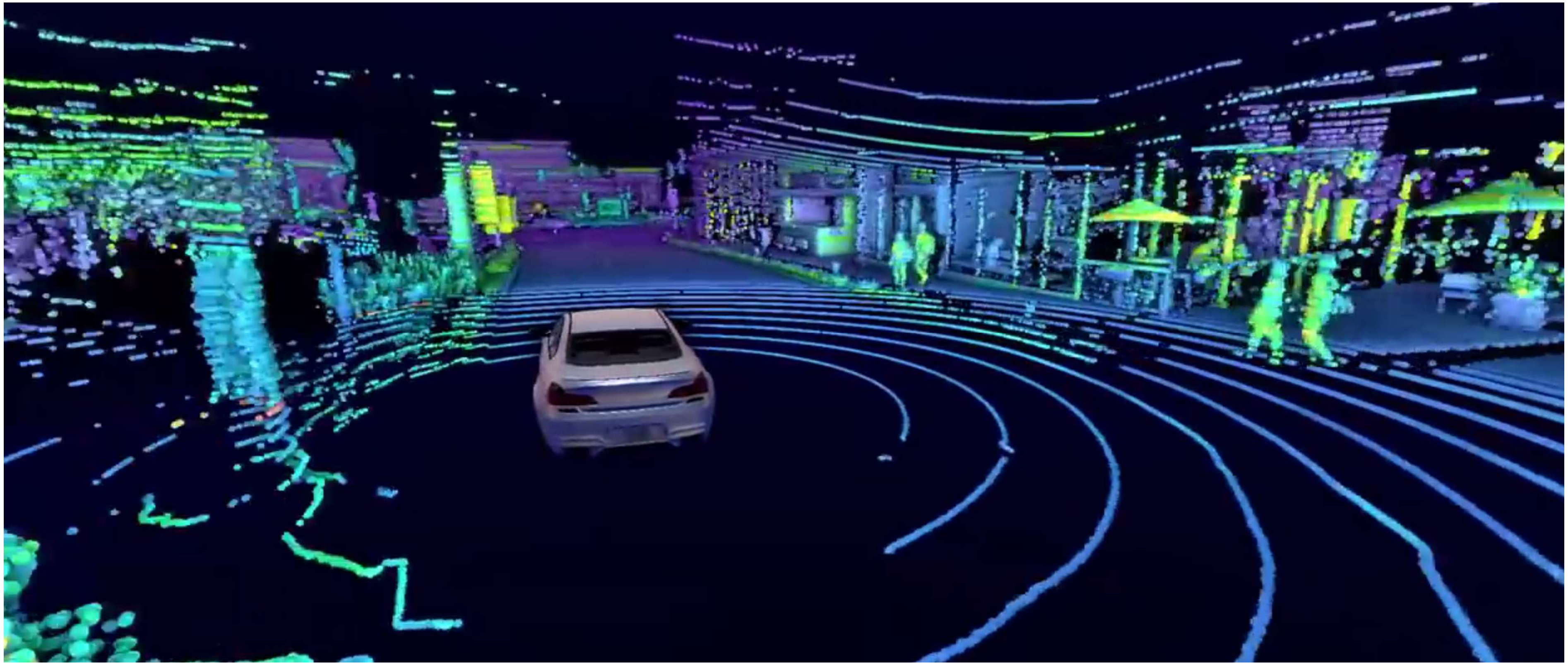
- A LIDAR (Light Detection and Ranging) system is based on the Time of Flight (ToF) method.
- ToF is used to determine the time that a laser pulse needs to overcome a certain distance in a particular medium.
- In the automotive sector, laser pulses with a length of 3 to 20 nanoseconds are used for the ToF method
- The shorter laser pulses provide a better accuracy. LIDAR sensors in the automotive industry can reliably detect objects within ranges of up to 300 meters.





Sensors for ADAS

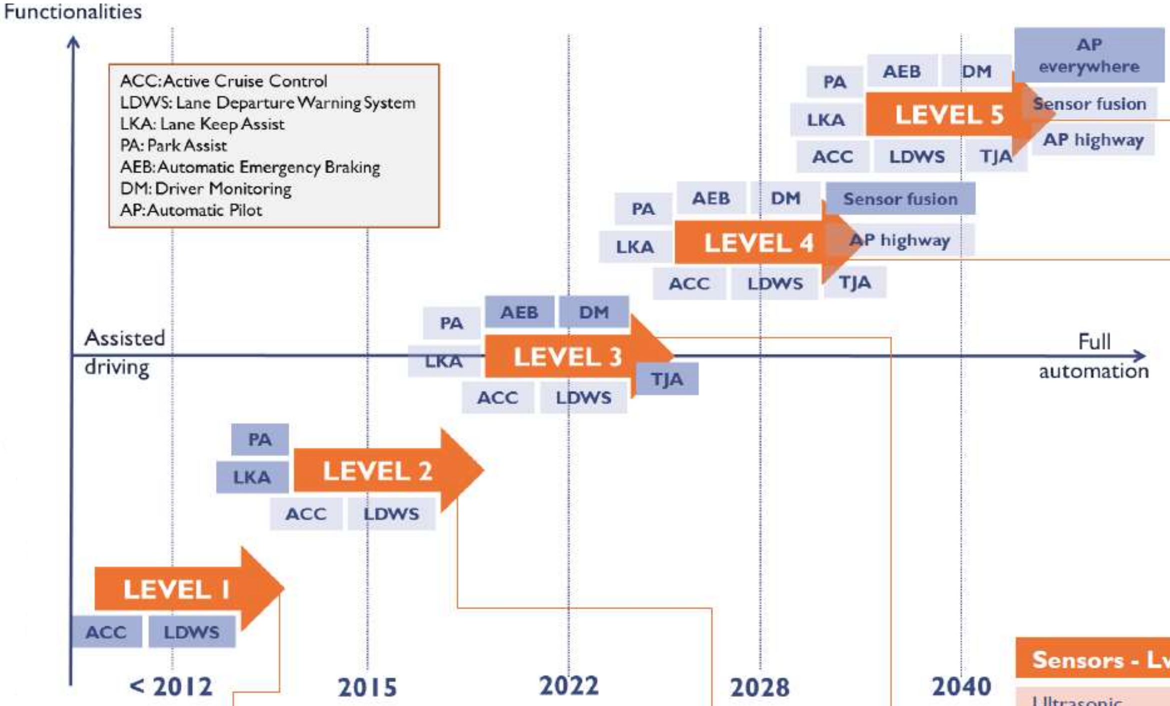
What does a LIDAR*) sensor see?



*) Light Detection and Ranging (Laser – Sensor)

Source: Velodyne

Exemplary Road Map for Different SAE-Levels



Sensors - Lvl 1	#	Cost
Ultrasonic	4	
Radar LRR	1	
Camera for surround	1	
TOTAL	6	

Sensors - Lvl 2	#	Cost
Ultrasonic	8	
Radar LRR	1	
Radar SRR	4	
Camera for surround	4	
TOTAL	17	

Sensors - Lvl 3	#	Cost
Ultrasonic	10	
Radar LRR	2	
Radar SRR	6	
Long distance cam	2	
Camera surround	5	
Stereo camera	1	
µbolo	1	
LIDAR	1	
Dead reckoning	1	
TOTAL	29	

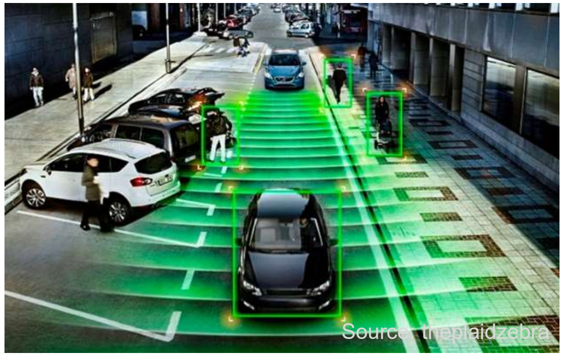
Sensors – Lvl 4	#	Cost
Ultrasonic	10	
Radar LRR	2	
Radar SRR	6	
Long distance cam	2	
Camera surround	5	
Stereo camera	1	
µbolo	1	
LIDAR	1	
Dead reckoning	1	
TOTAL	29	

Sensors – Lvl 5	#	Cost
Ultrasonic	10	
Radar LRR	2	
Radar SRR	6	
Long distance cam	4	
Camera surround	5	
Stereo camera	2	
µbolo	1	
LIDAR	1	
Dead reckoning	1	
TOTAL	32	

Source: MAGNA, Yole Développement, 2017

New Challenges of Complex Safety Development

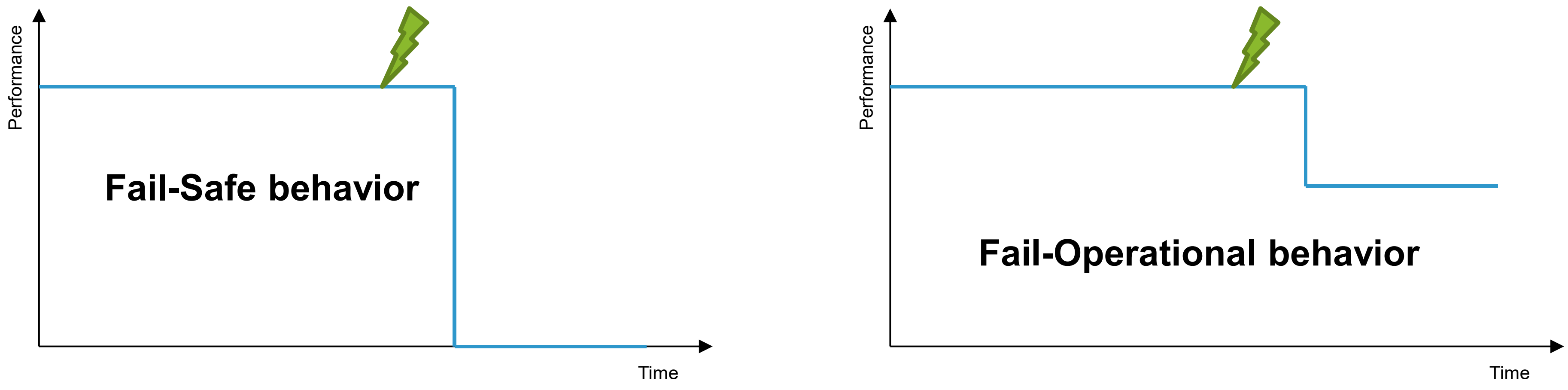

Source: sartre


Source: theplaidzebra


Source: Google

- In general, the errors of the E/E components are the same as in other applications (same behavior and same critically).
- Malfunctions of systems involved in autonomous driving may have high damage impact, because the driver (as corrective instance) is out of the loop.
- => Basic methods of functional safety development (e.g. according to the ISO 26262 have to be enhanced by new approaches.
  - Role of the driver → is not or restricted able to apply corrective measures (risk handling gets more difficult)
  - In case of errors, the systems are not allowed to be switched off → trend to fail-operational systems
  - Correct working systems become more important in view of safe operation → „Safety of the intended function“
  - New security approaches are required (communication)

New Challenges of Complex Safety Development



- Fail-operational systems have to provide relevant functions for a certain (required) duration → a safe state is not a passive state anymore.
- Approach: Combination of robust design and redundant systems
- Challenges:
  - Previous automotive safety standards (e.g. ISO 26262) were intended and developed for fail-safe (not safe operational) systems → modifications are necessary.
  - New solutions are needed, that are able to scope with the boundary conditions of automotive industry (costs, package, weight …).
  - New warning concepts and driver involvement strategies have to be developed.

Source: MAGNA Powertrain, A. Schnellbach

New Challenges of Complex Safety Development Examples

Exemplary weaknesses of sensor systems and SW algorithms

- Misinterpretation of camera sensed pictures e.g. in object recognition algorithms that are in use in camera systems for autonomous driving cars.

Unintended environmental conditions

- e.g. 5000 ducks are crossing a road
- Challenge for automated driving, e.g. object recognition by a camera based system to activate brake. => consideration in sensor system design, SW development and validation (testing)

Thx for your attention!

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