L1.1 Introduction and Overview

Zonghua Gu 2023

Course Logistics

- Course homepage: https://guzonghua.github.io/saav/
- Lectures Mon & Wed 15:30-17:00 via Zoom.
  Link: https://umu.zoom.us/j/62818040552
- Instructor: Zonghua Gu, zonghua.gu@umu.se

My Instruction Style

- No textbook. Will discuss classic techniques as well as latest research advances.
- I provide detailed, self-contained PowerPoint slides.
  - All exam questions come from these slides. Some slides may be verbose for the sake of completeness.
- In-class questions and discussions are welcome. You can either speak up during lecture, or type in the chat window. For questions after class, please use the Canvas discussion board so everyone can see the discussions.
- Lecture videos are recorded and available in UmU Play, so in-class attendance is not mandatory.

Lecture Schedule (Tentative)

- I will put lecture materials here instead of on Canvas. Please bookmark this link
  - https://guzonghua.github.io/saav/ (under construction)
  - Since slides may be updated slightly after each class, it is more convenient to put them here
- Previous course homepages available on https://guzonghua.github.io/saav2022/ and https://guzonghua.github.io/saav2021/
  - Contents updated every year

Grade Distribution

- Final exam (open-book): 60%
- Lab sections: 40%

Three Labs

- Lab1 in W3-4. Adversarial attack on CNN for traffic sign classification
- Lab2 in W7-8. PID control
- Lab3 in W9-10. Planning for Highway Driving with DQN RL
- https://github.com/guzonghua/saavlabs

Details of Labs

- We will keep the programming workload relatively low, e.g., you may be given a semi-complete program, and asked to tune some hyper parameters, or fill in a few lines of missing code (no large-scale coding)
- We will keep the computing demands low, so you can use Google Colab, or work on your own computer without powerful GPUs. (Programming language is Python.)

Final Exam Format

- Multiple choice questions, e.g.
  - Which path planning algorithm(s) are guaranteed to find the optimal solution?
  - A. A* algorithm
  - B. Rapidly-exploring Random Tree (RRT)
  - C. Probabilistic Roadmap (PRM)
  - D. All of them
  - E. None of them
- Simple calculation questions, e.g.,
  - Convolutional Neural Networks I
  - Input volume: 56×56×64 ($W1$=$H1$=$N1$=56,$D1$=64). 32 1×1×64 filters (K=32,F=1) w. stride S=1, no pad P=0. Show the formulas and calculation process.
  - 1) Calculate the dimensions of the output volume, including spatial size and depth.
  - 2) Calculate the total number of parameters, including weights and biases.

Pass or Fail?

- In the past, the vast majority of students pass the course, if they put in reasonable effort
- The course workload is not very high. Most students manage it quite well
  - Use the anonymous feedback link to provide comments on course pace, level of difficulty, etc.

Today's Agenda

- I will give a broad overview of the major issues involved in AD.
  - Background
  - Sensors and perception
  - HD maps
  - Hardware platforms
  - Software platforms
  - V2X
  - Ethical Issues

Autonomous Vehicles (AVs)

- Can refer to any type of Autonomous Mobile Robot.
  - Not just Self-Driving Cars (SDCs)
- Many techniques for SDCs covered in this course are generally applicable to other types of AVs.

Self-Driving Cars

Drones

Warehouse Robots

Indoor-Cleaning Robots

Why AD?

- Reduced traffic accidents and fatalities
  - In the USA: in 2019, an estimated 38,800 people lost their lives to car crashes. About 4.4 million people were injured seriously enough to require medical attention in crashes.
- Reduced congestion and pollution
- More productive time spent on the road
- Autonomous Mobility-on-Demand (AMoD) with a fleet of AVs
  - Low-cost, safe and efficient mode of transportation that may make vehicle ownership obsolete.
  - The dream of Uber (and many other companies)

Advanced Driver Assistance (ADAS)

- Since the initial introduction of Cruise Control in 1948, ADAS functions are increasingly prevalent in modern vehicles.
  - Adaptive cruise control (ACC), Anti-lock braking system, Collision avoidance system (Pre-crash system), Driver Monitoring System (DMS), Electronic Stability Control (ESC), Forward Collision Warning (FCW), Lane Departure Warning (LDW), Lane Change Assistance, Surround View…

https://en.wikipedia.org/wiki/Advanced_driver-assistance_systems

DARPA Grand Challenge (2004)

- Held in the Mojave Desert region of the USA, along a 150-mile route.
- None of the robot vehicles finished the route. Carnegie Mellon University's Red Team and car Sandstorm (a converted Humvee) traveled the farthest distance, completing 7.32 mi of the course before getting hung up on a rock after making a switchback turn.
- No winner was declared, and the cash prize was not given.

DARPA Grand Challenge (2005)

- Vehicles passed through three narrow tunnels and negotiated more than 100 sharp left and right turns.
- Five vehicles successfully completed the 132 mi course. Stanford's Stanley won the $2M top prize.

Vehicle	Team Name	Team Home	Time Taken (h:m)	Result
Stanley	Stanford Racing Team	Stanford University, Palo Alto, California	6:54	First place
Sandstorm	Red Team	Carnegie Mellon University, Pittsburgh, Pennsylvania	7:05	Second place
H1ghlander	Red Team		7:14	Third place
Kat-5	Team Gray	The Gray Insurance Company, Metairie, Louisiana	7:30	Fourth place
TerraMax	Team TerraMax	Oshkosh Truck Corporation, Oshkosh, Wisconsin	12:51	Over 10-hour limit, fifth place

DARPA Urban Challenge (2007)

- Held at the site of the now-closed George Air Force Base. The course involved a 60 mi urban area course, to be completed in less than 6 hours. Rules included obeying all traffic regulations while negotiating with other traffic and obstacles and merging into traffic.
- The 3 Grand Challenge races jump-started the Self-Driving Car industry. Faculty and students from winning teams such as Stanford and CMU later became leaders in SDC projects at companies like Google/Waymo and Uber and numerous startups.

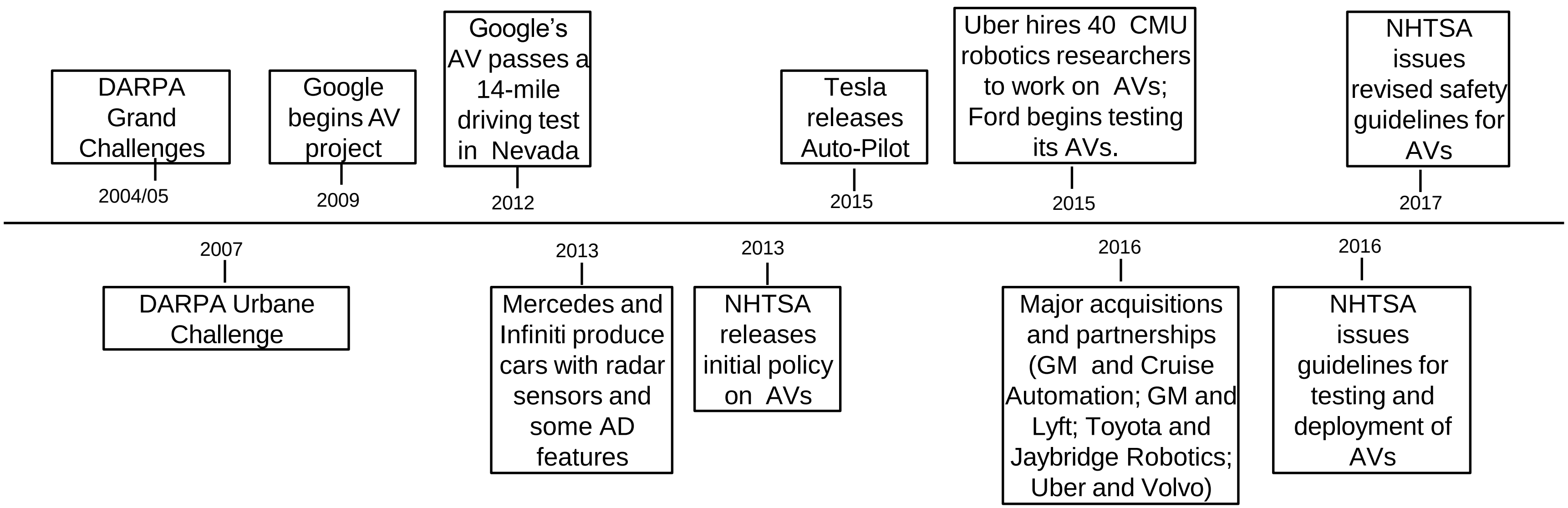
Team Name	ID#	Vehicle	Type	Team Home	Time Taken (h:m:s)
Tartan Racing	19	Boss	2007 Chevy Tahoe	Carnegie Mellon University, Pittsburgh, Pennsylvania	4:10:20
Stanford Racing	03	Junior	2006 Volkswagen Passat Wagon	Stanford University, Palo Alto, California	4:29:28
VictorTango	32[11]	Odin	2005 Ford Hybrid Escape	Virginia Tech, Blacksburg, Virginia	4:36:38
MIT	79	Talos	Land Rover LR3	MIT, Cambridge, Massachusetts	Approx. 6 hours
The Ben Franklin Racing Team	74	Little Ben	2006 Toyota Prius	University of Pennsylvania, Lehigh University, Philadelphia, Pennsylvania	No official time.
Cornell	26	Skynet	2007 Chevy Tahoe	Cornell University, Ithaca, New York	No official time.

Highway vs. City Driving

- Highway driving is perceived as an easier problem than city driving.
  - Has potential of massive displacement of truck driver jobs
  - But traffic merging is tricky and may require human operator assistance

	Highway Driving	**City Driving**
Travel Speed	High	Low to medium
Traffic Volume	High	Medium to high
Number of Lanes	Large (6-8)	Small (2-4)
Others	Entry and exit points for traffic merging	Many intersections with traffic lights

Brief History of AVs



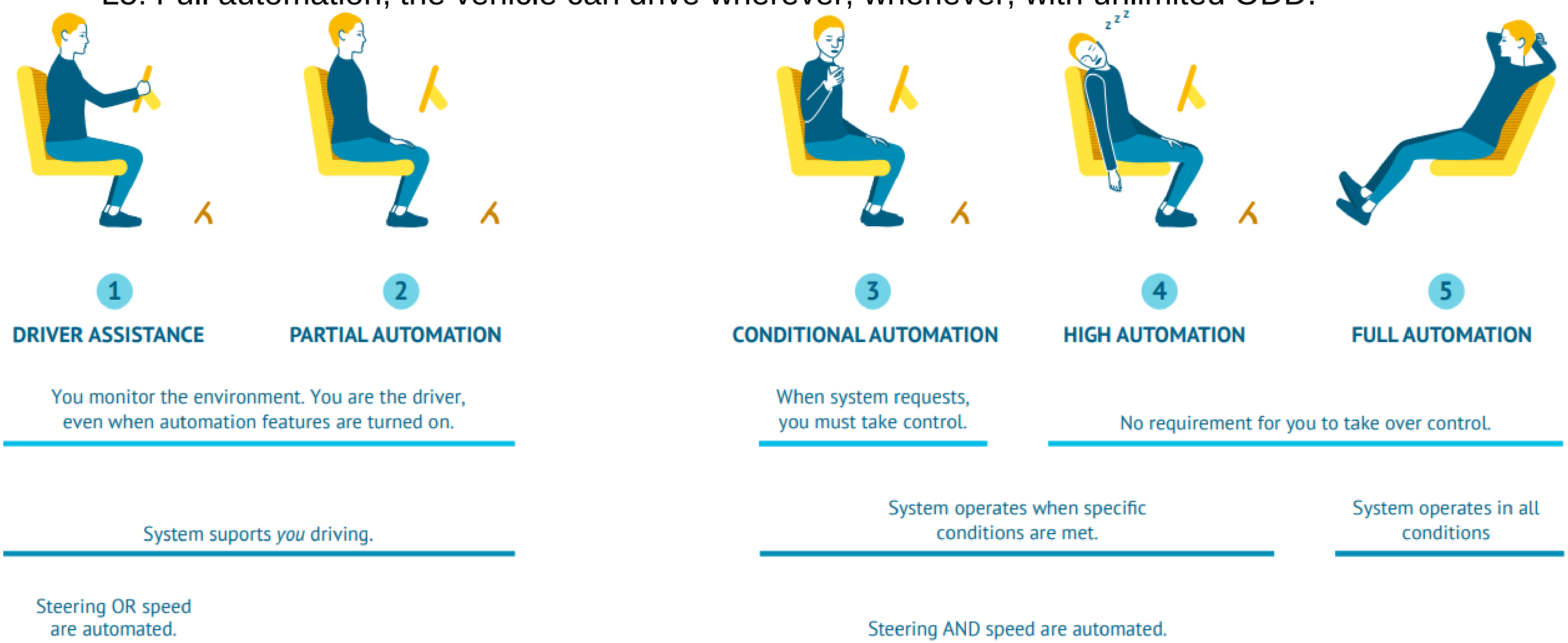
https://www.mcca.com/wp-content/uploads/2018/04/Autonomous-Vehicles.pdf

Operational Design Domain (ODD)

- The ODD defines the conditions under which a vehicle is designed to function and is expected to perform safely. The ODD includes (but isn’t limited to) environmental, geographical, and time-of-day restrictions, as well as traffic or roadway characteristics.
  - e.g., an autonomous freight truck might be designed to transport cargo from a seaport to a distribution center 30 Km away, via a specific route, in day-time only. This vehicles ODD is limited to the prescribed route and time-of-day, and it should not operate outside of it

Five Levels of Automation

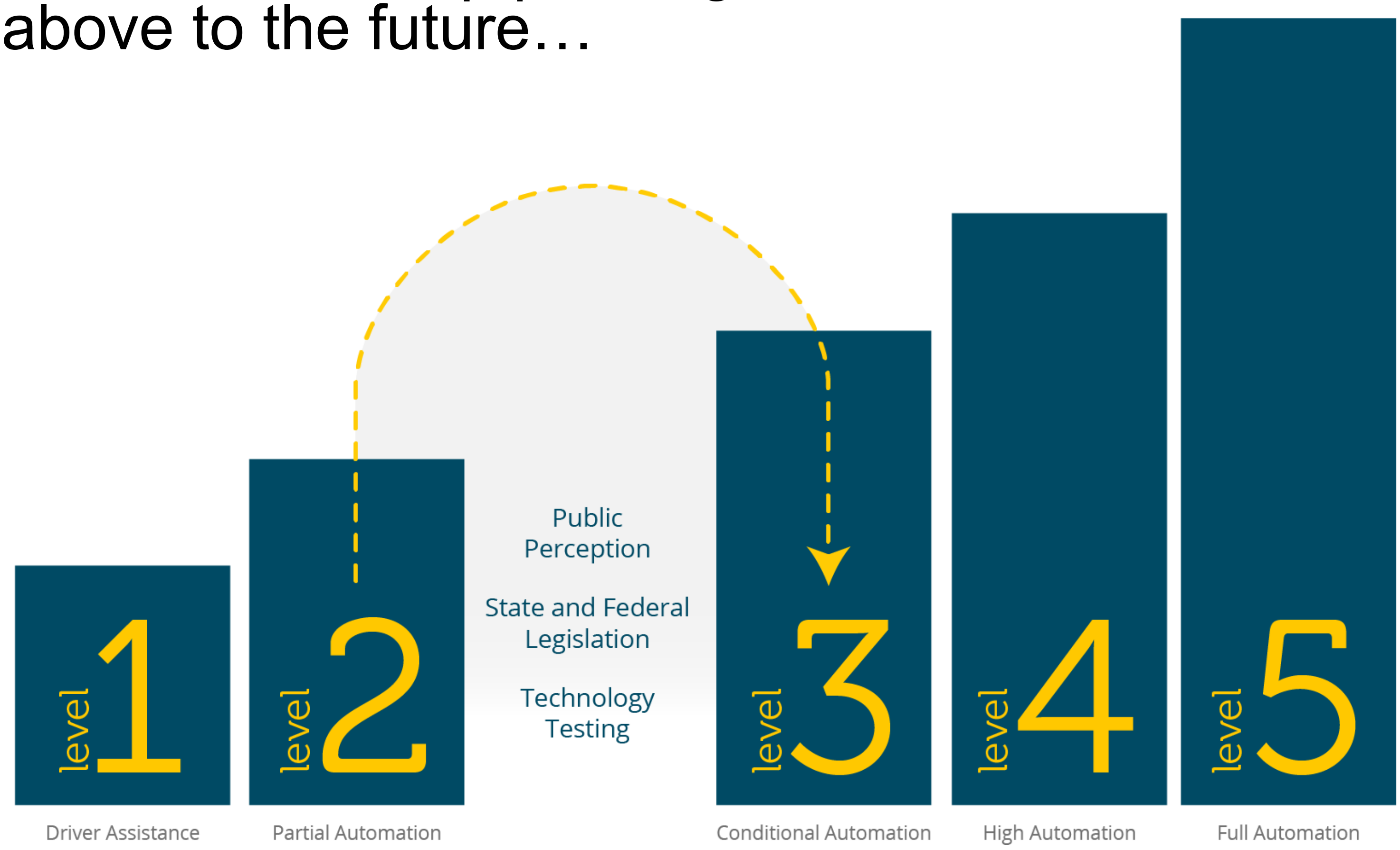
- L1: ADAS features that either control steering or speed to support the driver.
- L2: both steering and acceleration are simultaneously handled by AD system. The human driver still monitors the environment and supervises the support functions.
- L3: Conditional automation: the system can drive without the need for a human to monitor and respond. However, the system might ask a human to intervene, so the driver must be able to take control at all times.
- L4: These systems have high automation and can fully drive themselves under certain conditions. The vehicle won’t drive if not all conditions are met.
- L5: Full automation, the vehicle can drive wherever, whenever, with unlimited ODD.



https://www.wevolver.com/article/2020.autonomous.vehicle.technology.report

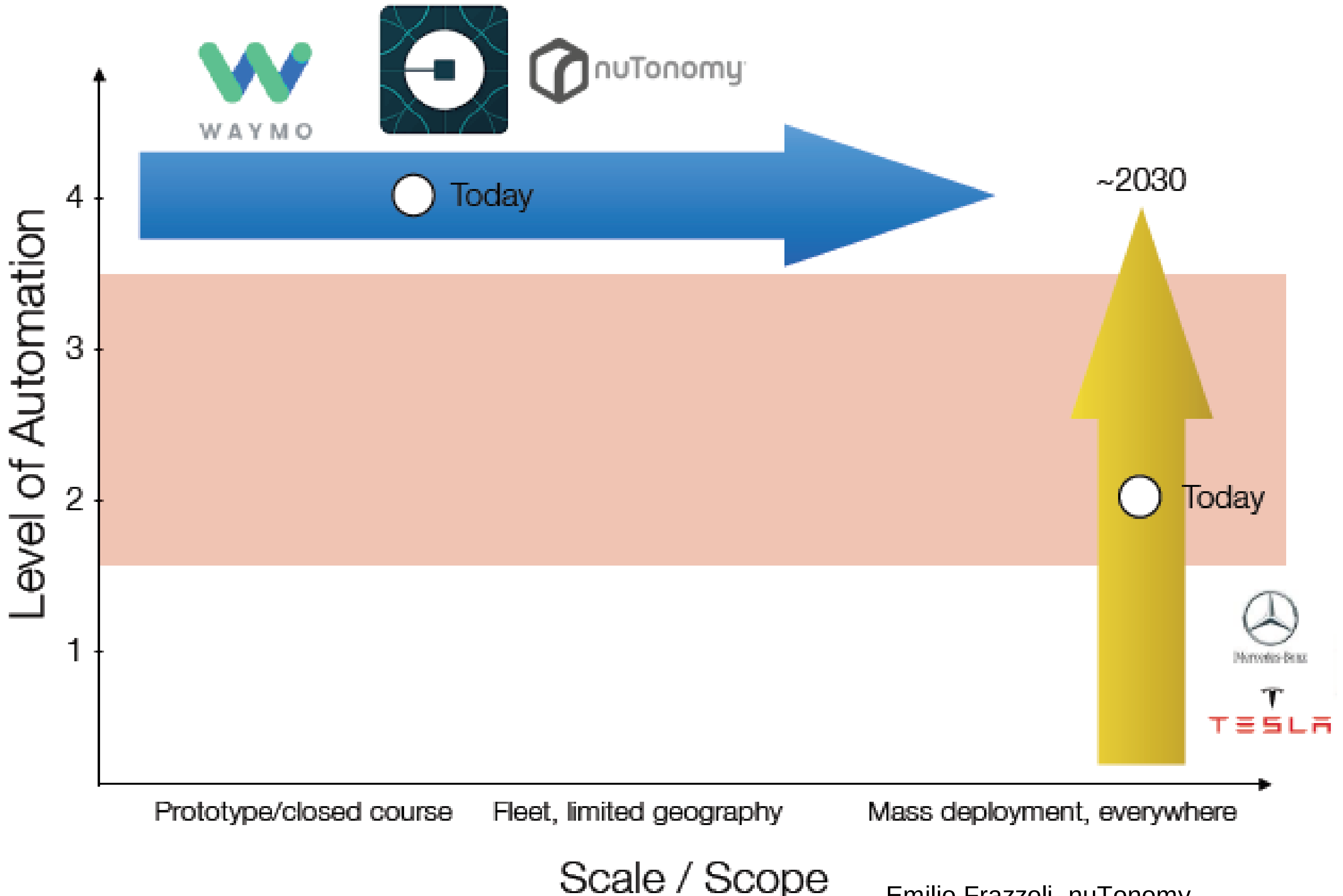
State of the Art

- Current commercial products are at most L2 (e.g., Tesla Autopilot)
- L2 to L3 is perceived to be a giant leap
- Automakers keep pushing the timeline of L3 and above to the future…



Two Different Paths to L4/5

- Tesla starts from L2 and mass deployment, and gradually moves to L4/5.
- Waymo, nuTonomy…starts from L4 in limited ODD, and gradually expands deployment



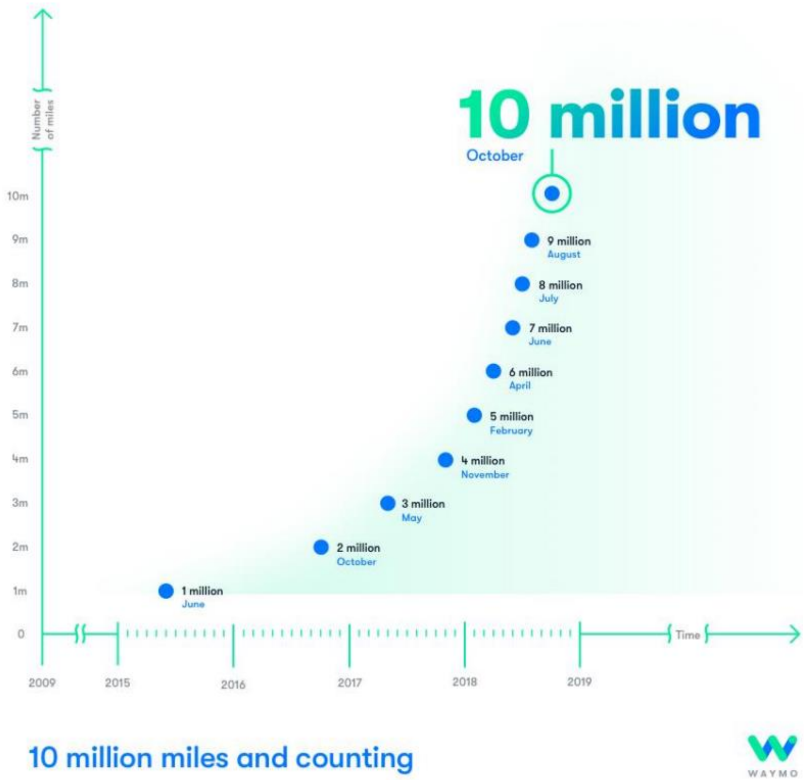
AD Safety Evaluation Metric: Miles Driven?

- Not All Miles are Equal.
  - Driving conditions may be dramatically different.
  - Companies may be incentivized to avoid difficult driving conditions.

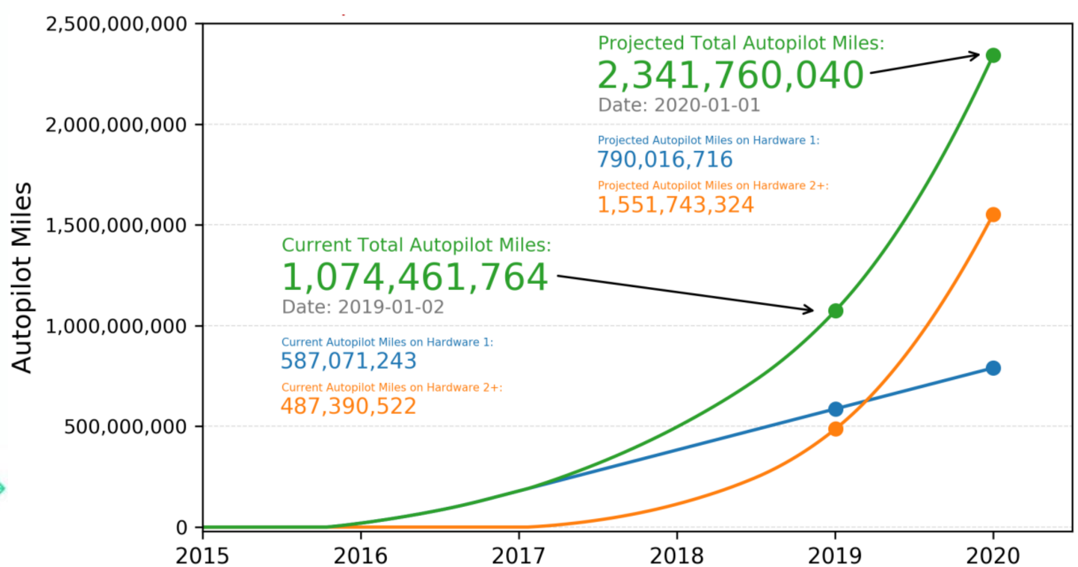
Miles driven here

Not the same as here

Total Miles Driven

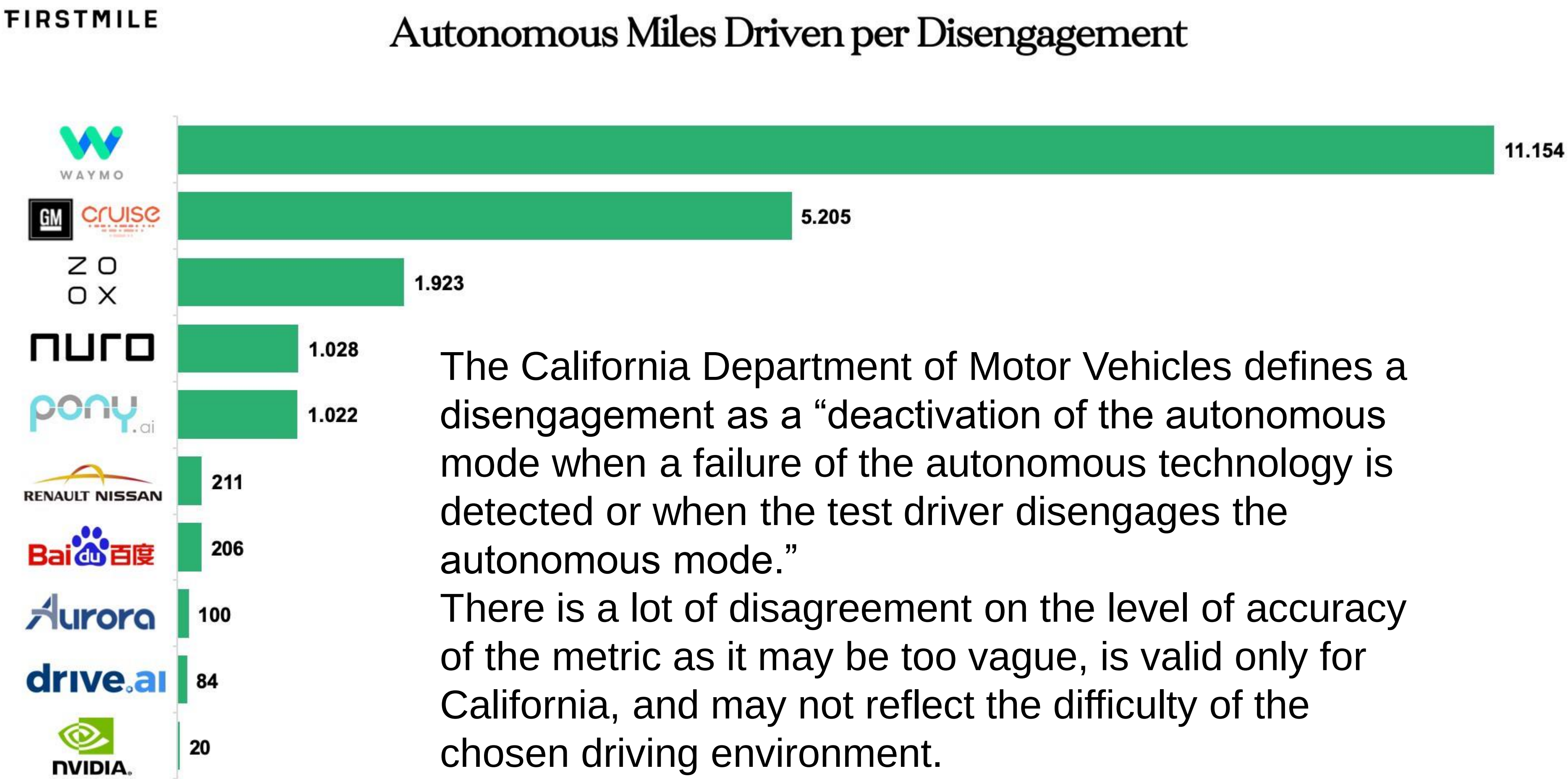


Waymo Reaches 10 Million Miles



Tesla Autopilot Reaches 1 Billion Miles in 2019

Miles Driven per Disengagement (2018)



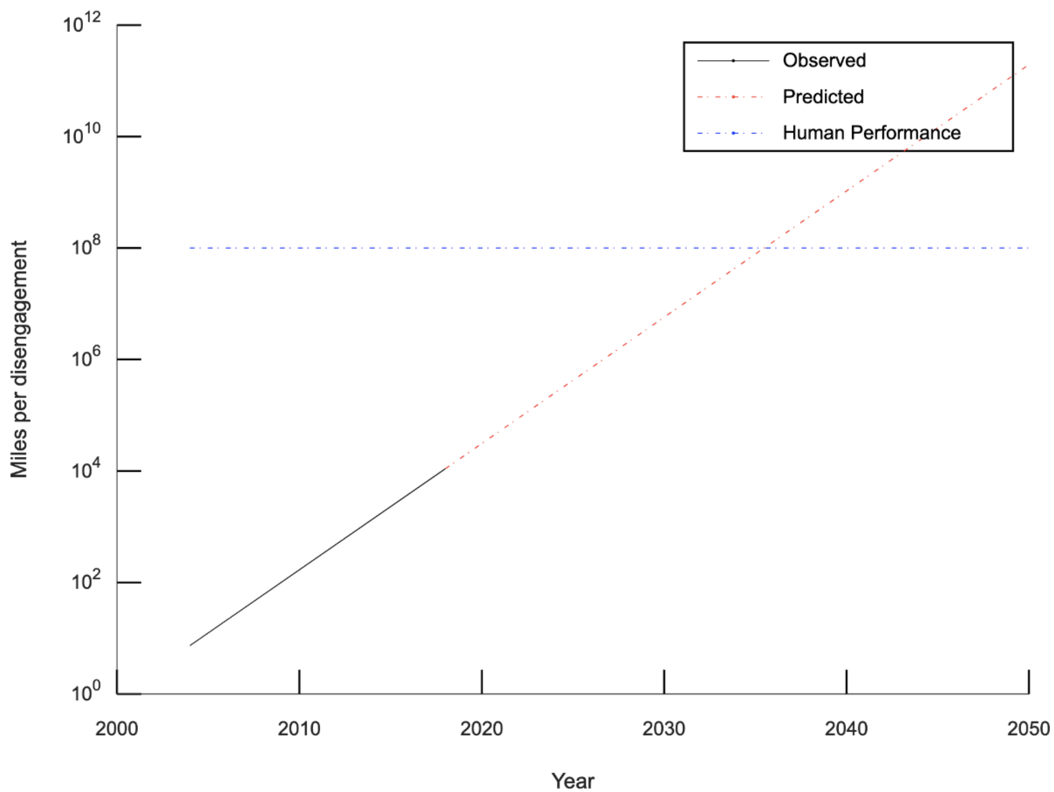
The California Department of Motor Vehicles defines a disengagement as a “deactivation of the autonomous mode when a failure of the autonomous technology is detected or when the test driver disengages the autonomous mode.”
There is a lot of disagreement on the level of accuracy of the metric as it may be too vague, is valid only for California, and may not reflect the difficulty of the chosen driving environment.

Sources: California Department of Motor Vehicles Disengagement Reports February 2019

Decoding the Autonomous Driving Landscape July 2019 | Firstmile | www.firstmile.de

“The Moore’s Law for Self-Driving Vehicles”, Edwin Olson, CEO of May Mobility

- Moore’s law in the semiconductor industry says that “the number of transistors on a chip doubles approximately every 18 months”, i.e., w. exponential growth rate
- Can we have a Moore’s law for AD? “The number of miles between disengagements will double approximately every 16 months.”
  - Between human performance (10^8 miles per fatality) and the best-reported self-driving car performance (10^4 miles per disengagement) is a gap of 10,000x. Even with performance doubling every 16 months, it will reach human levels of performance in 2035.



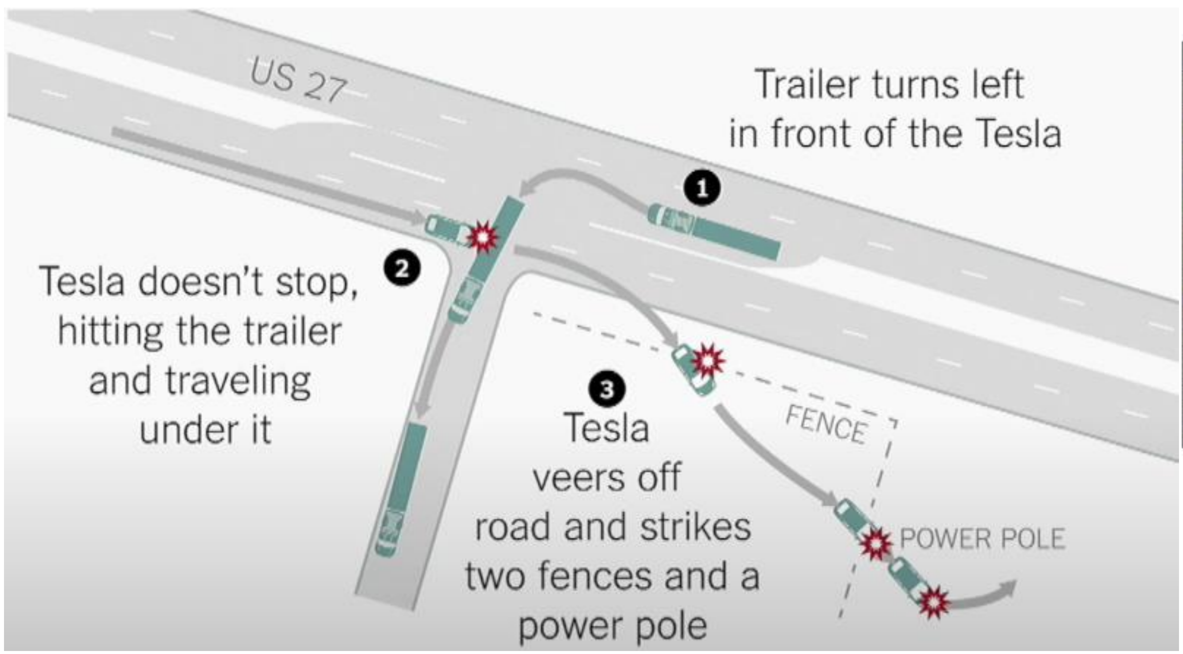
https://medium.com/may-mobility/the-moores-law-for-self-driving-vehicles-b78b8861e184

When will AD Really Arrive?

- Chris Urmson, co-founder and CEO of Aurora:
  - “In 5 years” - 2009
  - “In 5 years” - 2012
  - “In 5 years” - 2015
  - “In 5 years” - 2018

The Tesla Fatality in May 2016

- The Tesla Model S (L2) was driving 74 mph on the highway when it was struck by a semitruck
- The driver's hands were off the steering wheel for a total of 37 minutes during the 37.5 minutes of time the car was in Autopilot, despite repeated visual warnings
- Tesla: "Neither Autopilot nor the driver noticed the white side of the tractor trailer against a brightly lit sky, so the brake was not applied."
  - A failure of computer vision algorithm for object detection; maybe a lidar could have prevented the accident.
- Tesla used to use Mobileye's hardware platform EyeQ, but they broke up after the accident, and Tesla started to develop its hardware platform FSD.



The Tesla Fatality in Mar 2018

- In 2018, a man died from a high-speed crash because his Tesla Autopilot system steered the car into a median on Highway 101 in Mountain View, CA.
- NTSB's investigation report, released in Feb 2020, lists 23 findings that enumerate all the factors that contributed to the fatal collision.
  - Limitations on Tesla's Autopilot Lane-Keeping Assistance (LKA) caused the vehicle to veer into the median and failed to provide an alert to the driver in the seconds leading to the crash.
  - The collision avoidance system was not designed to detect a crash attenuator, which resulted in a severe crash in which the automatic braking and collision warning systems failed to activate.
  - A failure of computer vision algorithm for lane tracking.
- Tesla Autopilot 2 almost crashes Into Barrier (similar to this crash)
  - https://www.youtube.com/watch?v=TIUU1xNqI8w

A Tesla Model X is surrounded by firefighting foam after crashing and catching fire on Highway 101 in Mountain View in March 2018. An NTSB investigation blamed the car's Autopilot system for steering into the median divide, and said the driver likely failed to react because he was playing a video game. Courtesy of Mountain View Fire Department

https://www.mv-voice.com/news/2020/02/25/ntsb-teslas-autopilot-steered-model-x-into-highway-median-causing-fatal-mountain-view-crash

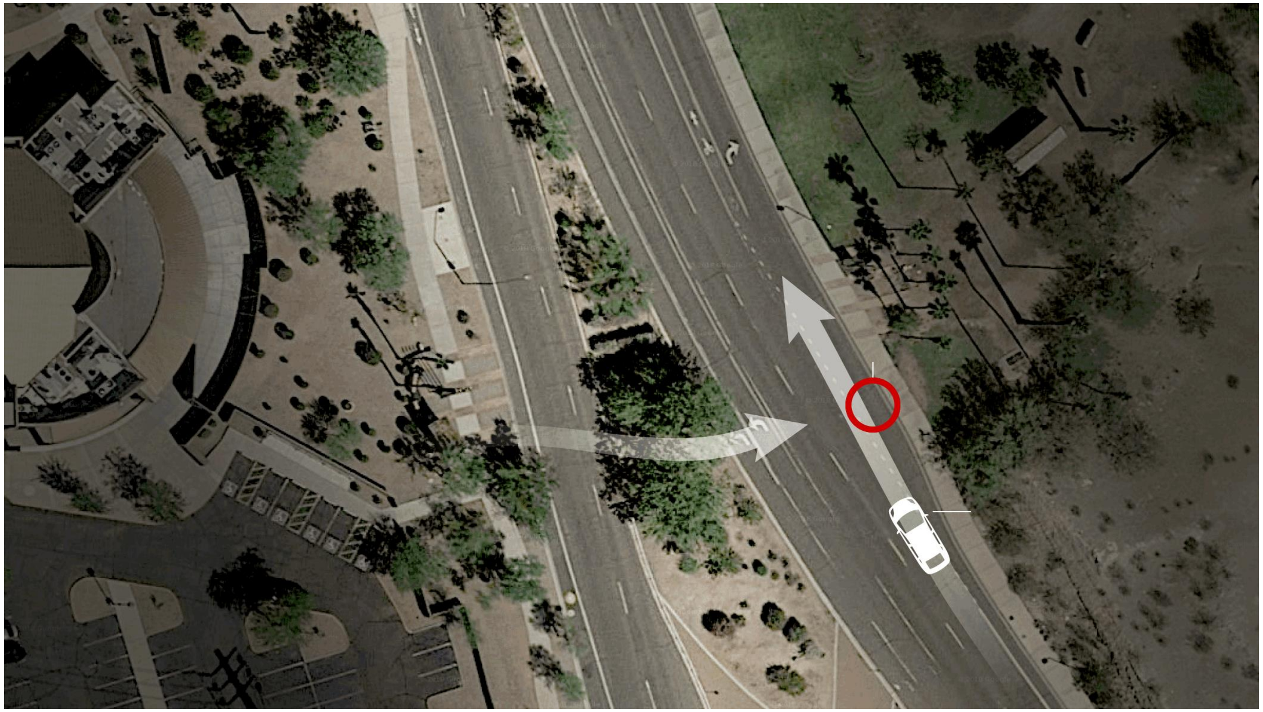
Tesla still cannot recognize white trucks in 2020

- Tesla on autopilot crashes into overturned truck on busy highway in Taiwan
  - https://www.youtube.com/watch?v=X3hrKnv0dPQ

Tesla on autopilot crashes into overturned truck

The Uber Pedestrian Fatality in Mar 2018

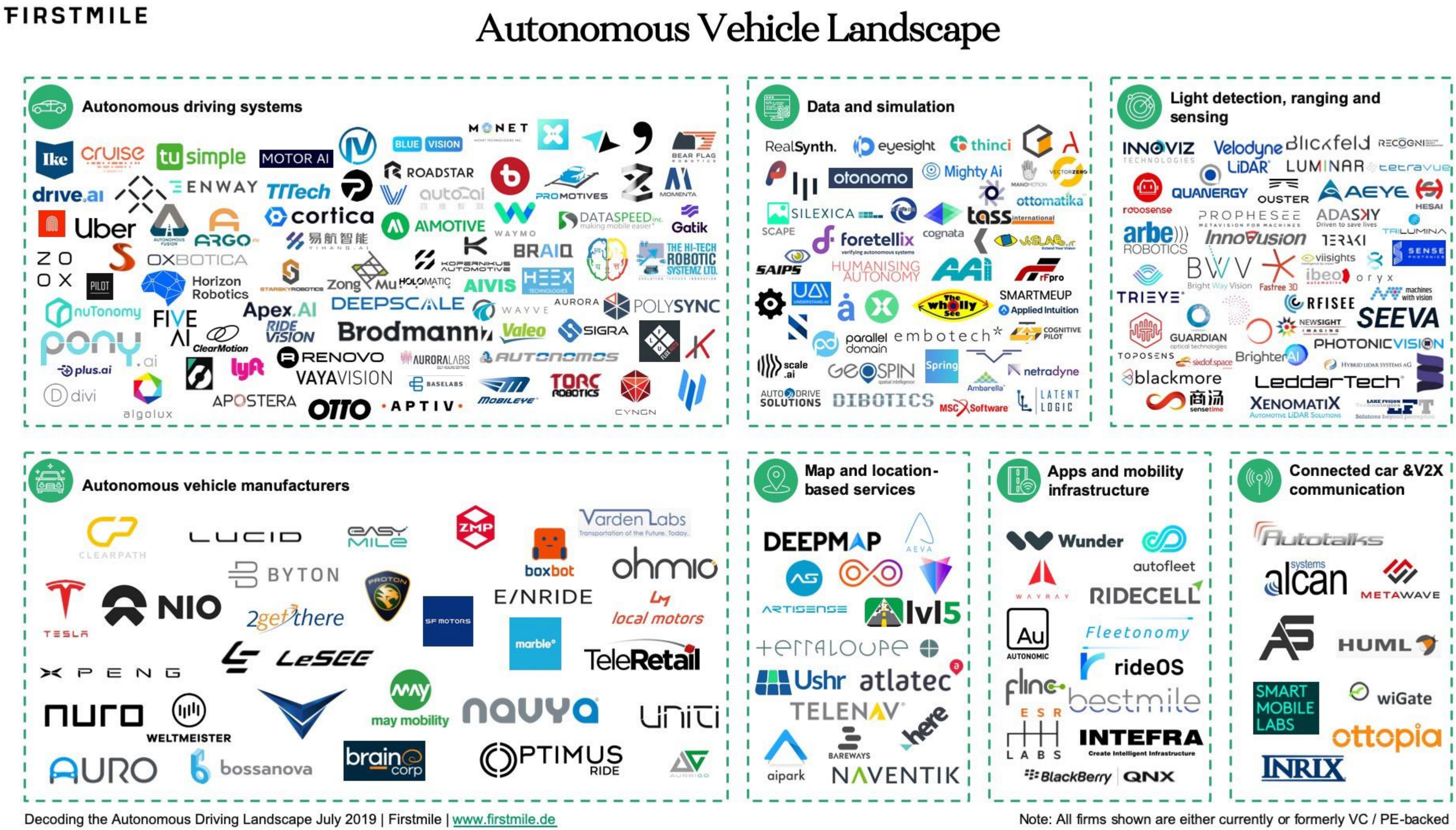
- Police release video of Uber collision that killed pedestrian
  - https://www.youtube.com/watch?v=q7d90ZFhg28
- “The recorded telemetry showed the system had detected Herzberg six seconds before the crash, and classified her first as an unknown object, then as a vehicle, and finally as a bicycle, each of which had a different predicted path according to the autonomy logic.”



The Uber Pedestrian Fatality in Mar 2018

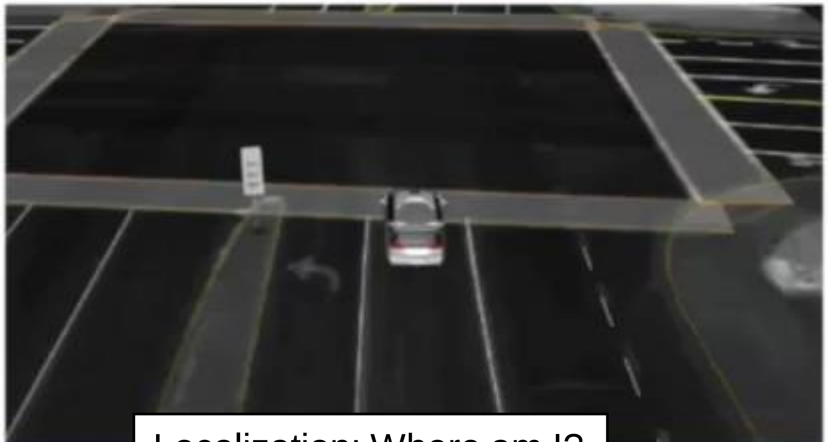
- The AV (L3/4) was equipped with both Lidar and Radar. After the woman was detected on the road (6 sec before)
  - first classified as unknown object
  - then misclassified as a vehicle
  - then a bicycle
- 1.3 sec before, the Volvo system tried to do emergency braking maneuver
  - but Uber had disabled it for testing
- The safety driver was not watching the road moments before the vehicle struck her.
  - It was probably too dark for the driver to see her in time.

AD Landscape Today

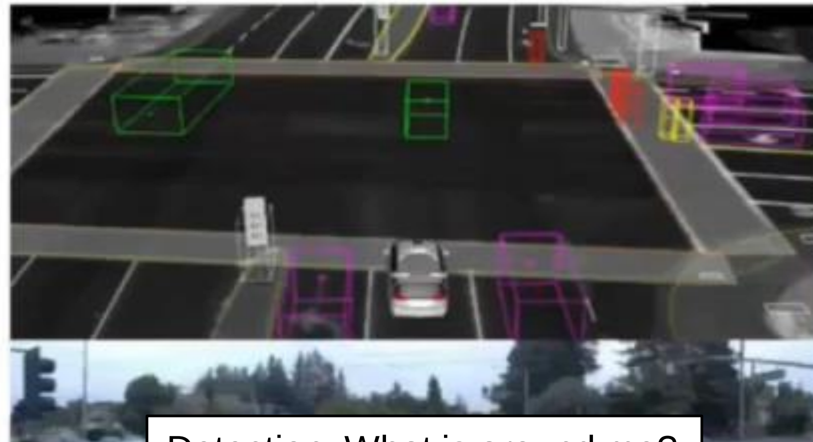


https://medium.com/@firstmilevc/avlandscape-8a21491f1f54

Four Major Tasks of an AV

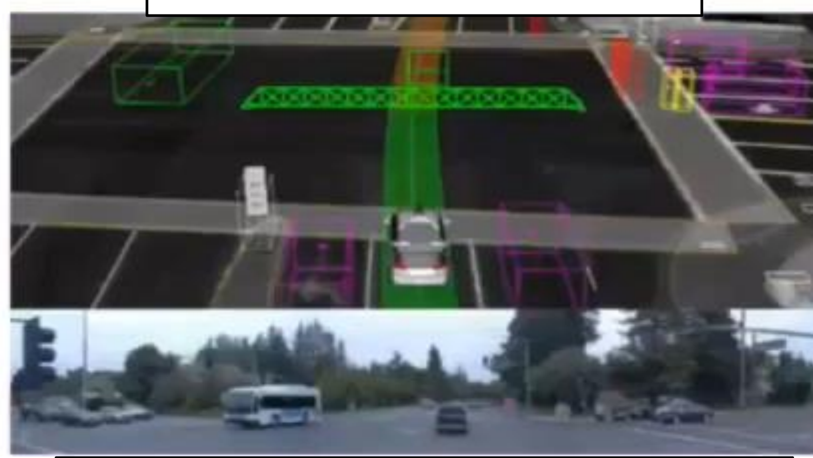


Localization: Where am I?



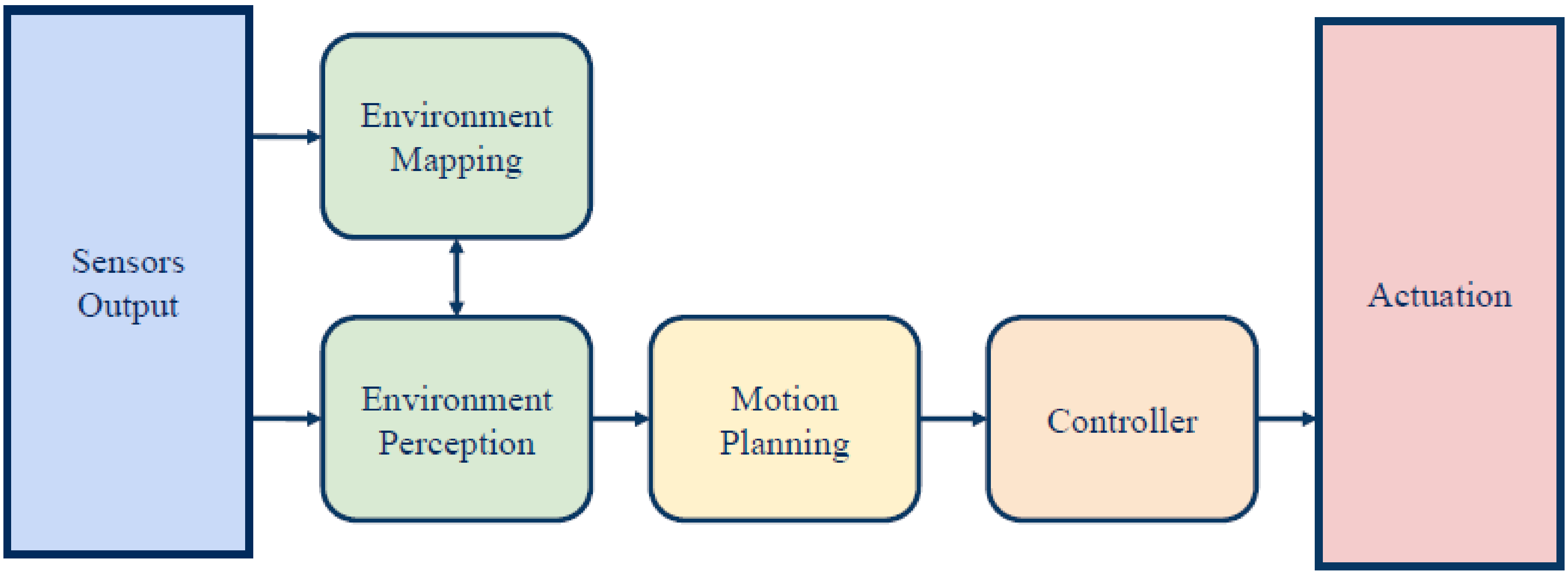
Detection: What is around me?

Prediction: Where are they going?



Planning and Control: Where should I go?

AD Processing Pipeline

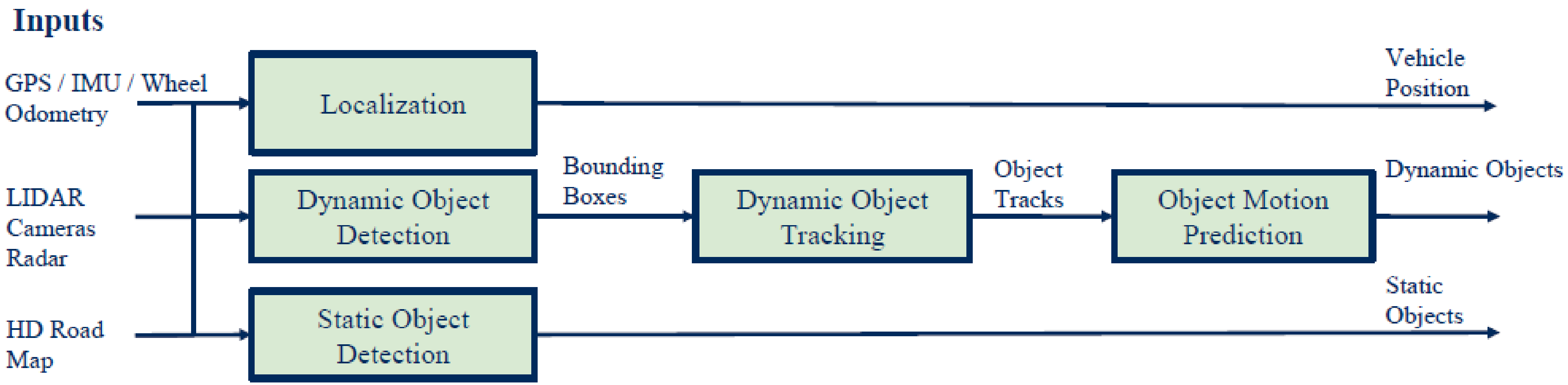


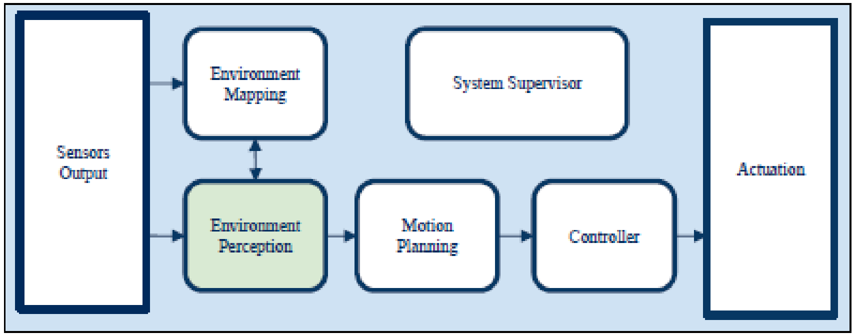
Sensing:
Understanding the surrounding environment, incl. localization, detection, prediction

Planning:
Decision making in the context of other road users

Acting:
Moving the vehicle to follow the planned trajectory

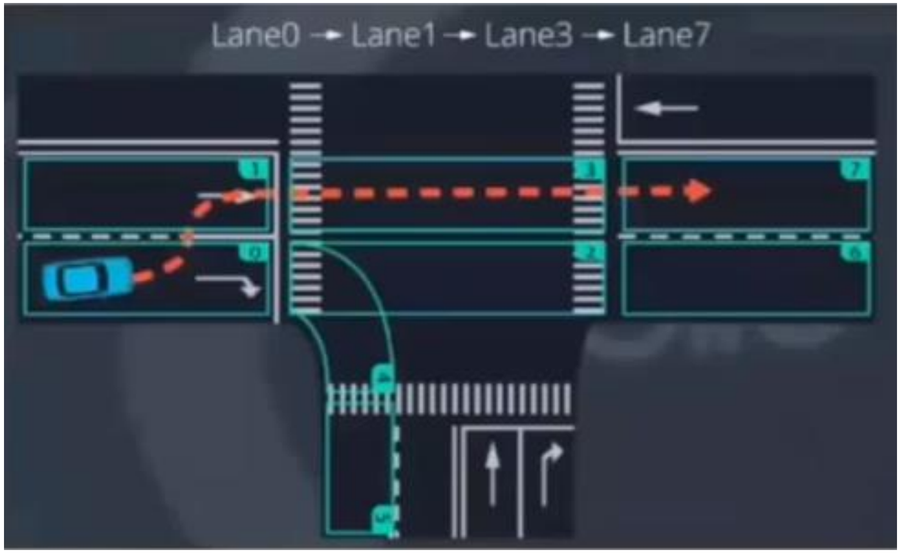
Environment Perception



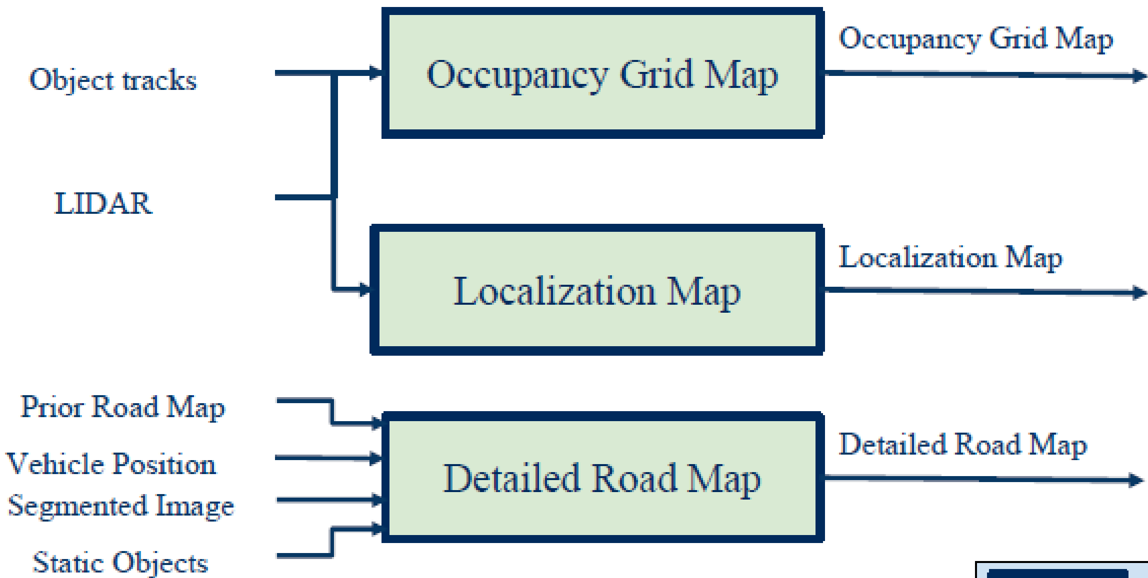


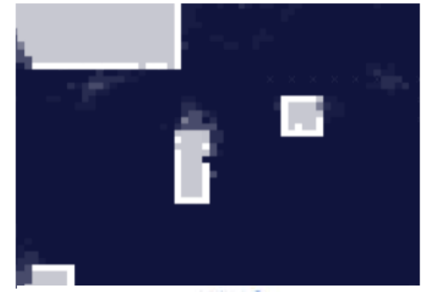
Prediction

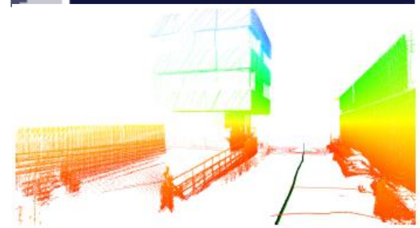
- Based on state
  - Kalman filter
  - Particle filter
- Data-driven
  - ML-based classification
- Pedestrian intention prediction
  - Based on visual cues such as pose, etc.
  - Very difficult problem

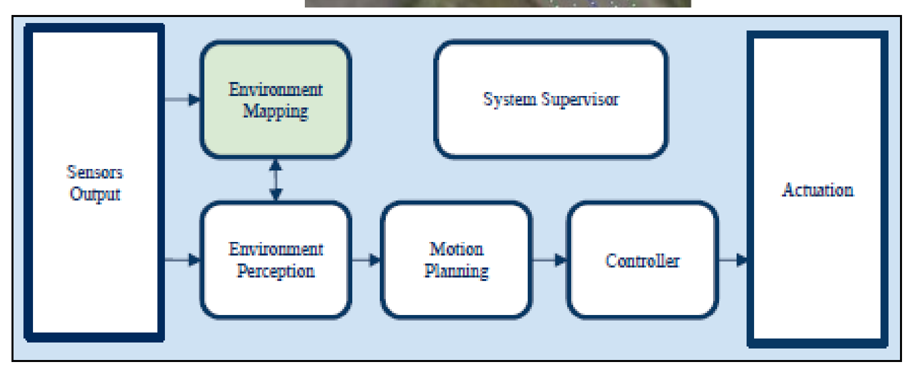


Environmental Maps

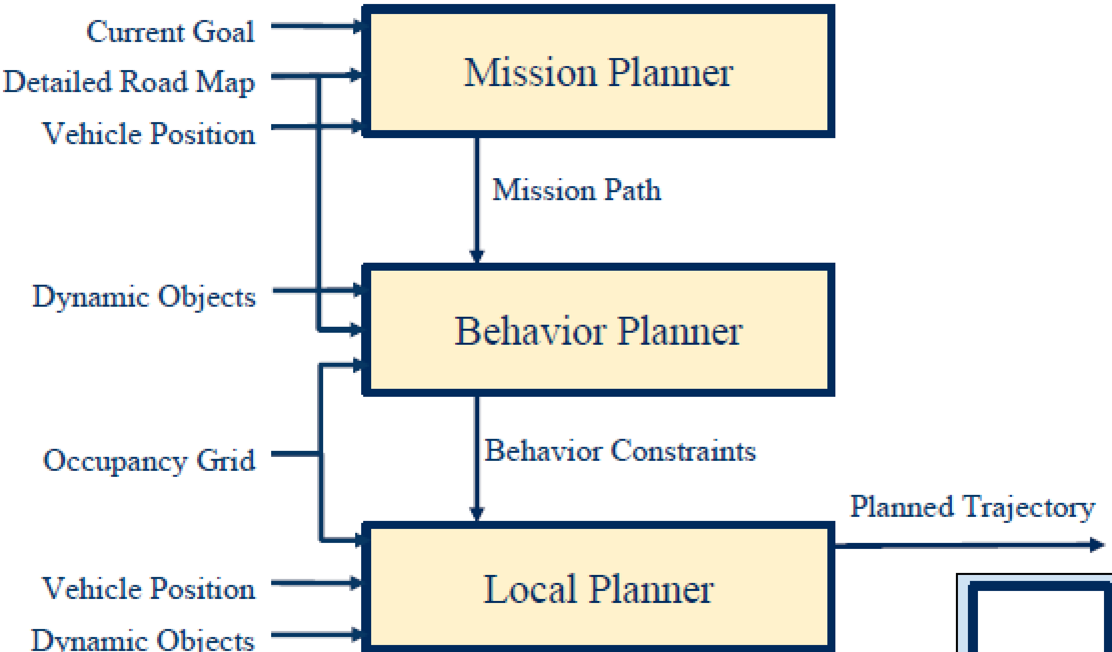


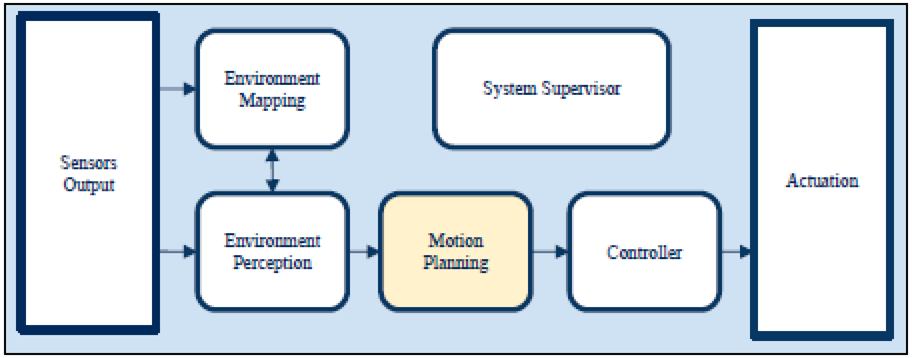






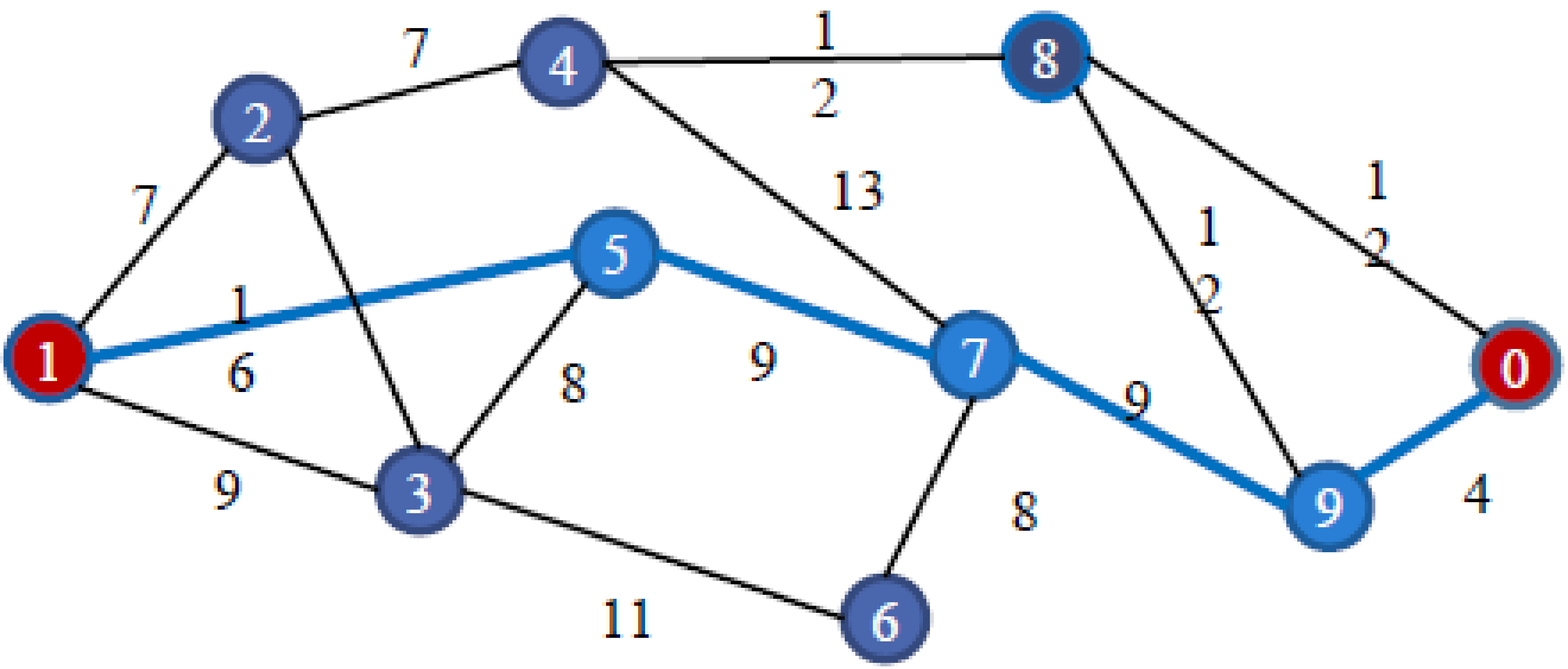
Motion Planning





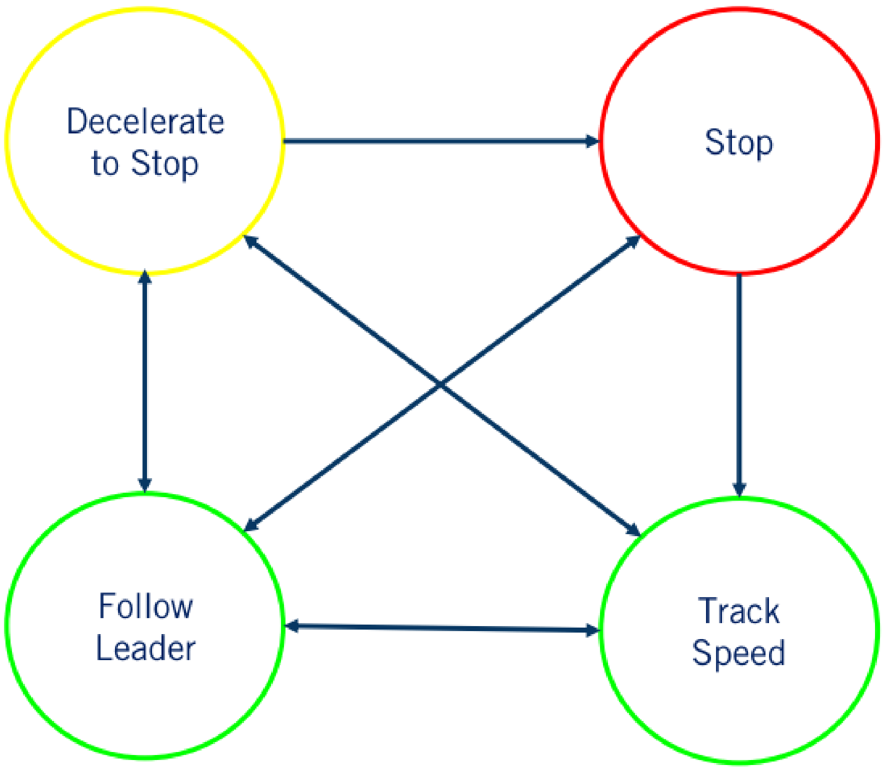
Mission Planner

- Use graph search to find a path from source to destination on the map



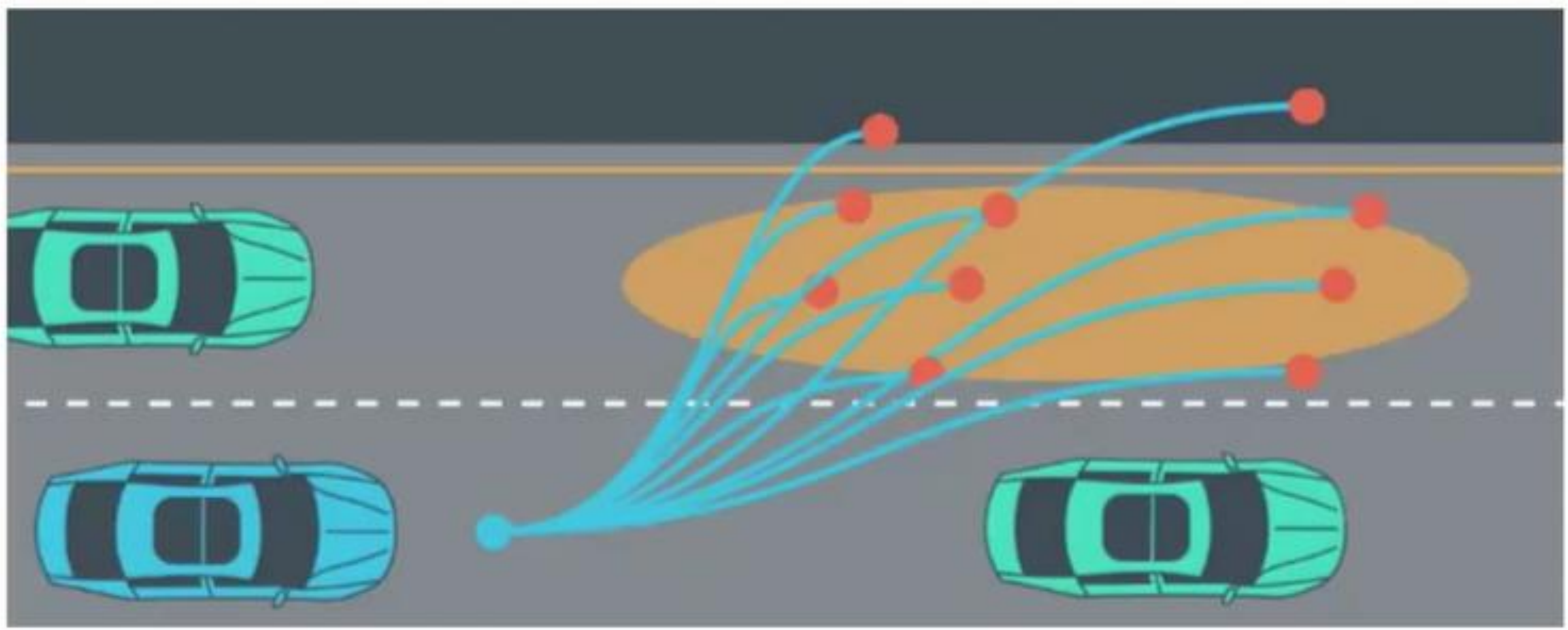
Behavior Planner

- Plan the set of high-level driving actions or maneuvers to safely achieve the driving mission under various driving conditions



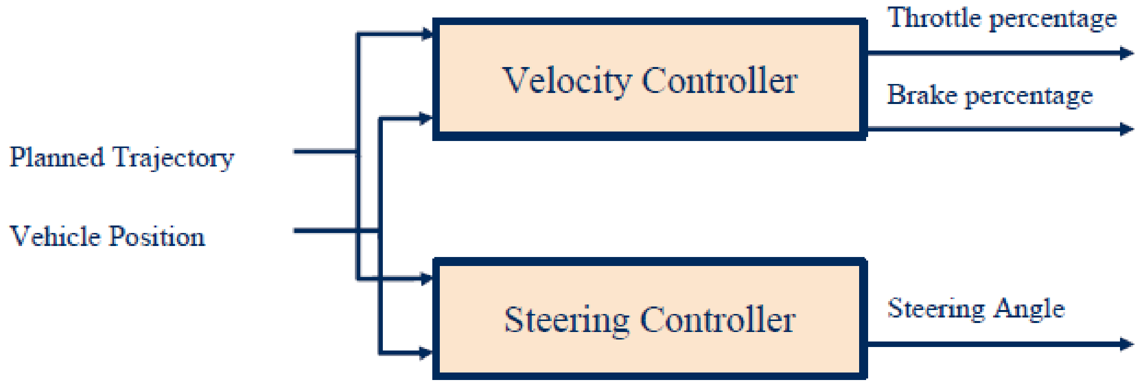
Local Planner

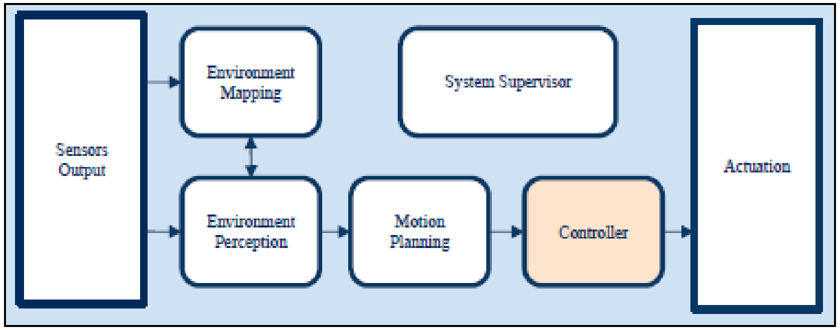
- Plan a safe and smooth trajectory (vehicle pose as function of time)



Controller

- Velocity controller for longitudinal speed control
- Steering controller for lateral speed control
- Common control algorithms
  - PID: Proportional Integral Derivative
  - MPC: Model-Predictive Control





Classic Pipeline vs. ML/DL

- Classic AD processing pipeline: separate algorithms for each processing stage.
- Where does ML/DL come in?
  - CNN (Convolutional Neural Networks) for perception is well accepted.
  - DNN trained with Imitation Learning (IL) or Reinforcement Learning (RL) is still in the early-research stage.
    - "End-to-end" mapping from pixels to control commands
    - Many variants of hybrid approaches, e.g., "half-way" mapping from pixels to waypoints used for planning
    - Several companies are making a bet on it, incl. Waymo, Voyage, Wayve…