Self-Driving Cars

Lecture 1 – Introduction

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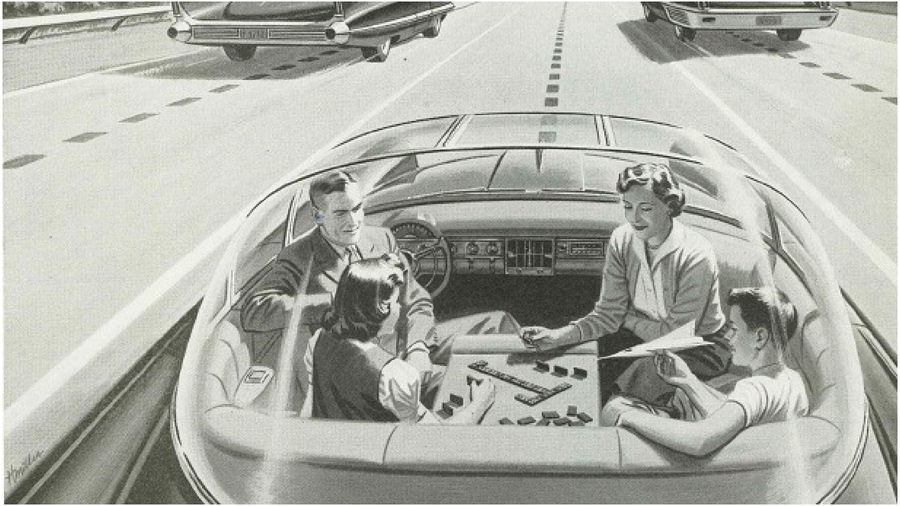
Self-Driving - A Human Dream



Agenda

1.1
Organization

Contents

Goal: Develop an understanding of the capabilities and limitations of autonomous driving solutions and gain a basic understanding of the entire system comprising perception, planning and vehicle control. Training agents in simple environments.

- History of self-driving cars
- End-to-end learning for self-driving (imitation/reinforcement learning)
- Modular approaches to self-driving
- Perception (camera, lidar, radar)
- Localization (with visual and road maps)
- Navigation and path planning
- Vehicle models and control algorithms

Prerequisites

Linear Algebra:

- Vectors: $\mathbf{x}, \mathbf{y} \in \mathbb{R}^n$
- Matrices: $\mathbf{A}, \mathbf{B} \in \mathbb{R}^{m \times n}$
- Operations: $\mathbf{A}^T$, $\mathbf{A}^{-1}$, $\mathrm{Tr}(\mathbf{A})$, $\det(\mathbf{A})$, $\mathbf{A} + \mathbf{B}$, $\mathbf{AB}$, $\mathbf{Ax}$, $\mathbf{x}^\top \mathbf{y}$
- Norms: $\|\mathbf{x}\|_1$, $\|\mathbf{x}\|_2$, $\|\mathbf{x}\|_\infty$, $\|\mathbf{A}\|_F$
- SVD: $\mathbf{A} = \mathbf{UDV}^\top$

Prerequisites

Probability and Information Theory:

- Probability distributions: $P(X = x)$
- Marginal/conditional: $p(x) = \int p(x,y)dy$, $p(x,y) = p(x|y)p(y)$
- Bayes rule: $p(x|y) = p(y|x)p(x)/p(y)$
- Conditional independence: $x \perp\!\!\!\perp y \mid z \Leftrightarrow p(x,y|z) = p(x|z)p(y|z)$
- Expectation: $\mathbb{E}_{x\sim p}\left[f(x)\right] = \int_x p(x)f(x)dx$
- Variance: $\mathrm{Var}(f(x)) = \mathbb{E}\left[(f(x) - \mathbb{E}[f(x)])^2\right]$
- Distributions: Bernoulli, Categorical, Gaussian, Laplace
- Entropy: $H(x)$, KL Divergence: $D_{KL}(p\|q)$

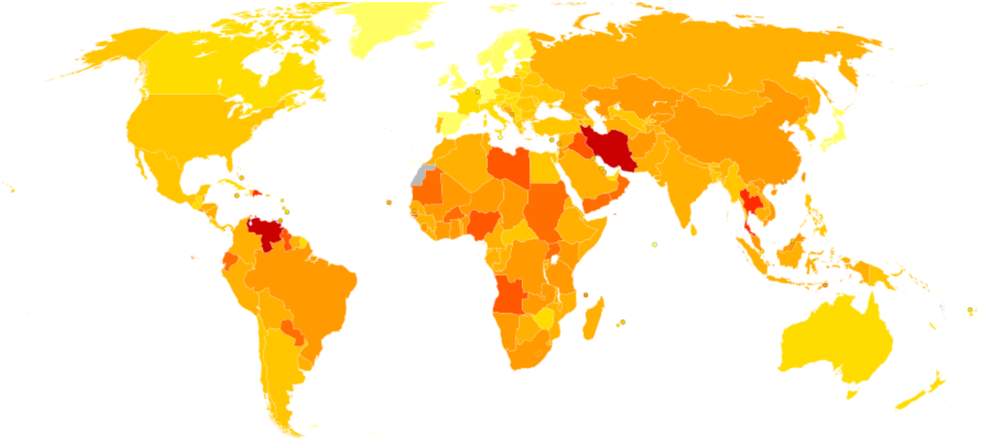
Thank You!

Looking forward to our discussions

1.2
Introduction

Why Self-Driving Cars?

Road Fatalities in 2017



- USA: 32,700 Germany: 3,300 World: 1,300,000
- Main factors: speeding, intoxication, distraction, etc.

Benefits of Autonomous Driving

- Lower risk of accidents
- Provide mobility for elderly and people with disabilities
  - In the US 45% of people with disabilities still work
- Decrease pollution for a more healthy environment
- New ways of public transportation
  - Car pooling
  - Car sharing
- Reduce number of cars (95% of the time a car is parked)

Uber Commercial (2018)

Uber Fatal Accident (2018)

Self-driving is Hard

Human performance: 1 fatality per 100 mio miles

Error rate to improve on: 0.000001 %

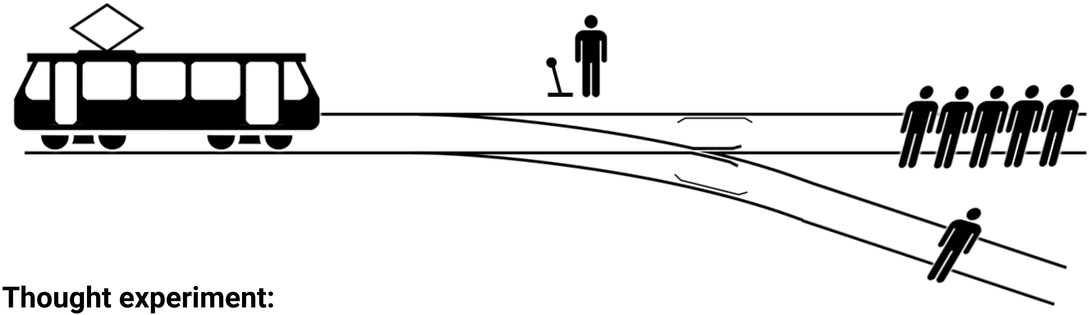
Challenges:

- Snow, heavy rain, night
- Unstructured roads, parking lots
- Pedestrians, erratic behavior
- Reflections, dynamics
- Rare and unseen events
- Merging, negotiating, reasoning
- Ethics: what is good behavior?
- Legal questions

http://theoatmeal.com/blog/google_self_driving_car

Unstructured Traffic

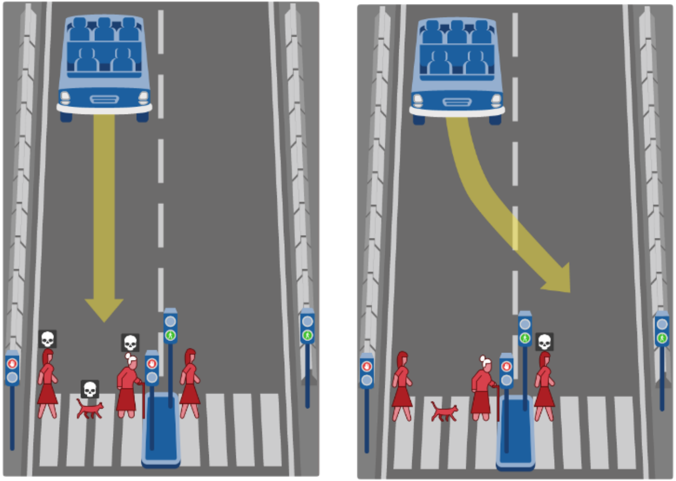
The Trolley Problem (1905)



Thought experiment:

- You observe a train that will kill 5 people on the rail tracks if it continues
- You have the option to pull a lever to redirect the train to another track
- However, the train will kill one (other) person on that alternate track
- What is your decision? What is the correct/ethical decision?

The MIT Moral Machine



http://moralmachine.mit.edu/

1.3
History of Self-Driving

The Automobile

1886: Benz Patent-Motorwagen Nummer 1

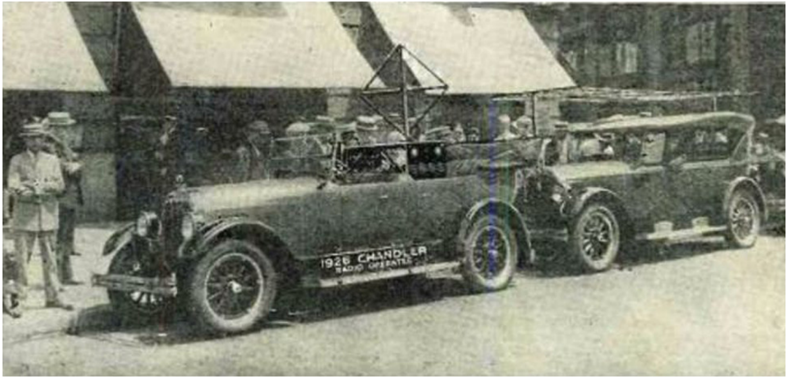
1886: Benz Patent-Motorwagen Nummer 1

- Benz 954 cc single-cylinder four-stroke engine (500 watts)
- Weight: 100 kg (engine), 265 kg (total)
- Maximal speed: 16 km/h
- Consumption: 10 liter / 100 km (!)
- Construction based on the tricycle, many bicycle components
- 29.1.1886: patent filed
- 3.7.1886: first public test drive in Mannheim
- 2.11.1886: patent granted, but investors stayed skeptical
- First long distance trip (106 km) by Bertha Benz in 1888 with Motorwagen Nummer 3 (without knowledge of her husband) fostered commercial interest
  - First gas station: pharmacy in Wiesloch near Heidelberg

1886: Benz Patent-Motorwagen Nummer 1

Self-Driving Cars

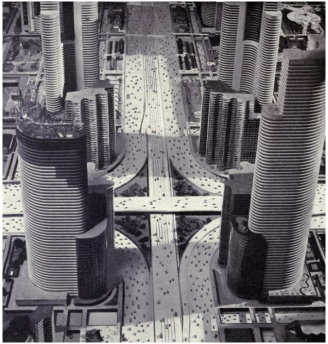
1925: Phantom Auto – "American Wonder" (Houdina Radio Control)

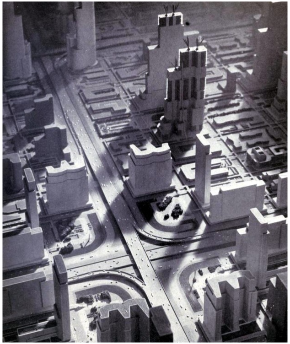


In the summer of 1925, Houdina's driverless car, called the American Wonder, traveled along Broadway in New York City—trailed by an operator in another vehicle—and down Fifth Avenue through heavy traffic. It turned corners, sped up, slowed down and honked its horn. Unfortunately, the demonstration ended when the American Wonder crashed into another vehicle filled with photographers documenting the event. (Discovery Magazine)

https://www.discovermagazine.com/technology/the-driverless-car-era-began-more-than-90-years-ago

1939: Futurama – New York World's Fair

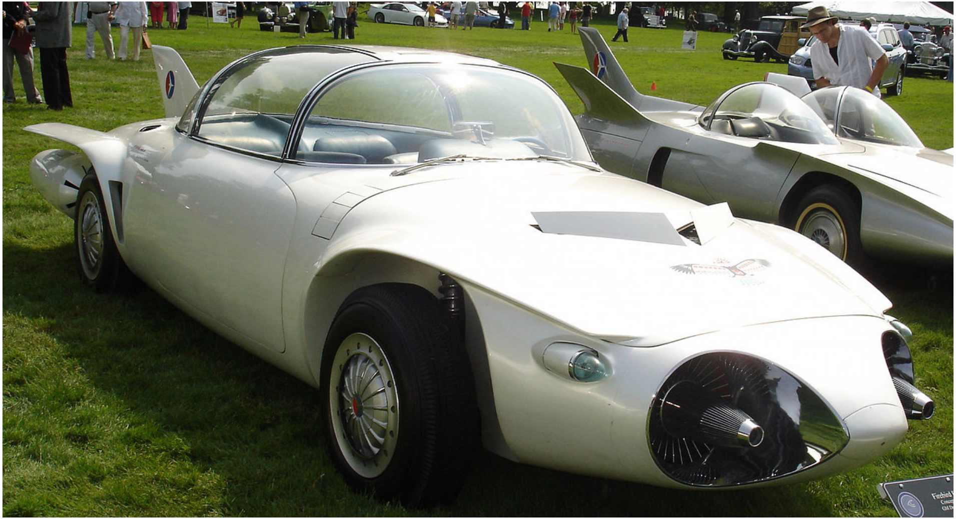




- Exhibit at the New York World's Fair in 1939 sponsored by General Motors
- Designed by Norman Bel Geddes' - his vision of the world 20 years later (1960)
- Radio-controlled electric cars, electromagnetic field via circuits in roadway
- #1 exhibition, very well received (great depression), prototypes by RCA & GM

https://www.youtube.com/watch?v=sClZqfnWqmc

1956: General Motors Firebird II



https://www.youtube.com/watch?v=cPOmuvFostY

1956: General Motors Firebird II

"PROGRESS POSSIBILITY"

The Electronically Controlled Car on the Safety Autoway of Tomorrow

For several years General Motors has played an important role in the continuing campaign to bring our highways up to date.

At the same time, our designers and engineers have continuously planned and worked to make the motorcar an ever safer form of transportation.

Now the Styling Section of General Motors—under the leadership of Harley J. Earl, GM Vice President in charge of Styling—has created for the Motorama of 1956 a dramatic and daring concept of a Highway of Tomorrow.

Shown on VistaVision film in Technicolor, and on the Motorama stage, this amazing concept places control of the motorcar in the hands of an "electronic brain" —actually releasing the driver from the wheel.

Though the realization of such a "dream highway" belongs in the far, far future—it utilizes present-day knowledge and experience gained through electronic control and computation, radar and television – all now in operation.

To present this spectacular vision on film – General Motors built a replica of such a highway on the Arizona desert—as well as a more complete miniature highway on a Hollywood stage for filming purposes. What's more, they incorporated, in the Firebird II, elements helpful in demonstrating such an electronically controlled operation.

https://www.youtube.com/watch?v=cPOmuvFostY

1956: General Motors Firebird II

These include a Dashboard View screen which has two panels. The left panel is for "internal communication" between car and driver (information he would normally receive from visible instruments as to fuel supply, engine operation and temperature). It also reveals a radar pattern when he guides the car onto the electronic control-strip for automatic steering.

"External communication" from the control tower in his Autoway Zone also appears on this panel.

The right-hand panel supplies normal television reception, and two-way television communication with motels, other cars, etc.

Rearview mirror is replaced by a small circular view screen on the left side of the dashboard which projects images picked up by a TV camera at the rear of the car.

The steering control handles are designed to slide forward out of the way when car is on automatic control.

Extending from the two engine air scoops on each side of the nose of the car are probes or antennas which pick up wave impulses from the conductor strip in the center of the control lane.

None of these features is operative in the Firebird II. They serve merely to complete the demonstration of how an electronically controlled car should be equipped to function on the electronic Safety Autoway.

https://www.youtube.com/watch?v=cPOmuvFostY

1960: RCA Labs' Wire Controlled Car & Aeromobile

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Reporter Rides Driverless Car

"Smart Road" Used to Test "Smart Auto"

By Doc Quigg

PRINCETON, N. J. (UPI)—Washington Irving put the headless horseman on paper. A corporation named RCA now has put the driverless car on the road. The automation tends to be as scary as the ghost, until you get used to it. But someday we may have to live with it.

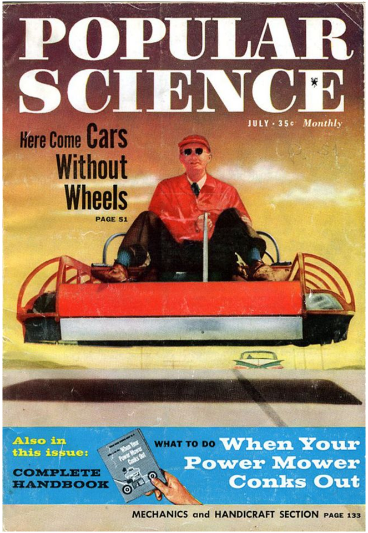
The road is a private one, souped up mightily with loops and lengths of electronic gear buried within the asphalt pavement, at the research center of the Radio Corp. of Ameria. It's about as automatic as a road can get, and in effect it does the driving.

The "electronic highway" can sense the presence of any metallic vehicle on its surface and tell you where the vehicle is, how fast it is going, and in what direction. RCA engineers admitted that a herd of cattle would not be detected, unless they were dressed in armor—but then, the limited access highway of the future will be closed to cows.

Smart Road

Given such a smart road, it remained to smarten up the auto-

DRIVERLESS CAR—Engineers at the RCA research center at Princeton, N. J., are experimenting with a driverless automobile that scoots around an electronic test track shown in diagram above. The elements of the test track include a series of rectangular wire loops, a continuous guidance cable buried beneath the pavement, and a chain of transistorized detector circuits along the roadside, each linked to one of the buried loops.



https://spectrum.ieee.org/selfdriving-cars-were-just-around-the-cornerin-1960

1970: Citroen DS19

- Steered by sensing magnetic cables in the road, up to 130 km/h

https://www.youtube.com/watch?v=MwdjM2Yx3gU

1986: Navlab 1

- Vision-based navigation

Jochem, Pomerleau, Kumar and Armstrong: PANS: A Portable Navigation Platform. IV, 1995.

Navlab Overview

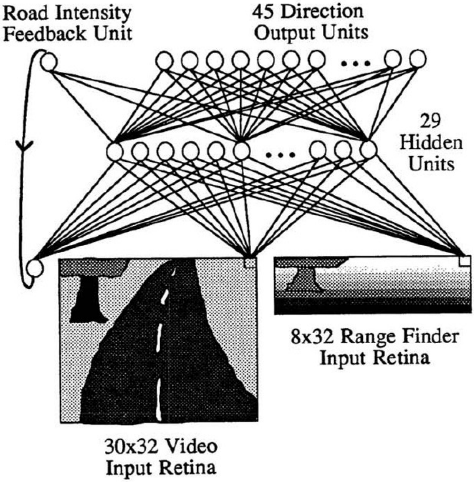
- Project at Carnegie Mellon University, USA
- 1986: Navlab 1: 5 computer racks (Warp supercomputer)
- 1988: First semi-autonomous drive at 20 mph
- 1990: Navlab 2: 6 mph offroad, 70 mph highway driving
- 1995: Navlab 5: “No Hands Across America” (2850 miles, 98 % autonomy)
- PANS: Portable Advanced Navigation Support
- Compute: 50 Mhz Sparc workstation (only 90 watts)
- Main focus: lane keeping (lateral but no longitudinal control, i.e., no steering)
- Position estimation: Differential GPS + Fibre Optic Gyroscope (IMU)
- Low-level control: HC11 microcontroller

Jochem, Pomerleau, Kumar and Armstrong: PANS: A Portable Navigation Platform. IV, 1995.

1988: ALVINN

ALVINN: An Autonomous Land Vehicle in a Neural Network

- Forward-looking, vision based driving
- Fully connected neural network maps road images to vehicle turn radius
- Directions discretized (45 bins)
- Trained on simulated road images
- Tested on unlined paths, lined city streets and interstate highways
- 90 consecutive miles at up to 70 mph



Pomerleau: ALVINN: An Autonomous Land Vehicle in a Neural Network. NIPS, 1988.

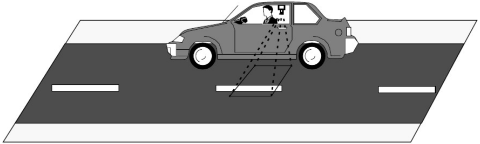
1988: ALVINN

Pomerleau: ALVINN: An Autonomous Land Vehicle in a Neural Network. NIPS, 1988.

1995: AURORA

AURORA: Automative Run-Off-Road Avoidance System

- Downward-looking (mounted at side)
- Adjustable template correlation
- Tracks solid or dashed lane marking
- shown to perform robustly even when the markings are worn or their appearance in the image is degraded
- Mainly tested as a lane departure warning system ("time to crossing")



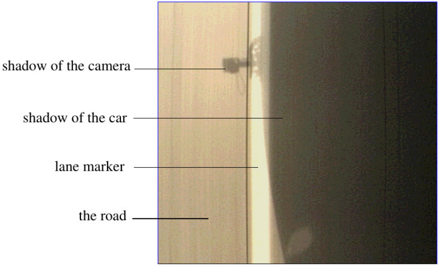


Figure 2: A typical image of a lane marker on the road

Chen, Jochem and Pomerleau: AURORA: A Vision-Based Roadway Departure Warning System. IROS, 1995.

1986: VaMoRs – Bundeswehr Universität Munich

- Developed by Ernst Dickmanns in context of EUREKA-Prometheus (€800 mio.)
  (PROgraMme for a European Traffic of Highest Efficiency and Unprecedented Safety, 1987- 1995)
- Demonstration to Daimler-Benz Research 1986 in Stuttgart
- Longitudinal & lateral guidance with lateral acceleration feedback
- Speed: 0 to 36 km/h

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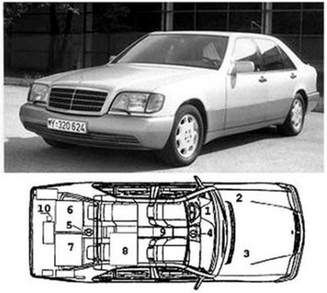
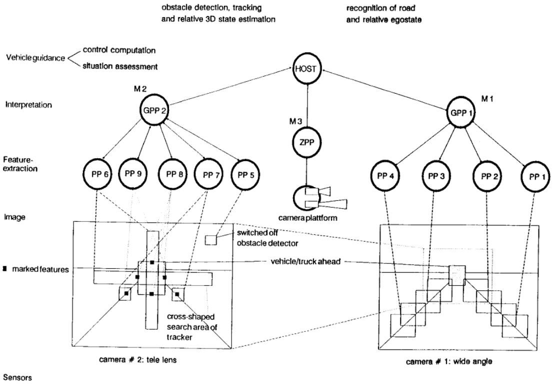
1994: VAMP – Bundeswehr Universität Munich



1 Torque motor for steering
2 brake system
3 electric throttle control
4 front platform } for 2 CCD
5 rear platform } cameras
6, 8 Transputer system, image processing
7 processors for gaze & locomotion control
8 user interface
9 linear accelerometers
10 angular rate sensors

- 2nd Generation Transputer (60 processors), bifocal saccade vision, no GPS
- 1678 km autonomous ride Munich to Odense, 95% autonomy (up to 158 km)
- Autonomous driving speed record: 180 km/h (lane keeping)
- Convoi driving, automatic lane change (triggered by human)

1992: Summary Paper by Dickmanns



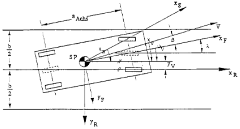


Fig. 7. Substitute model for lateral vehicle motion.

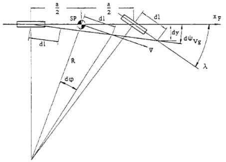


Fig. 8. Steering kinematics.

The steer angle is set by a stepping motor, the dynamic behavior of which is roughly modeled as an integrator

$$\dot{\lambda} = k_\lambda \cdot U. \tag{30}$$

Collecting these relations results in a linear velocity-dependent fourth-order state model

$$\begin{aligned}
\dot{\lambda} &= k_\lambda \cdot U \\
\dot{\beta} &= -2K \cdot \beta + (V/a - K) \cdot \lambda \\
\dot{y}_v &= V \cdot (\psi_v + \beta) \\
\dot{\psi} &= V/a \cdot \lambda - V \cdot C_{0h}
\end{aligned}$$

or in matrix-vector notation

$$\dot{\mathbf{x}}_v = \mathbf{A}_v \cdot \mathbf{x}_v + \mathbf{b}_v \cdot U + \mathbf{B}_c \cdot C_{0h} \tag{31}$$

where

$$A_v = \begin{bmatrix} 0 & 0 & 0 & 0 \\ b_F & a_F & 0 & 0 \\ 0 & V & 0 & V \\ c_F & 0 & 0 & 0 \end{bmatrix};$$

$$x_v = \begin{bmatrix} \lambda \\ \beta \\ y_v \\ \psi_v \end{bmatrix}; b_v = \begin{bmatrix} k_\lambda \\ 0 \\ 0 \\ 0 \end{bmatrix}; b_c = \begin{bmatrix} 0 \\ 0 \\ 0 \\ -V \end{bmatrix}$$

with the elements

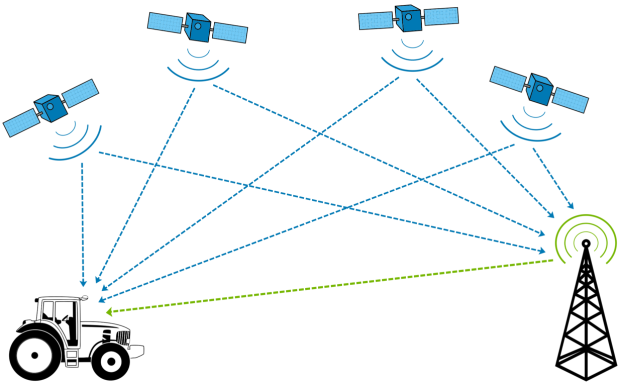
$$c_F = V/a, \quad b_F = c_F - K$$

Dickmanns and Mysliwetz: Recursive 3-D Road and Relative Ego-State Recognition. PAMI, 1992.

1995: Invention of Adaptive Cruise Control (ACC)

- 1992: Lidar-based distance control by Mitsubishi (throttle control & downshift)
- 1997: Laser adaptive cruise control by Toyota (throttle control & downshift)
- 1999: Distronic radar-assisted ACC by Mercedes-Benz (S-Class), level 1 autonomy

2000: First Technological Revolution: GPS, IMUs & Maps



- NAVSTAR GPS available with 1 meter accuracy, IMUs improve up to 5 cm
- Navigation systems and road maps available
- Accurate self-localization and ego-motion estimation algorithms

2004: Darpa Grand Challenge 1 (Limited to US Participants)

- 1st competition in the Mojave Desert along a 240 km route, \$1 mio prize money
- No traffic, dirt roads, driven by GPS (2935 points, up to 4 per curve).
- None of the robot vehicles finished the route. CMU traveled the farthest distance, completing 11.78 km of the course before hitting a rock.

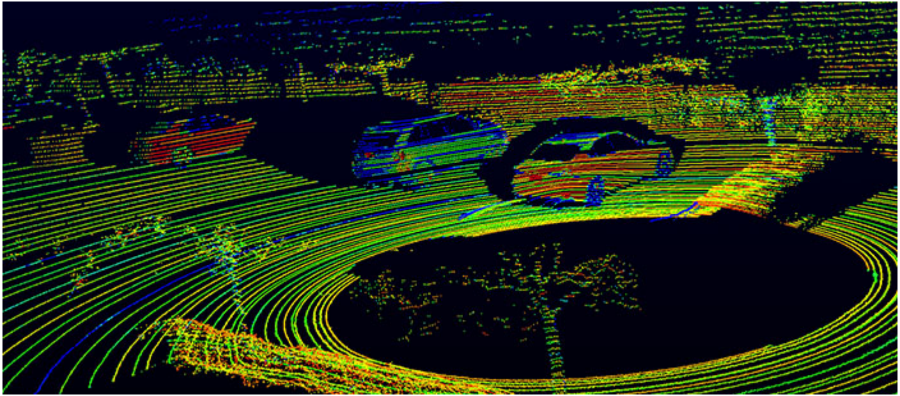
2005: Darpa Grand Challenge 2 (Limited to US Participants)

- 2nd competition in the Mojave Desert along a 212 km route, $2 mio prize money
- Five teams finished (Stanford team 1st in 6:54 h, CMU team 2nd in 7:05 h)

2006: Park Shuttle Rotterdam

- 1800 meters route from metro station Kralingse Zoom to business park Rivium
- One of the first truly driverless car, but dedicated lane, localization via magnets

2006: Second Technological Revolution: Lidars & High-res Sensors



- High-resolution Lidar
- Camera systems with increasing resolution
- Accurate 3D reconstruction, 3D detection & 3D localization

2007: Darpa Urban Challenge (International Participants)

- 3nd competition at George Air Force Base, 96 km route, urban driving, $2 mio
- Rules: obey traffic law, negotiate, avoid obstacles, merge into traffic
- 11 US teams received $1 mio funding for their research
- Winners: CMU 1st (4:10), Stanford's Stanley 2nd (4:29). No non-US participant.

2009: Google starts working on Self-Driving Car

- Led by Sebastian Thrun, former director of Stanford AI lab and Stanley team
- Others: Chris Urmson, Dmitri Dolgov, Mike Montemerlo, Anthony Levandowski
- Renamed “Waymo” in 2016 (Google spend $1 billion until 2015)

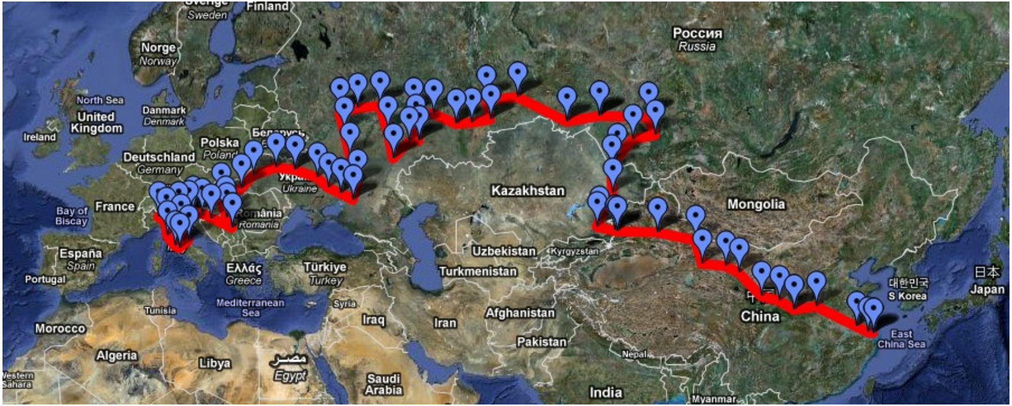
https://waymo.com/

2010: VisLab Intercontinental Autonomous Challenge (VIAC)

- July 20 to October 28: 16,000 kilometres trip from Parma, Italy to Shanghai, China
- The second vehicle automatically followed the route defined by the leader vehicle by following it either visually or thanks to GPS waypoints sent by the lead vehicle

Broggi, Medici, Zani, Coati and Panciroli: Autonomous vehicles control in the VisLab Intercontinental Autonomous Challenge. Annu. Rev. Control, 2012.

2010: VisLab Intercontinental Autonomous Challenge (VIAC)



- July 20 to October 28: 16,000 kilometres trip from Parma, Italy to Shanghai, China
- The second vehicle automatically followed the route defined by the leader vehicle by following it either visually or thanks to GPS waypoints sent by the lead vehicle

2010: Pikes Peak Self-Driving Audi TTS

- Pikes Peak International Hill Climb (since 1916): 20 km, 1440 Hm, Summit: 4300 m
- Audi TTS completes track in 27 min (record in 2010: 10 min, now: 8 min)

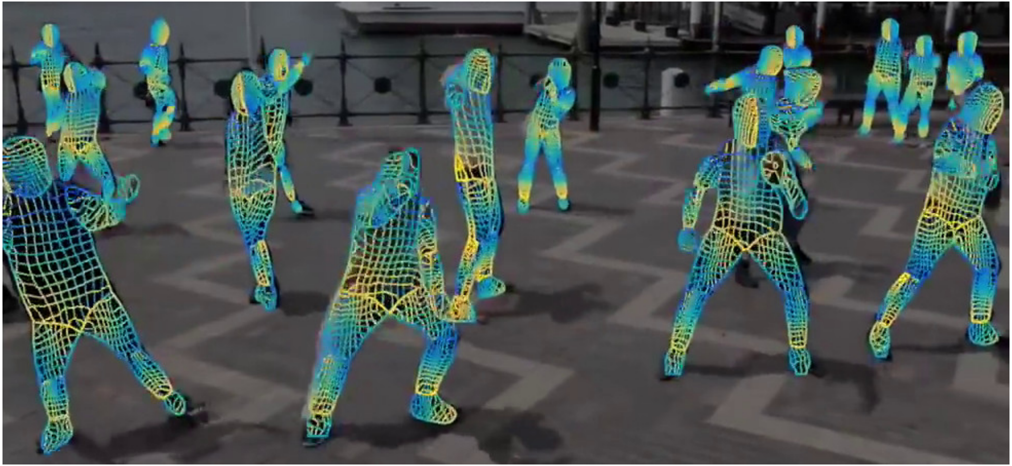
https://www.youtube.com/watch?v=Arx8qWx9CFk

2010: Stadtpilot (Technical University Braunschweig)

- Goal: geofenced innercity driving based on laser scanners, cameras and HD maps
- Challenges: traffic lights, roundabouts, etc. Similar efforts by FU Berlin and others

Saust, Wille, Lichte and Maurer: Autonomous Vehicle Guidance on Braunschweig's inner ring road within the Stadtpilot Project. IV, 2011.

2012: Third Technological Revolution: Deep Learning



- Representation learning boosts in accuracy across tasks and benchmarks

Güler et al.: DensePose: Dense Human Pose Estimation In The Wild. CVPR, 2018.

2012: Third Technological Revolution: New Benchmarks

Geiger, Lenz and Urtasun: Are we ready for Autonomous Driving? The KITTI Vision Benchmark Suite. CVPR, 2012.

2013: Mercedes Benz S500 Intelligent Drive

- Autonomous ride on historic Bertha Benz route by Daimler R&D and KIT/FZI
- Novelty: close to production stereo cameras / radar (but requires HD maps)

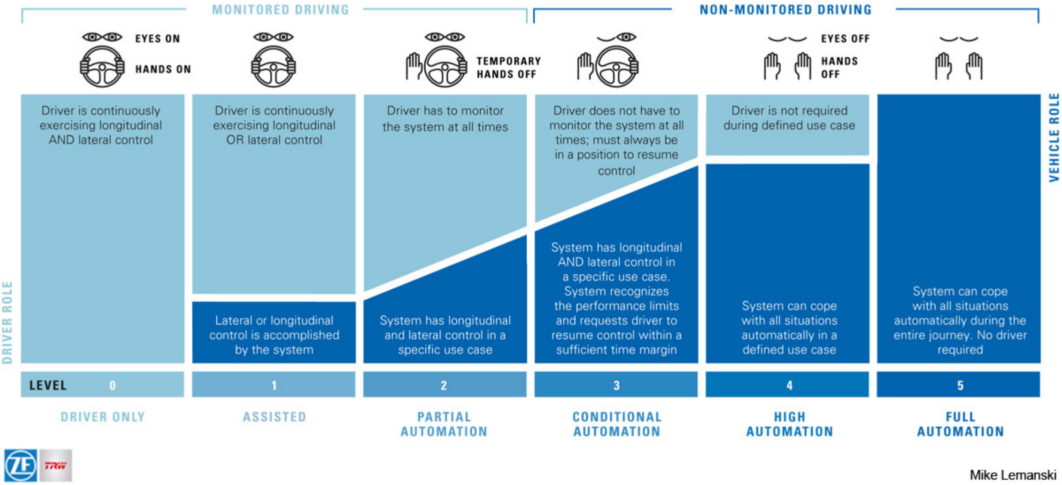
Ziegler et al.: Making Bertha Drive - An Autonomous Journey on a Historic Route. IEEE Intell. Transp. Syst. Mag., 2014.

2014: Mercedes S Class

Advanced ADAS (Level 2 Autonomy):

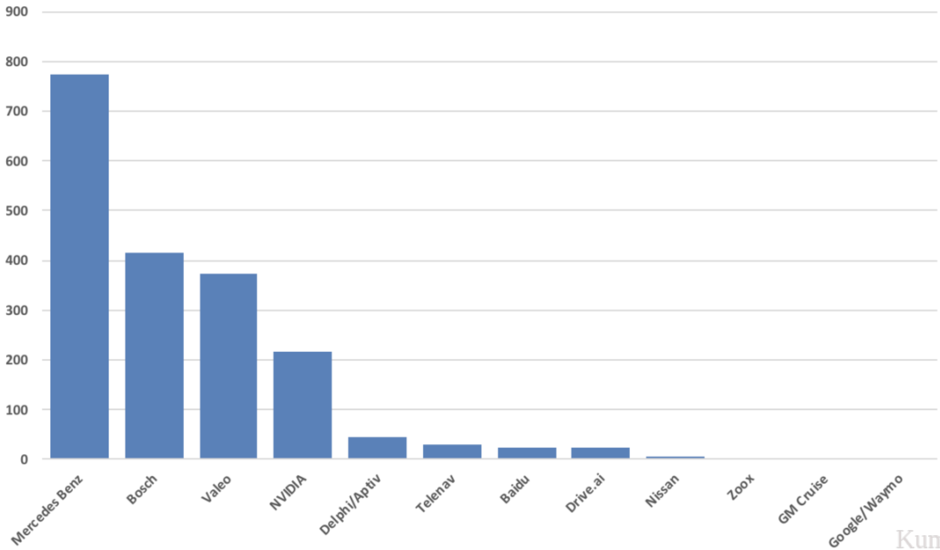
- Autonomous steering, lane keeping, acceleration/braking, collision avoidance, driver fatigue monitoring in city traffic and highway speeds up to 200 km/h

2014: Society of Automotive Engineers: SAE Levels of Autonomy



- Lateral control = steering, Longitudinal control = gas/brake

Disengagement per 1000 miles (California Dept. of Motor Veh., 2017)



2015: Uber starts Self-Driving Research

- Uber hires 50 robotic researchers and academics from CMU, shut down in 2020

2016: OTTO

- Self-driving truck company, bought by Uber for $625 mio., later shut down

2015: Tesla Model S Autopilot

Tesla Autopilot 2015 (Level 2 Autonomy):

- ► Lane keeping for limited-access highways (hands off time: 30-120 seconds)
- ► Doesn’t read traffic signals, traffic signs or detect pedestrians/cyclists

2016: Tesla Model S Autopilot: Fatal Accident 1

2018: Tesla Model X Autopilot: Fatal Accident 2

2018: Tesla Model X Autopilot: Fatal Accident 2

The National Transportation Safety Board (NTSB) said that four seconds before the 23 March crash on a highway in Silicon Valley, which killed Walter Huang, 38, the car stopped following the path of a vehicle in front of it. Three seconds before the impact, it **sped up** from 62mph to 70.8mph, and the car **did not brake** or steer away, the NTSB said. After the fatal crash in the city of Mountain View, Tesla noted that the driver had received multiple warnings to put his hands on the wheel and said he did not intervene during the five seconds before the car hit the divider. But the NTSB report revealed that these alerts were made more than 15 minutes before the crash. In the 60 seconds prior to the collision, the driver also had his hands on the wheel on three separate occasions, though not in the final six seconds, according to the agency. As the car headed toward the barrier, there was **no precrash braking** or evasive steering movement, the report added.

The Guardian (June, 2018)

2018: Waymo (former Google) announced Public Service

- In 2018 driving without safety driver in a geofenced district of Phoenix
- By 2021 also in suburbs of Arizona, San Francisco and Mountain View

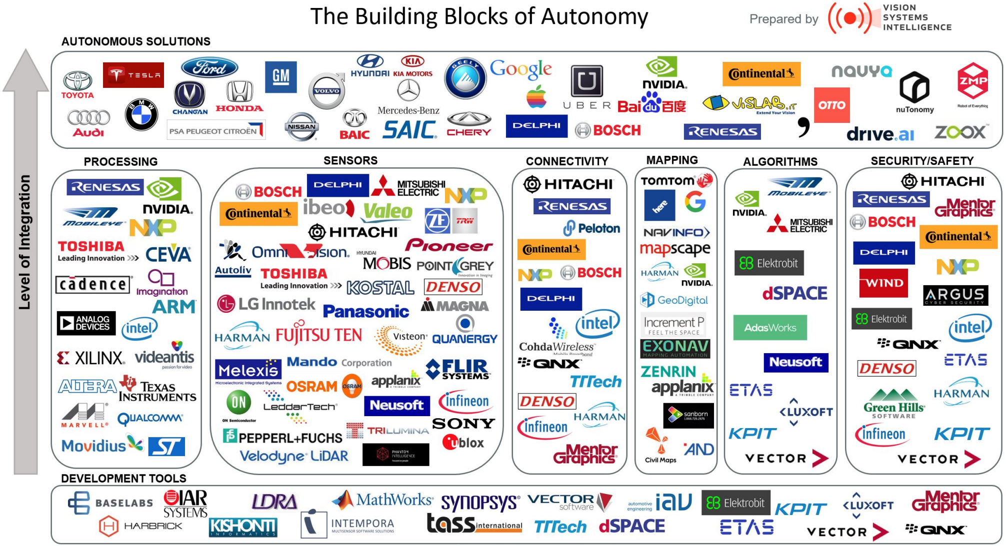
2018: Nuro Last-mile Delivery

- Founded by two of the Google self-driving car engineers

Self-Driving Industry

- NVIDIA: Supplier of self-driving hardware and software
- Waabi: Startup by Raquel Urtasun (formly Uber)
- Aurora: Startup by Chris Urmson (formerly CMU, Google, Waymo)
- Argo AI: Startup by Bryan Salesky (now Ford/Volkswagen)
- Zoox: Startup by Jesse Levinson (now Amazon)
- Cruise: Startup by Kyle Vogt (now General Motors)
- NuTonomy: Startup by Doug Parker (now Delphi/Aptiv)
- Efforts in China: Baidu Apollo, AutoX, Pony.AI
- Comma.ai: Custom open-source dashcam to retrofit any vehicle
- Wayve: Startup focusing on end-to-end self-driving

Self-Driving Industry



Business Models

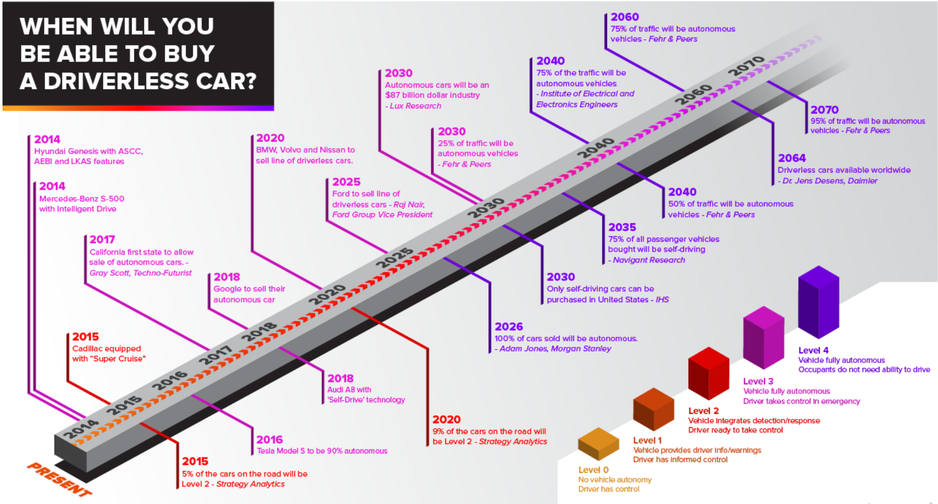
Autonomous or nothing (Google, Apple, Uber)

- Very risky, only few companies can do this
- Long term goals

Introduce technology little by little (all car companies)

- Car industry is very conservative
- ADAS as intermediate goal
- Sharp transition: how to maintain the driver engaged?

Wild Predictions about the Future of Self-Driving



Sources: Mercedes-Benz, GM News, Strategy Analytics, Automotive News, Nissan News, Navigant Research, Volvo News, Fehr & Peers, Lux Research, IHS

Summary

- Self-driving has a long history
- Highway lane-keeping of today was developed over 30 years ago
- Increased robustness $\Rightarrow$ introduction of level 3 for highways in 2019
- Increased interest after DARPA challenge and new benchmarks (e.g., KITTI)
- Many claims about full self-driving (e.g., Elon Musk), but level 4/5 stays hard
- Waymo introduced first public service end of 2018 (with safety driver)
- Waymo/Tesla seem ahead of competition in full self-driving, but no winner yet
- But several setbacks (Uber, Tesla accidents)
- Most existing systems require laser scanners and HD maps (exception: Tesla)
- Driving as an engineering problem, quite different from human cognition