SELF-DRIVING CARS INTRODUCTION

Photogrammetry & Robotics Lab

Introduction to Techniques for Self-Driving Cars

Stachniss, Behley, Mersch

Self-Driving Cars

[Courtesy of S. Thrun, S. Jurvetson, Grendelkhan]

Aims of this Lecture

- Introduction to self-driving cars
- Getting to know key building blocks
- Gaining practical experience realizing simplified building blocks in Python
- Test your own developments in a car simulator
- Perspective from academia & industry

What Do Self-Driving Cars Need to Do?

Basic Steps Executed by a Self-Driving Car

- Must have the right prior knowledge
- Estimate the own state
- Perceive the surroundings
- Predict what is going to happen
- Reason and plan what to do
- Act – execute steering commands

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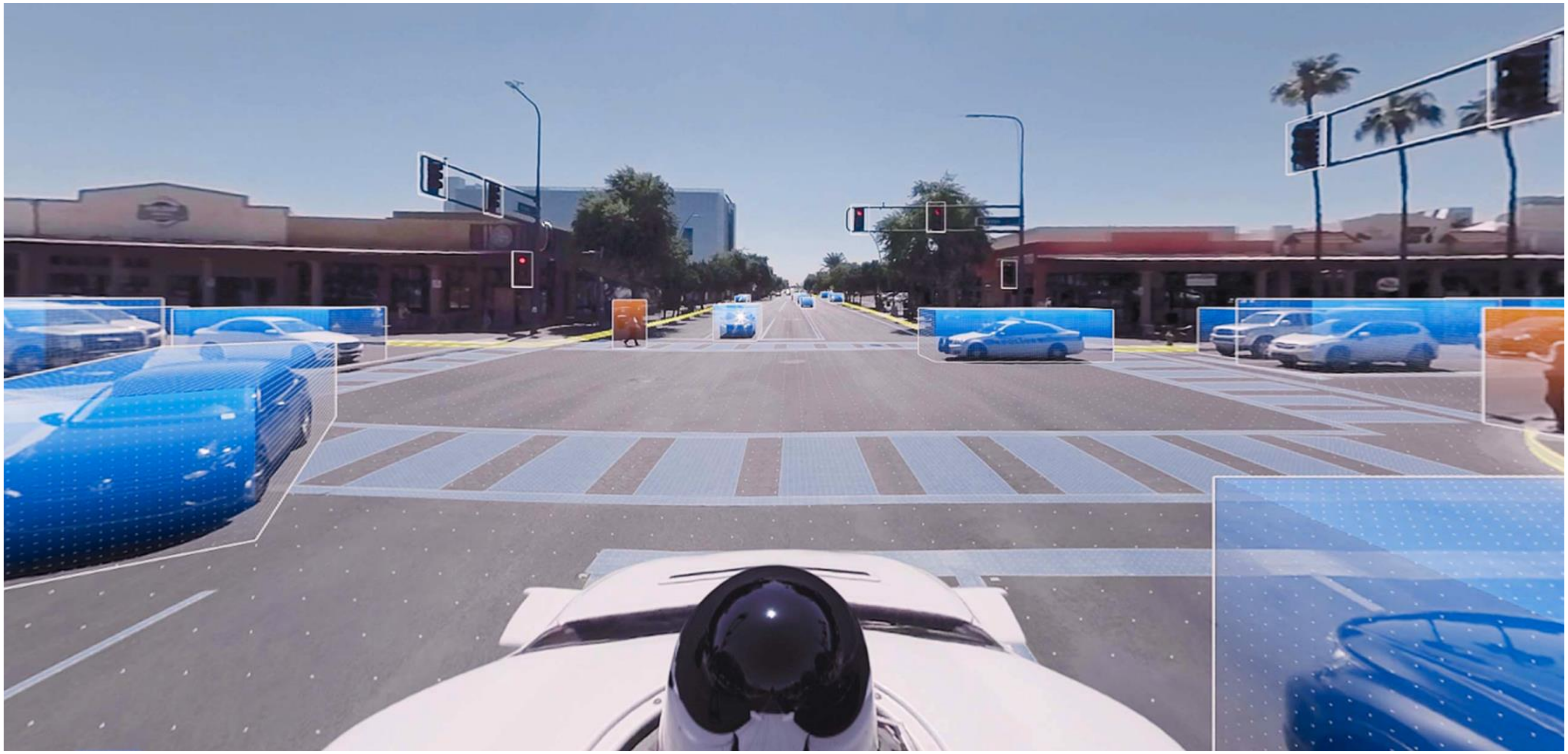
Prior Knowledge & Own State

E.g., map of the environment & pose

[Courtesy of Waymo]

Perception & State Estimation

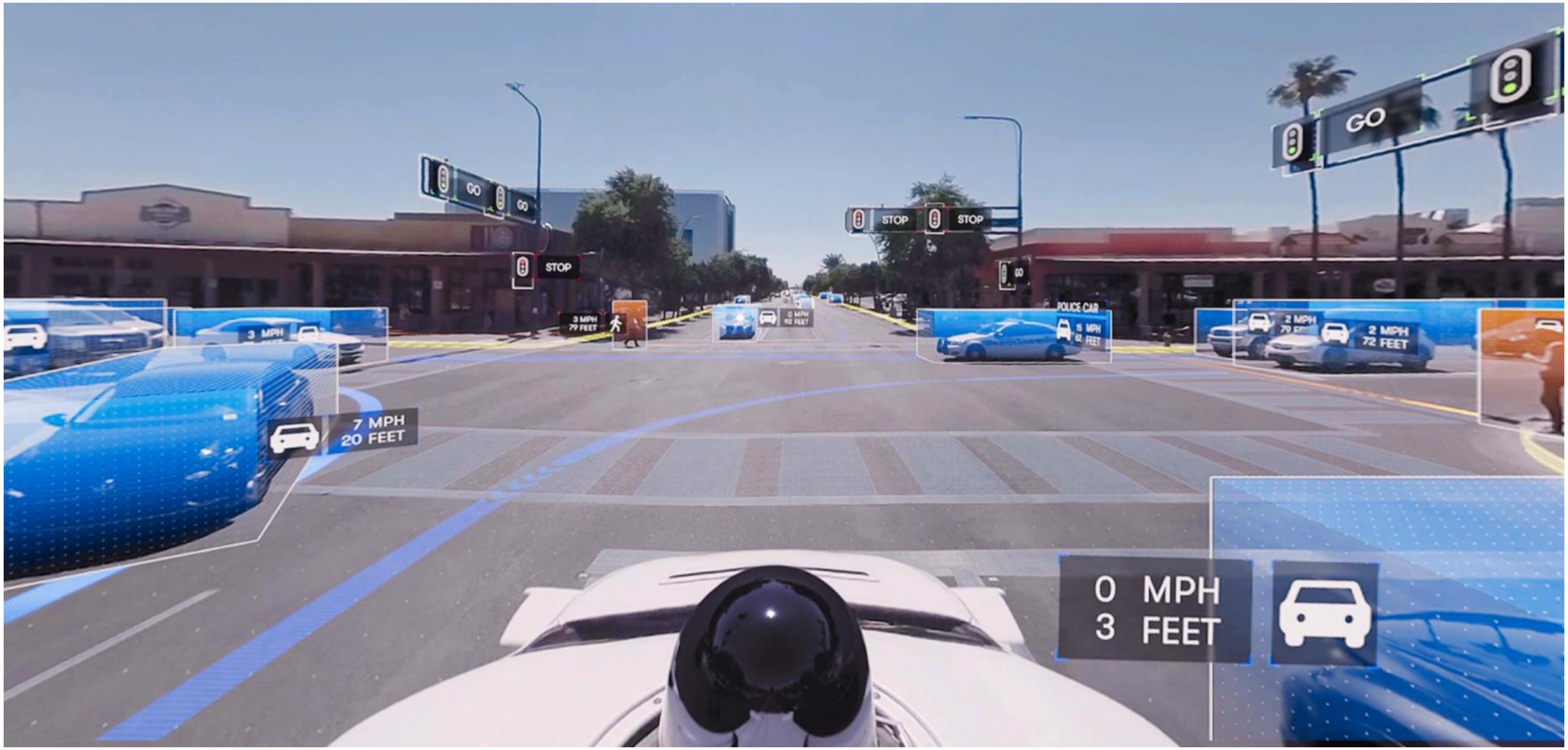
E.g., what is around me and where?



[Courtesy of Waymo]

Prediction

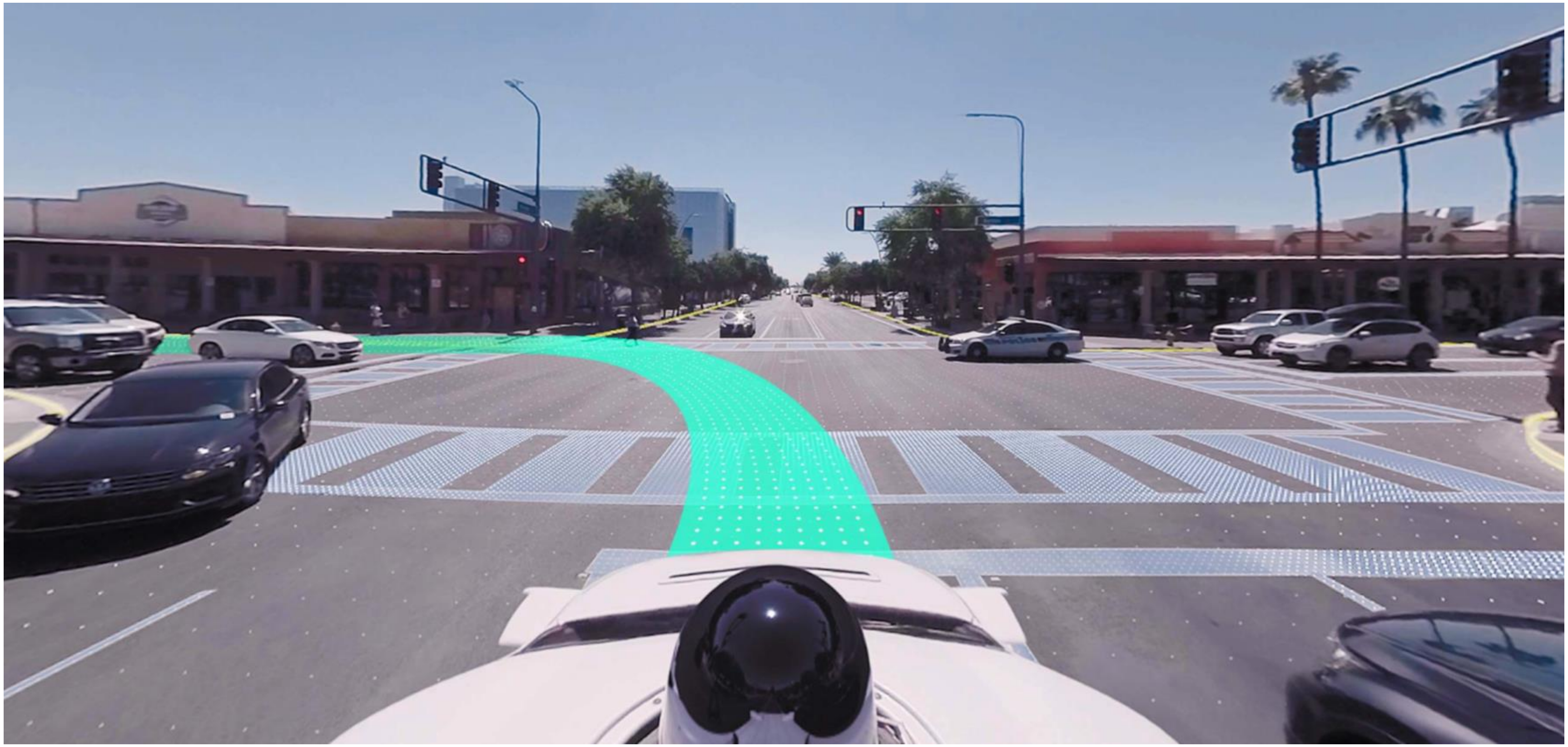
E.g., what will the others do?



[Courtesy of Waymo]

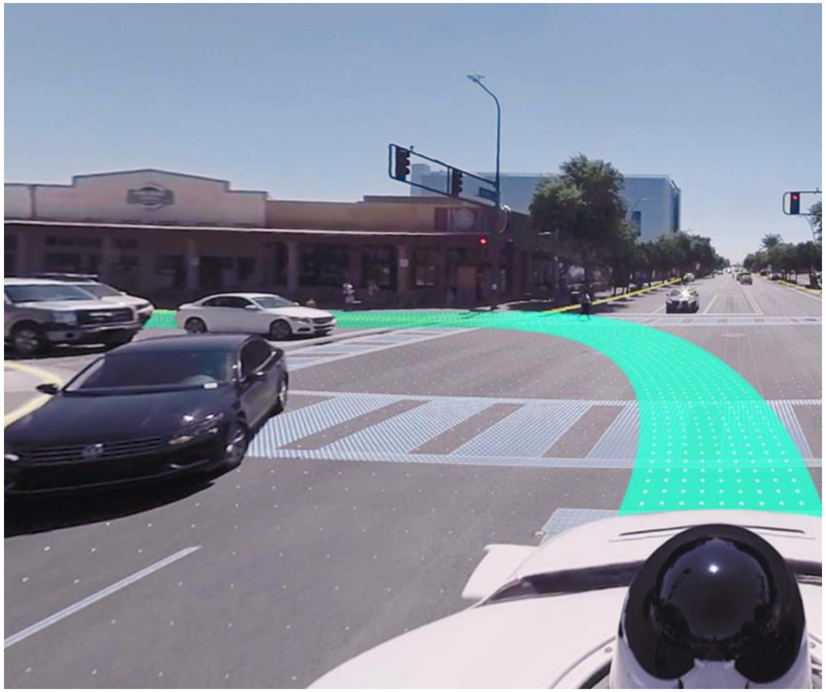
Act

E.g., where should I drive to and how?



[Courtesy of Waymo]

Two Key Topics Primarily Addressed in This Course



Perception:
"Making the car see."

Planning and control:
"Making the car act."

[Courtesy of Waymo]

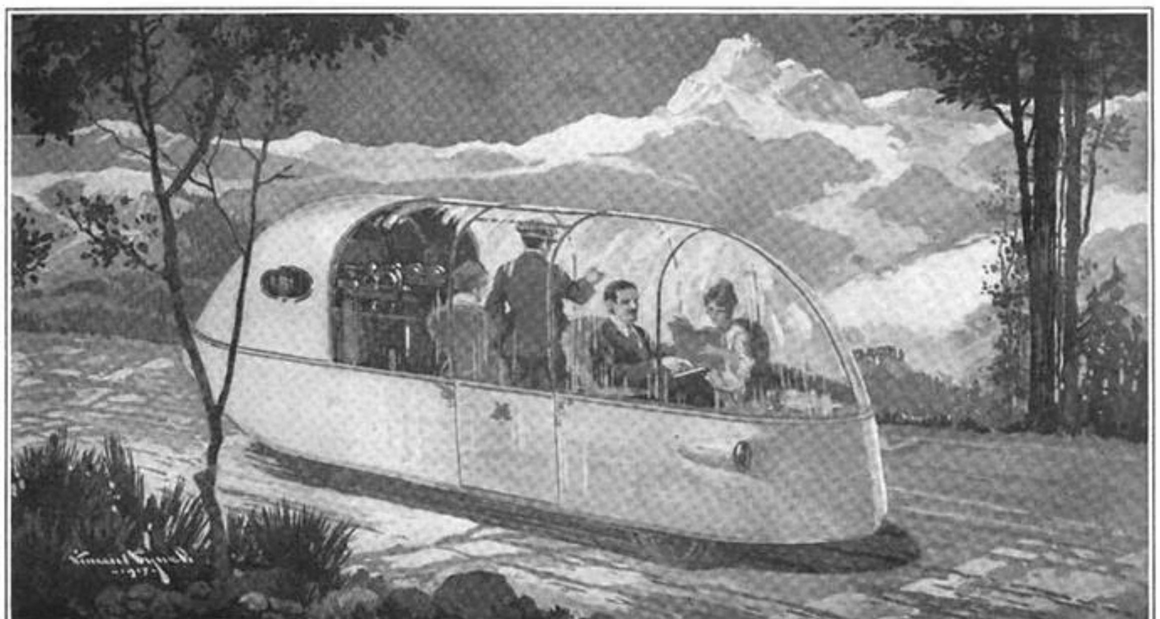
The Dream Started in 1918…

SEVENTY-FOURTH YEAR

SCIENTIFIC AMERICAN

THE WEEKLY JOURNAL OF PRACTICAL INFORMATION

VOLUME CXVIII. NUMBER 1 | NEW YORK, JANUARY 5, 1918 | 15 CENTS A COPY $4.00 A YEAR



The motorist's dream: a car that is controlled by a set of push buttons

[Courtesy of Scientific American (January 5, 1918)]

History of Self-Driving Cars

- 1918: Scientific American describes “a motorist’s dream: a car that is controlled by a set of push buttons”
- 1921: First radio-controlled car
- 1930-1970/80ies: several predictions
- 1977: First street vehicle (Tsugawa et al. 1977)
- 1985: DARPA Autonomous Land Vehicle (ALV)
- 1987-94: Dickmann’s EUREKA project
- 1993/4: BOSCH/Toyota: line detection and following vehicle
- 1994: PROMETHEUS drives 1,700+km: Munich ⇔ Denmark
- 1996: Project ARGO: 2,000km driving (Italy)
- 1997: Driving demonstration on I-15 (San Diego)

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History of Self-Driving Cars: Tsukuba Mechanical Eng. 1977

History of Self-Driving Cars: Dickmann’s Achievements

[Courtesy of E. Dickmann]

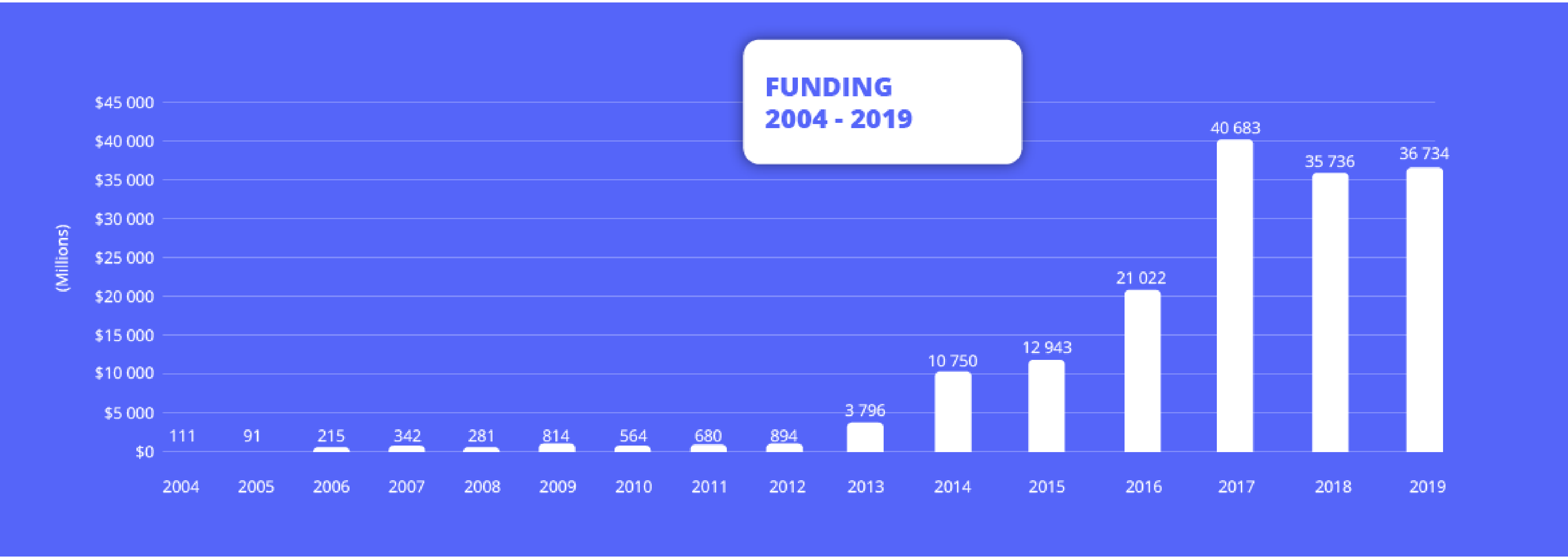
History of Self-Driving Cars: Dickmann's Achievements

[Courtesy of E. Dickmann]

Self-Driving Cars Since 2004

- 2004: DARPA Gran Challenge, broad interest in self-driving
- 2005: Stanley, who won the Gran Challenge
- 2005: First startups enter the scene
- 2007: DARPA Urban Challenge
- 2009: Google self-driving car project (=> Waymo)
- 2012: Stanford race-car drives up Pikes Peak autonomously
- 2013-2017: Substantial increase in funding for self-driving and several new startups enter the scene
- 2017-2020: Funding stagnates, some consolidation
- 2017-2020: Several large-scale collaborations/joint ventures
- 2020: Companies claim to be close to market but several people have doubts that it will be very close
- 2020/21: Tesla starts Autopilot
- 2022/23: Autonomous taxi services available in selected cities in the US (L4)

Funding for Self-Driving Companies



[Courtesy of E. Boutan]

Some of the Players in the Field

- Waymo (Google X)
- GM Cruise
- Tesla
- Apple
- Baidu Apollo
- Oxa (Oxbotica)
- Apex.AI
- VW/Cariad
- Toyota/Woven/TRI
- Daimler-Bosch
- Aptiv
- Auroa
- Zoox
- Holomatic
- comma.ai
- Wayve
- Lyft

… and several others …

What Means “Self-Driving”?

Levels of Autonomy

Self-driving cars are not all created equal. While researchers predict 8 million autonomous vehicles will be on the road by 2025, their self-driving capabilities will differ. SAE International updated the SAE J3016 in 2021 to clarify how the automotive industry can define driver support systems and advanced driver assistance systems.

[Courtesy of ASME; This infographic was originally published on www.asme.org]

Levels of Autonomy

THE LEVELS OF AUTOMATION IN VEHICLES BREAKS DOWN INTO SIX DIFFERENT CATEGORIES:

LEVEL 0	**No Driving Automation**	**LEVEL 3**	**Conditional Driving Automation**
LEVEL 1	**Driver Assistance**	**LEVEL 4**	**High Driving Automation**
LEVEL 2	**Partial Driving Automation**	**LEVEL 5**	**Full Driving Automation**

Today's car market offers different autonomous capabilities, and the selection of vehicles is growing. So let us explore the different driving levels and which cars are better equipped to dominate the road.

[Courtesy of ASME; This infographic was originally published on www.asme.org]

Levels of Autonomy

No Driving Automation → LEVEL 0

At this level, the human driver is entirely in control and performs all the dynamic driving tasks (DDT). Cars with active safety systems that may provide alerts or momentary emergency actions. Such subsystems as blind-spot detection, stability control, forward-collision warning, or automatic emergency braking are considered level 0 because the safety systems do not drive the vehicle.

VEHICLES: The majority of cars on the road today are Level 0.

[Courtesy of ASME; This infographic was originally published on www.asme.org]

Levels of Autonomy

Driver Assistance → LEVEL 1

Level 1 is the simplest form of vehicle automation with at least one driver support. The system can perform a sustained and operational design domain (ODD) specific subtask in either the lateral or longitudinal direction as part of a DDT automation. The driver must supervise the driving automation system by performing the object and event detection and response (OEDR) and other dimensions of the vehicle motion. The automation is short-term and meant to assist the driver.

VEHICLES: The Audi 2021 lineup has both adaptive cruise control and hands-on lane-centering.

[Courtesy of ASME; This infographic was originally published on www.asme.org]

Levels of Autonomy

Partial Driving Automation → LEVEL 2

In comparison to Level 1, Level 2 performs DDT automation for longer periods. The ODD performs extended motion in the lateral and longitudinal direction, but the driver is still expected to have their hands on the wheel for any emergency OEDR actions. The SAE J3016 classifies this as automated movement under the driver's supervision.

VEHICLES: The 2021 Genesis G70 can perform adaptive cruise control down to a stop.

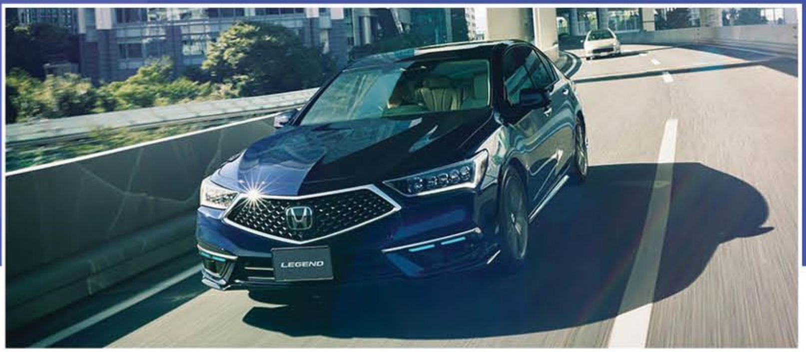
[Courtesy of ASME; This infographic was originally published on www.asme.org]

Levels of Autonomy

Conditional Driving Automation ....▸ LEVEL 3

The Level 3 of self-driving automation is a significant step up from Level 2 and is not legal yet on U.S. roads. Conditional driving automation introduces sustained and ODD-specific performance by an automated driving system (ADS). Here the driver is not constantly supervising the vehicle but instead is on standby and must be ready to take control in an emergency. However, the car is driven entirely by the ADS and artificial intelligence software to make movement decisions based on its environment. An example of Level 3 driving is a vehicle capable of performing all DDT in a low-speed area or in stop-and-go freeway traffic.

VEHICLES: The Honda Legend became the world's first commercially available Level 3 autonomous car in 2021.



[Courtesy of ASME; This infographic was originally published on www.asme.org]

Levels of Autonomy

High Driving Automation .... LEVEL 4

High driving automation is a complete ADS and does not require any human interaction to operate the vehicle, even in emergencies, as the car is programmed to stop in the event of a system failure or emergency. These cars are expected to be the future of autonomous taxis and public transportations. Depending on the vehicle features, certain Level 4 vehicles may require human intervention to finish the route or handle transitions, such as exiting the freeway, and their capabilities may be restricted to a given geographical region. An external dispatcher may also be needed to program the destination of the vehicle.

VEHICLES: Waymo, owned by Alphabet Inc., is a Level 4 vehicle, and is currently testing its self-driving taxi service out of Phoenix, Arizona.

[Courtesy of ASME; This infographic was originally published on www.asme.org]

Levels of Autonomy

Full Driving Automation .... LEVEL 5

The highest level of automation, Level 5, requires no human interaction whatsoever. The route planning, the vehicle DDT, and the transitions between low and high-speed zones are controlled entirely by the ADS. These vehicles are not bound geographically, nor are they affected by external conditions such as weather or congested traffic environments. The only human action needed is to pick a destination.

VEHICLES: There are currently no Level 5 vehicles on the road today.

[Courtesy of ASME; This infographic was originally published on www.asme.org]

Levels of Autonomy (by SAE)

SOCIETY OF AUTOMOTIVE ENGINEERS (SAE) AUTOMATION LEVELS

Full Automation

0	1	2	3	4	5
No Automation	**Driver Assistance**	**Partial Automation**	**Conditional Automation**	**High Automation**	**Full Automation**
Zero autonomy; the driver performs all driving tasks.	Vehicle is controlled by the driver, but some driving assist features may be included in the vehicle design.	Vehicle has combined automated functions, like acceleration and steering, but the driver must remain engaged with the driving task and monitor the environment at all times.	Driver is a necessity, but is not required to monitor the environment. The driver must be ready to take control of the vehicle at all times with notice.	The vehicle is capable of performing all driving functions under certain conditions. The driver may have the option to control the vehicle.	The vehicle is capable of performing all driving functions under all conditions. The driver may have the option to control the vehicle.

Society of Automotive Engineers (SAE)

[Courtesy of SAE]

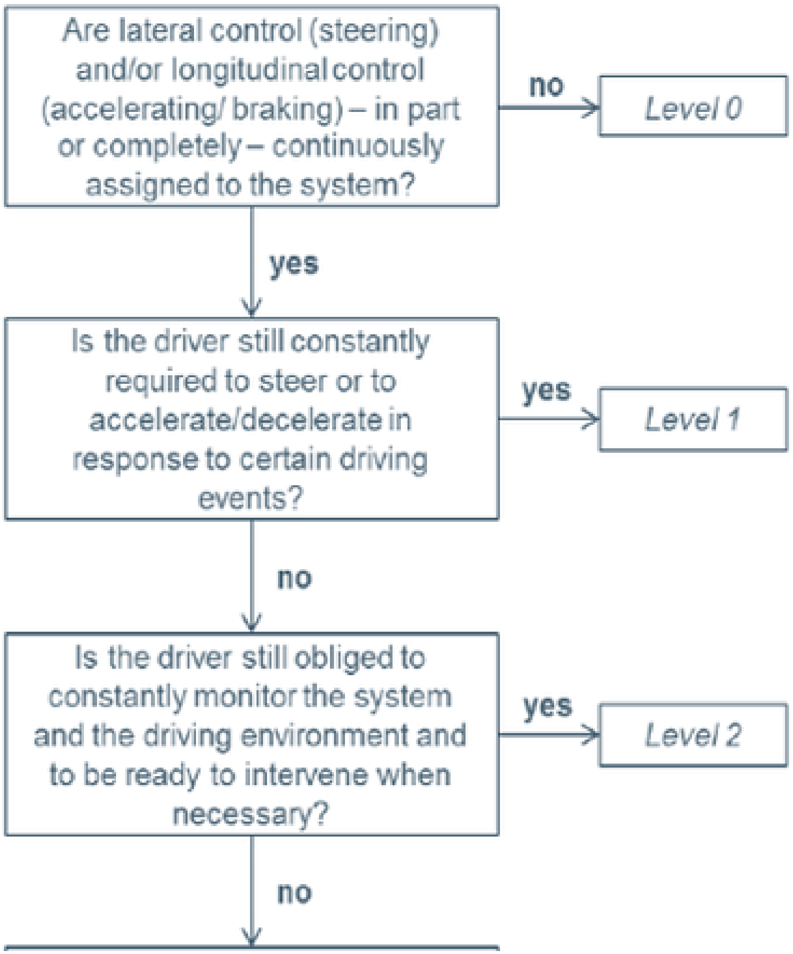
Levels of Autonomy: L0-L2

- **L0: No** automation
- **L1: Small steering or acceleration tasks** without human intervention, but everything else is fully under human control
- **L2: Car controls** itself (steering and acceleration) and can automatically take safety actions but the **driver needs to stay alert and monitor the environment.**

Levels of Autonomy: L3-L5

- **L3: some safety-critical functions** performed by the vehicle, under certain conditions. The **human is still required**
- **L4:** Autonomous driving **almost all the time** without human input. Driving may be limited to mapped areas and may not work under all weather conditions or similar. No human interaction in regular operation
- **L5:** Full automation in **all conditions**

Decision Tree for Determining the SAE Level



Source: U. Eberle, "AdaptIVe" Final Event, 2017 (Opel Automobile)

[Image Courtesy of Eberle]

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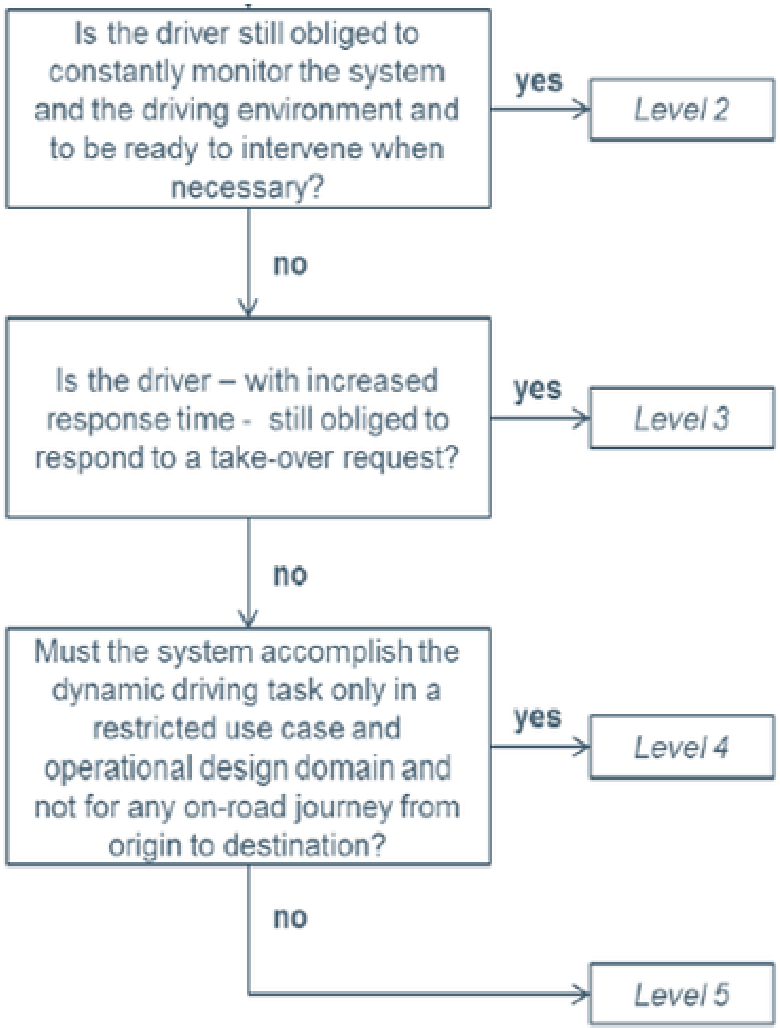

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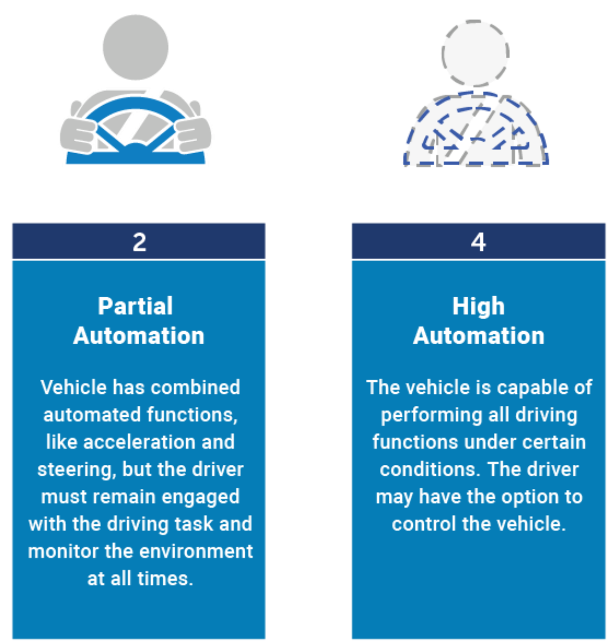
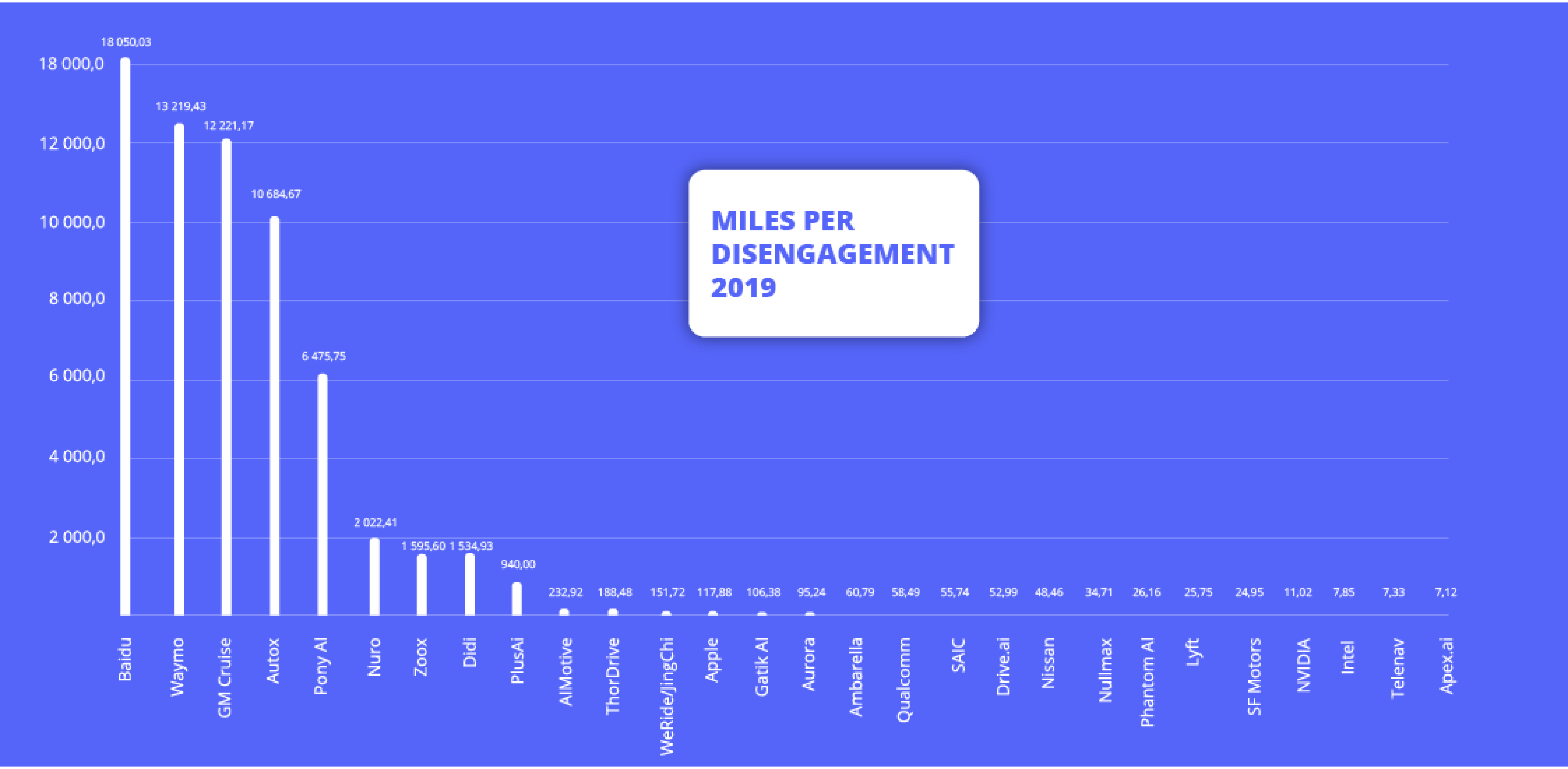
[Image Courtesy of Eberle]

Current Target: Level 2 or 4

- Most players head for L2 or L4
- L2 as intelligent cruise control but human in charge (advancement of current cars)
- L4 as as fully “self-driving car”

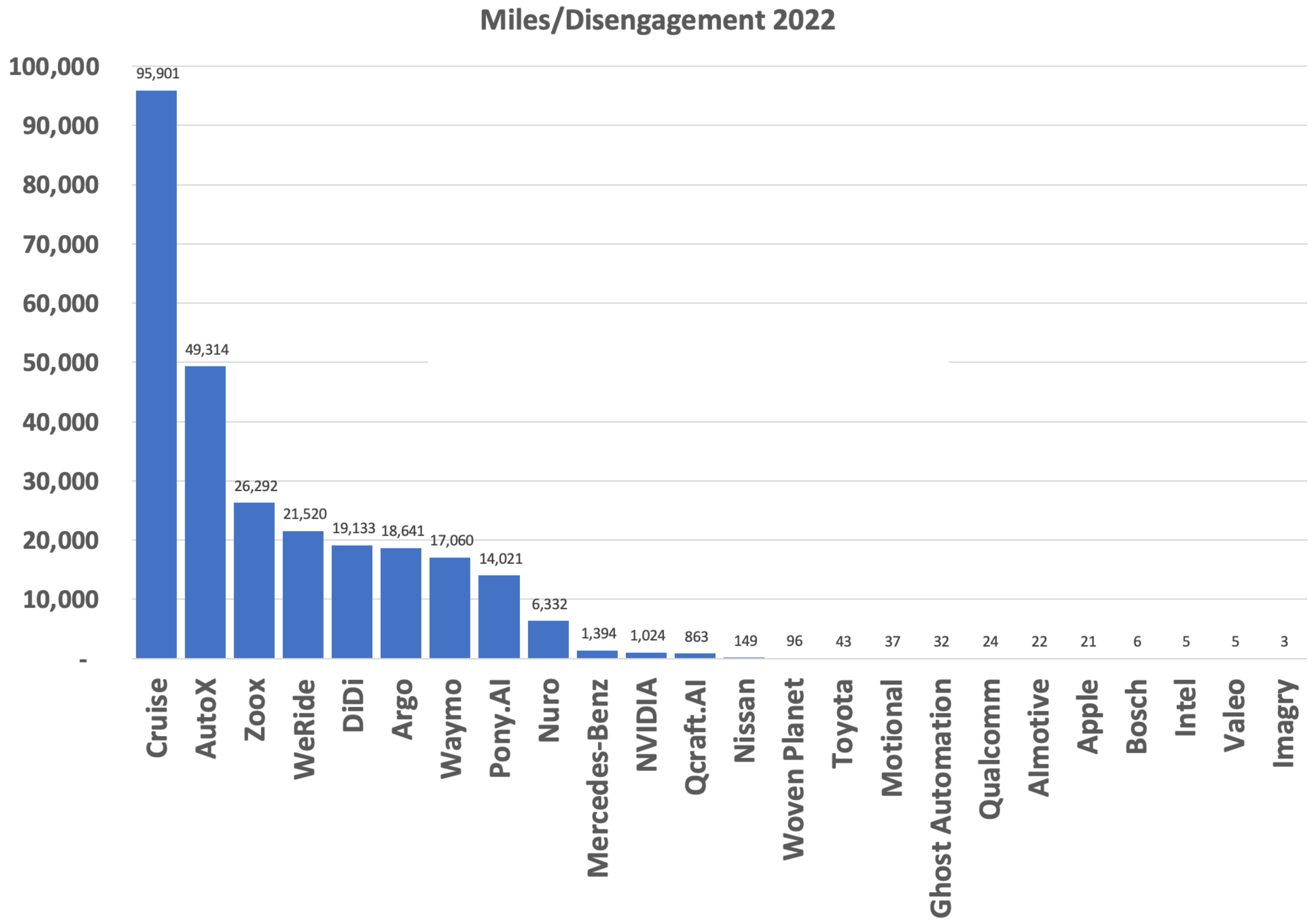


Miles per Disengagement Driven in California in 2019



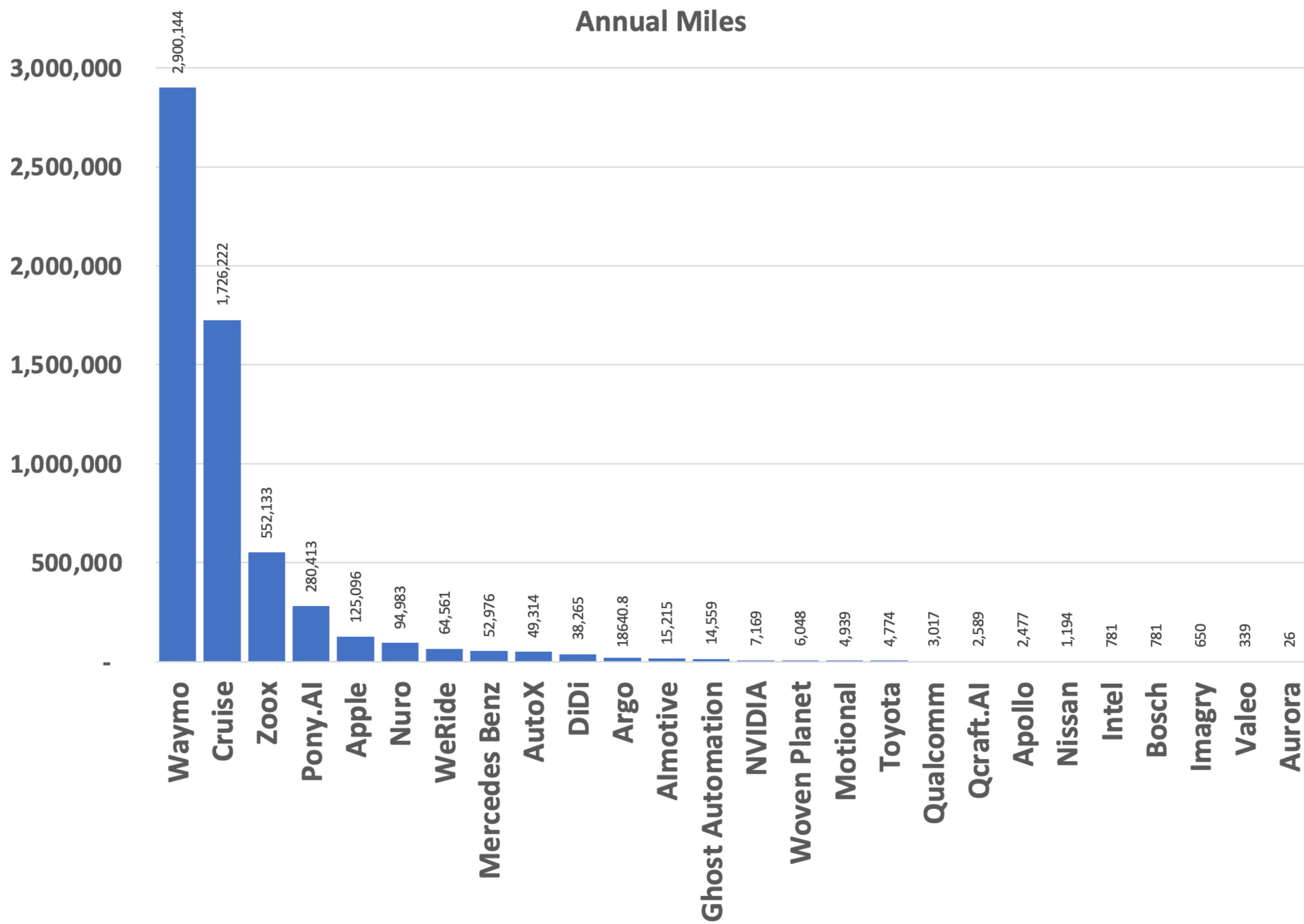
[Courtesy of E. Boutan]

Miles per Disengagement Driven in California in 2022



[Courtesy of thelastdriverlicenseholder]

Annual Miles Driven in California in 2022



[Courtesy of thelastdriverlicenseholder]

No-Driver-in-the-Car Miles Driven in California in 2022

Companies with driverless licensees in CA: Apollo, AutoX, Cruise, Nuro, Waymo, WeRide, and Zoox

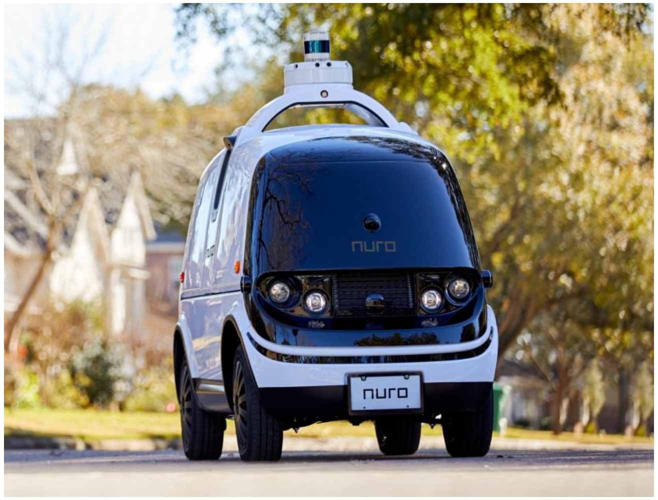
	Miles	**Kilometers**	**Vehicles**
Apollo (Baidu)	21,774	34,838	4
Cruise	546,492	874,388	222
Nuro	924	1,479	9
Waymo	51,639	82,623	317
WeRide	2,859	4,575	3
	623,689	**997,903**	**555**

[Source: 2022 Disengagement Report from California]

Example Vehicles

[Courtesy of Waymo, Pony.ai, Baidu, Cruise]

Example Vehicles

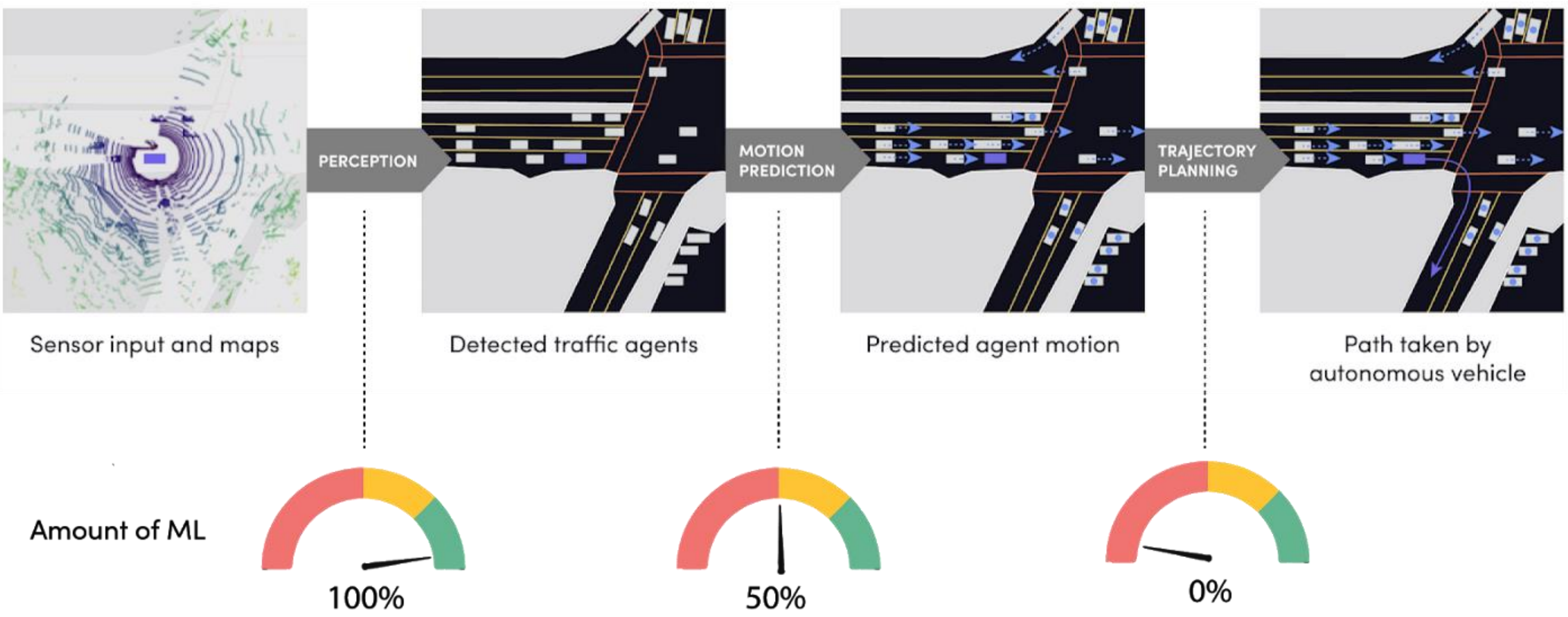


[Courtesy of Uber, Nuro.ai, Tesla, AID]

Technology in Self-Driving Cars: Perceive – Estimate – Predict – Act

- **Online state estimation:**
  e.g., localization, SLAM, sensor fusion, …
- **Machine learning/deep learning:**
  e.g., detection, semantics, behavior prediction, imitation learning, …
- **Planning & control:**
  e.g., path planning, high-level behavior, planning under uncertainty, control, …
- **…**

Learning in Self-Driving Cars



[Courtesy: Ondruska, Lyft]

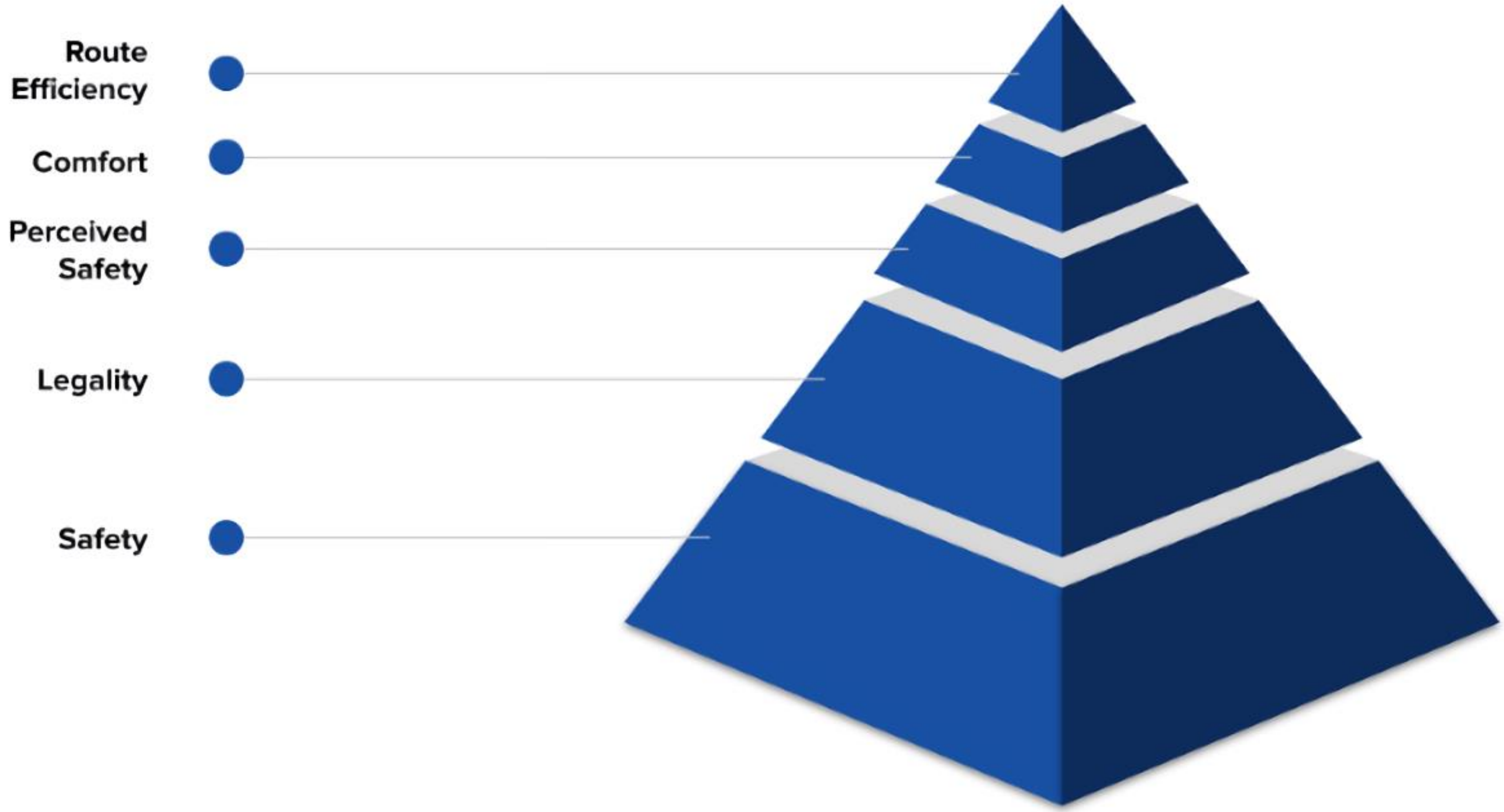
End-to-End Approaches

Directly learn mapping from camera data to steering commands

First End-to-End Driving in London in Summer 2021

[Courtesy of Wayve]

What Is Most Important?



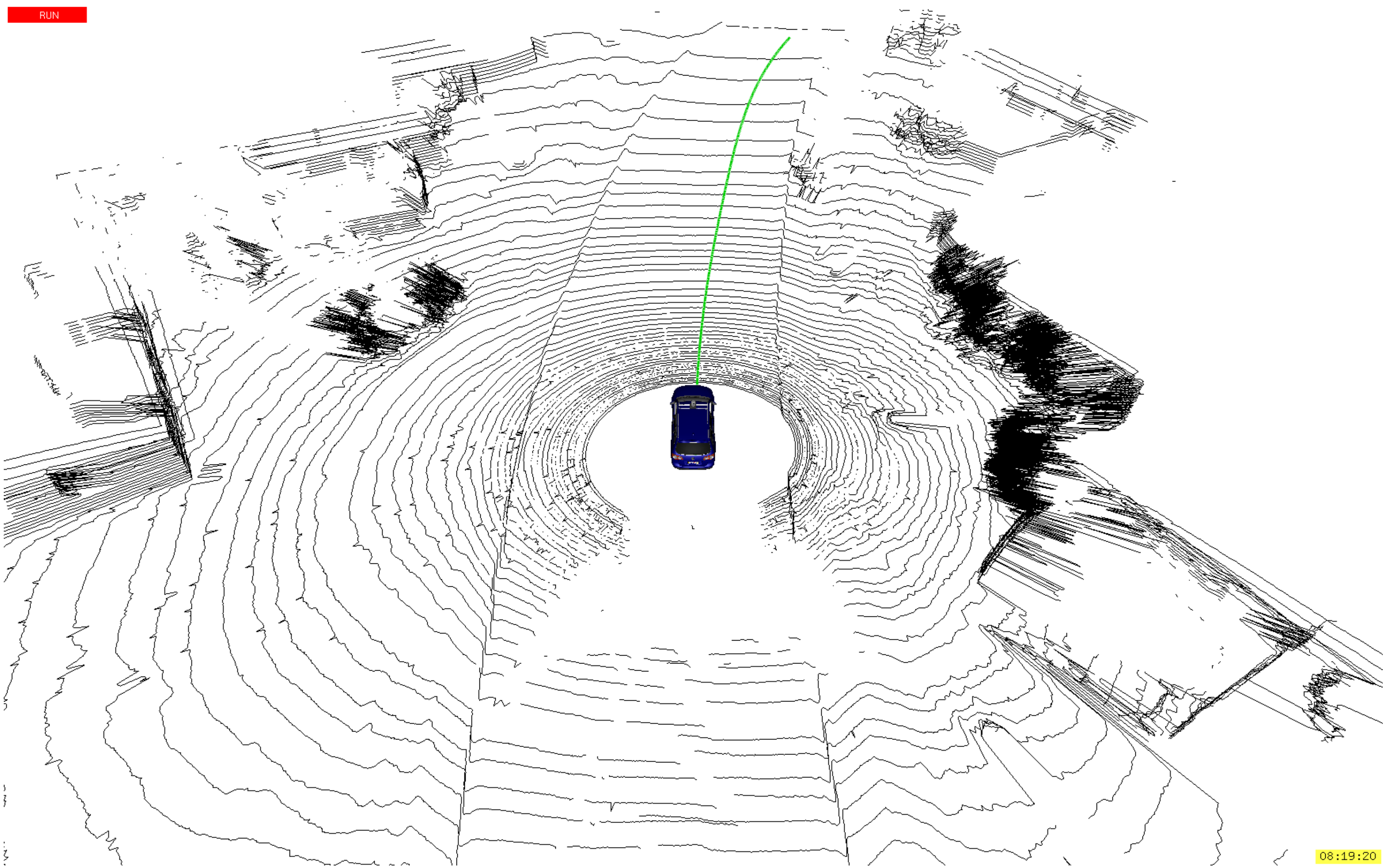
[Courtesy of Lyft]

What Do Cars See?

Google Car (~2009)

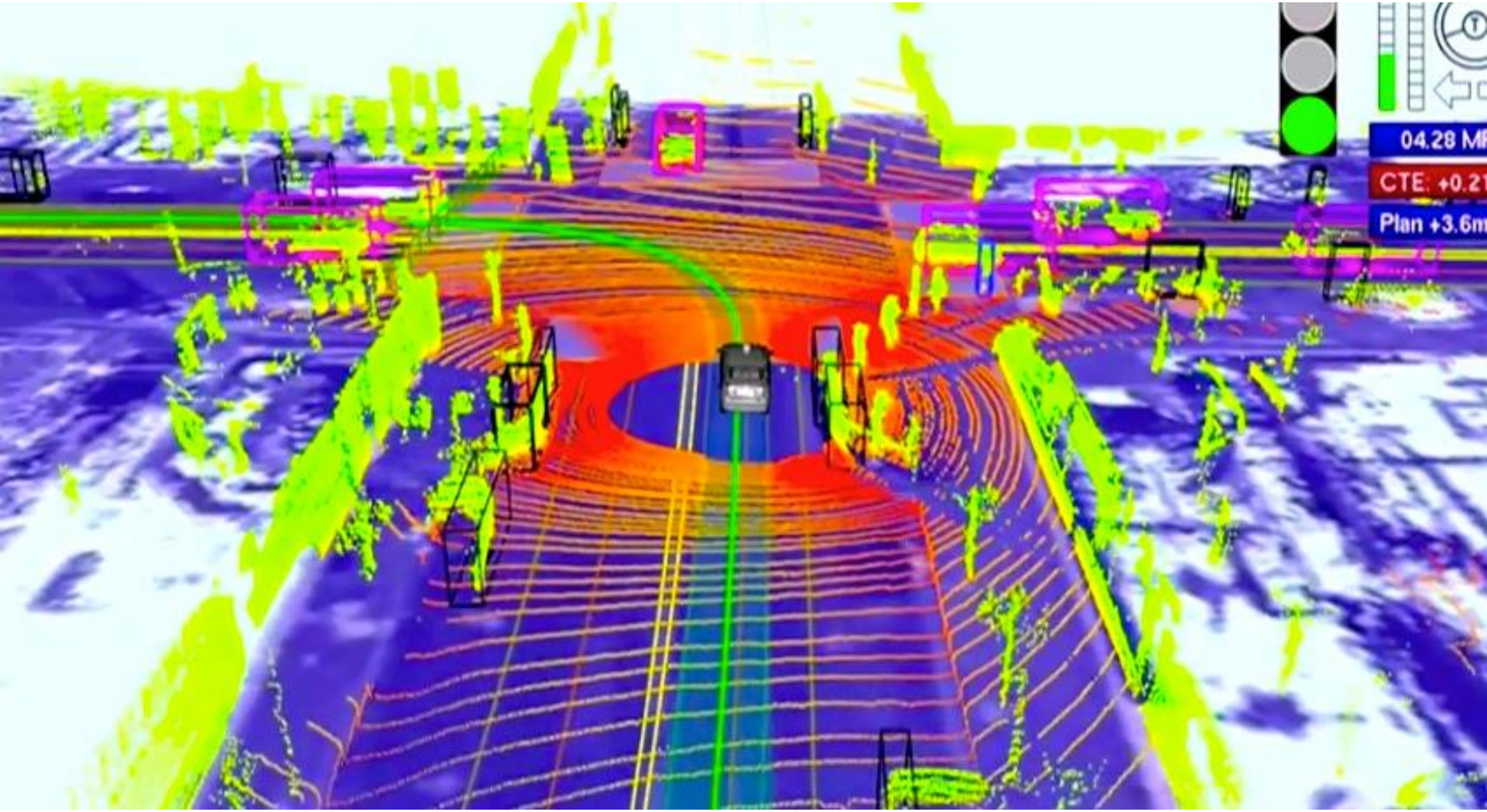
[Courtesy: Google]

What Did the Car See? (~2009)



[Courtesy: Google]

What Did the Car See? (~2009)



[Courtesy: Google]

First Public Demonstration

[Courtesy: Google]

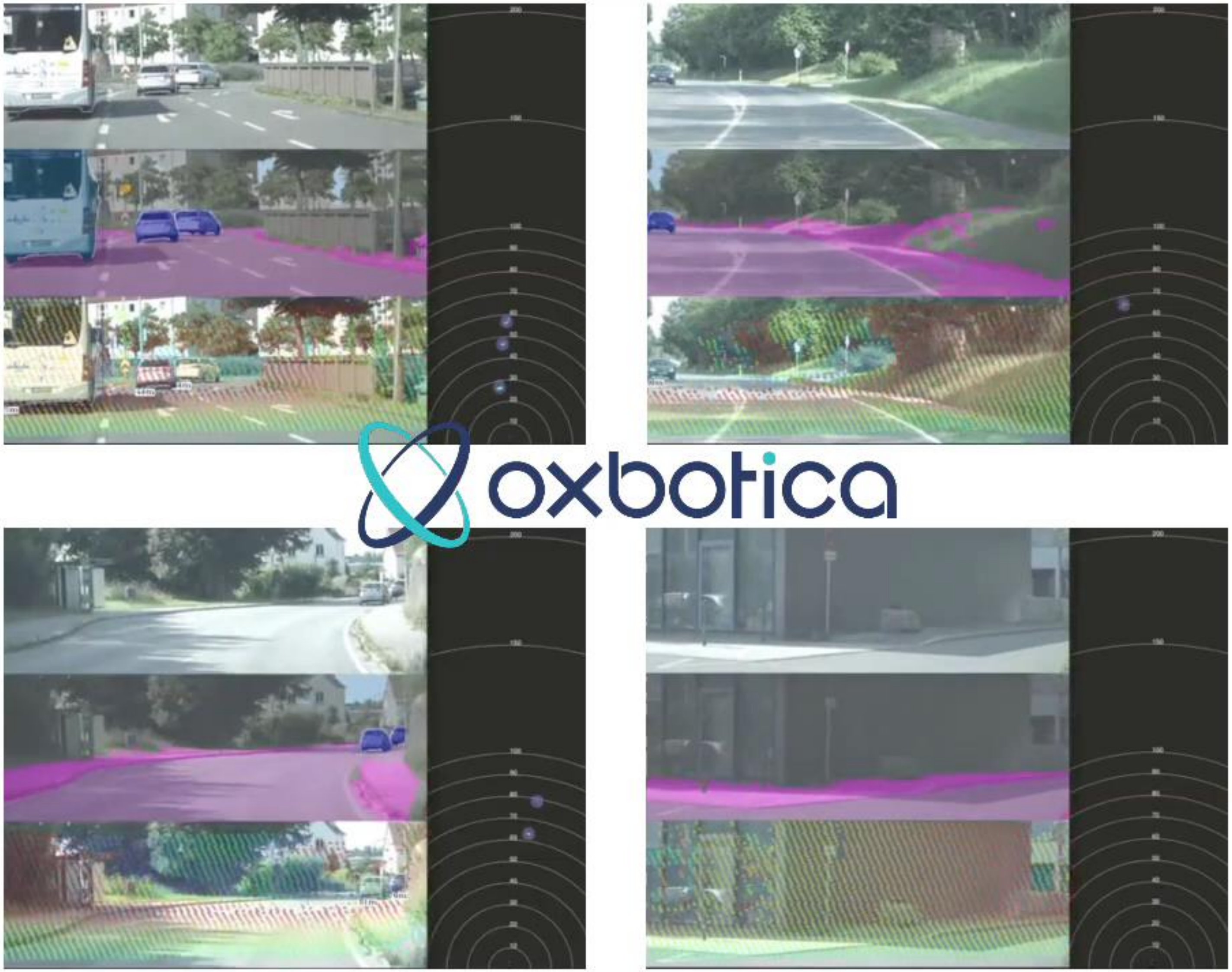
Driving in Urban Environments

[Courtesy: Oxbotica P. Newman/B. Upcroft]

Driving in Urban Environments

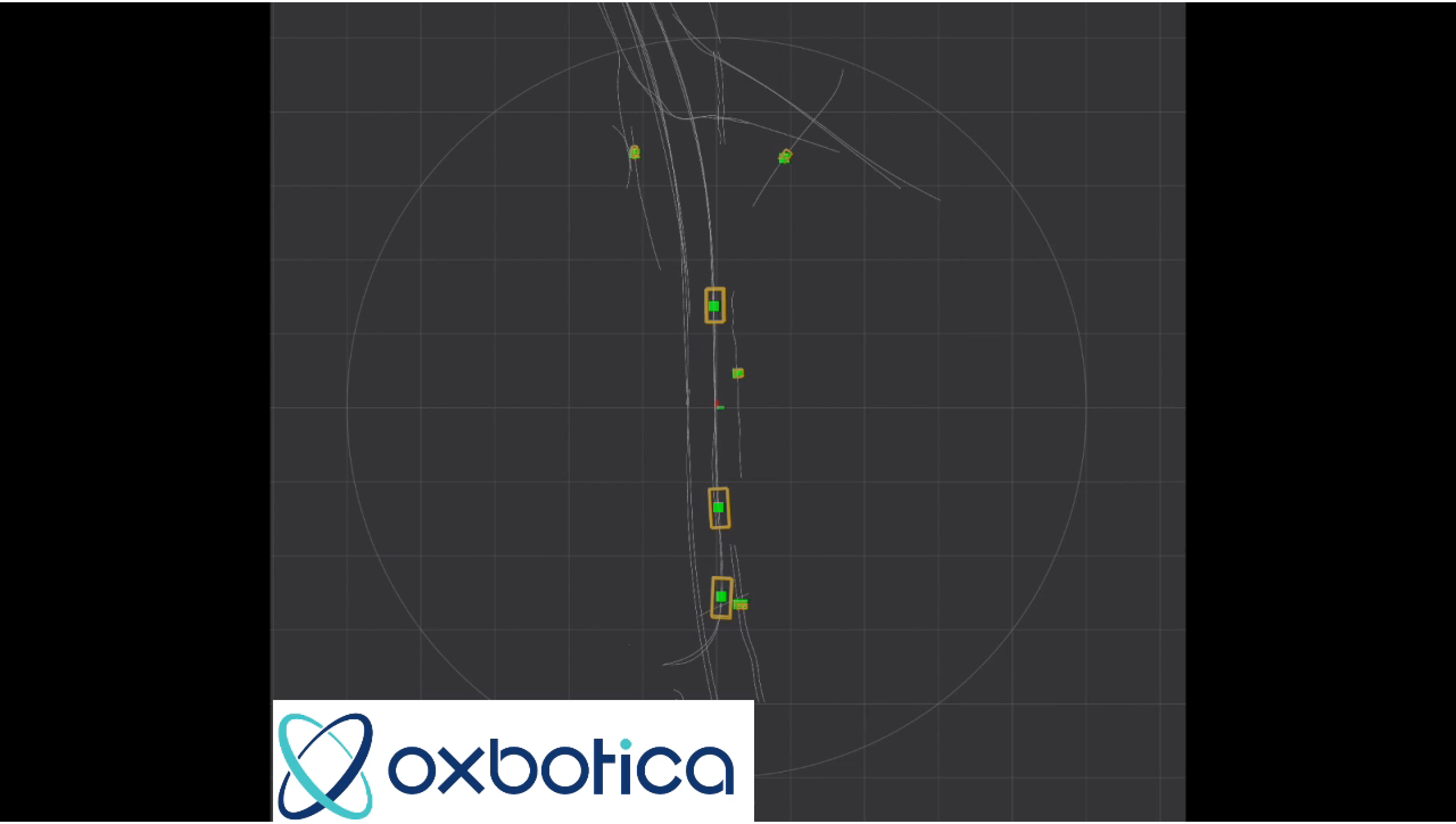
[Courtesy: Oxbotica P. Newman/B. Upcroft]

Learning-based Perception



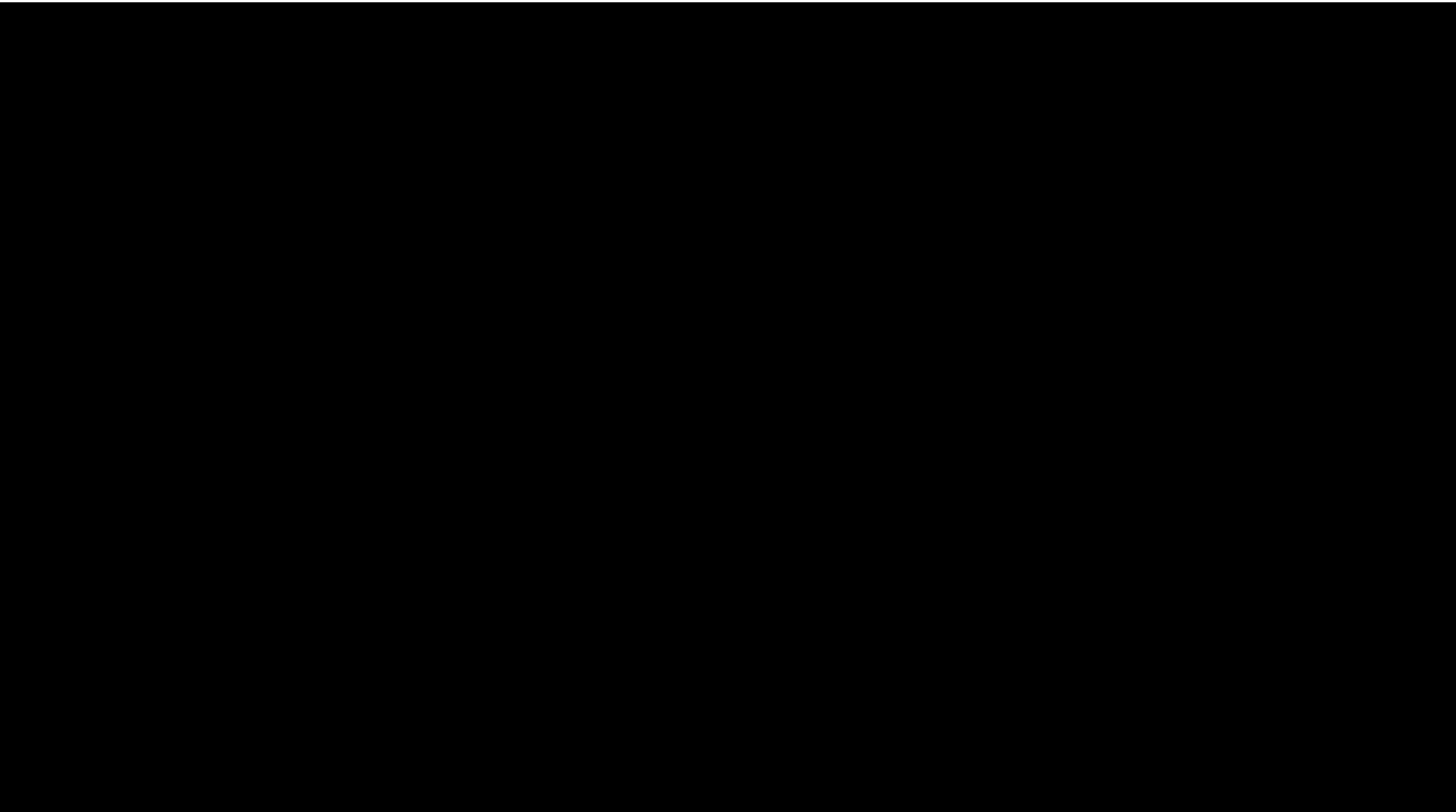
[Courtesy: Oxbotica P. Newman/B. Upcroft]

Estimating What Happens



[Courtesy: Oxbotica P. Newman/B. Upcroft]

Current State (Waymo, ~2019)



[Courtesy: Waymo]

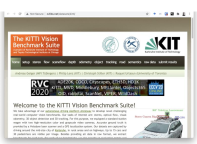
How to Test and Evaluate?

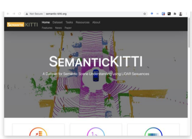
How to Test the Developments

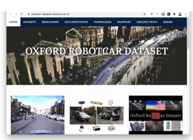
- Real testing is slow and expensive
- How to test at large scale?
- How to evaluate different approaches objectively?
- How to test behaviors in dangerous situations?
- What happens after changes in the code base? Run all real tests again?
- How to get ground truth data?

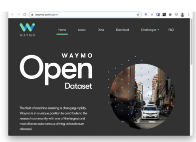
Datasets

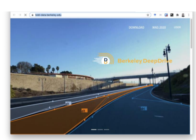
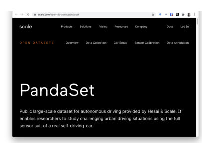
- Datasets recorded from vehicles are a key building block in development
- More and more datasets have been released within the past 2 years
- More vehicles, more variations, more locations, more drivers, …

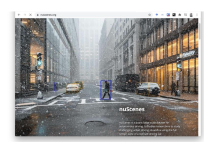


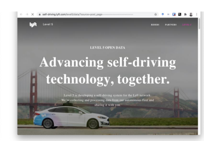


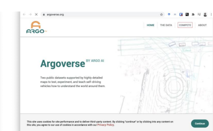




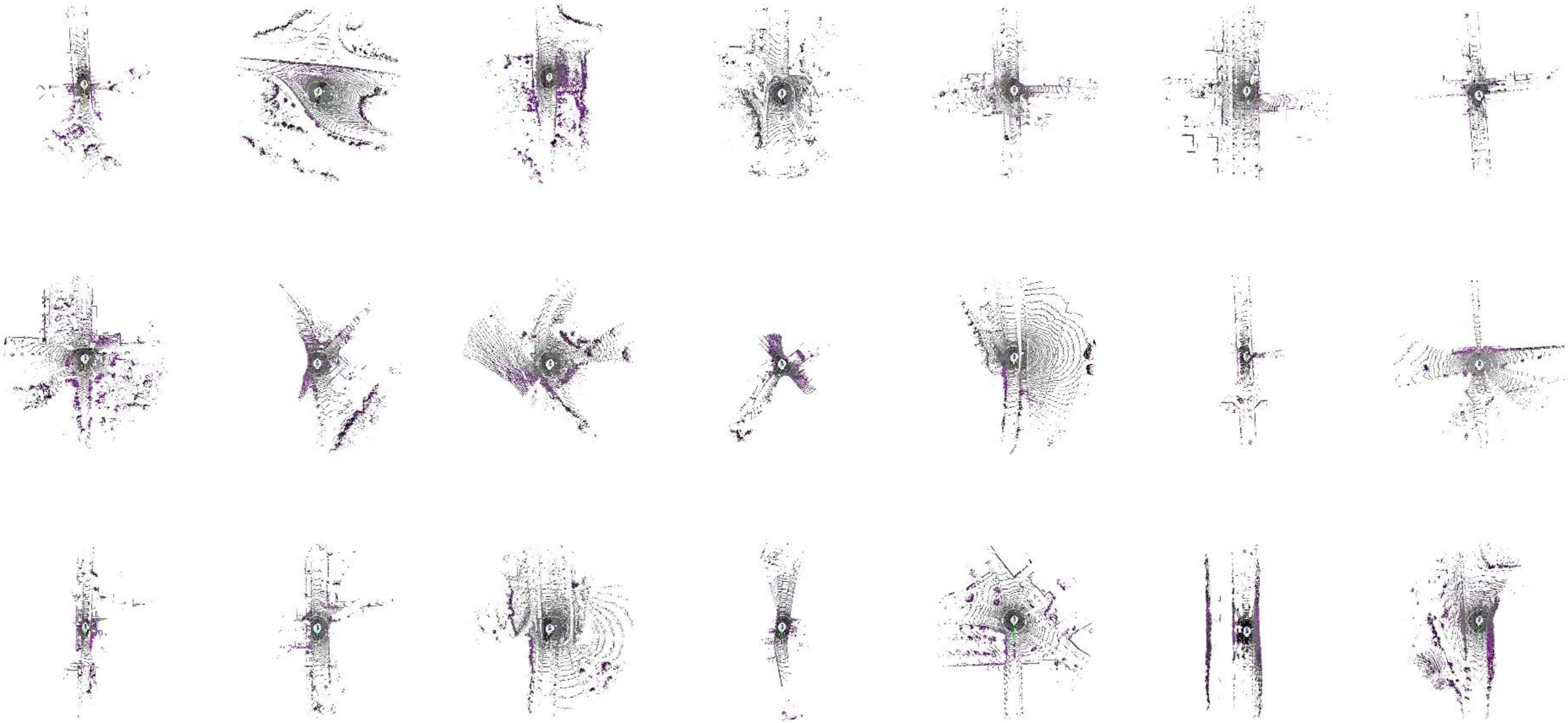









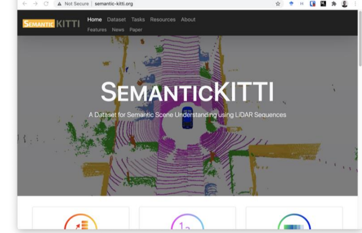
Example: LiDAR SLAM on KITTI



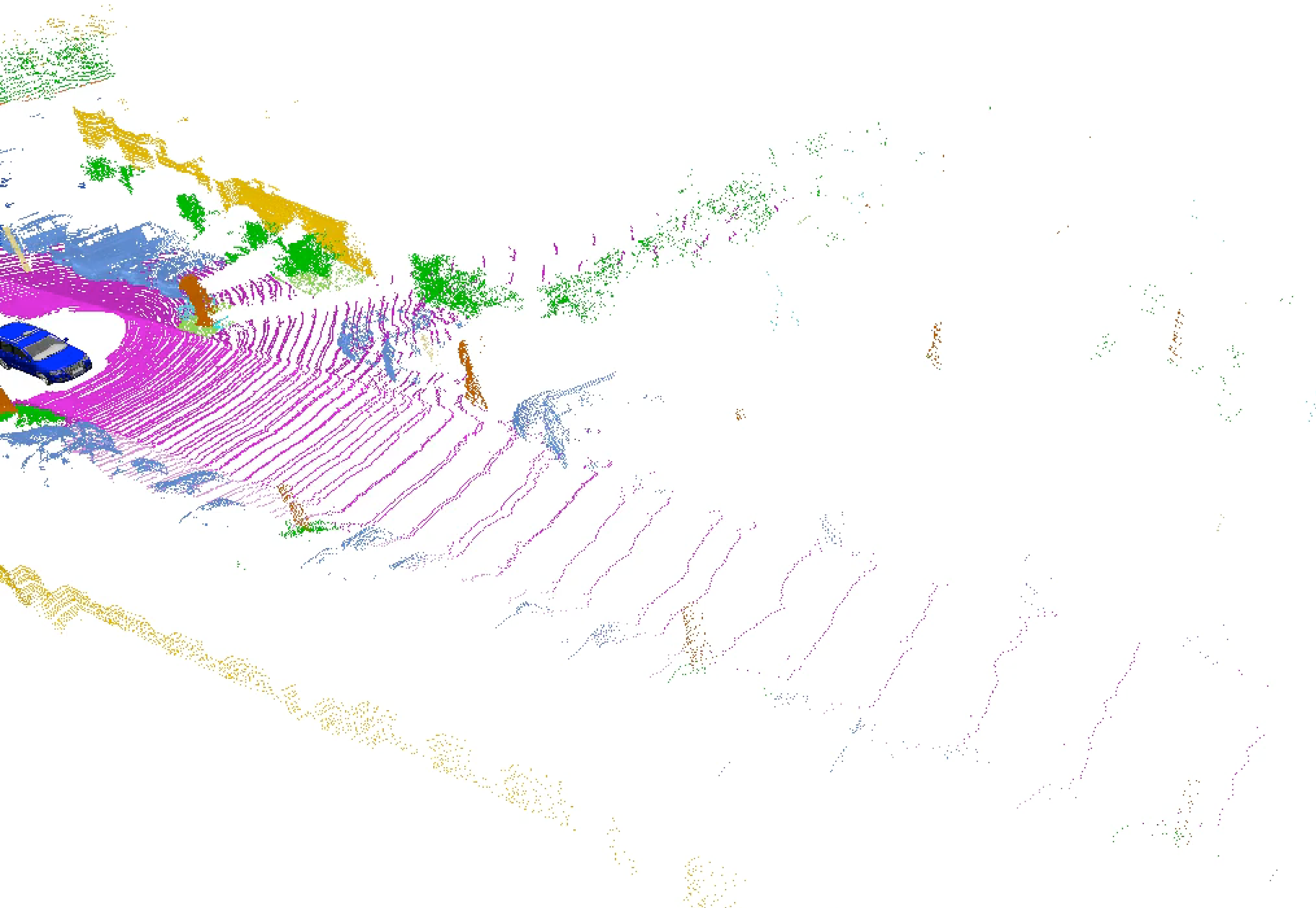
KITTI Dataset 2012

- Are we ready for Autonomous Driving? The KITTI Vision Benchmark Suite
- Heavily used for state estimation tasks (VO, SLAM, depth from vision,…)
- Comes with own benchmarks

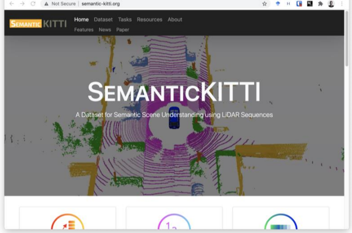
KITTI & Semantic KITTI

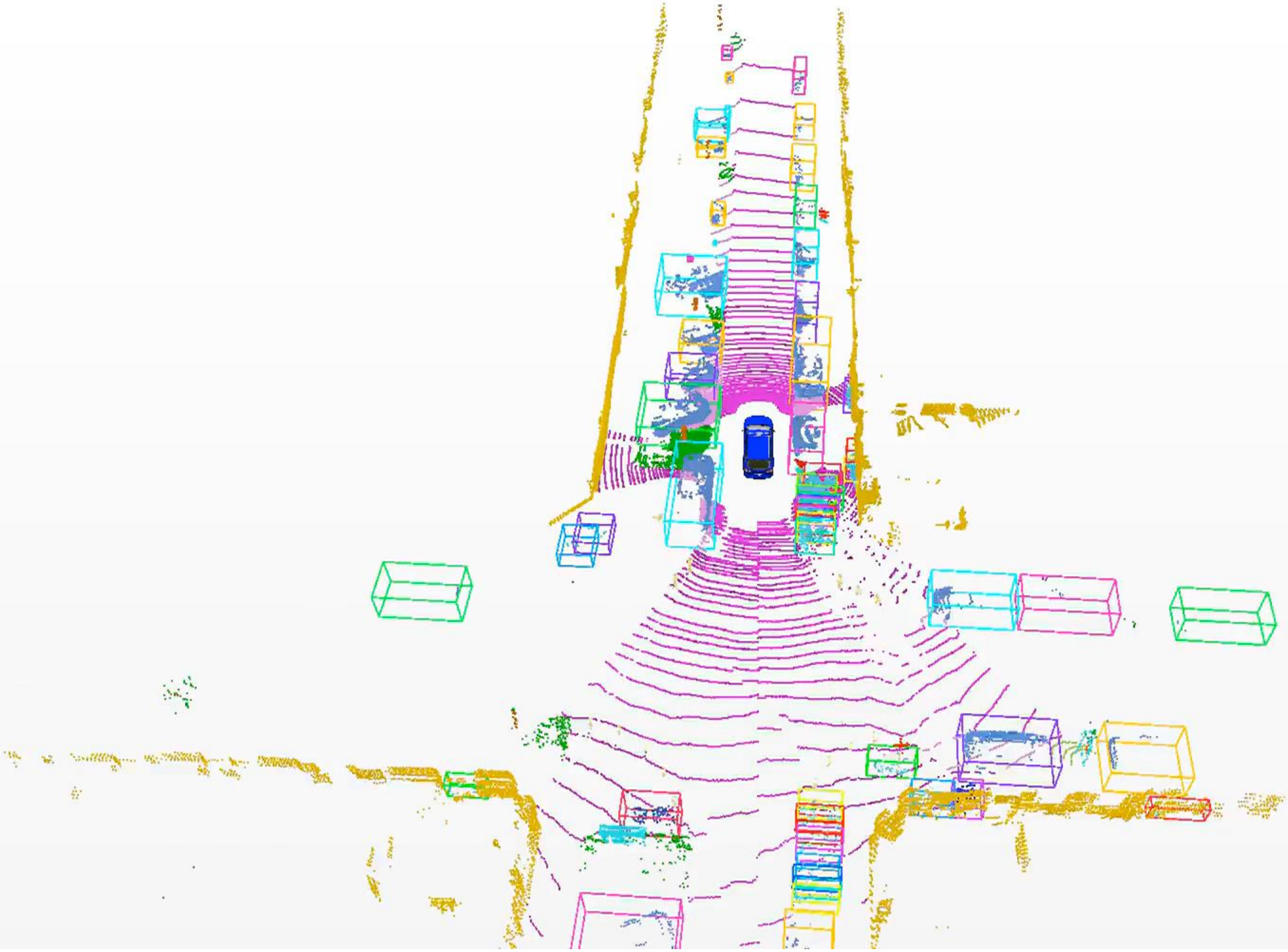


“A semantic label for every 3D point.”



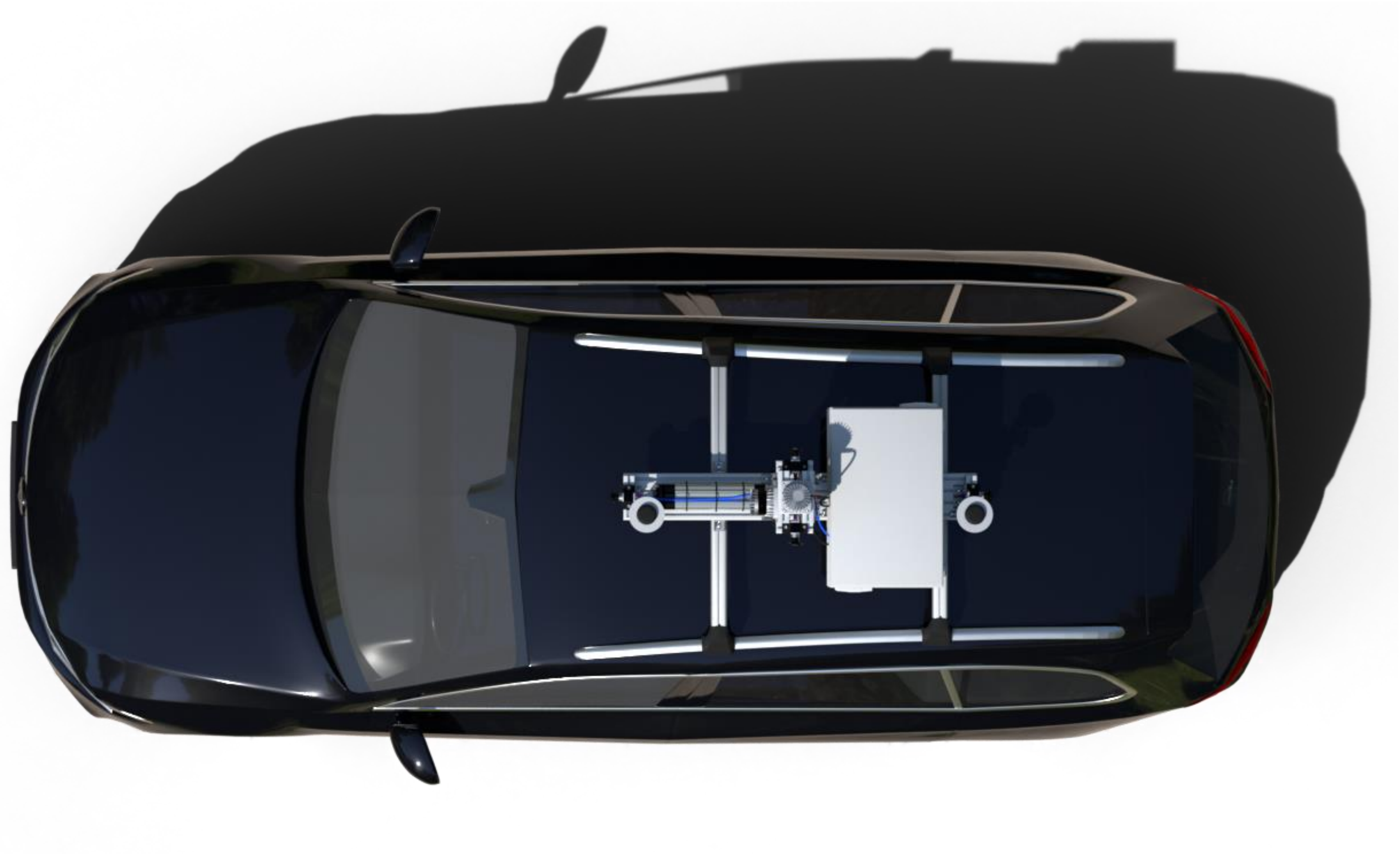
Semantic KITTI Instances



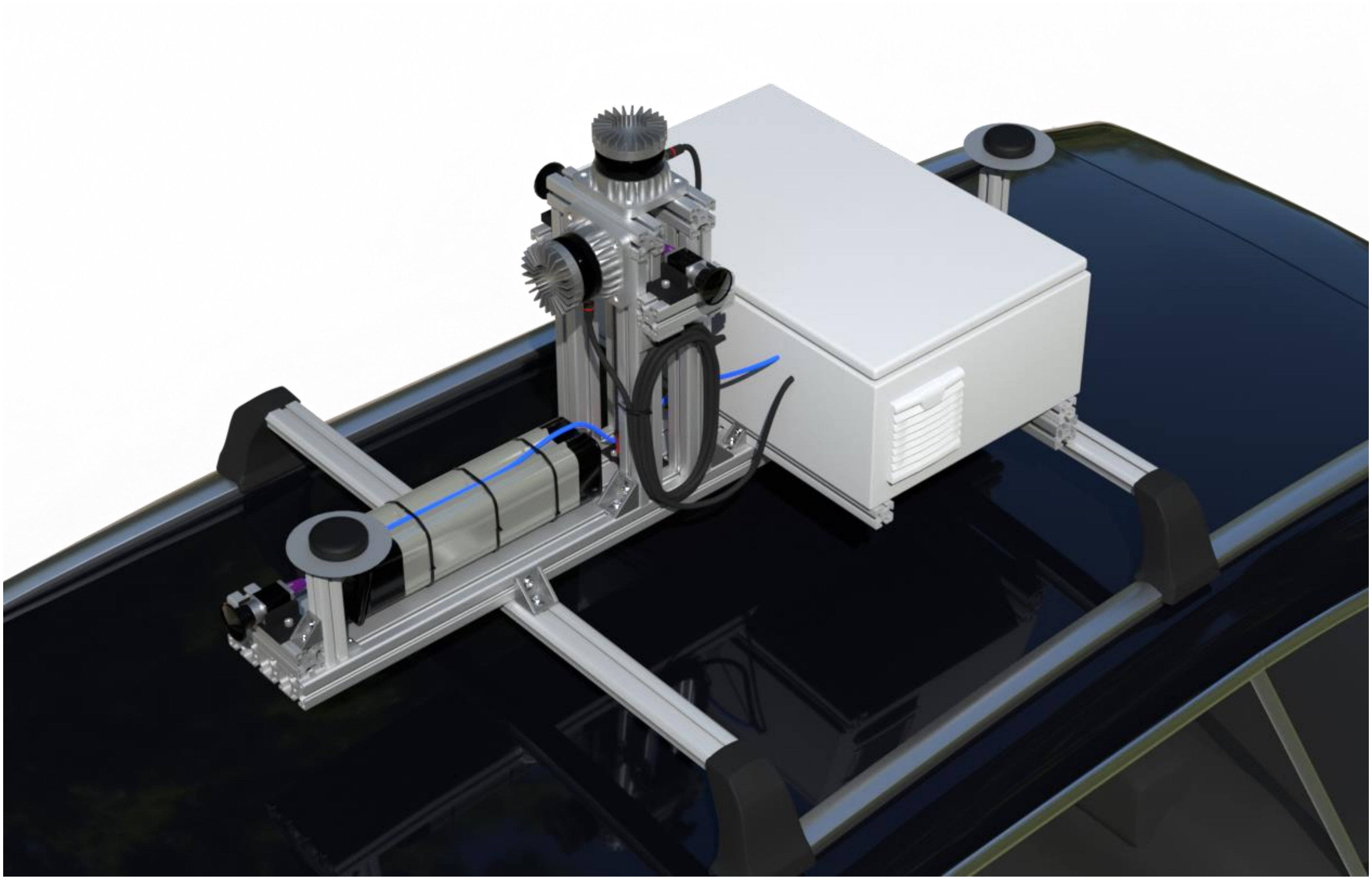


IPB Car

IPB Car



IPB Car Sensor Setup



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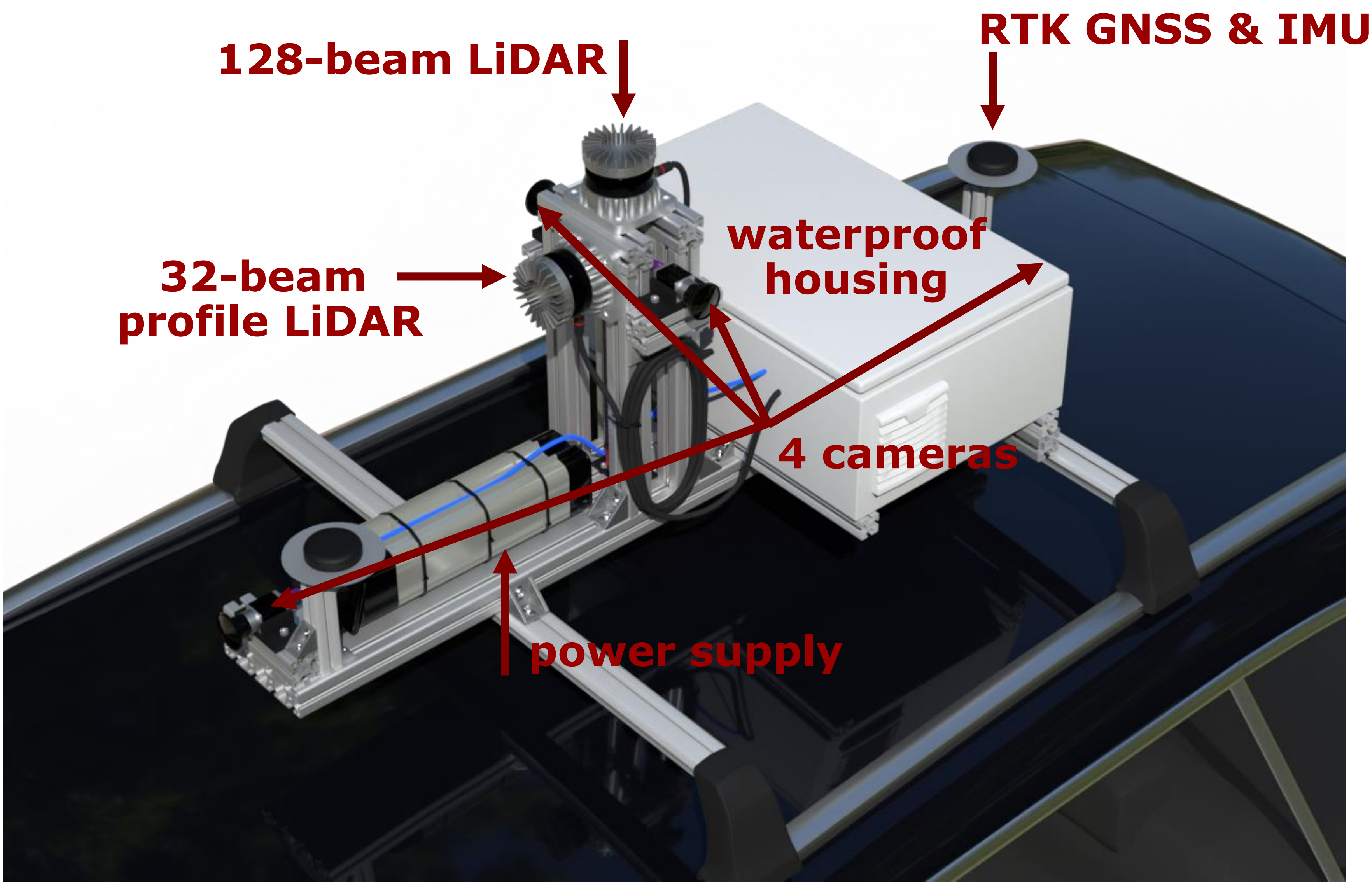
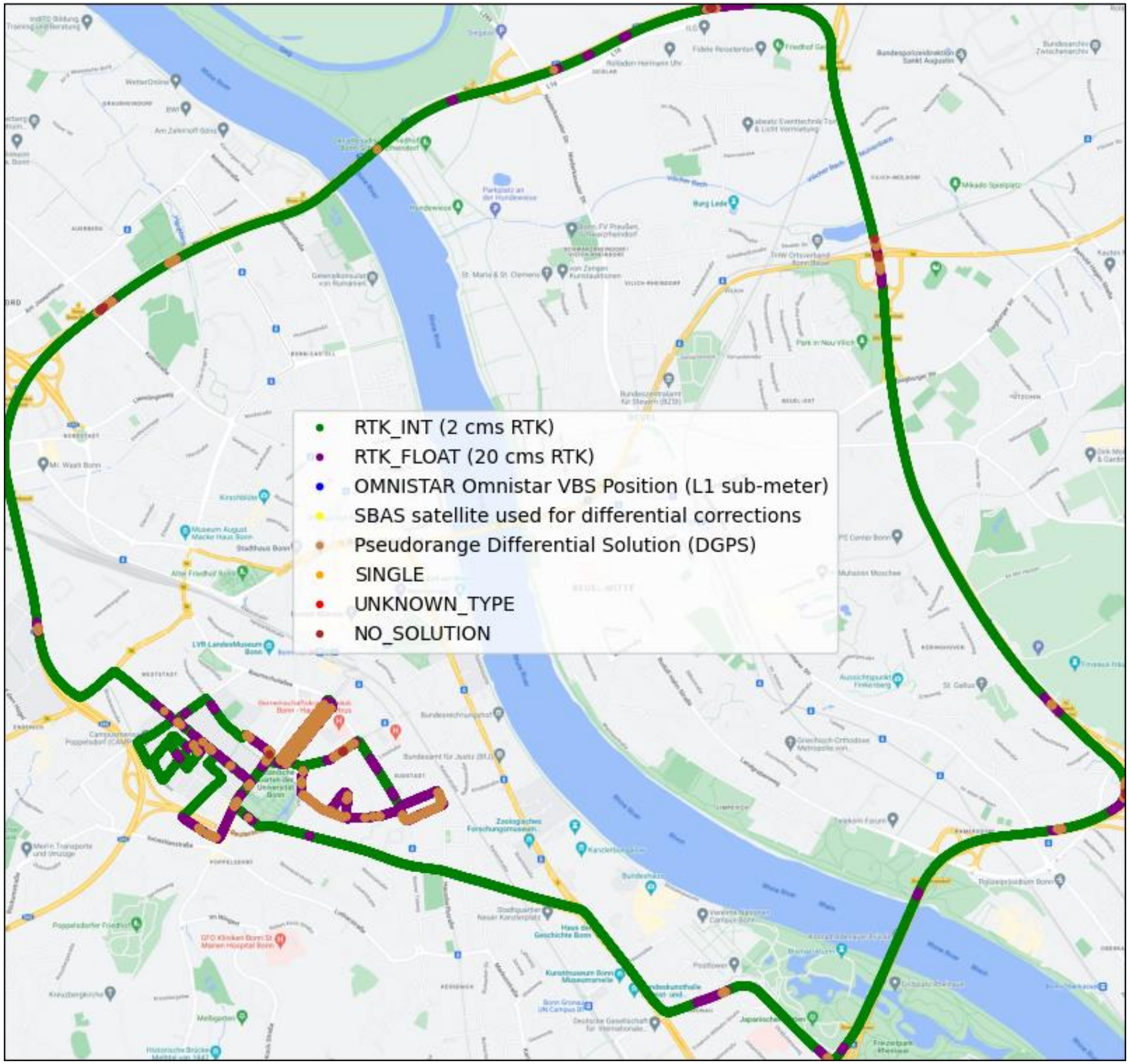


Data Recorded in Bonn



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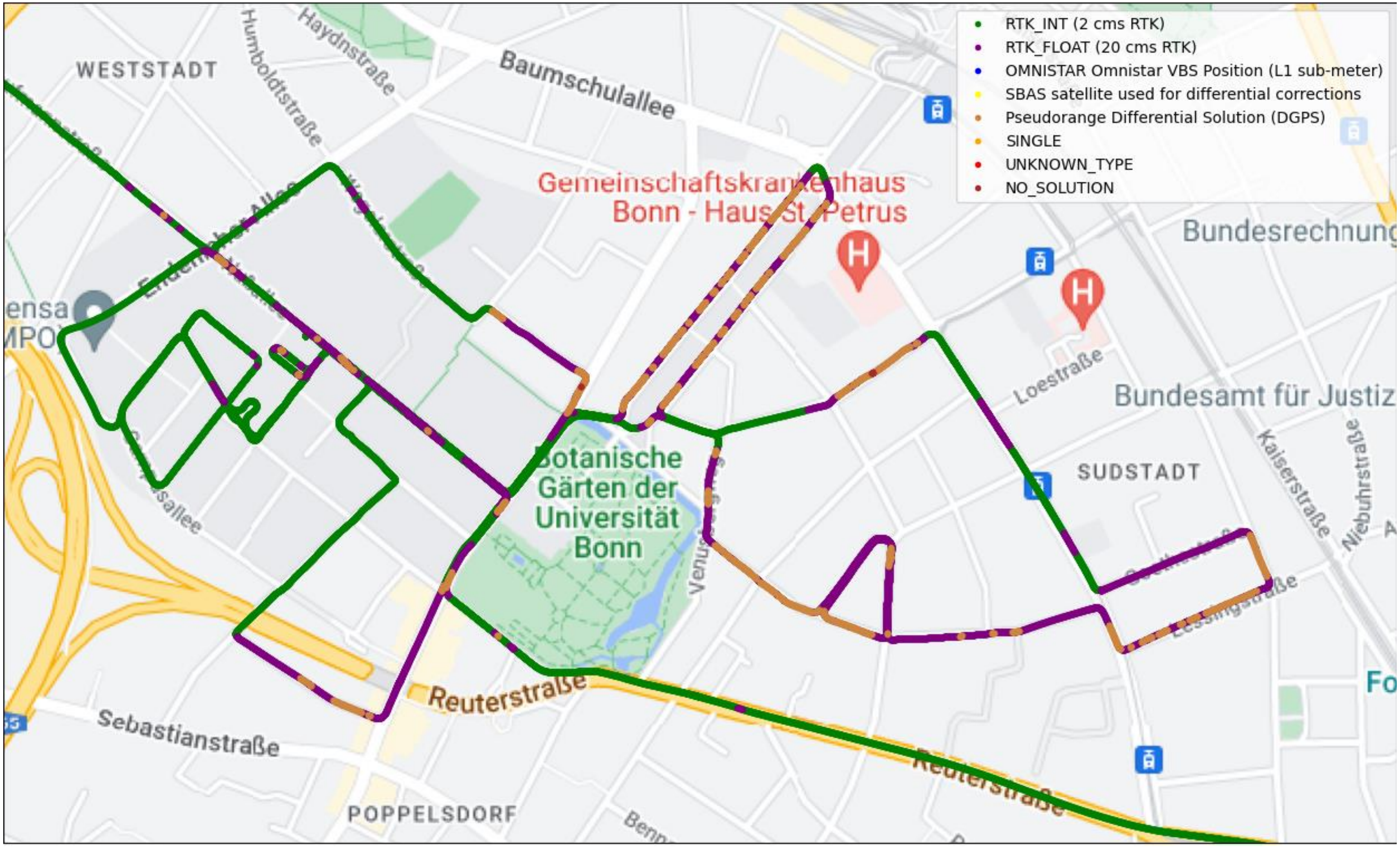

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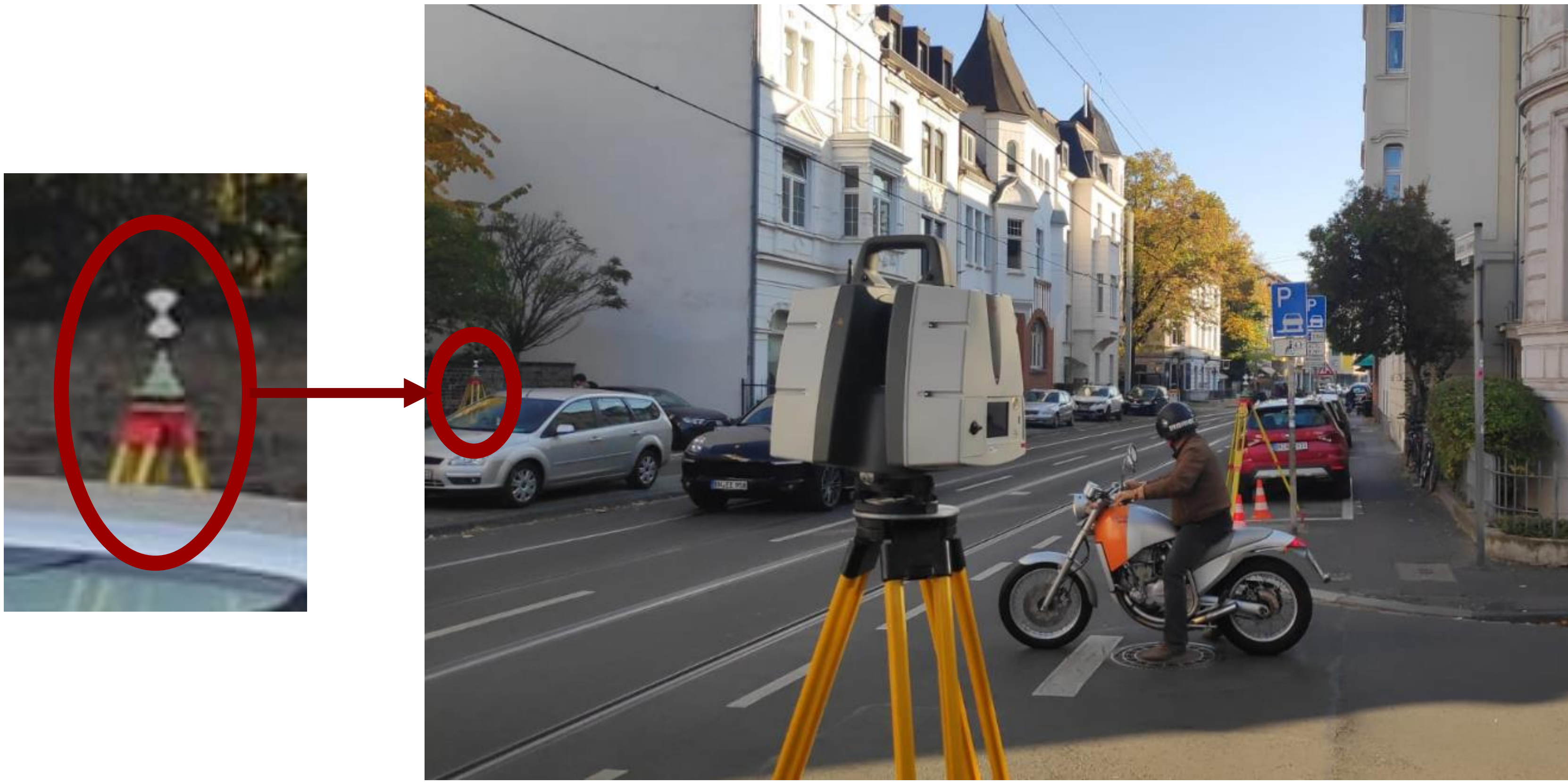

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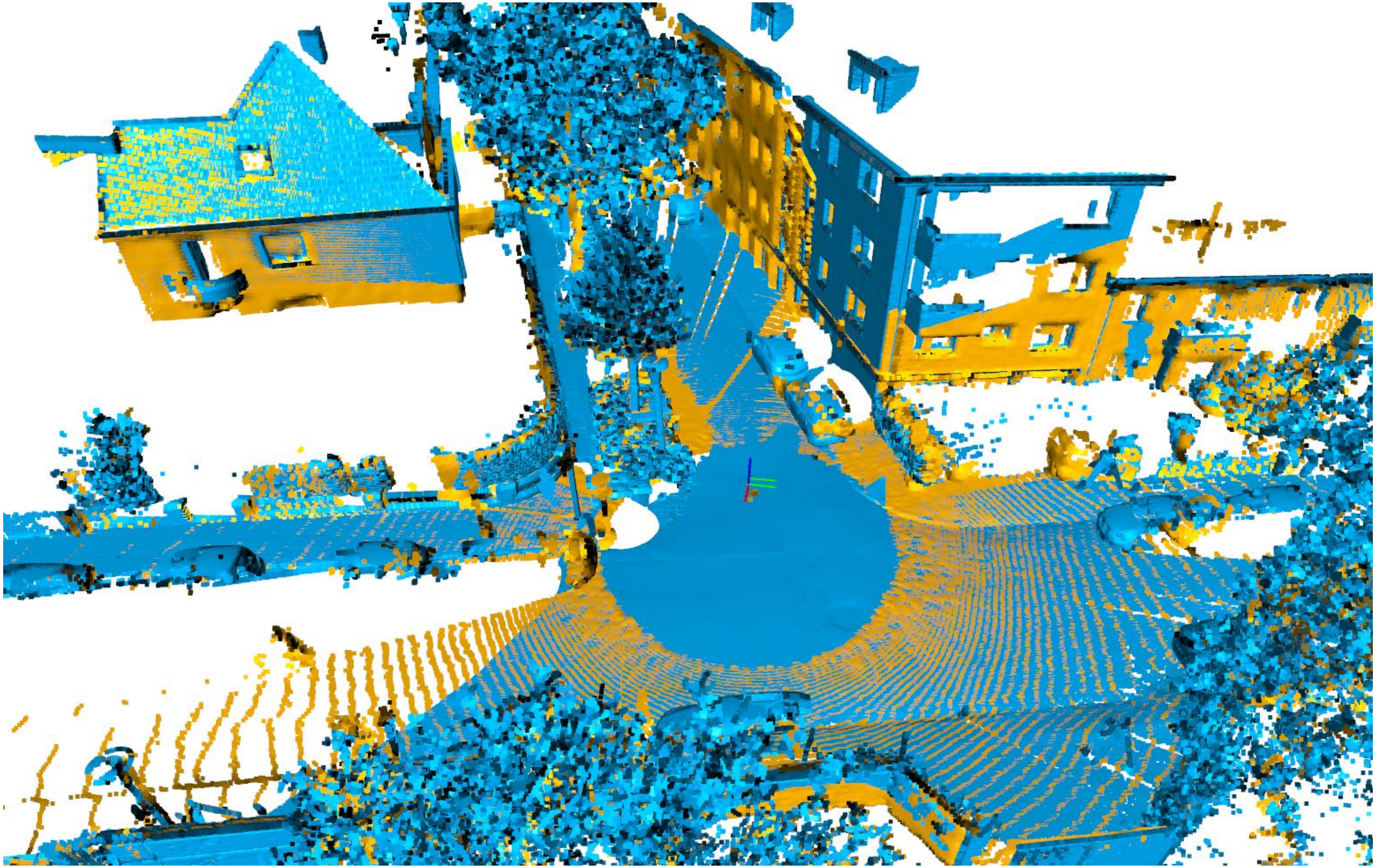
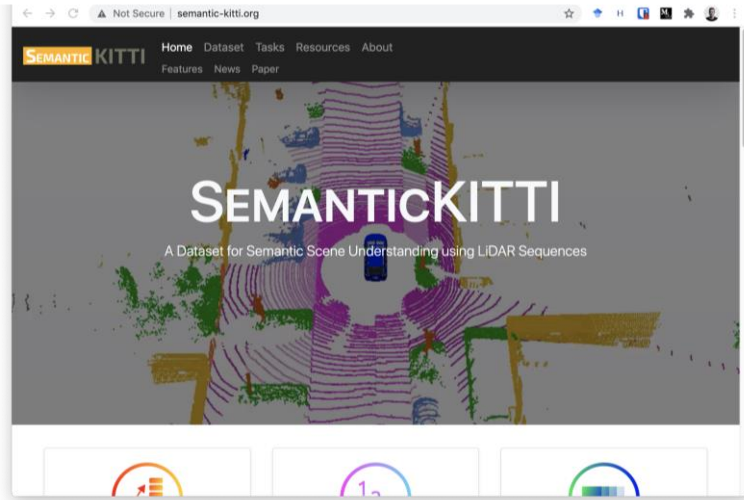
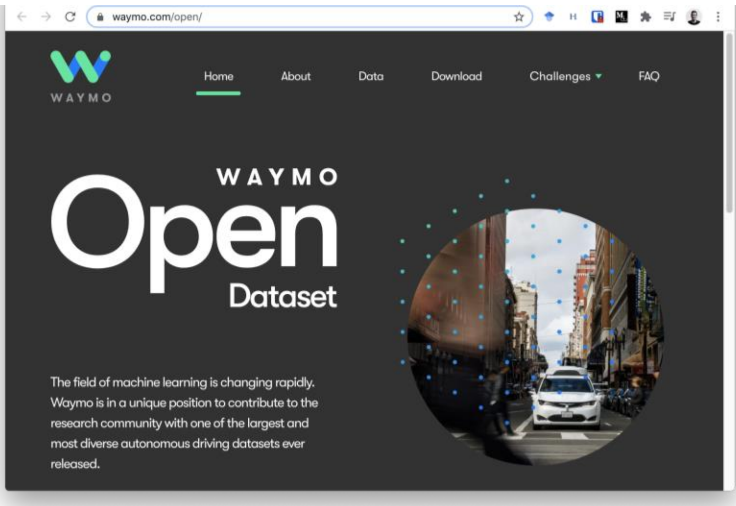
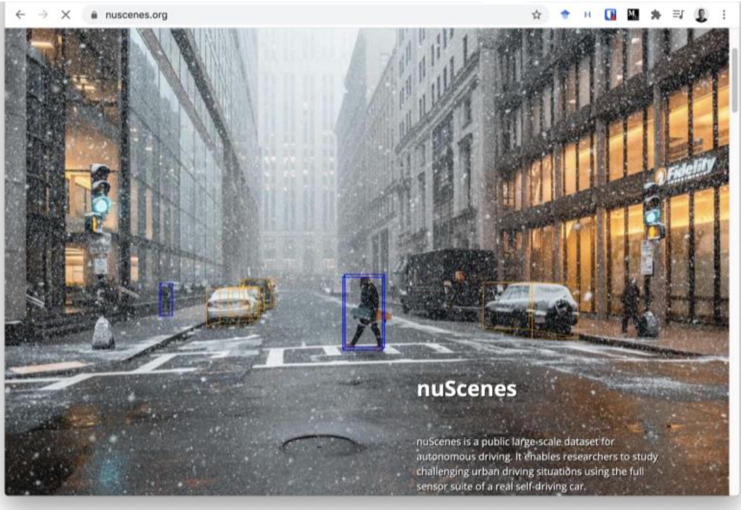


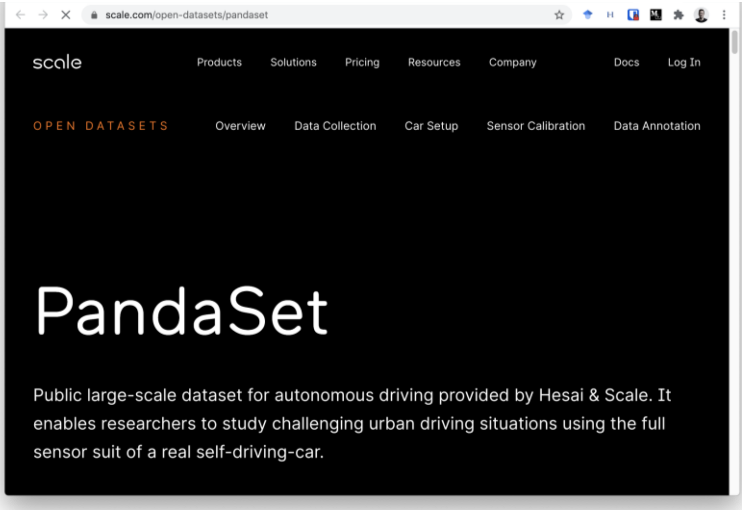
Popular Datasets (1)

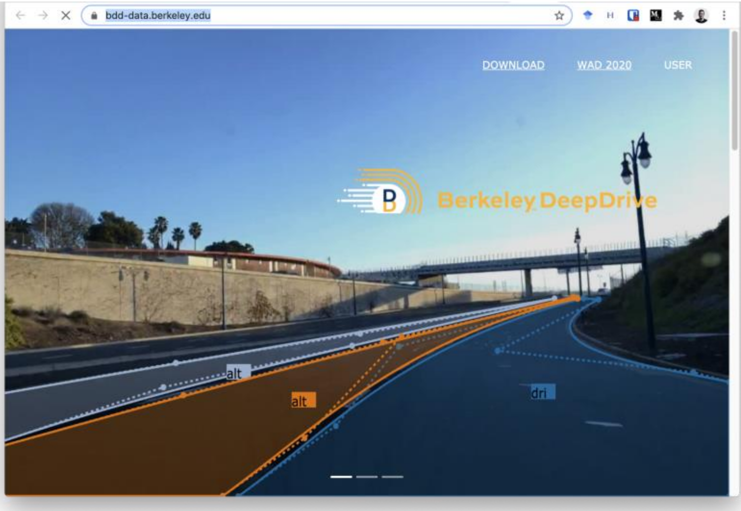


Popular Datasets (2)

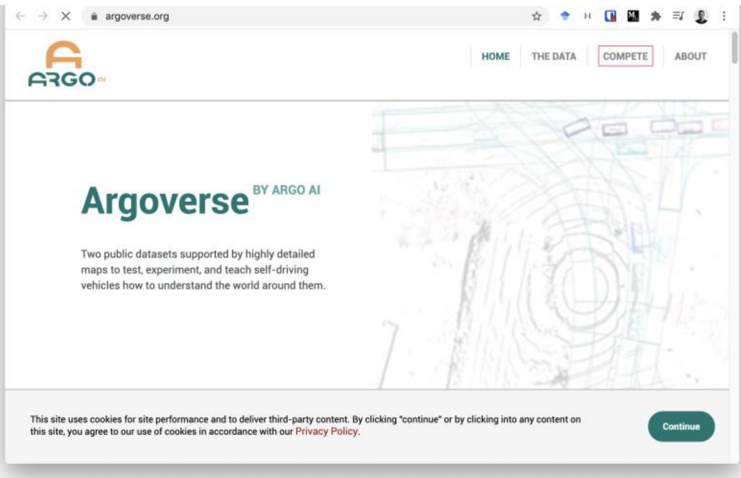


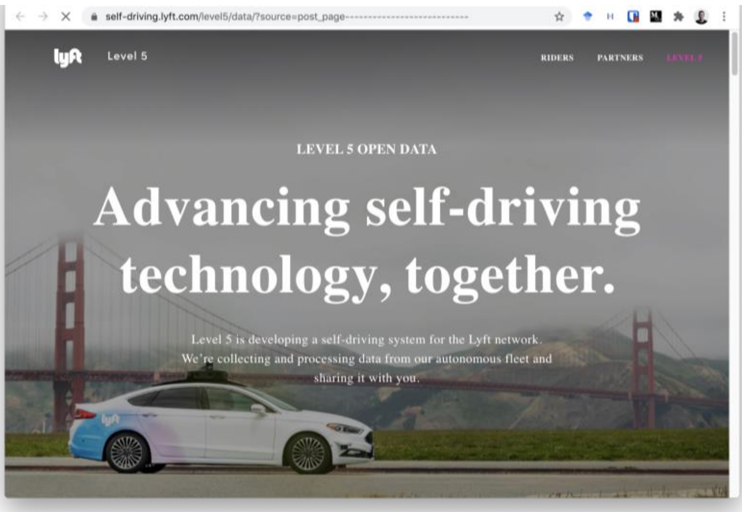


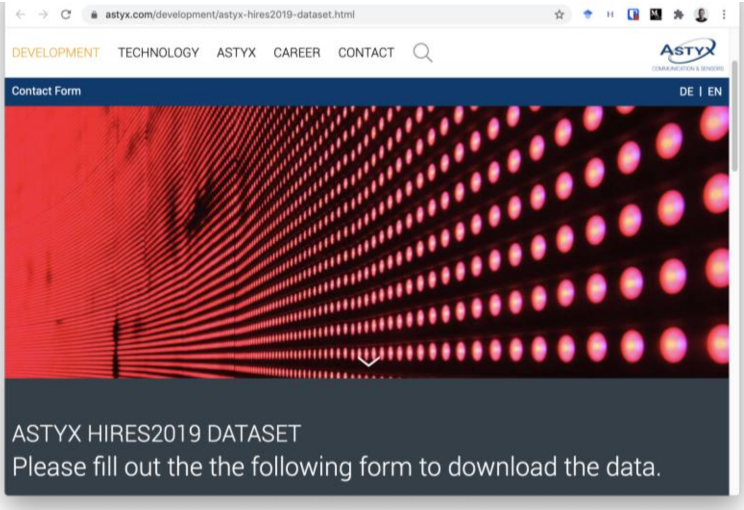




Popular Datasets (3)







...

Links to Popular Datasets

- http://www.cvlibs.net/datasets/kitti/
- http://semantic-kitti.org/
- https://waymo.com/open/
- https://www.argoverse.org/
- https://www.nuscenes.org/
- https://bdd-data.berkeley.edu/
- https://self-driving.lyft.com/level5/data/
- https://robotcar-dataset.robots.ox.ac.uk/
- https://scale.com/open-datasets/pandaset
- https://www.highd-dataset.com/
- https://www.astyx.com/development/astyx-hires2019-dataset.html

Datasets

- Real-world data
- Used to train learning models
- Regression testing

But:

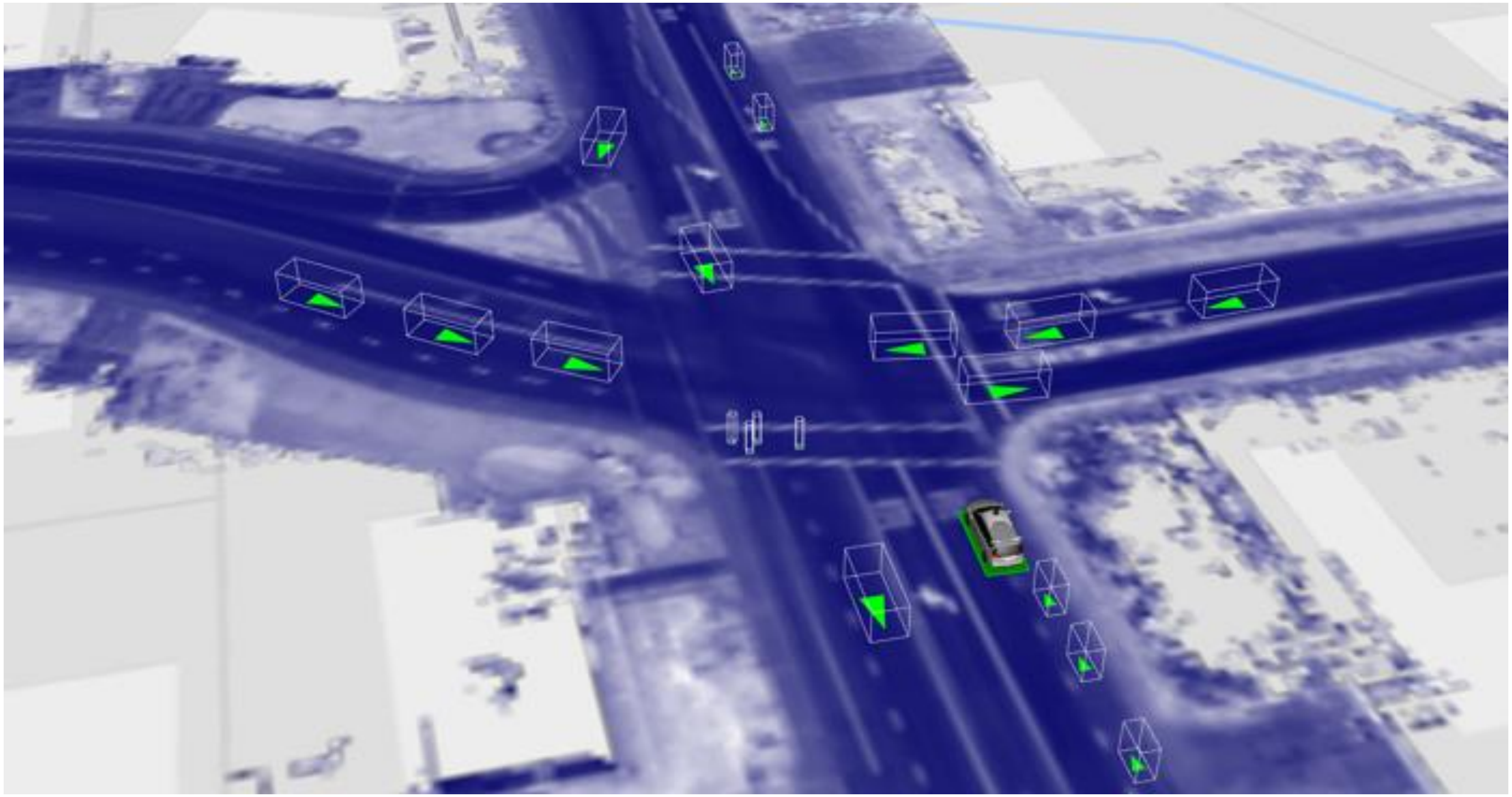
- Datasets are passive: How to test a planning algorithm on a dataset?
- Limited view of the world
- What if the sensor setup changes?

Simulations Play a Key Role

- Simulators became a critical infrastructure for autonomous driving
- Dmitri Dolgov (Waymo CTO): "We've driven more than 10 million miles in the real world, and over 10 billion miles in simulation."

Waymo’s Carcraft Simulator

25,000 virtual cars collectively drive about 10 million miles every day (2019)



[Courtesy: Waymo]

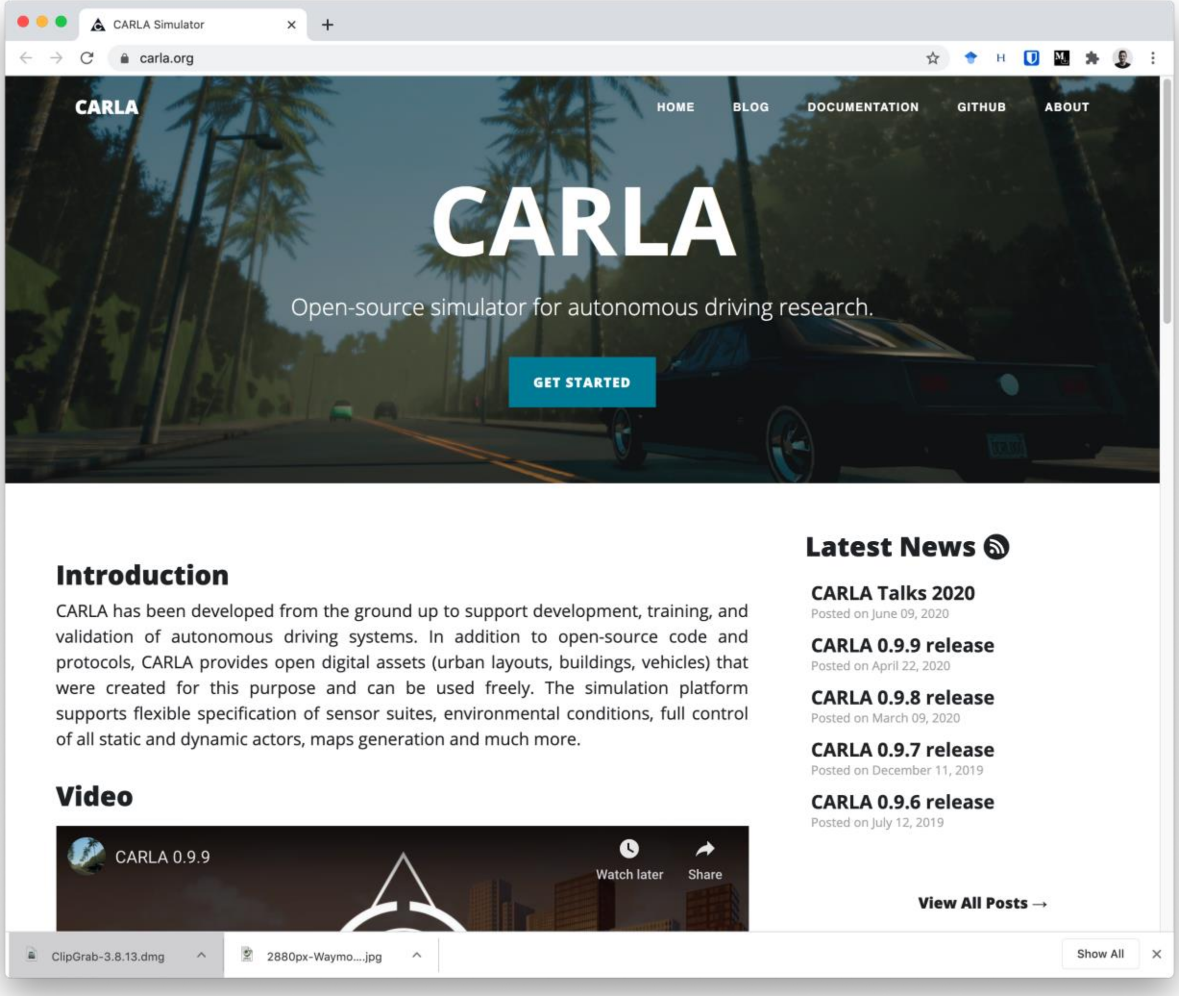
Great Things About Simulation

- Allow for automated and parallel testing (e.g., test after every commit)
- Can generate identical situations over and over again
- Allow for focusing on tricky situations
- Allow for testing dangerous situations
- Can provide ground truth data for learning algorithms

Issues with Simulations

- They are only a abstracted model of the real world
- Realistic perceptions/noise/outliers?
- Physics simulation vs. “looks good”?
- Do other traffic participants behave as they would in the real world?
- Are rare cases simulated appropriately?
- Has everything been considered?

CARLA Simulator

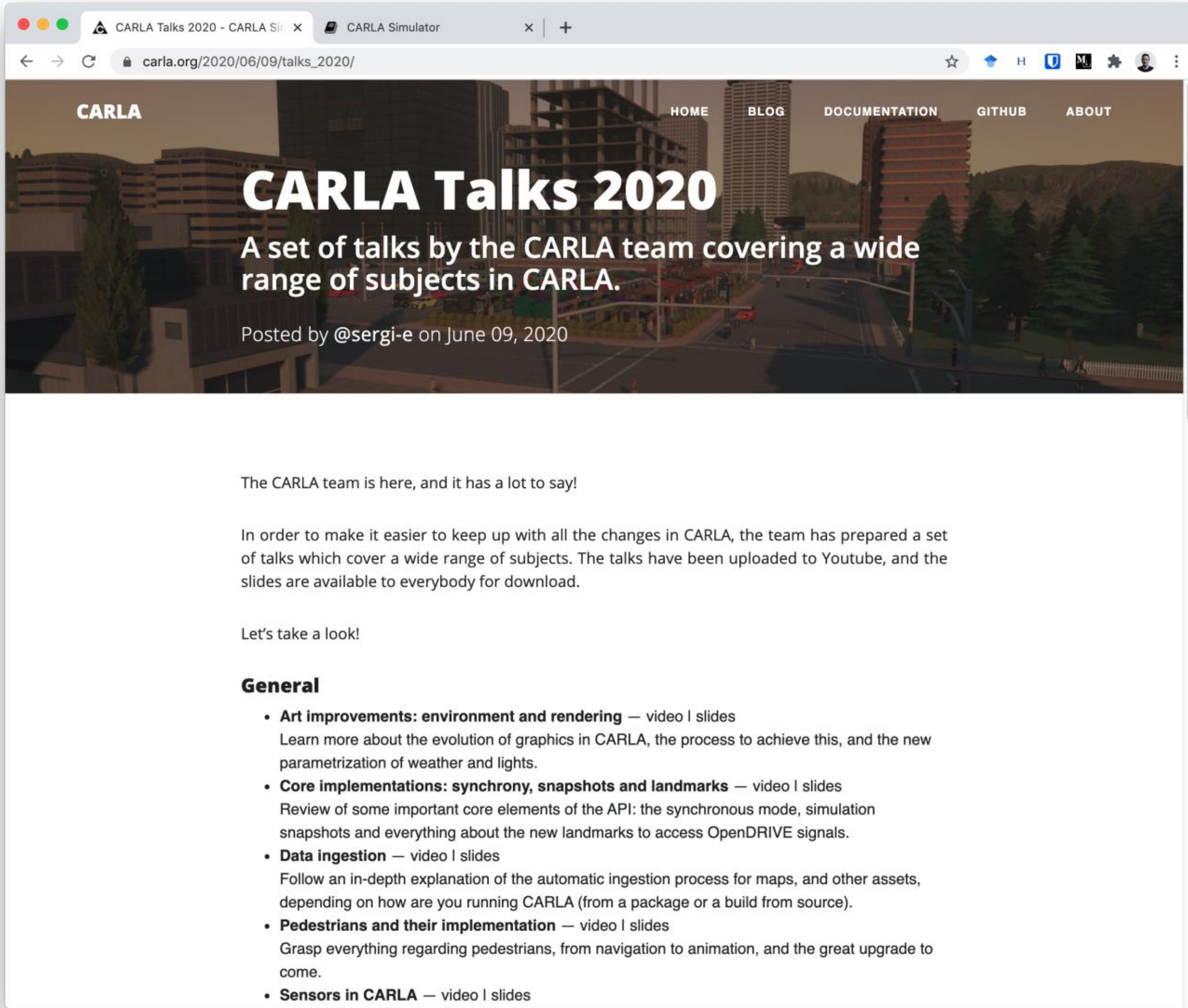


http://carla.org

CARLA Simulator

- Use own worlds
- Autonomous driving sensor suite
- Simulation for planning and control
- Traffic scenarios simulation
- Autonomous Driving baselines
- ROS integration
- Flexible API
- Server – multi-client architecture

CARLA Video Talks



https://carla.org/2020/06/09/talks_2020/

Summary

- Self-driving cars have a high potential to change the transportation industry
- Overview of self-driving car ecosystem
- Cars require solutions to several robotics and perception problems
- Key tasks:
  - Perceive and estimate
  - Predict
  - Plan & act

People Who Contributed to the Development of the Course







Thank you for your attention