

Deep Dive into Waymo

The Self-Driving Car Cook Book

10/31/2018
HAKUSHO CHIN



Executive Summary

Execution

- Make sure your Lv4 is a local solution
- Launch Early Rider Program

Self-Driving Car technology

- Your car should solve planning & perception edge cases
- Detailed classification & scene understanding

Data center & Simulation

- Create “data center and simulation” infrastructure
- Your simulation is able to drive 10million miles a day
- Auto-record disengagement and abnormal behavior
- Auto-machine learning, a neural network defines a problem, to train other neural network

Business Model

- Make Concierge, or recommendation since they make big money
- Make your cars are driverless and operates 24/7

Foreword

- This document is the summarization of Waymo's recent self-driving car related R&D until Oct,2018
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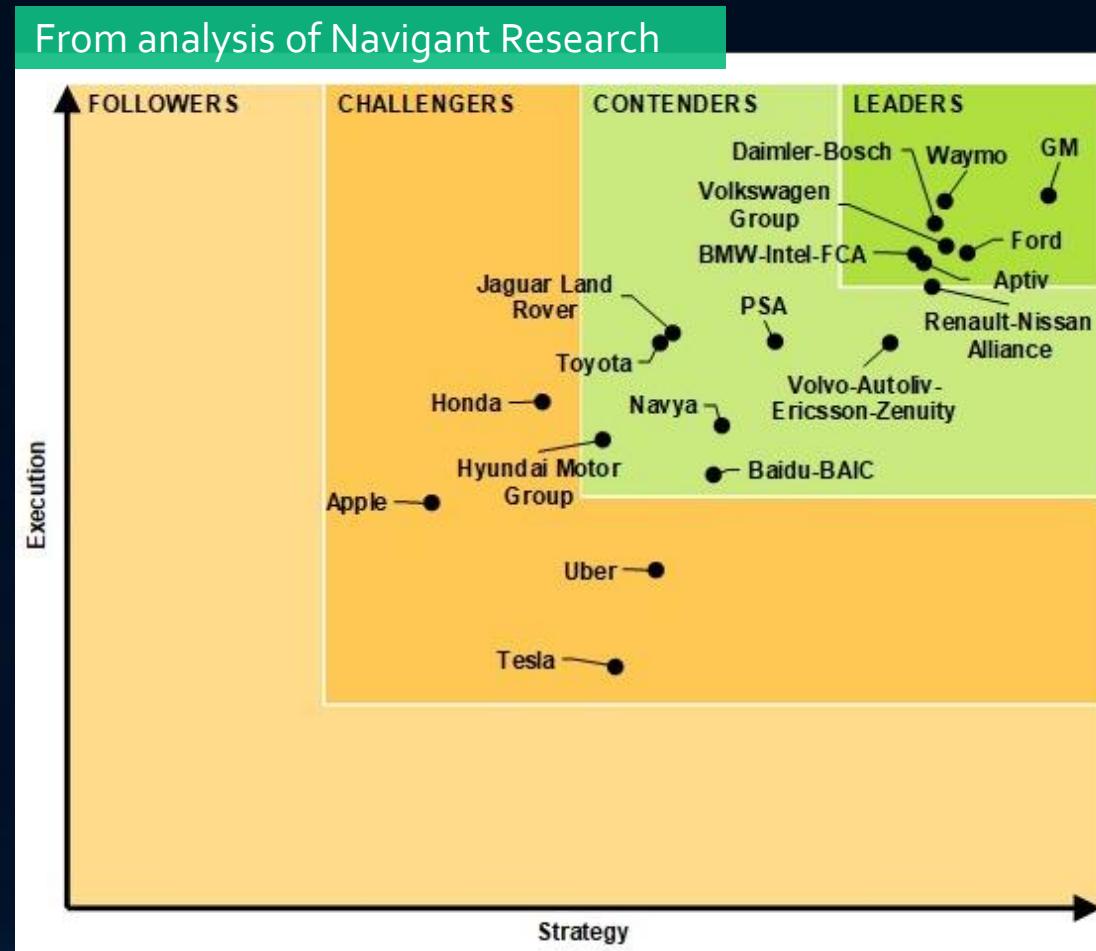
Speaker



Hakusho Chin
Computer Vision Engineer | Self-Driving Car Strategy Consultant
@Automotive Parts company

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There is a **WAR** going on...for a self-driving car

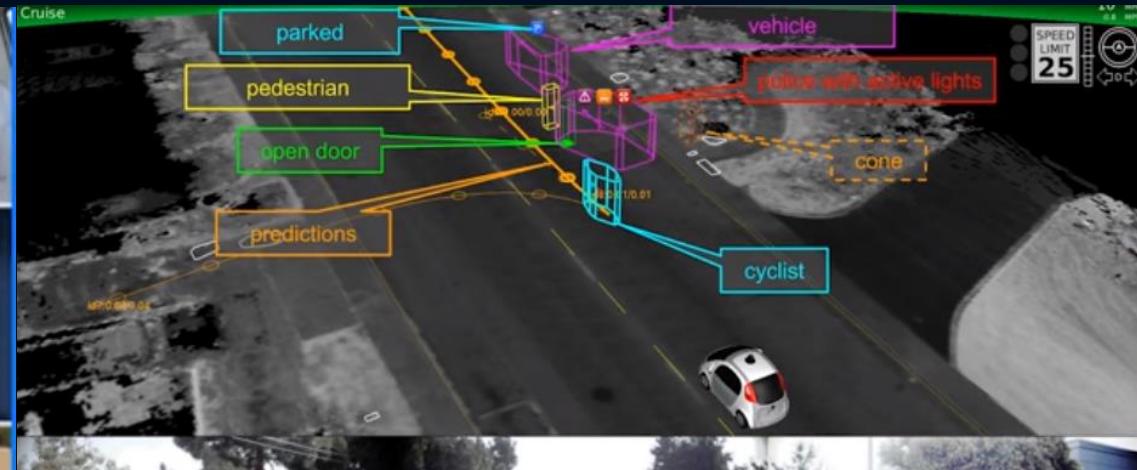


How to cook a self-driving car?



Waymo can be our master chef!





- Executions



- Self-Driving Car Technology



- Data center & Simulation



- Business Model

Takeaways

■ Self-Driving Car Cook Book

- Executions
- Self-Driving Car Technology
- Data Center & Simulation
- Business Model

Executions

- What is the achievement?
- How do they execute R&D?
- How do they conduct service?

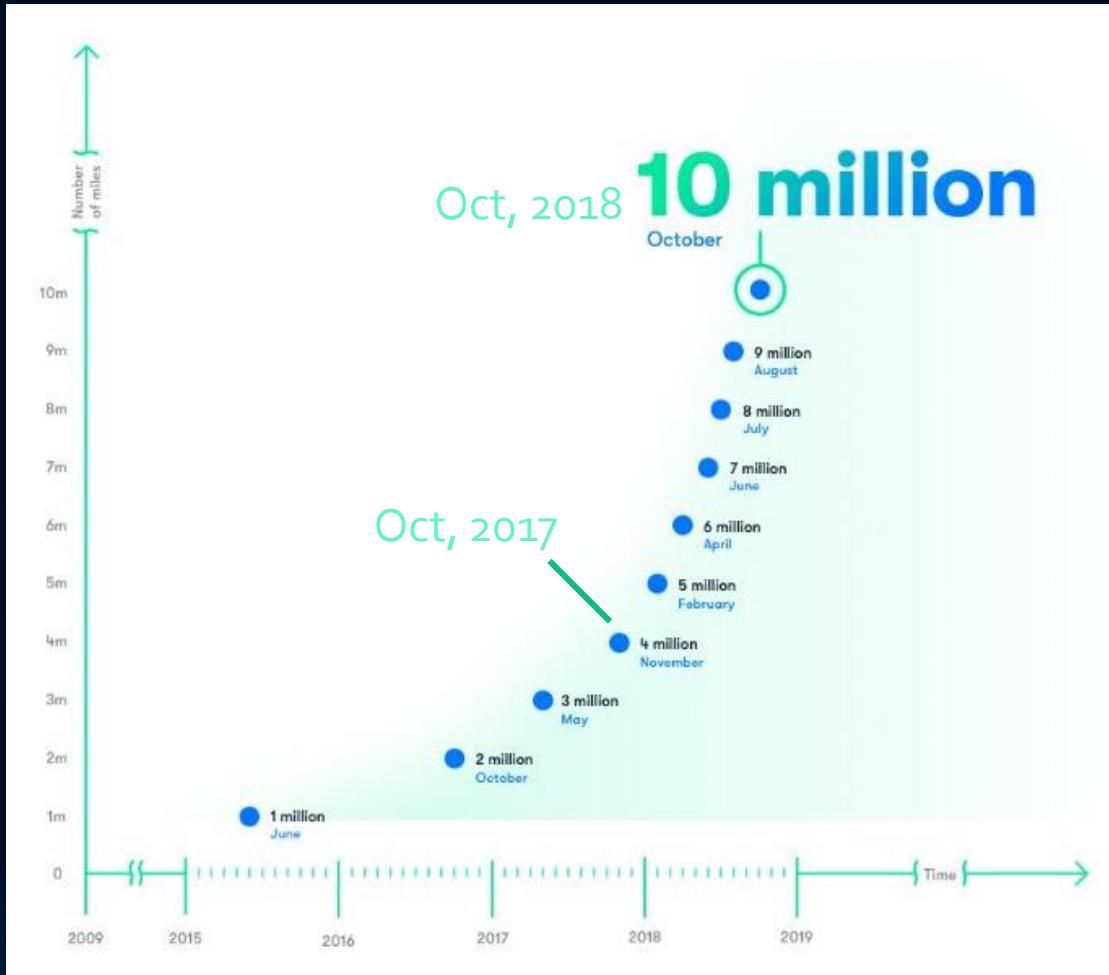


10M Miles Driven



402X around Earth!!

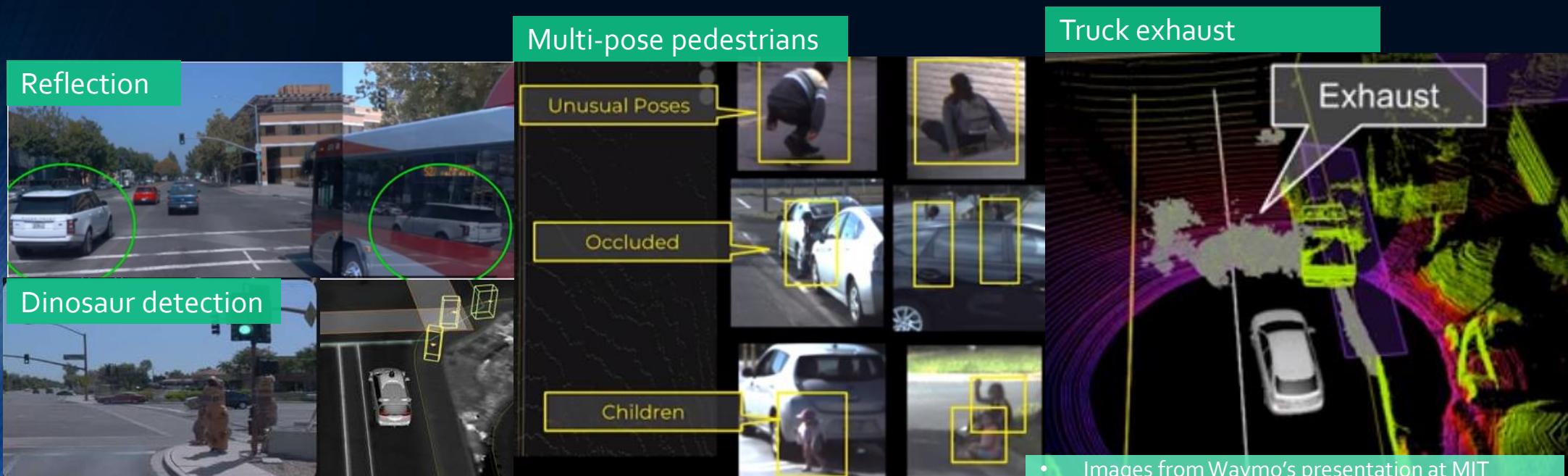
Service & Testing @25 cities and counting



Why “drive, drive and redrive”?

- To find edge cases
- “When you’re 90% done, you still have 90% to go”

-Sacha Arnoud, Director of Engineering, Waymo



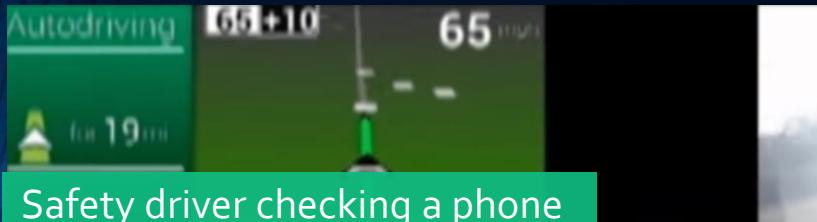
How smart?

- Disengagements every 5000 miles in 2017
- Drove 350000 miles in California autonomously, 63 disengagements

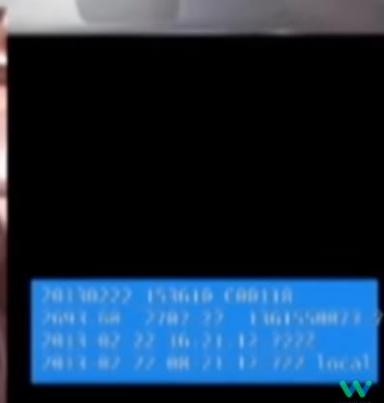
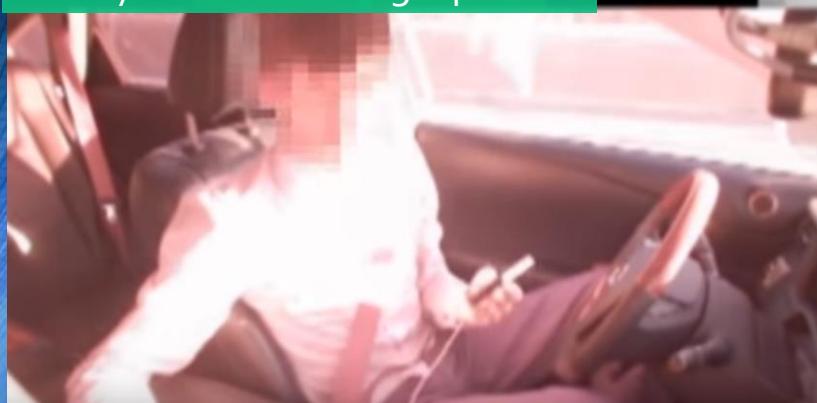
| Month | Number of disengagements | Autonomous miles on public roads |
|-------|--------------------------|----------------------------------|
| Total | 63 | 352,544.6 |

Why Lv4?

- At Lv3, Trained Employees “put too much trust”, “Handoff Problem”
- At Lv4, Self-triggered Minimum Risk Condition is safer
- Two false over ride has been reported



Safety driver checking a phone



Safety driver sleeping



Early Rider Program

- Launched Apr, 2017, operates in Phoenix Metropolitan Area
- At Oct, 2018, 24/7 Operation, started “charging”@
\$1.7/mi

“Thank you car”, telling to an in-car camera



Person sleeping at driverless Waymo taxi



Early Riders

- A father send his daughters to a school with Waymo
- Visually handicapped gentleman comments “gave back a huge portion of my life”



Why ride Waymo?

- No.1 Use: To Work



Is it really, “driverless”?

In Phoenix Metropolitan Area,

- Some car are manned, some are driverless, portion unknown
- Driverless car is under watch of an operation center
- In an initial paid service, there will be a “chaperone”

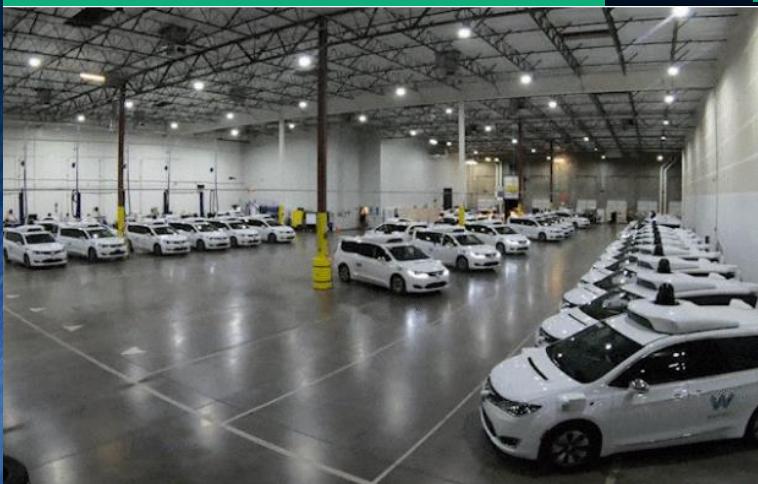
In El Camino Real, CA,

- Testing vehicles are manned

Operation Center

- Operation center at Phoenix
- Emergency response, Remote decision making, Rider support
- Fleet dispatcher to minimize ETA

Inside Waymo operation center



Rider Support team

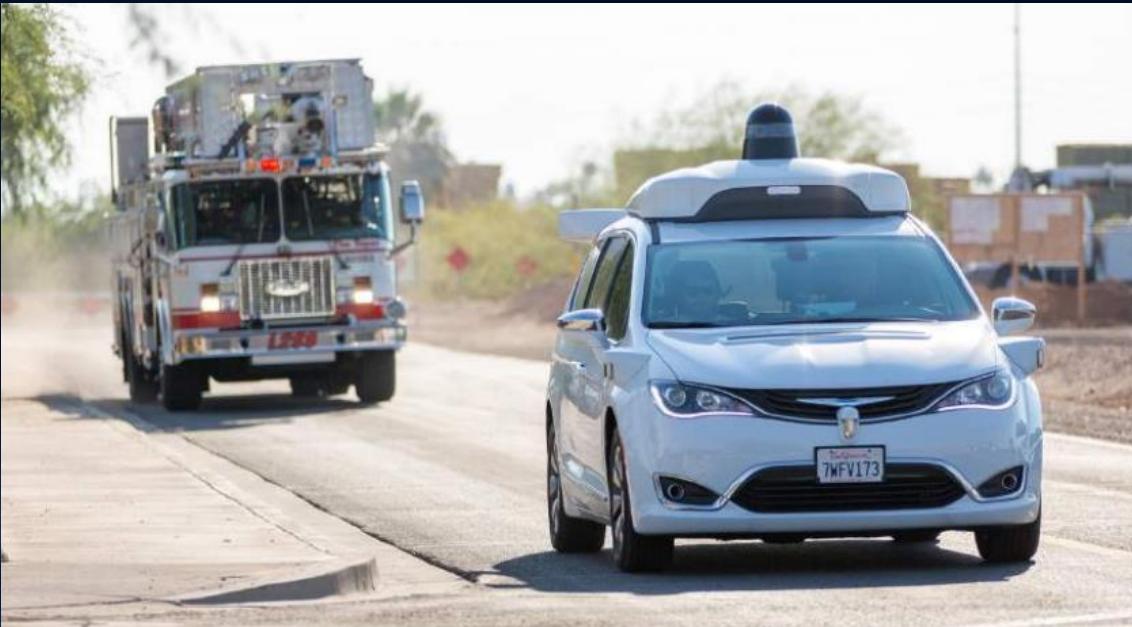


Remote monitoring system



Law Enforcement

- Waymo's car respond properly when there is an emergency vehicle
- There is a protocol, in such case operator talks to the law enforcement



 WAYMO

Waymo Law Enforcement Interaction Protocol

After nearly a decade of working on this technology, self-driving over 4 million miles on public roads, conducting tens of thousands of comprehensive tests during closed course testing, and driving billions of miles in simulation, Waymo introduced fully self-driving ("driverless") vehicles without a test driver in the driver's seat, in parts of the Phoenix metro area in October 2017. These vehicles travel within a defined geographic area where they have already been tested extensively with Waymo's test drivers. Later this year, Waymo intends to deploy these vehicles for commercial use, consistent with applicable federal and state statutes, regulations, guidance, and other applicable criteria.

In this Law Enforcement Interaction Protocol, Waymo outlines the procedures that we will follow with police, firefighters, and other first responders for driverless testing and operation in every jurisdiction. This Protocol supplements the overview of how we design, test, and validate our technology in the [Waymo Safety Report](#). Waymo will review this protocol on a regular basis and update it as changes are needed or at least on an annual basis.

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[Waymo.com/LawEnforcementProtocol](#)

ODD: Operational Design Domain

- At least 25 regions are under Waymo's ODD

Testing at China & Italy also started



ODD: Operational Design Domain

Where they test = Where they start their service

- Mountain View: To-be-in service



- Phoenix Metropolitan Area: In closed service



How to expand ODD

- “Start-from-one-straight road” strategy
- “Expand-by-intense-driving” strategy to find edge cases
- “Auto Machine Learning” to make every driving data count
- “Rigorous simulation” to improve planning

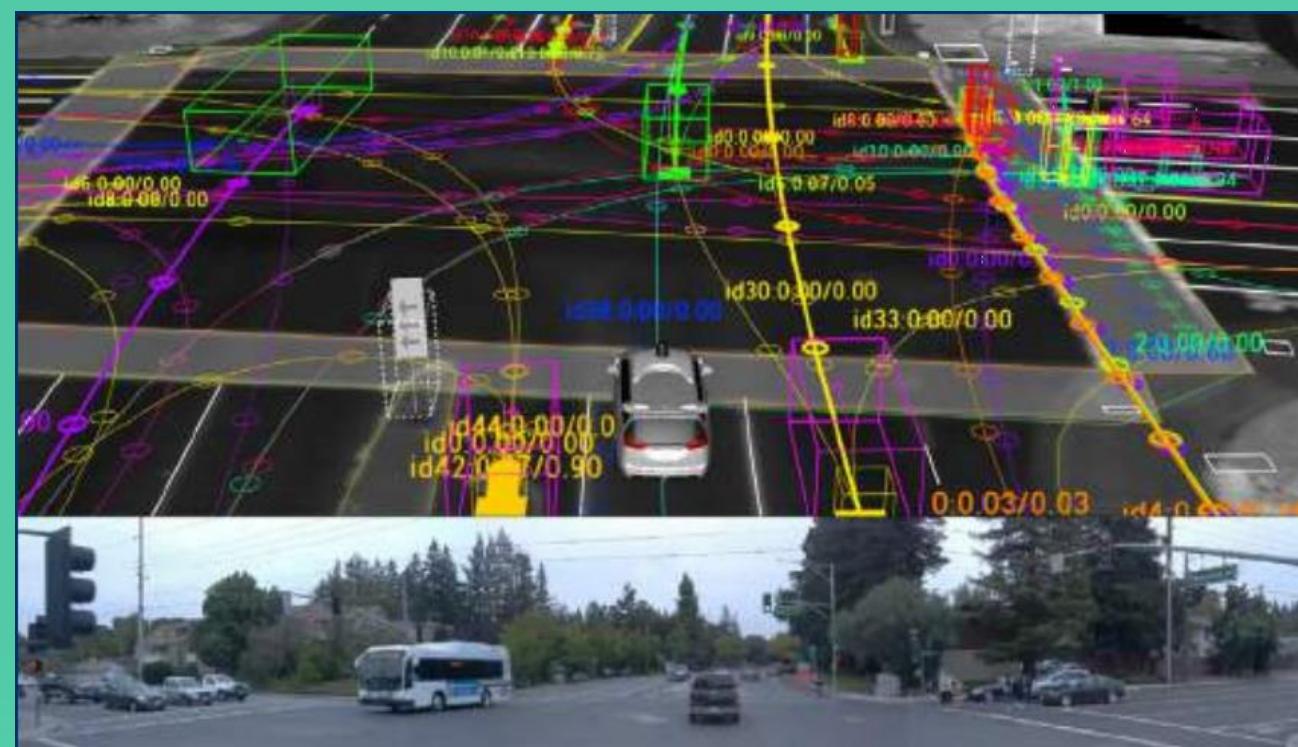
Parallel ODD-expansion operation at 25+ locations

Lv4 is a LOCAL solution,
NOT an universal solution like Lv3 and below

So how good are they?

Self-Driving Car Technology

- How good is Waymo?
- Why it is good?
- What is the challenge?



ODD: Spec sheet @Mountain View

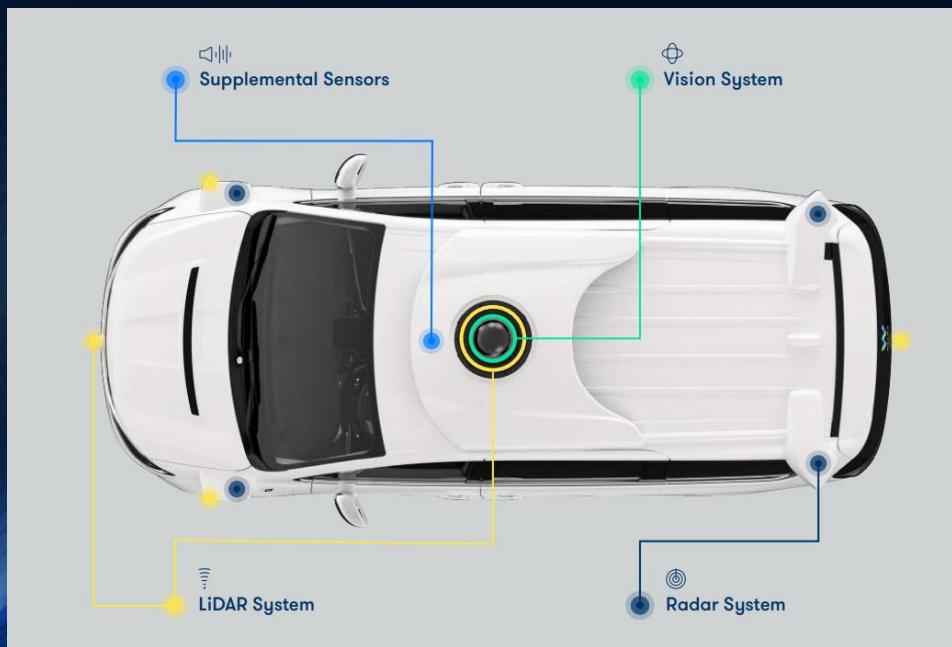
| | |
|---------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Roadway Type | During driverless testing, the intended operational design domain of Waymo's vehicles will include the following roadway types: <ul style="list-style-type: none"> • Freeways, highways,^a city streets, rural roads, and other roadways. • Parking lots |
| Speed Range | During driverless testing, the intended operational design domain of Waymo's vehicles will include roadways with posted speed limits up to 65 miles per hour. |
| Inclement Weather | During driverless testing, the intended operational design domain of Waymo's vehicles will include the following inclement weather situations: <ul style="list-style-type: none"> • Light Rain • Fog |
| Time of Day | During driverless testing, the Intended operational design domain of Waymo's vehicles will include all times of day and night. |
| Geographic Area for Driverless | Waymo will provide local jurisdictions with information regarding the geographic area where our vehicles are involved in driverless testing. |

| | |
|------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Types of Passengers During Driverless Testing | During driverless testing, Waymo's vehicles may transport the following categories of passengers: <ul style="list-style-type: none"> • Waymo employees, contractors, or agents. • Alphabet employees, contractors, or agents. • Alphabet affiliate company employees, contractors, or agents. • Members of the public as passengers during testing, without any fee charged. |
| Domain Constraints | <p>Waymo's intended operational design domain will not initially allow for driverless testing under the following conditions:</p> <ul style="list-style-type: none"> • Snow/icy conditions • Heavy rain • Flooded roadways • Offroad • One-way mountain roadway <p>During driverless testing, if any of these conditions are encountered, Waymo's vehicles will need to be capable of achieving a minimal risk condition without any human intervention.</p> <p>Controlling the operating domain of its driverless vehicles is a part of Waymo's dynamic testing program. For the purpose of driverless testing, Waymo may choose to change domain constraints for some or all of its vehicles at various times. For example, driverless testing may be limited to:</p> <ul style="list-style-type: none"> • Certain times of day • Roadways of slower posted speed limits than 65 miles per hour • Certain validated roadway features (including freeway ramps, merge lanes, turn lanes, intersections, construction zones, roundabouts, cul de sacs, roundabouts, covered parking lots, restricted speed zones, and rail and light transit crossings) • Non-inclement weather conditions. |

APPROVED

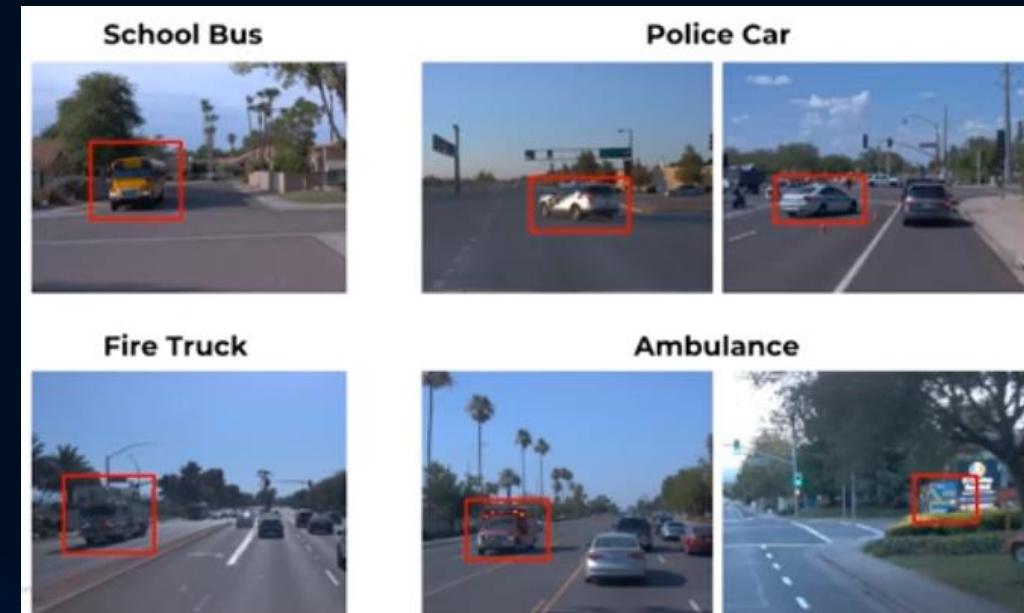
Sensors

- Rich sensors, claimed-to-be, “300m all around”
- Supplemental includes, acoustic and GPS
- Heavily depends on Deep Learning (Lv4 is a local solution…)

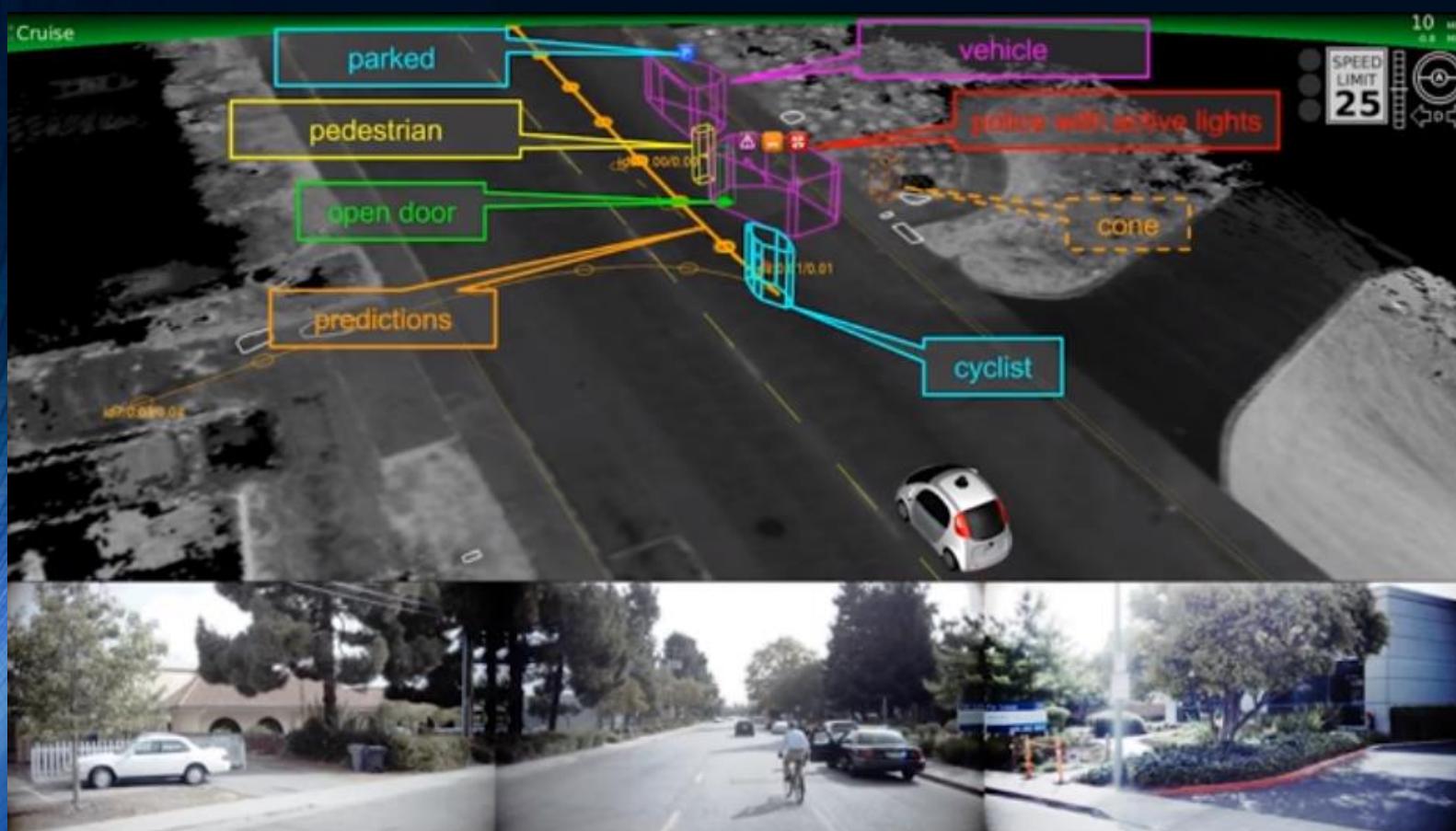


Object detection & Classification

- SSD to detects cones
- Classification of emergency vehicles, camera & audio

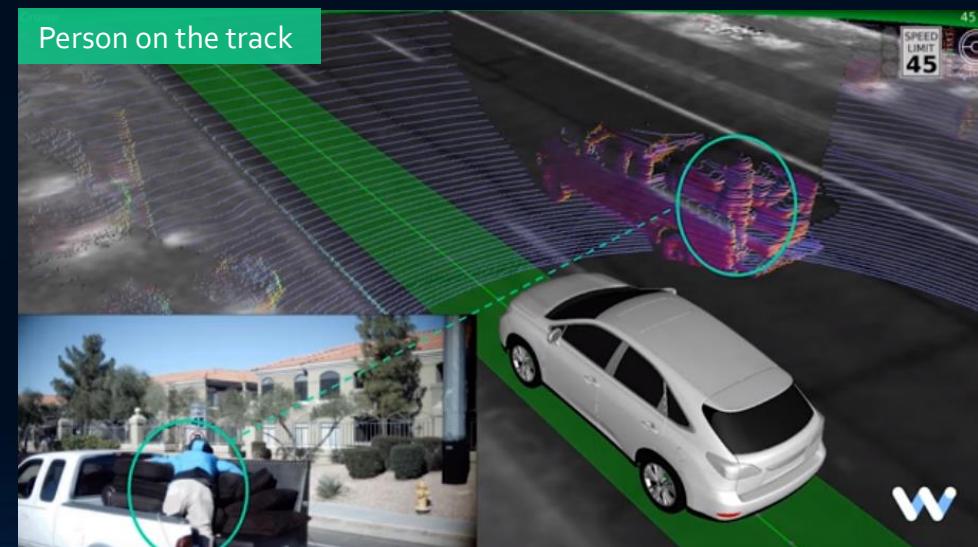
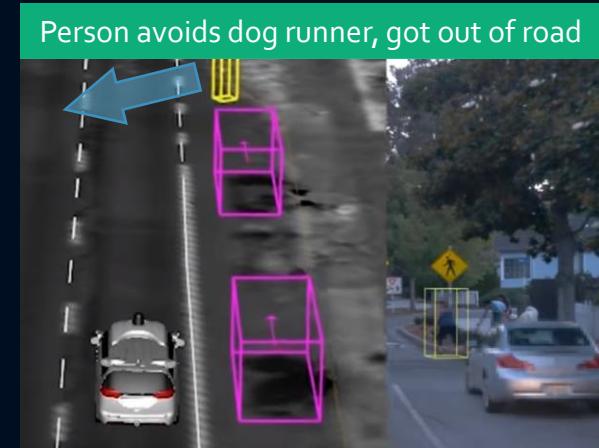
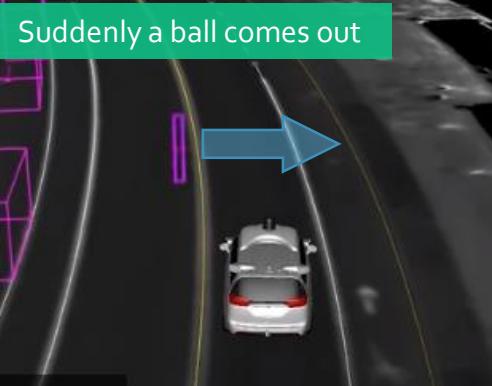


Scene understanding



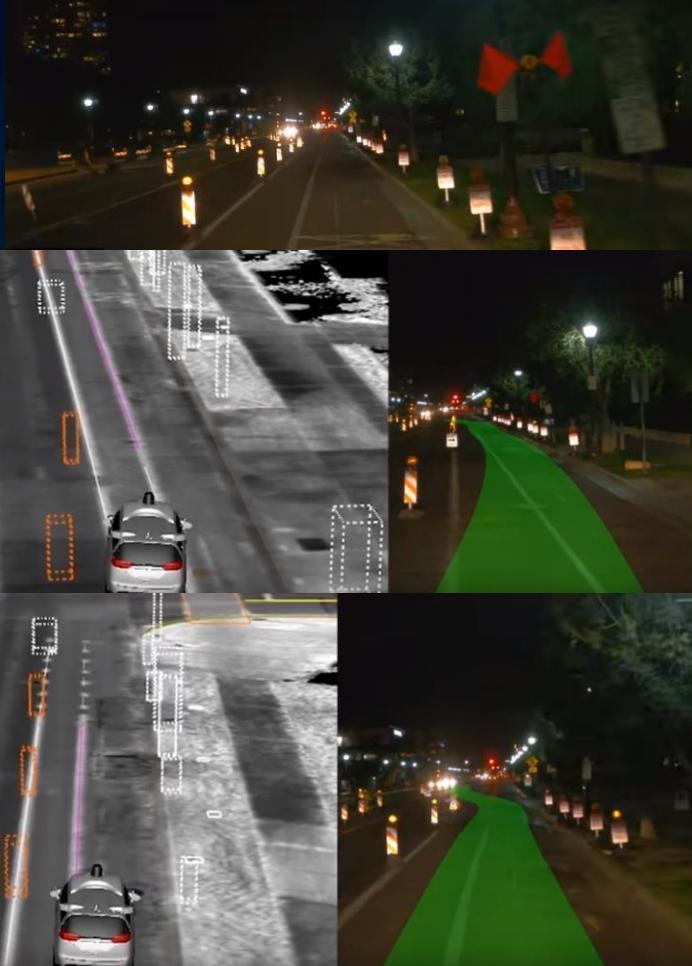
- Parked/unparked
- Pedestrian
- Open door
- Trajectory prediction of each object
- Cyclist/bike
- Cone
- Vehicle type(Car, truck, police...)
- Traffic signs
- Traffic lights
- Construction zone
- Interaction plan(yield/take over)

Edge cases

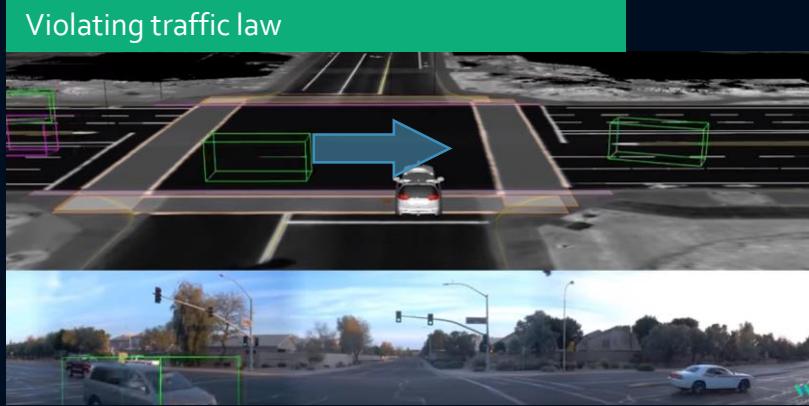


More edge cases

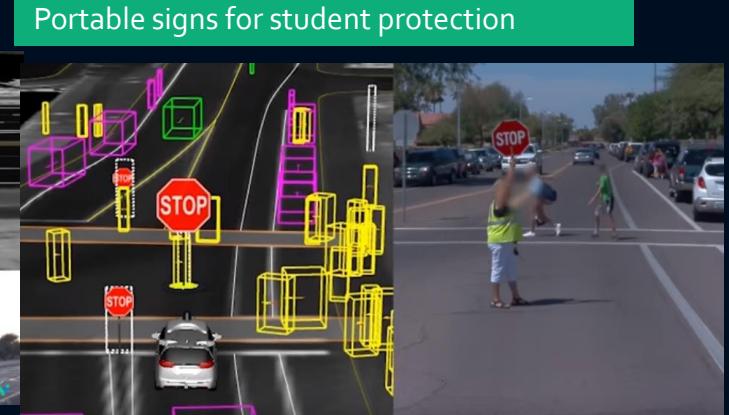
Cone detection to avoid construction zone



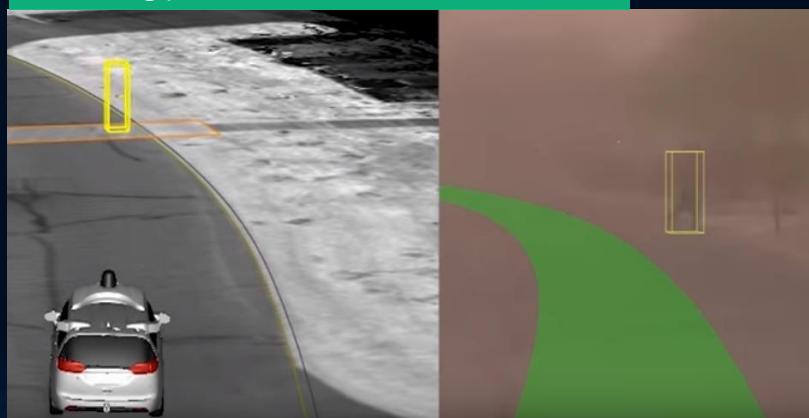
Violating traffic law



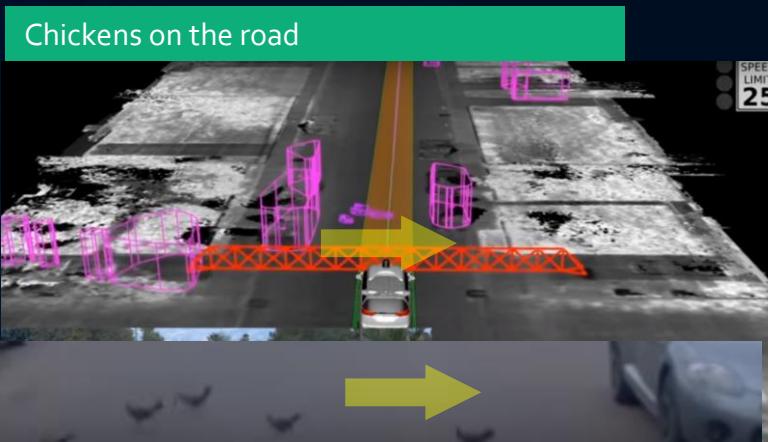
Portable signs for student protection



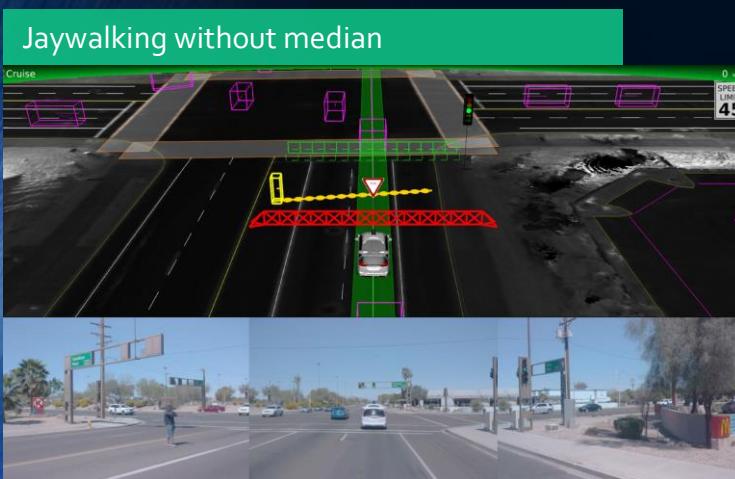
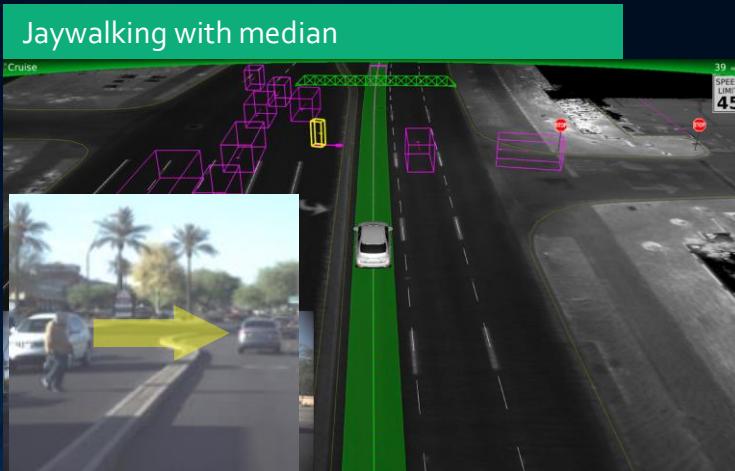
Detecting pedestrian in a dust storm



More edge cases

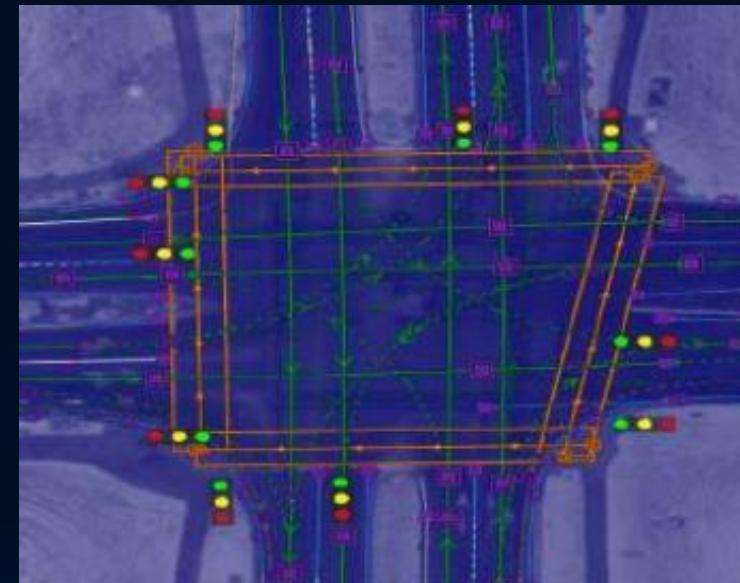
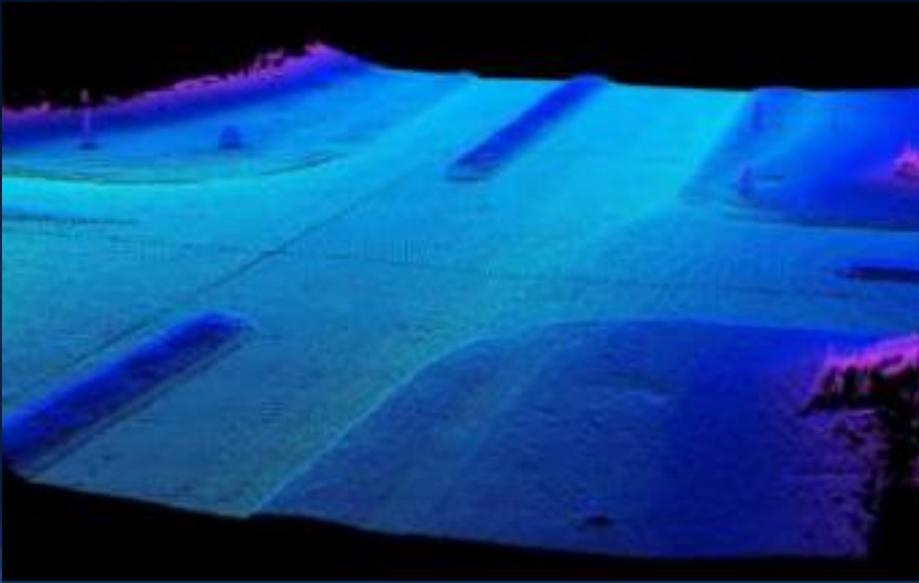


More edge cases



How to make a HD map

- Use dense LiDAR to create 3D map
- Register information(road types, crosswalks, lights, signage)
- If a part of map is non-passable, incident will be notified



Out of ODD sensing

- Waymo car is able to sense if it is out of ODD or not.
- MRC taken in such case
- Able to automatically call operator for remote decision making

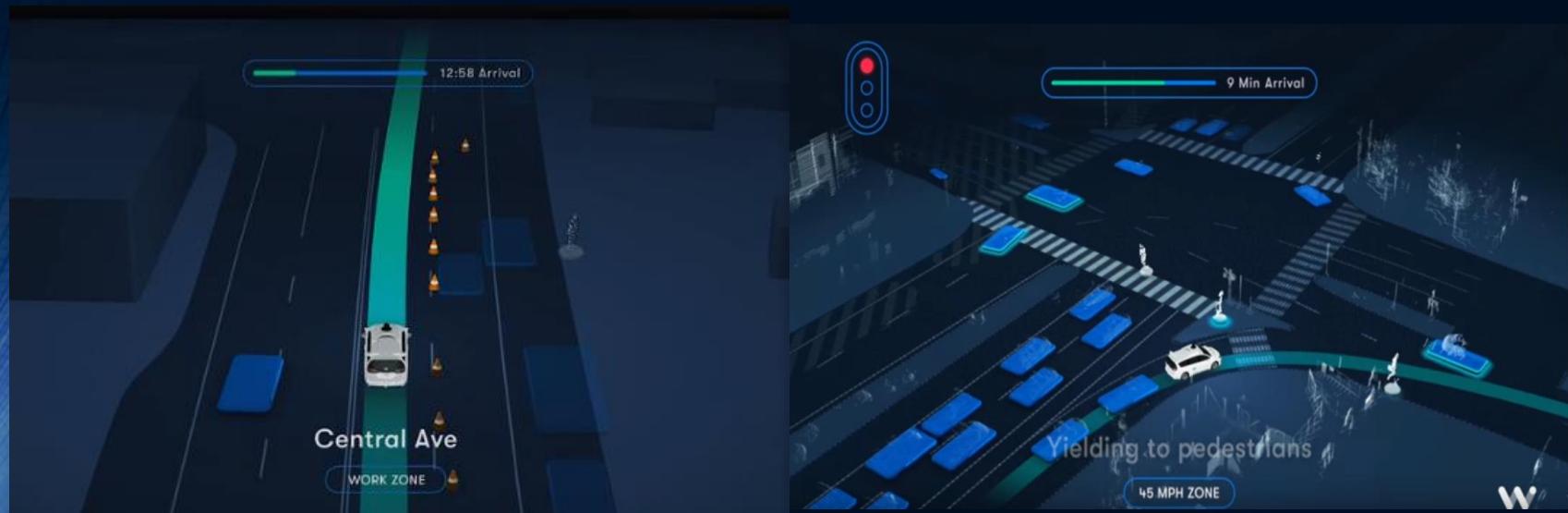


Minimum Risk Condition

- Able to automatically pull over, or come to a smooth stop
- Passenger can invoke pull over whenever they want

HMI: Source of comfort & safety

- “A couple of screens show the user just how much information we have of the world around us. It’s a **source of comfort**, we find that our riders are **very comfortable** in a relatively short period of time.” –John Krafcik, Waymo CEO



- Traffic light info
- Arrival time & time lapse
- Ego vehicle trajectory
- Why the car act like this
- Sensing result
- Map info
- Zone property
- Where you are

HMI: Start RIDE!

- HMI are designed for diversity of people, including handicapped, controlled with both visual and audio



- Call rider support team
- Lock & unlock door
- Pull over(Min Risk Cond)
- Start Ride
- In-car camera

Challenges

- So, Is Waymo perfect? No.
- Footage recorded in 2018@El Camino CA, vehicle is manned
<https://www.youtube.com/watch?v=1Jf1ZM-ho4o>

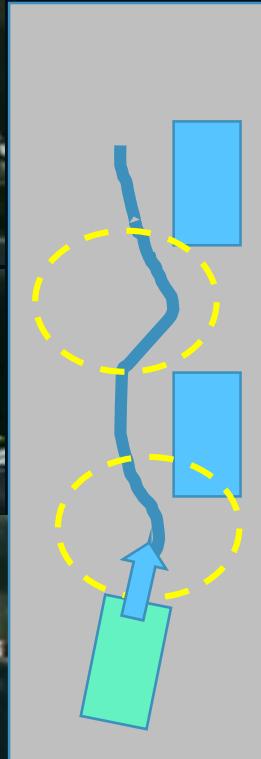


Challenges

- Blinking unnecessary braking

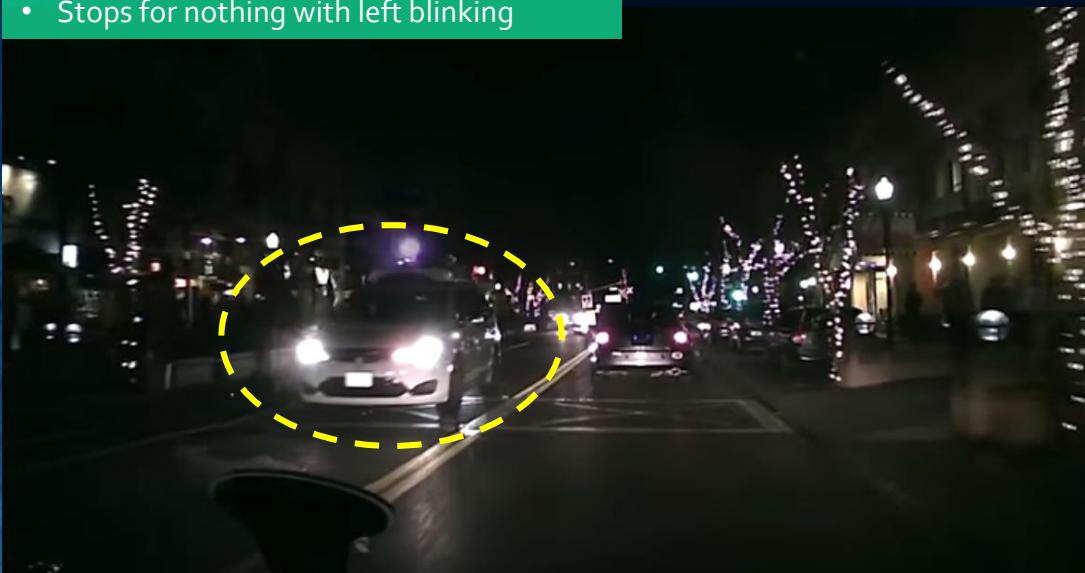


- Drive straight at parking car, avoidance failure

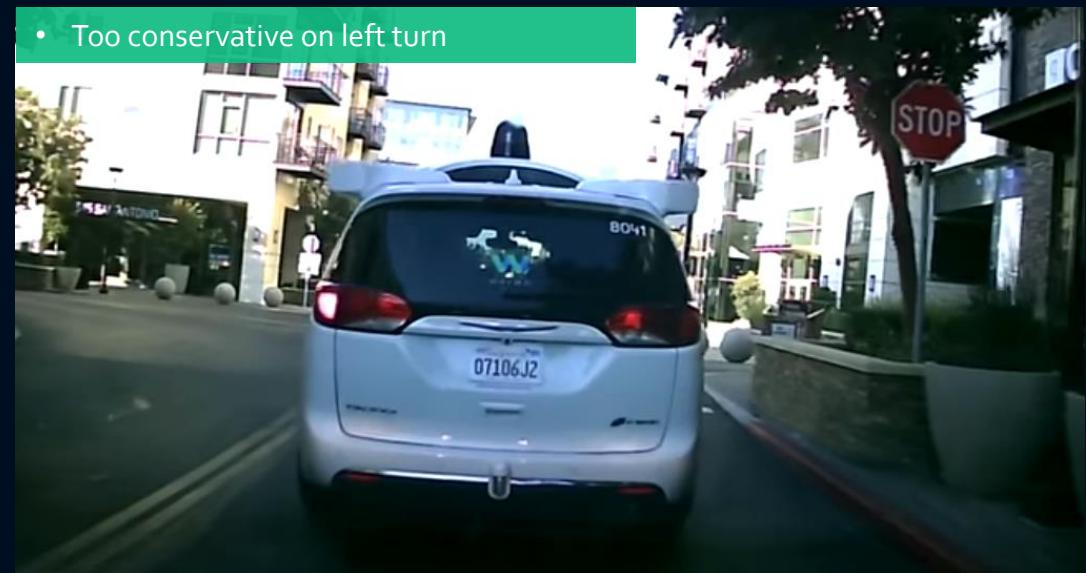


Challenges

- Stops for nothing with left blinking



- Too conservative on left turn

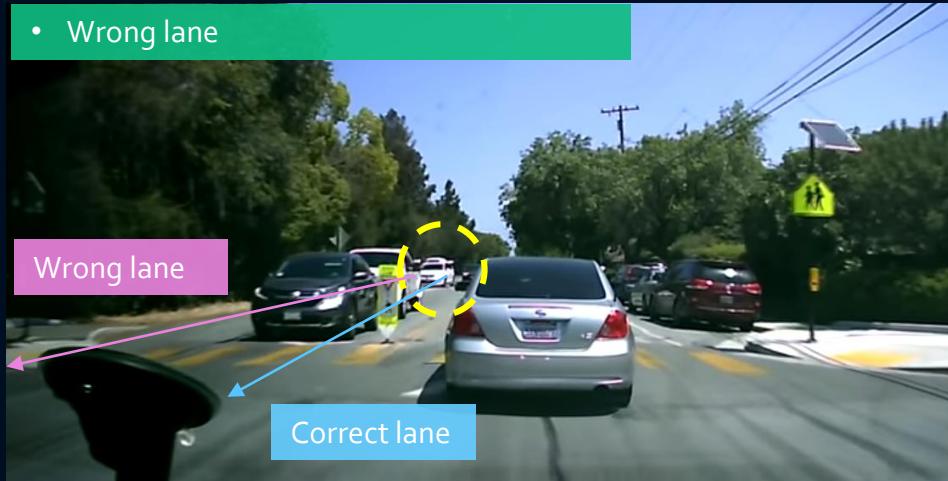


Challenges

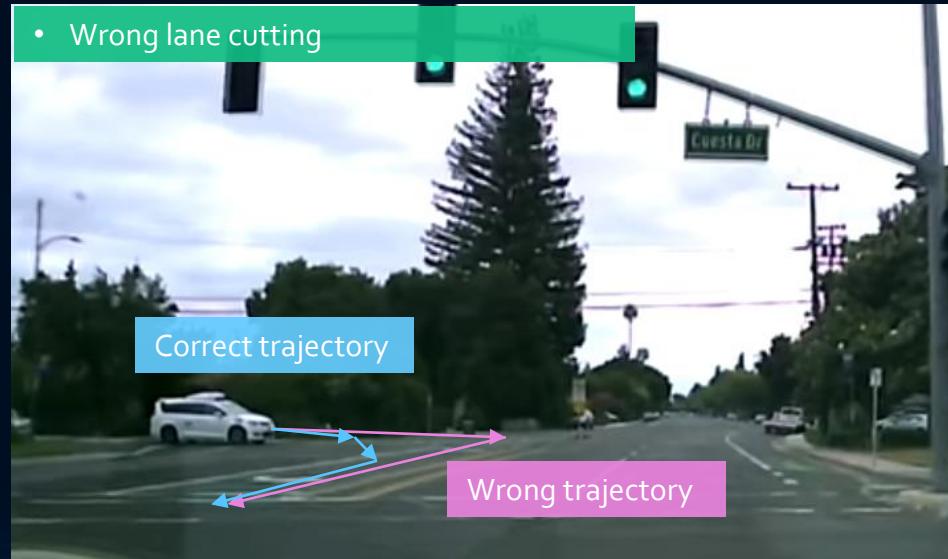
- Simply stuck in the deadend



- Wrong lane



- Wrong lane cutting



Challenges

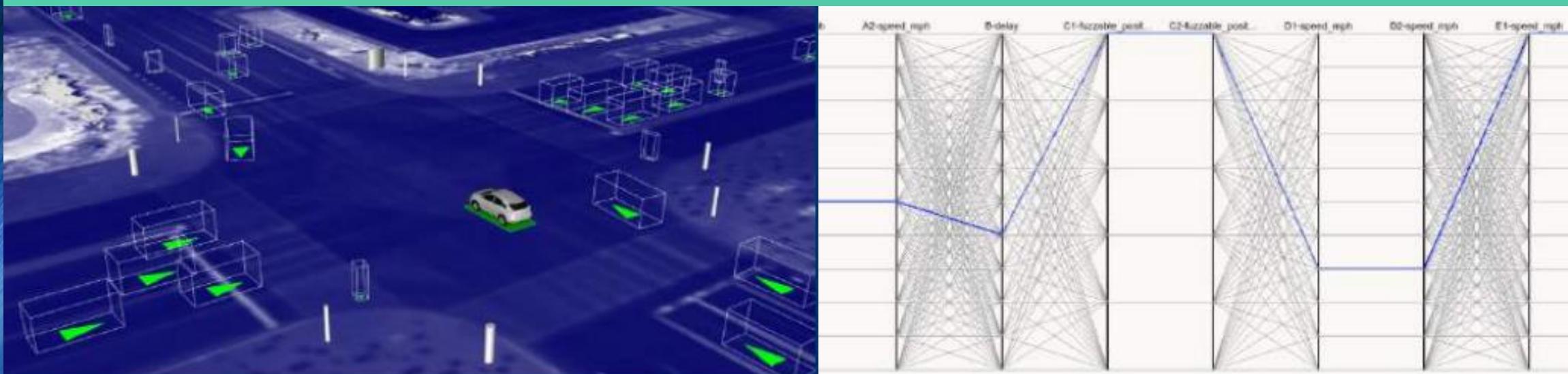
- Stuck in parking



Countermeasure?

Data center & Simulation

- What are the backbones of Waymo's technology?



Lv4 is a Local solution

Waymo car in
Phoenix



Drives@Phoenix



Waymo car in
Mountain View



Drives@Mnt. view



Waymo car in
Mountain View



Drives@Phoenix



Waymo car in
Phoenix



Drives@Mnt. view



What do the fleet share?

- Waymo at 25 locations

Share

- Basic Algorithm
- Global update

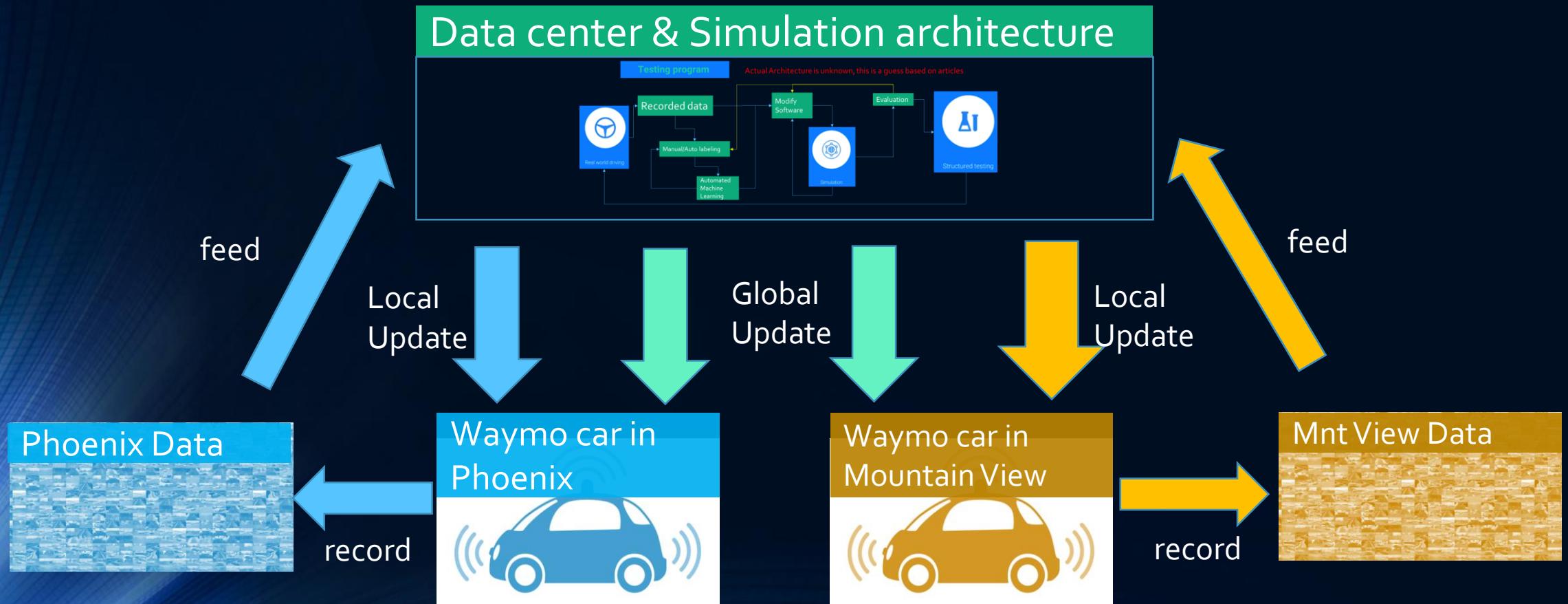
Not Share

- Local training data
- Local update

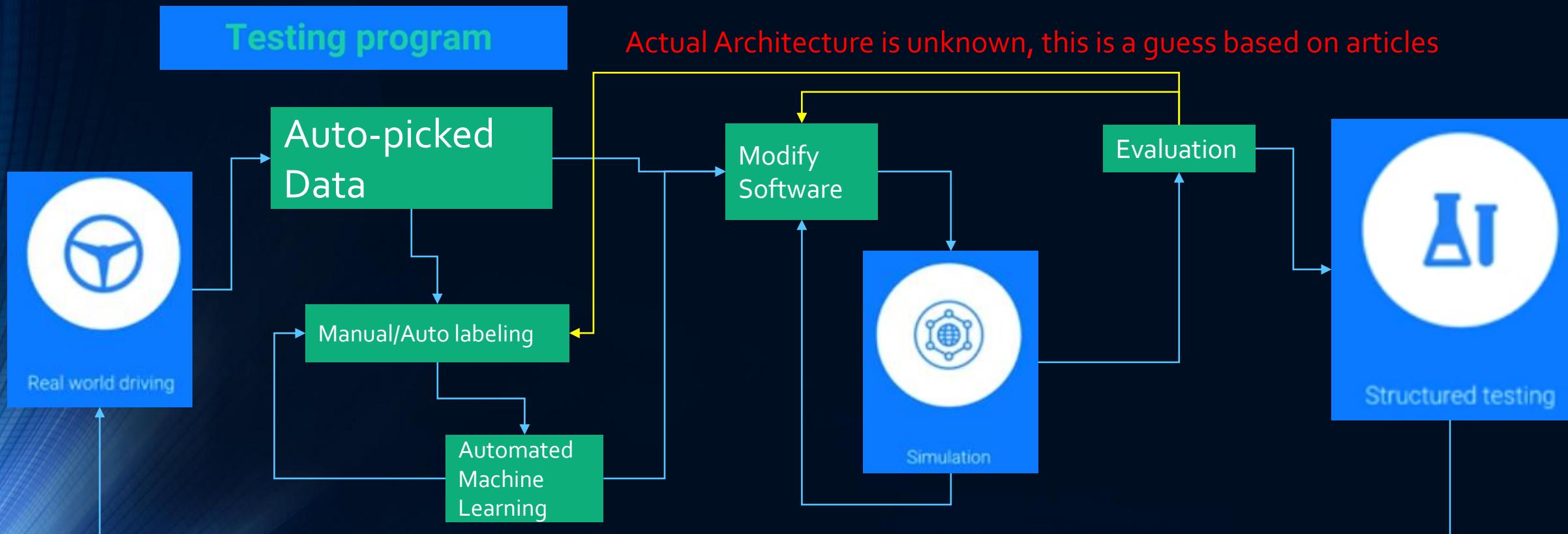
Lv4 is a LOCAL solution



The Core of Waymo Self-Driving

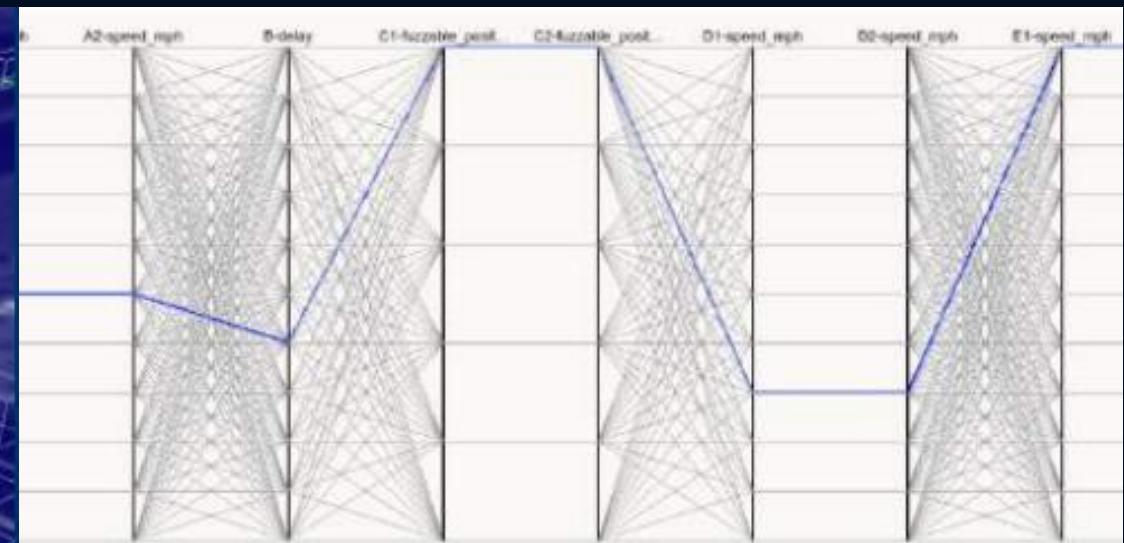
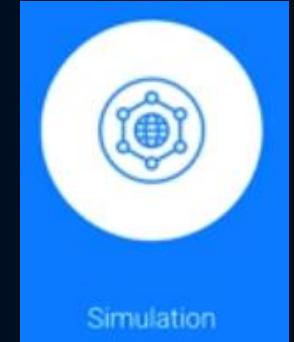


How to expand ODD



Simulation

- Use sensor data to recreate simulation world
- Fuzzing(test various parameters) to test algorithm
- 10Million simulation run/day



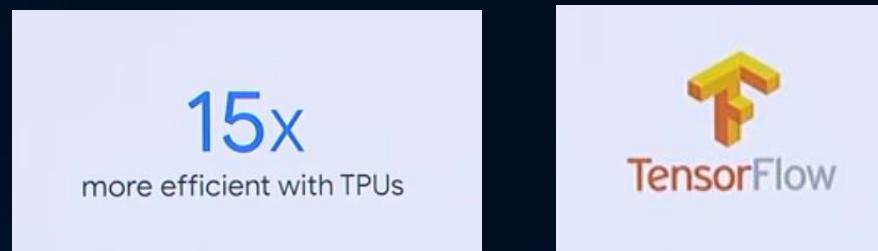
Simulation

“More important than the real world driving, though, has been the simulation work we’ve done. Right now we’re driving 10 million miles every day.”

-John Krafcik, Waymo CEO

Data center

- Uses “Automated-Machine Learning”, neural network to train a neural network
- AML is used in prediction, perception and planning
- Uses Semi-Auto labeling, 10 labels/sec
- Active Learning used(Learn only effective data)
- Multiply single unique edge case by fuzzing to train
- Training all data takes 4 months

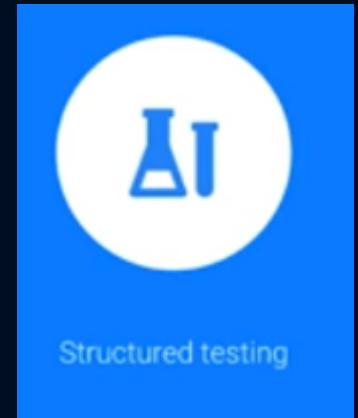


Data center

- Uses Tensorflow & TPU (No NVIDIA GPU used)
- TPUs are “orders of magnitude” faster than CPUs
- “We train AI machine learning that’s creating other AI models that actually solves the problem” -Sacha Arnoud, head of machine learning and perception division

This is the “key” to Waymo’s technology

Structured Test



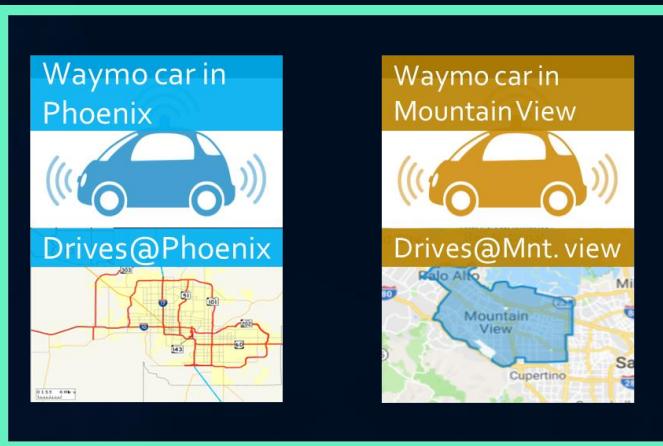
Car suddenly drives backward



Drops boxes from a trailer



Lv4 is a Local solution, How do we make money?



Business Model

- What are the Waymo's business model?
- What are the challenges in service?



4 business model

Ride hailing



Personal Vehicle



Tracking



Public transportation



Business partners

Ride hailing



Personal Vehicle



Tracking



Public transportation



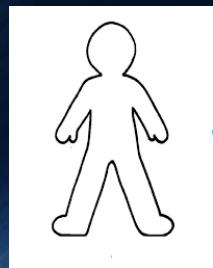
Why driverless?

- If one driver works 24/7 a year, it costs \$200,000

How to make money?

Ride hailing

- Get money from passenger, \$1.7/mi
- Get money from subscription
- Provide free ride to business partner



\$10 ride?



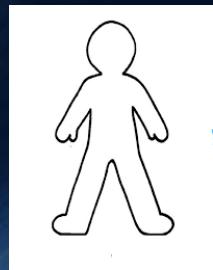
Free ride?



How to make money?

Ride hailing

- Concierge, provide “recommendation”
- Provide “coupon”, “date plan”



\$10 ride?



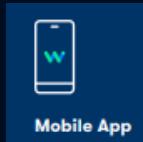
Free ride?
& Coupons



How to make money?

Ride hailing

- Being a service provider
- Make mobile app by their own



Ride hailing



How to make money?

Personal Vehicle

- Get money from sensor package
- Get money from mapping and testing
- FCA stated, “looking for Lv4 vehicle in a limited area by 2025”

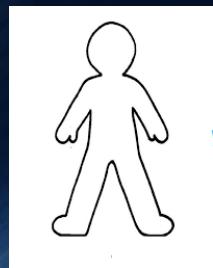


How to make money?

Public transport

- Get money from ride & subscription
- Provide multi-modal solution
- Provide **free ride** to business partner

Public transportation



\$10 ride?

Other public transport

Free ride & perfect transfer



How to make money?

Tracking

- Detail not known

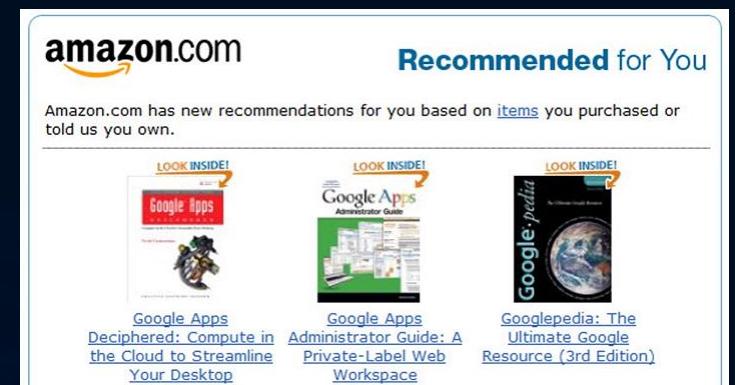
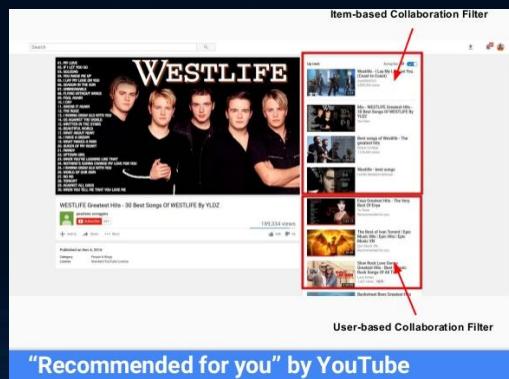
Tracking



How to make money?

Finally,

- Make the use of “Big data” to make a “flow in business”
- Recommendations to provide “an experience”
- “users could see promoted ride destinations **with free** or discounted rides”, -John Krafcik, Waymo CEO



How to make money?

Summary

- Lv4 is a local solution
- They make money from ride hailing & local subscriptions
- 25+ locations parallel

Challenges in service

Challenges@Jun, 2018

- On narrow streets, riders prefer to cross the road to reach a car, instead of having it drive to the end of a road, turn around and come back
- It needed to figure out how to accommodate people with service animals (it figured this out after a query from a passenger)
- The best way to wake sleeping passengers is with a little chime sound.

Challenges@Nov, 2018

- Difficult to navigate through parking lot, traffic rule is non-predictable
- Where you drop-off is not where you pick up, when you drop a passenger at Walmart entrance, the passenger want to be pick up by other location.(because of lots of shopping bags at entrance is no good!)

Self-Driving Car Cook Book



How to cook a self-driving car?



Cookbook summary

Execution

- ❑ Make sure your Lv4 is a local solution
- ❑ Launch Early Rider Program

Self-Driving Car technology

- ❑ Your car should solve planning & perception edge cases
- ❑ Detailed classification & scene understanding

Data center & Simulation

- ❑ Create “data center and simulation” infrastructure
- ❑ Your simulation is able to drive 10million miles a day
- ❑ Auto-record disengagement and abnormal behavior
- ❑ Auto-machine learning, a neural network defines a problem, to train other neural network

Business Model

- ❑ Make Concierge, or recommendation since they make big money
- ❑ Make your cars are driverless and operates 24/7

Executions

- ❑ Make sure your Lv4 do not aim for an universal solution
- ❑ Drive in real for a massive distance to find edge cases
- ❑ Record disengagement report
- ❑ Lv4 focused R&D
- ❑ Choose a location for testing, start service at that location
- ❑ Launch Early Rider Program
- ❑ Get customer feedback
- ❑ Make sure your Lv4 car can be used for work, restraint, school
- ❑ Make part of your car driverless, also train safety driver and operator
- ❑ Put chaperone in the charged service
- ❑ Make operation center, organize team into Rider support, Fleet technician, Fleet response, Fleet dispatch
- ❑ Operation center needs to respond in an emergency case(with a protocol)
- ❑ Remote decision making, and rider support
- ❑ Make hotline with local law enforcement and create a protocol
- ❑ Define your ODD
- ❑ Multi-location with parallel testing
- ❑ Start-from-one-straight road strategy
- ❑ Expand-by-intense-driving strategy
- ❑ Get local and governmental approval

Self-Driving Car technology

- ❑ Equip rich sensors to see zoom all around, camera, radar, Lidar
- ❑ Equip supplemental sensors like GPS, and audio sensor
- ❑ Make sure your perception is centered on Machine Learning
- ❑ Perception classify & detect: Vehicle, Pedestrian(multi-pause), Parked, Open door, trajectory prediction, cyclist, bike, cones, vehicle type, emergency vehicles(police, ambulance, school bus, fire truck), traffic signs, traffic lights, construction zone, interaction plan(yield, take over), misc objects(ball, chickens)
- ❑ Solve perception & prediction edge cases
- ❑ Your algorithm should respond correctly to surrounding actor's violation of traffic law
- ❑ Denoising of snow and rain
- ❑ Make HD map
- ❑ Sense if your vehicle is out of ODD
- ❑ Minimum risk condition maneuver(able to pull over and come to stop)
- ❑ Auto-call operator when self-driving system is in low confidence
- ❑ Design HMI to provide comfort
- ❑ HMI show: traffic light info, arrival times, time lapse, ego vehicle trajectory, cause of ego vehicle action, sensing result of surrounding actors, map info, zone property, where you are
- ❑ HMI includes physical buttons: call rider support team, lock and unlock door, pull over, start ride, in-car cam
- ❑ You car should solve planning edge cases

Data center & Simulation

- ❑ Your fleet share basic algorithm, and global software update
- ❑ Your fleet do not share local training data, and local update
- ❑ Self-driving cars in different locale are not interchangeable
- ❑ Create “data center and simulation” infrastructure
- ❑ Auto pick data system for your recorded data, use of active learning
- ❑ Auto-record disengagement and abnormal behavior
- ❑ Auto-machine learning, a neural network defines a problem, to train other neural network
- ❑ Manual and auto labeling to avoid low-quality data, auto labeling 10 label/sec
- ❑ modification of software should be tested in simulation, structured testing, real world driving
- ❑ Your simulation is able to drive 10million miles a day
- ❑ Simulation do “fuzzing”, use real-world sensor data for recreation
- ❑ Use of TPU and tensorflow
- ❑ Designed structured test

Business Model

- ❑ Local business at multiple location
- ❑ Business field: Ride hailing, personal vehicle, tracking, public transportation
- ❑ Find business partners in each field
- ❑ Make sure your car is driverless
- ❑ Get money from passenger
- ❑ Get money from subscription from stores, hotels, public transportation
- ❑ Ride can be free or discounted
- ❑ Make mobile app, do it by yourself
- ❑ Do NOT let service provider take over, they get the most of money do the service by yourself
- ❑ Sell sensor package and self-driving software to auto-makers
- ❑ Make money from mapping and testing as per request of auto-maker
- ❑ Provide multi-modal solution
- ❑ Record big data, customer preference
- ❑ Make Concierge, or recommendation since they make big money
- ❑ Solve challenges in service

Appendix

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