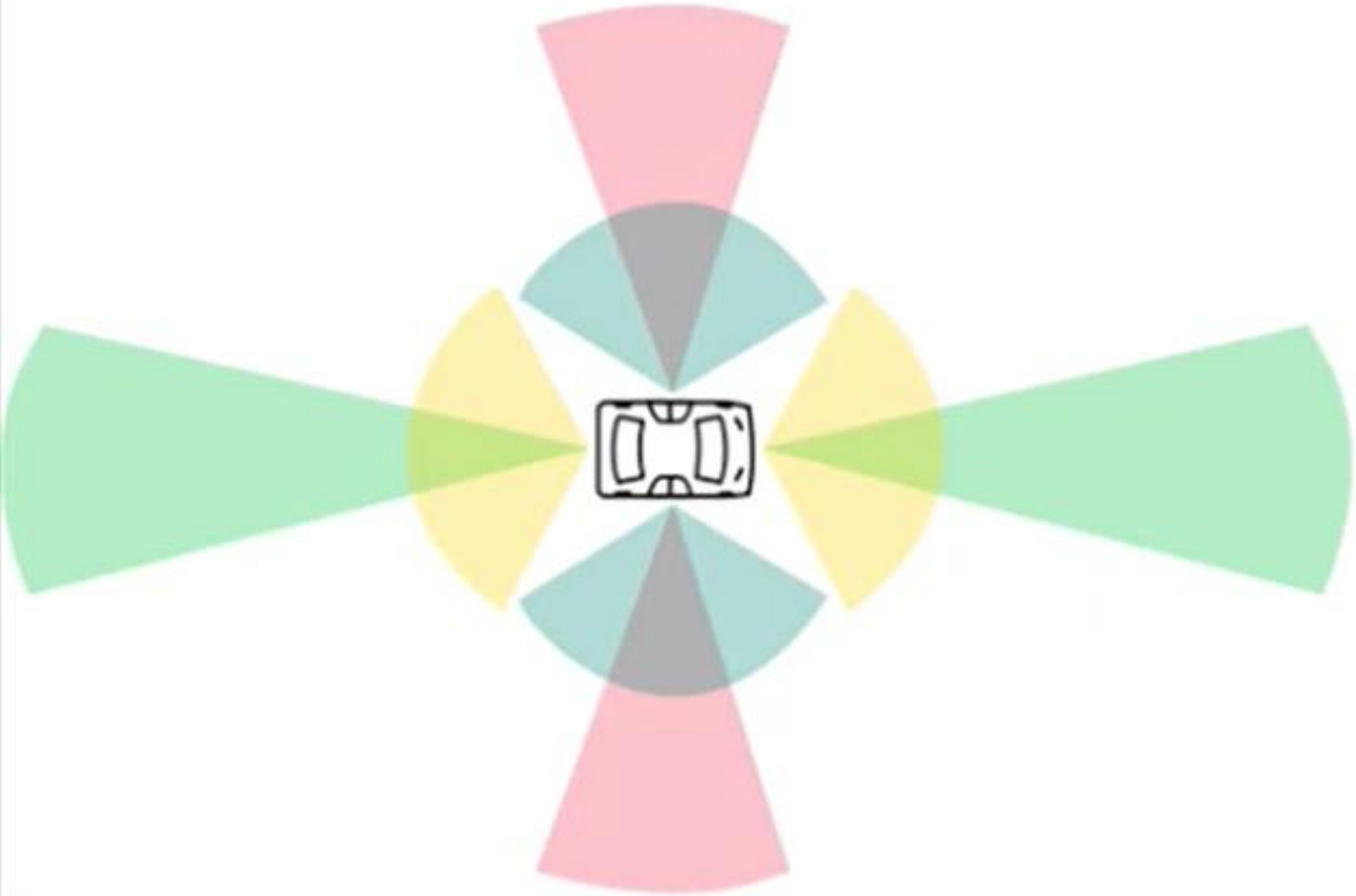
L1.2 AV Sensors, V2X, HD Maps

Zonghua Gu, Umeå University

Nov. 2023

AV Sensors

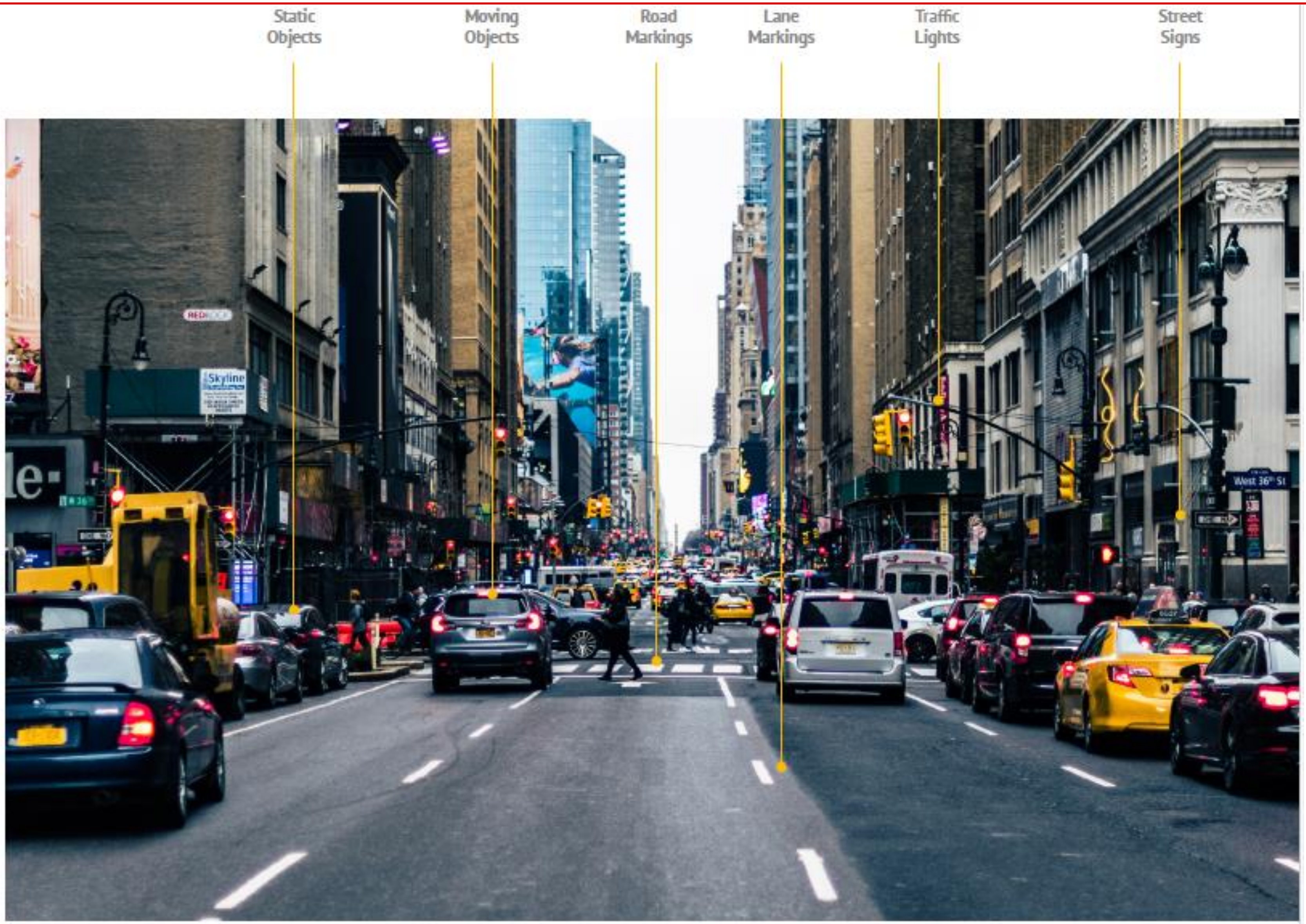


Perception Tasks

- Detection
  - Detect the existence of an object in the environment
- Classification
  - Identify what the object is, e.g., traffic sign, traffic light, pedestrian
- Tracking
  - Track a moving object across time
- Segmentation
  - Semantic segmentation: classify each pixel to its semantic category, e.g., road, car, sky…
  - Instance segmentation: classify each pixel to an object instance, e.g., car1, car2…

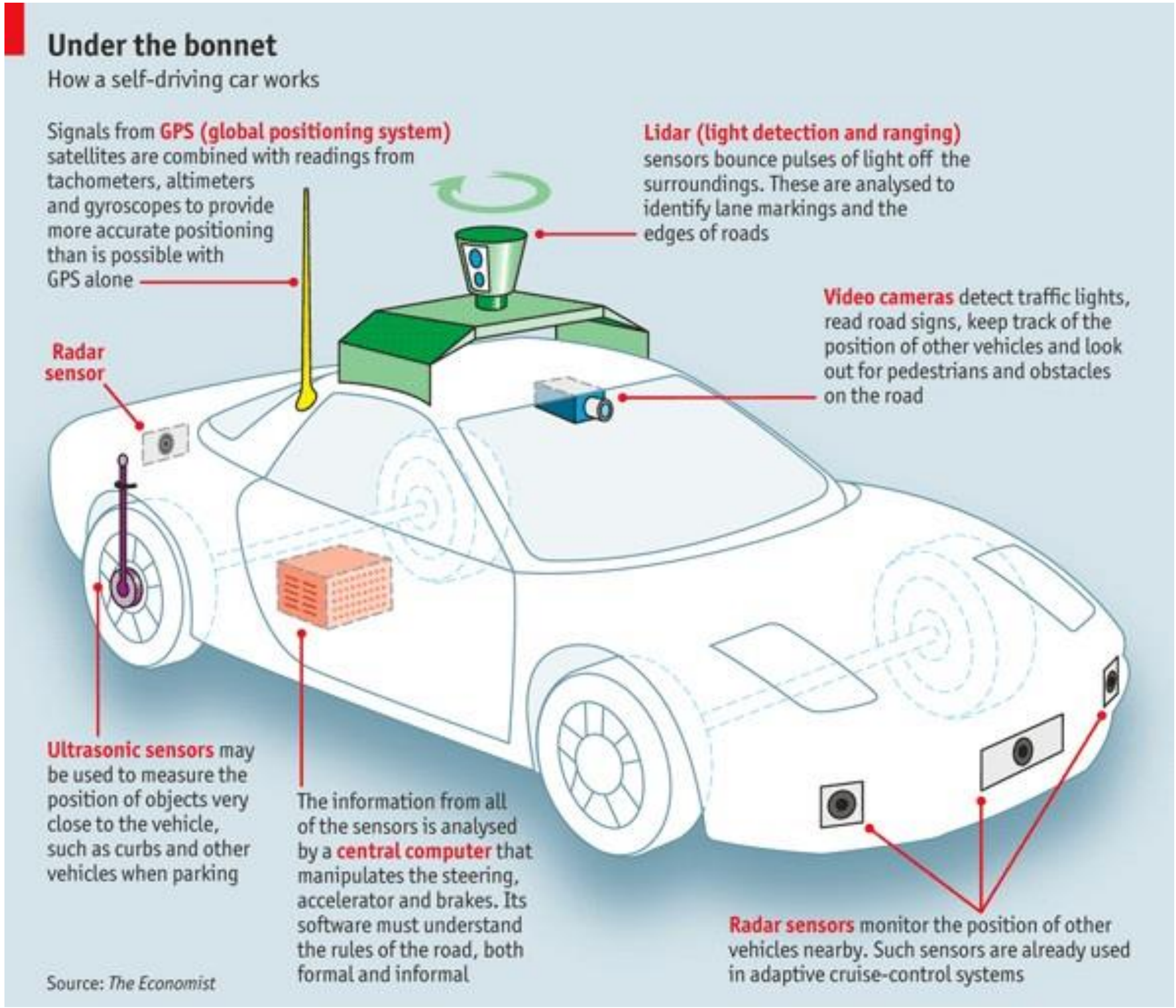
Udacity's Self-Driving Fundamentals featuring Apollo

The variety of static and moving objects that an AV needs to detect and recognize



Typical AV Sensors

- Cameras – perceive the environment with computer vision algorithms.
- Radar – Radio waves detect short & long-range depth.
- LIDAR – Measures distance by illuminating target with pulsed laser light and measuring reflected pulses with sensors to create 3-D map of area.
- GPS – Triangulates position of car using satellites.
- Ultrasonic Sensors – Uses high-frequency sound waves and bounce-back to calculate distance. Best in close range.



https://www.economist.com/the-economist-explains/2015/05/12/how-does-a-self-driving-car-work

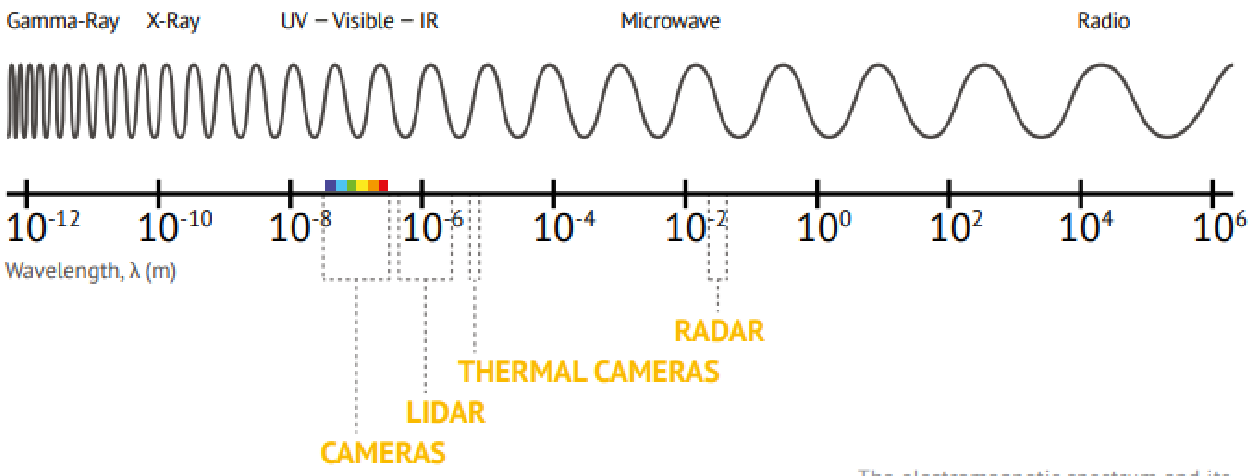
Sensor Configurations of Some Commercial AVs

- Most AVs rely on multiple sensor types.
- Tesla is unique in that it uses only cameras, not Lidar, Radar or Ultrasound.
  - “In 2021, we began our transition to Tesla Vision by removing radar from Model 3 and Model Y, followed by Model S and Model X in 2022. In 2022 we took the next step in Tesla Vision by removing ultrasonic sensors from Model 3 and Model Y for most global markets, followed by all Model S and Model X in 2023.” From https://www.tesla.com/en_eu/support/transitioning-tesla-vision.
  - “In my view, Lidar is a crutch that will drive companies to a local maximum that they will find very hard to get out of. Perhaps I am wrong, and I will look like a fool. But I am quite certain that I am not.” Elon Musk, 2017.

	Uber	Waymo	GM Cruise	Navya Autonomy Cab	Drive.ai	Nissan	Tesla FSD
Cameras	8	8	16	6	10	12	8
Lidars	1	6	5	10	4	6	0
Radars	4	4	8	4	2	9	0

Passive vs. Active Sensors

- Passive sensors detect existing energy, like light or radiation, reflecting from objects in the environment.
  - Cameras
- Active sensors (also called range sensors) send their own signal and sense its reflection
  - Lidar, Radar, ultrasound



The electromagnetic spectrum and its usage for perception sensors .[16]

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

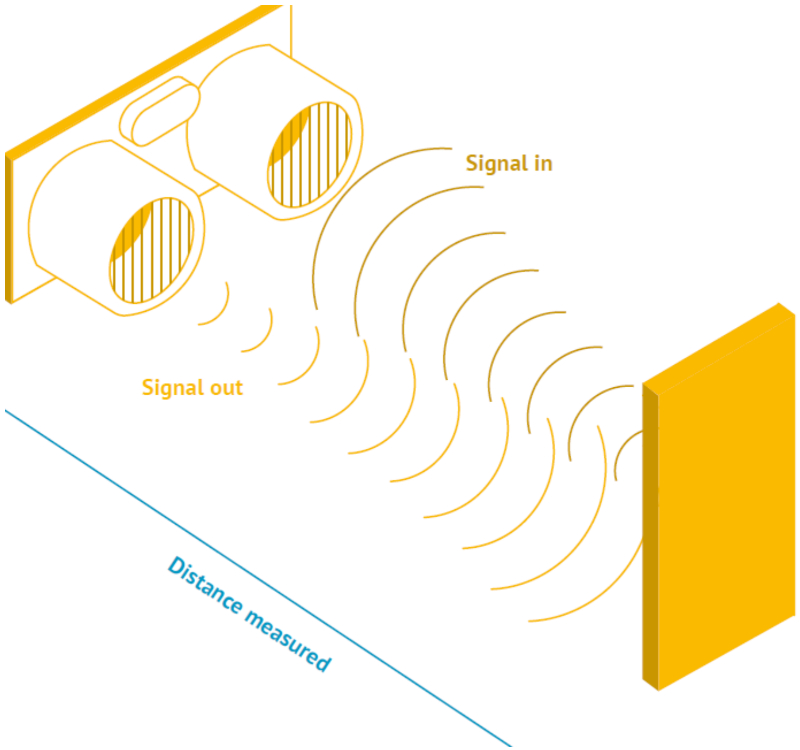
Camera

- Pros: cheap, versatile, stereo vision w. two cameras
- Cons: affected by illumination conditions, needs additional light at night
- Key parameters
  - Resolution
    - AV cameras typically use high-resolution in the range of 8-16 megapixels (MP) (c.f. iPhone camera has 12 MP)
  - Field of View (FOV)
    - The extent of the observable world that is seen at any given moment
    - Given same resolution, wider FOV results in large image distortion
  - Dynamic range
    - Maximum difference between the darkest and lightest pixel intensities in an image, measured in dB. An AV needs HDR (High-Dynamic-Range) cameras with at least 100dB

Tesla makes improvements to camera clarity in FSD Beta version 11.4.7 (Sep. 2023)

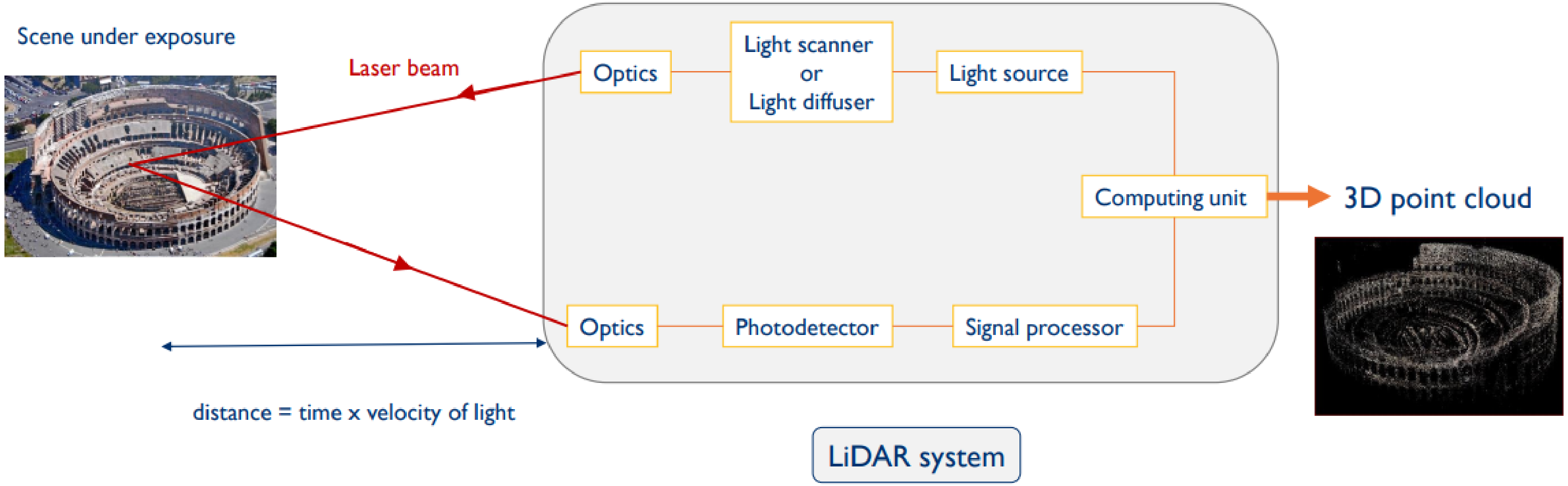
Range Sensors

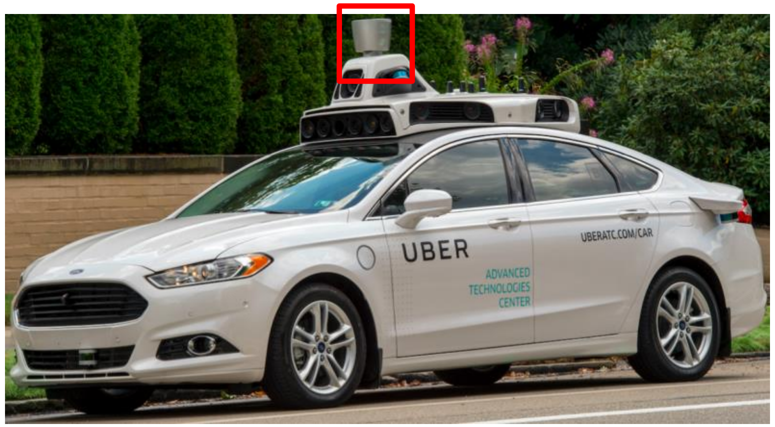
- They rely on Time of Flight (ToF) to measure distance (range)
  - Lidar uses electromagnetic waves.
  - Radar uses radio waves
  - Ultrasonic uses sound waves
- The traveled distance of a wave is given by $d = \frac{v*t}{2}$
  - d: distance; v: speed of wave propagation; t: ToF (roundtrip)
- Propagation speed v
  - Sound: 0.3 m/ms
  - Electromagnetic wave (incl. light): 0.3 m/ns (1 M times faster than sound)
- To travel 3 meters:
  - 10 ms for ultrasonic sensor; 10 ns for Lidar (hence Lidars are expensive.)
- The quality of range sensors depends on:
  - Inaccuracies in the time of fight measurement (laser range sensors)
  - Opening angle of transmitted beam (especially ultrasonic range sensors)
  - Interaction with the target (surface, specular reflections)
  - Variation of propagation speed (sound)
  - Speed of vehicle and target

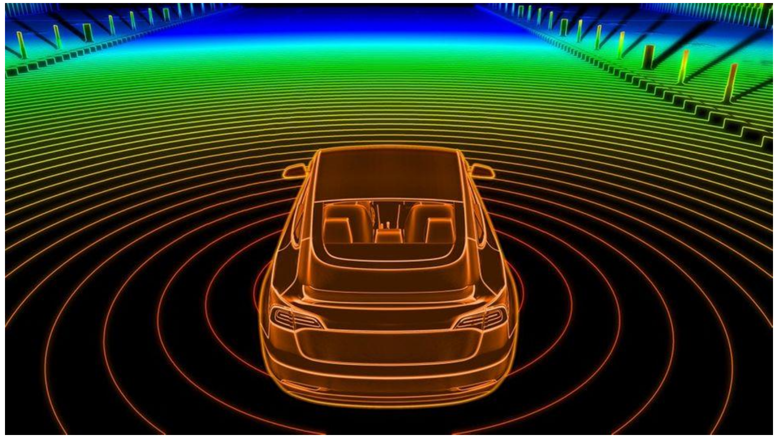


Lidar

- Lidar (Light Detection and Ranging Device) sends millions of light pulses per second in a well-designed pattern to generate Point Clouds that describe the 3D geometry of the surrounding environment
- Pros: independent of lighting conditions, precise distance measurements (up to 200 m) for 3D perception
- Cons: expensive, medium resolution
- Key parameters:
    - Laser beam count
    - Rotation Speed
    - Range distance (from tens to hundreds of meters)

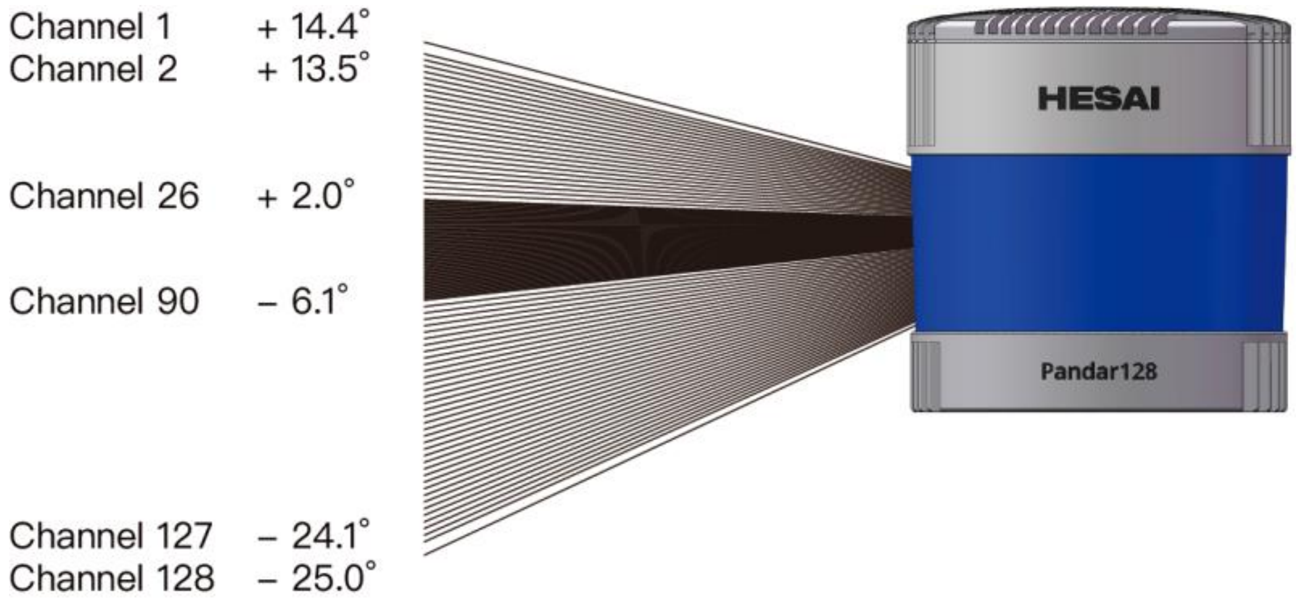






Product Example: HESAI Pandar128 128-Channel Mechanical LiDAR

- The vertical resolution is
  - 0.125° from Channel 26 to Channel 90
  - 0.5° from Channel 2 to Channel 26, as well as from Channel 90 to Channel 127
  - 1° between Channel 1 and Channel 2, as well as between Channel 127 and Channel 128



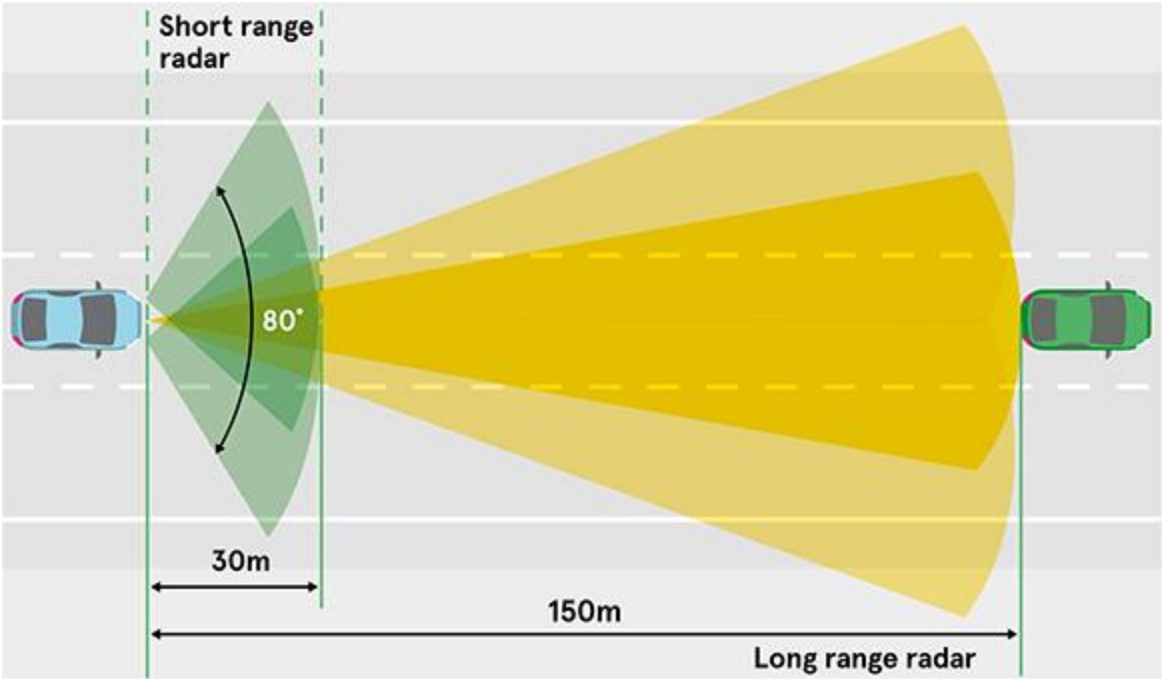
http://map4.jp/wp-content/uploads/2023/03/pandar128_manual.pdf

Apple iPAD Pro has Built-in Lidar (2020)

- It allows users to scan a depth-accurate depiction of the environment
- Main application: Augmented Reality (AR)
  - Needs depth information to place virtual objects in the environment

mmWave Radar

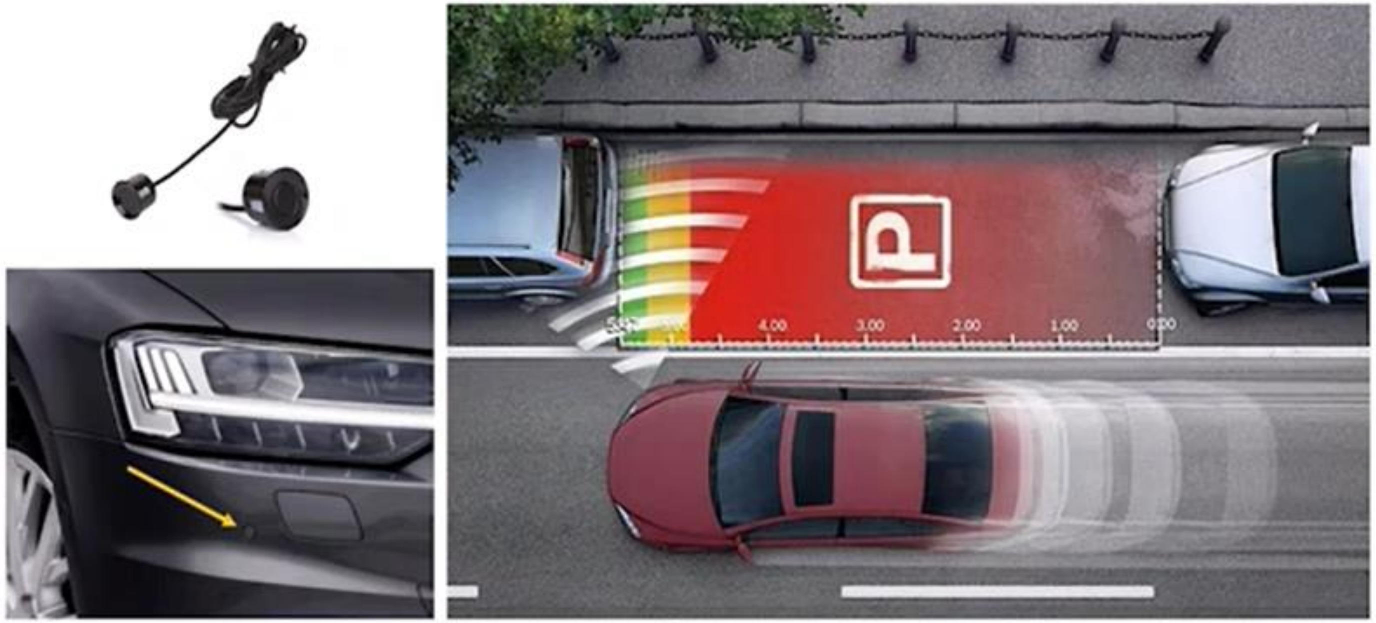
- Pros: provides both position and relative speed information; can operate in varied conditions (low-lighting, rain, fog…)
- Cons: low resolution
- Key parameters
  - Sensing distance, FOV, Position and velocity accuracy
- Two types
  - Short/medium range with wide FOV
  - Long range (up to 250 m) with narrow FOV



https://www.avnet.com/wps/portal/abacus/solutions/markets/automotive-and-transportation/automotive/comfort-infotainment-and-safety/automotive-radar/

Ultrasound

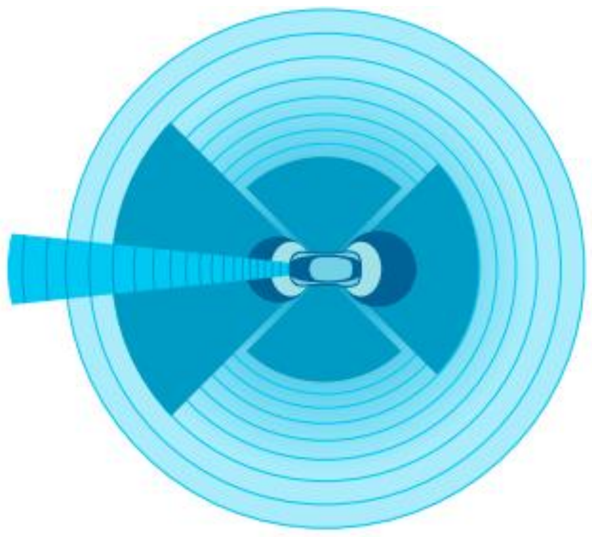
- Pros: not affected by lighting conditions, rain or fog
- Cons: short sensing range (mainly used for parking assistance)
- Key parameters
  - Sensing range
  - FOV

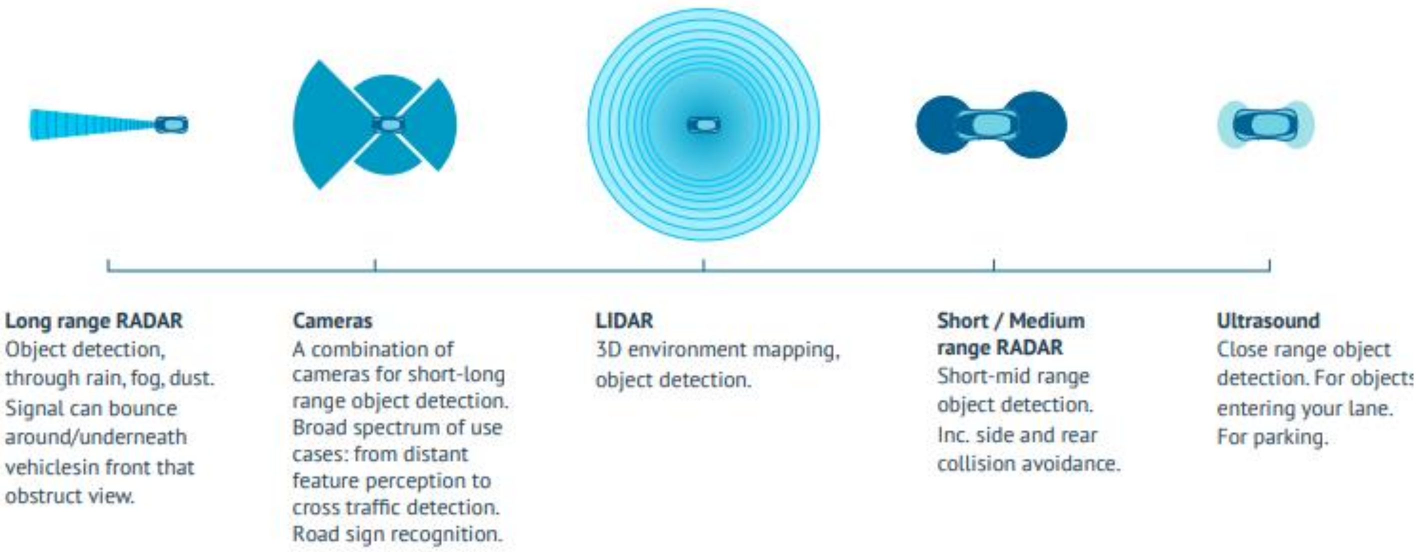


Comparison of Different Sensors

- Each sensor has its strengths and weaknesses
- Sensor fusion crucial for robust perception

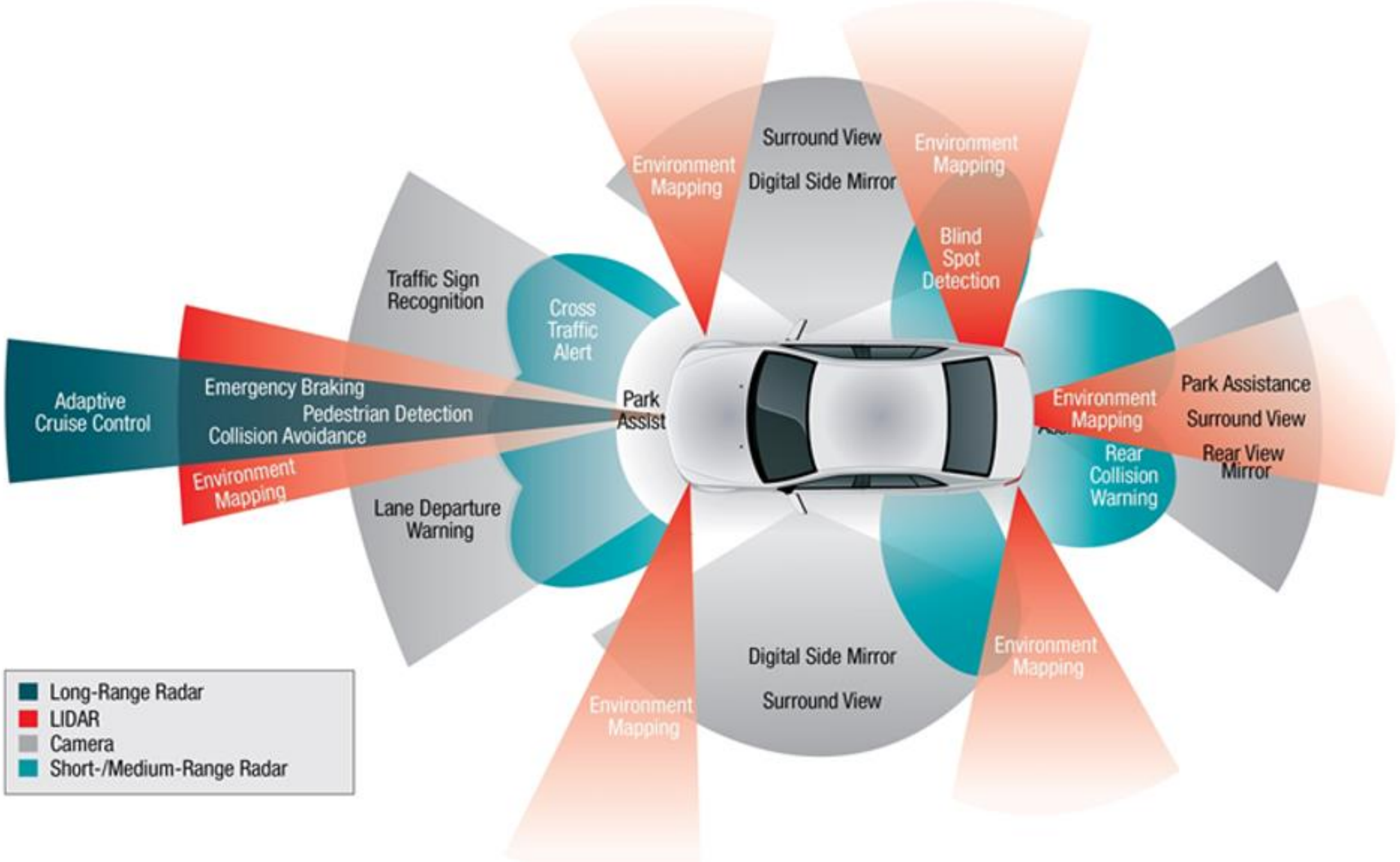
	Camera	Lidar	Radar
Sensing Range	Mixed	Mixed	Good
Functioning in bad weather	Poor	Mixed	Good
Functioning in poor lighting	Mixed	Good	Good
Object Detection	Mixed	Good	Mixed
Classification	Good	Mixed	Poor
Lane Tracking	Good	Poor	Poor





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

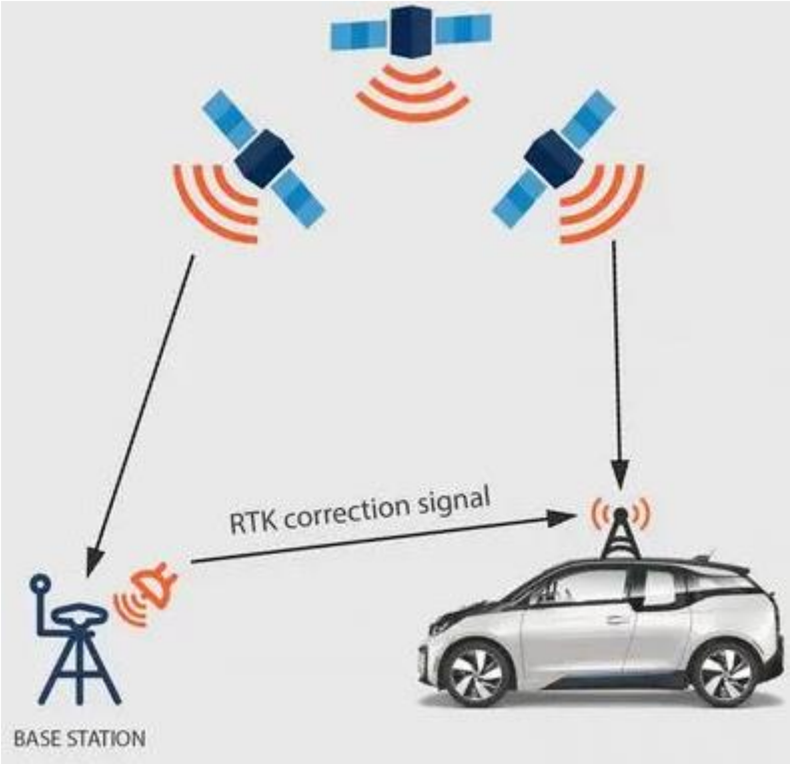
Typical AV Sensors and Ranges



wikimediacommons

GNSS/GPS

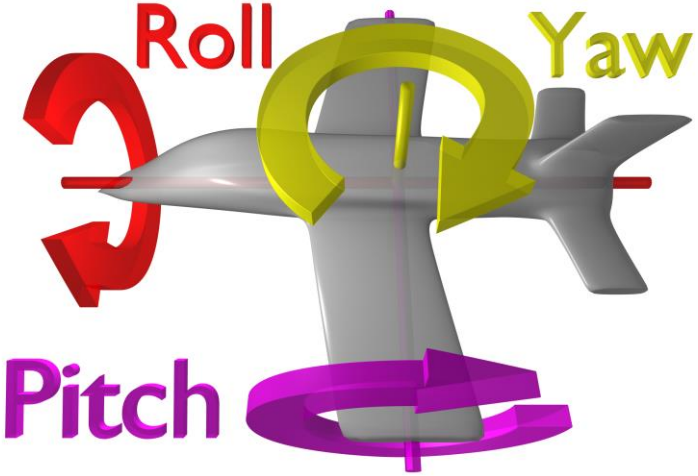
- GNSS (Global Navigation Satellite System) provides localization service for outdoor applications
  - GPS (USA), Beidou (China)
- Conventional GPS provides a few meters accuracy, affected by cloud covers and tall buildings
- RTK (Real-Time Kinematic) GPS can provide cm-level accuracy by calculating and transmitting differential correction data via radio to allow the roving GPS system to correct its position
- Pros:
  - High accuracy (depending on the system and environmental conditions)
  - Global coverage enables vehicles to determine their position anywhere on Earth.
- Cons:
  - Performance affected by factors such as signal blockage or multipath interference, which can occur in urban environments with tall buildings or in areas with dense foliage, or tunnels
  - Signals can be disrupted by atmospheric conditions or interference from other electronic devices
  - Dependent on the availability and reliability network of satellites and ground-based infrastructure



RTK GPS

IMU

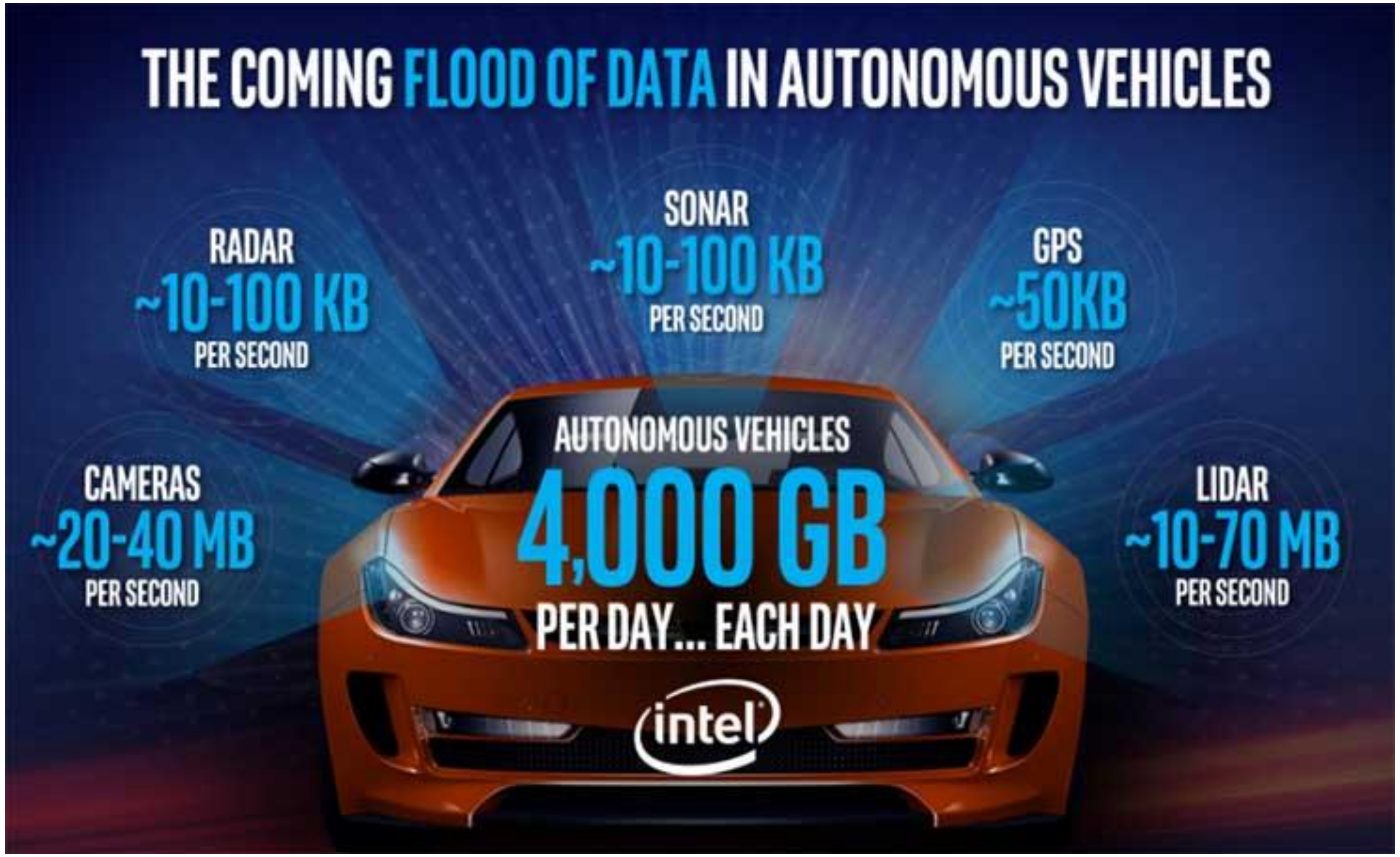
- IMU (Inertial Measurement System)
  - Accelerometers measure linear acceleration along three axes (x, y, and z)
  - Gyroscopes measure angular velocity around these axes. By integrating the data from these sensors, an IMU can estimate the vehicle's position, velocity, and orientation (yaw, pitch, roll) over time
  - Magnetometers, when included, can provide additional information about the vehicle's orientation by measuring the Earth's magnetic field
- Consider an AV driving on a curvy mountain road. The IMU
  - measures the AV's linear acceleration, detecting any changes in speed or direction. This helps the control system adjust the steering, braking, and acceleration to maintain stability
  - measures the AV's angular velocity, providing information about its rotational movement. This helps the control system make precise steering adjustments, especially when navigating sharp turns or avoiding obstacles



- Pros:
  - High-frequency data in the range of 100 to 1000 Hz, allowing for precise motion tracking and control.
  - Not affected by environmental factors, such as lighting conditions or weather
- Cons:
  - Prone to drift and accumulated errors over time, which can lead to inaccuracies in position and orientation estimates

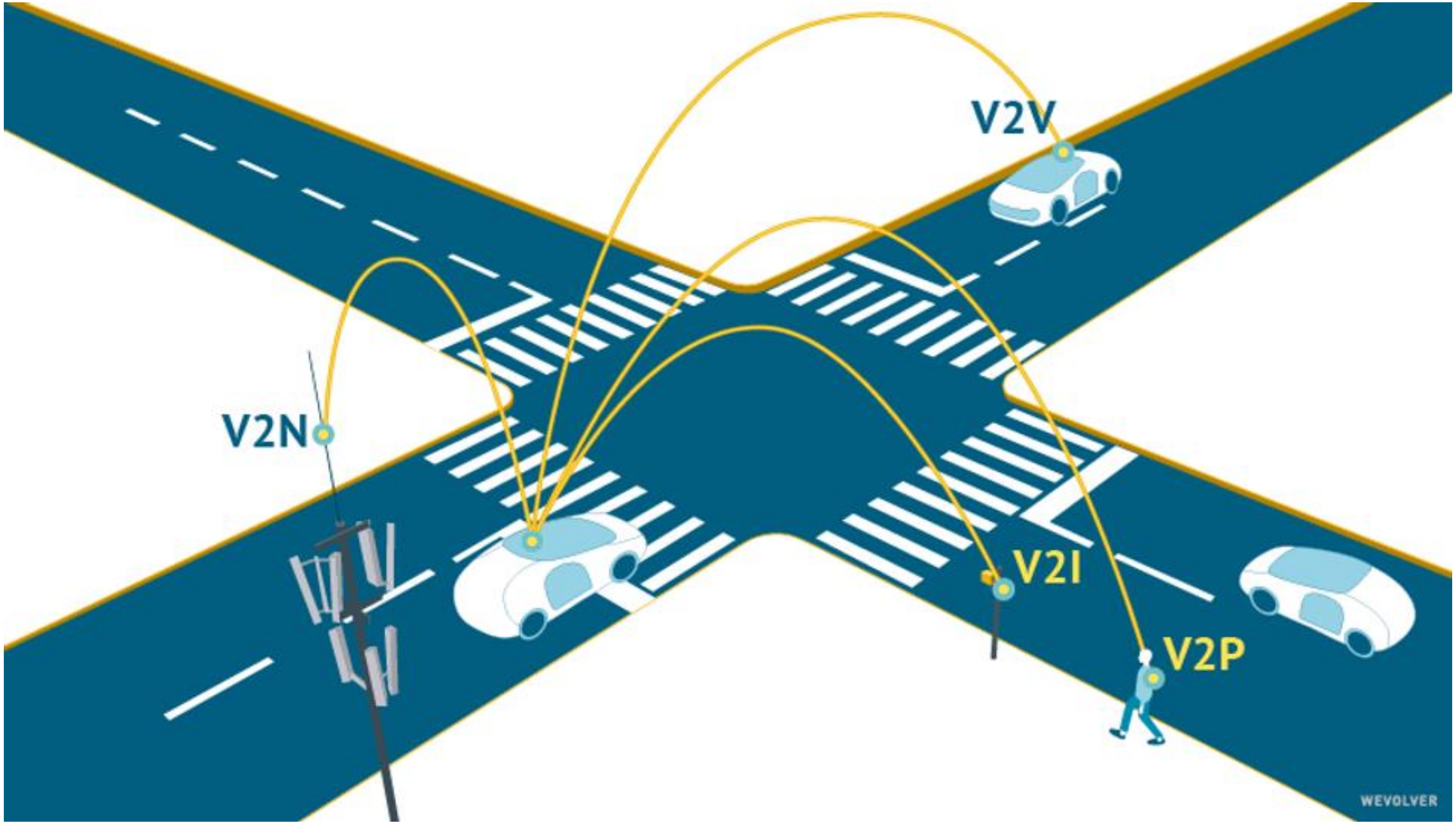
AV Sensors Generate Big Data

- High-bandwidth sensors (cameras and lidars) generate the most amount of data
- Sensor data must be processed in real-time by perception algorithms



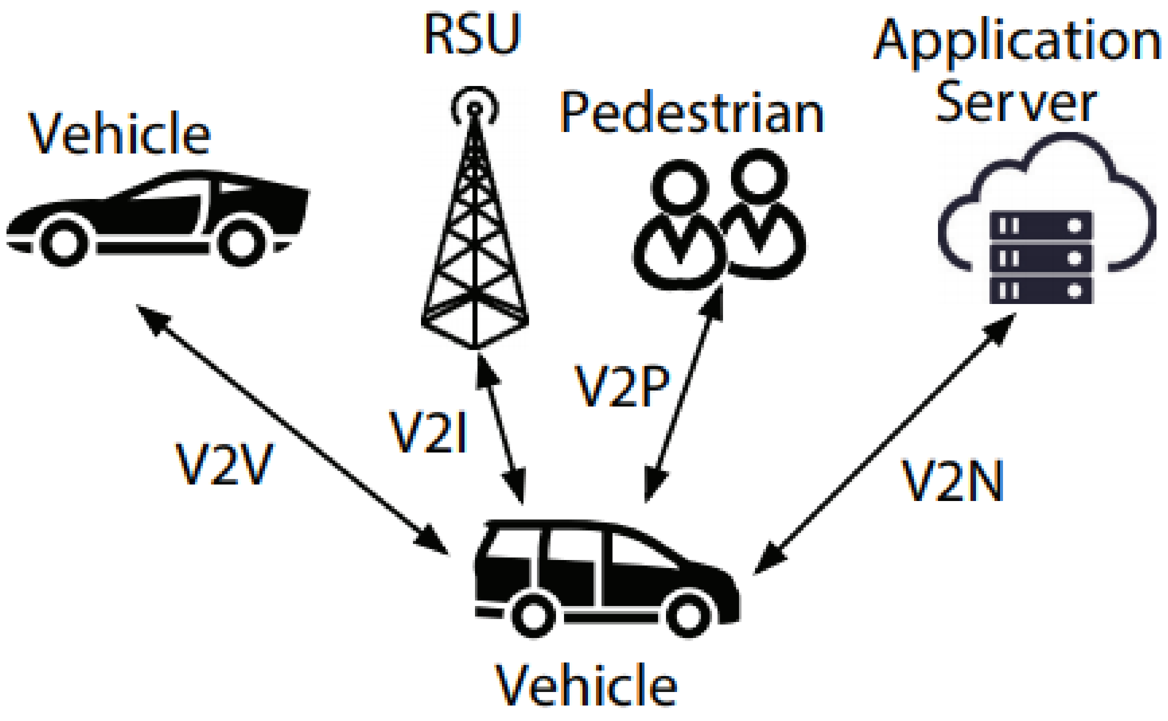
https://datacenterfrontier.com/autonomous-cars-could-drive-a-deluge-of-data-center-demand/

V2X



V2X Types

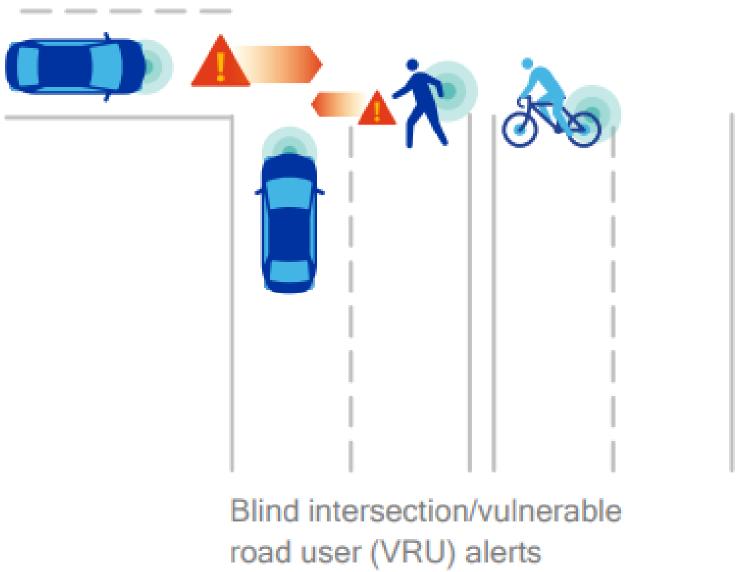
- Vehicle-to-Vehicle (V2V)
  - e.g., collision avoidance system
- Vehicle-to-Pedestrian (V2P)
  - e.g., safety alerts to pedestrians and bicyclists
- Vehicle-to-Infrastructure (V2I)
  - e.g., adaptive traffic light control, traffic-light optimal speed advisory
- Vehicle-to-Network (V2N)
  - e.g., real-time traffic routing, cloud services
  - Also called Vehicle-to-Cloud



V2X Applications

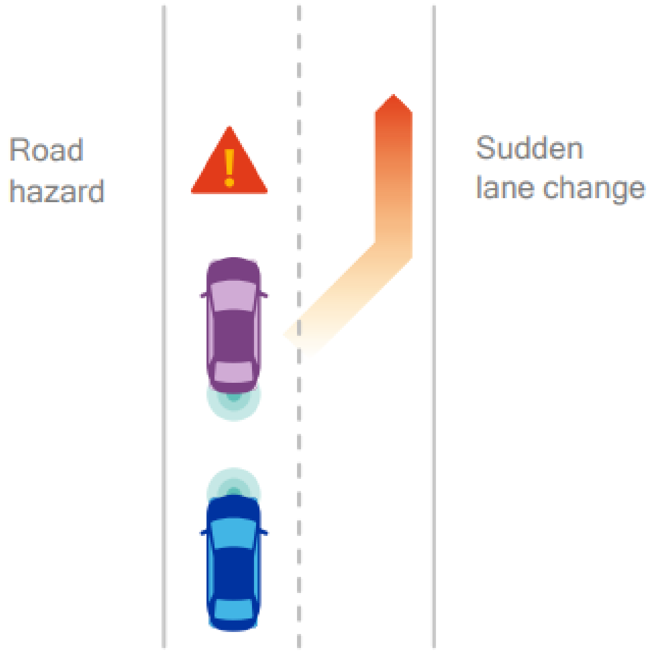
Non line-of-sight sensing

Provides 360˚ NLOS awareness, works at night and in bad weather conditions



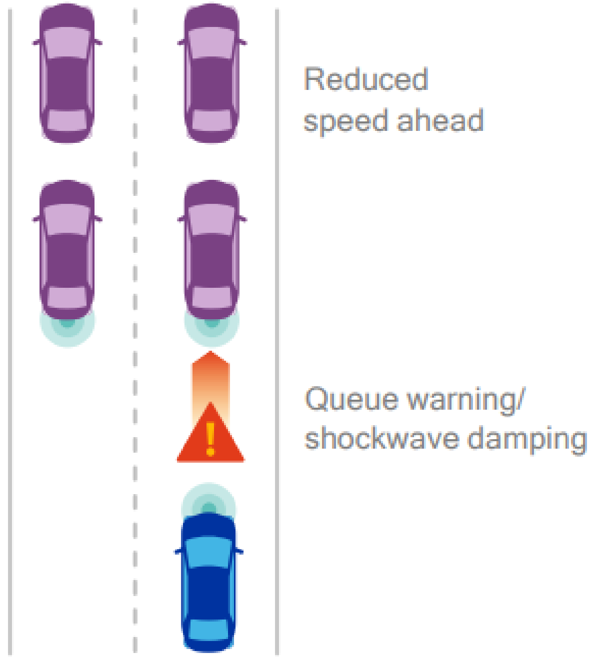
Conveying intent

Shares intent, sensor data , and path planning info for higher level of predictability



Situational awareness

Offers increased electronic horizon to support soft safety alerts and graduated warning



DSRC vs. C-V2X

- DSRC (Distributed Short-Range Communication): Toyota, GM…
  - Based on WiFi, i.e., 802.11p at 5.9GHz
  - For latency-sensitive applications.
- C-V2X (Cellular V2X): Qualcomm/Ford…
  - Traditionally for latency-tolerant applications e.g., Over-the-Air (OTA) updates.
  - With the advent of 5G, C-V2X will become more prevalent, used also for latency-sensitive applications.
- C-V2X seems to be winning over DSRC in recent years
  - The following slides are based on Qualcomm’s C-V2X approach

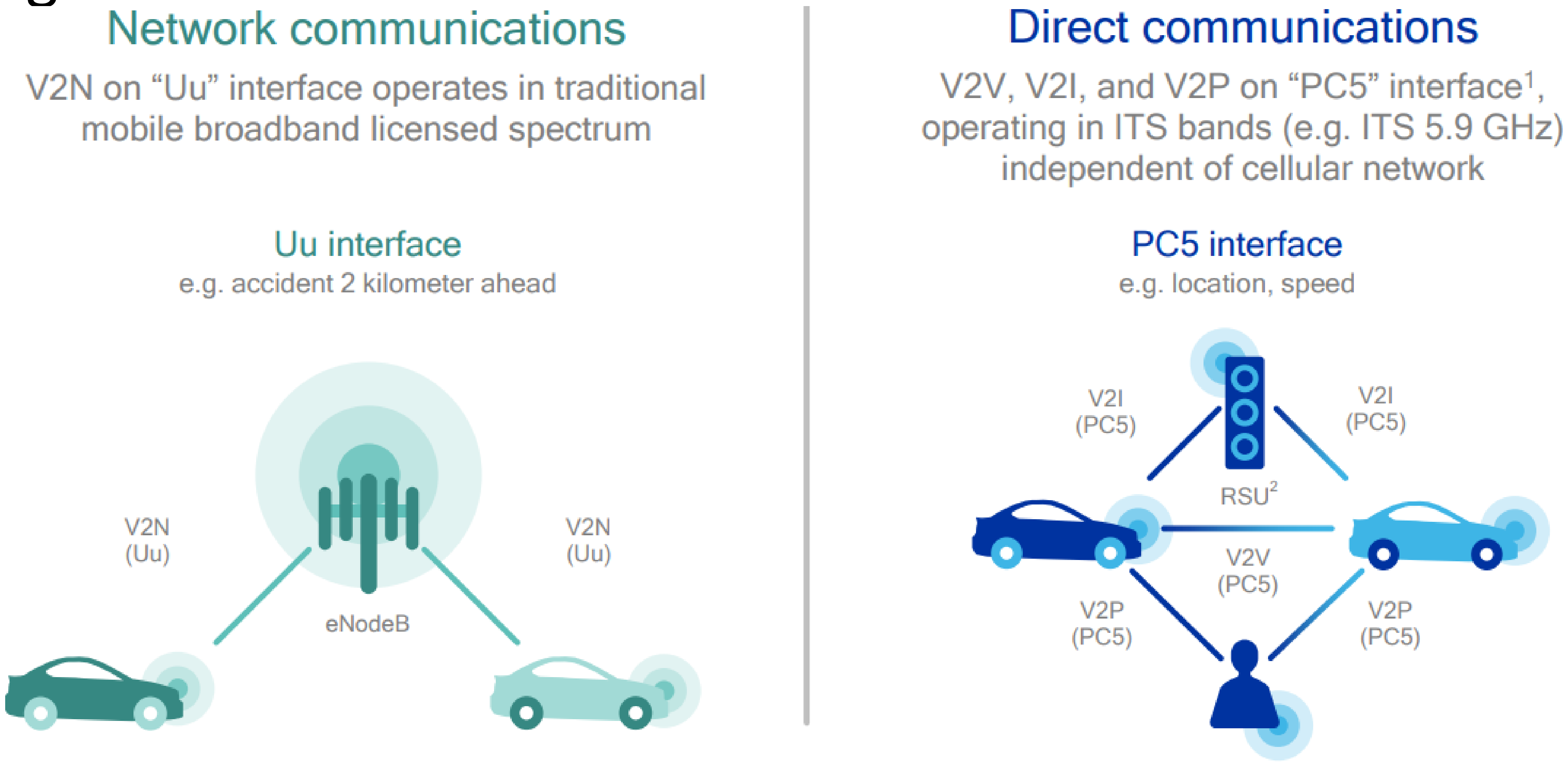
C-V2X Evolution towards 5G

- In Jul. 2020, 3GPP (3rd Generation Partnership Project) declared R16 to be frozen

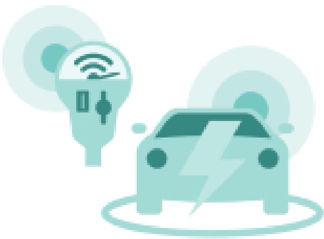
Network independent	No	Yes	Yes
Communications[1]	Broadcast only	Broadcast only	Broadcast + Unicast/Multicast
High speed support	No	Yes	Yes
High density support	No	Yes	Yes
Throughput		High throughput for enhanced safety	Ultra-high throughput
Latency		Low latency for enhanced safety applications	Ultra-low latency
Reliability		Reliability for enhanced safety application	Ultra-high reliability
Positioning	No	Share positioning information	Wideband ranging and positioning

C-V2X Defines 2 Transmission Modes

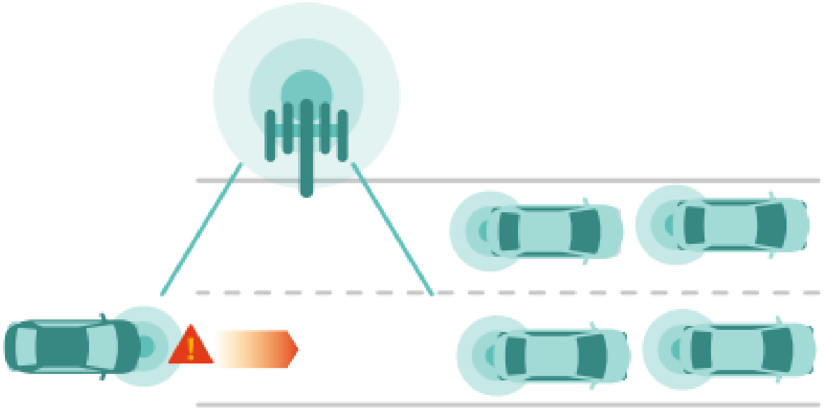
- V2X-Cellular: network communications going through base station (eNodeB)
- V2X-Direct: Device-to-Device direct communications without going through base station



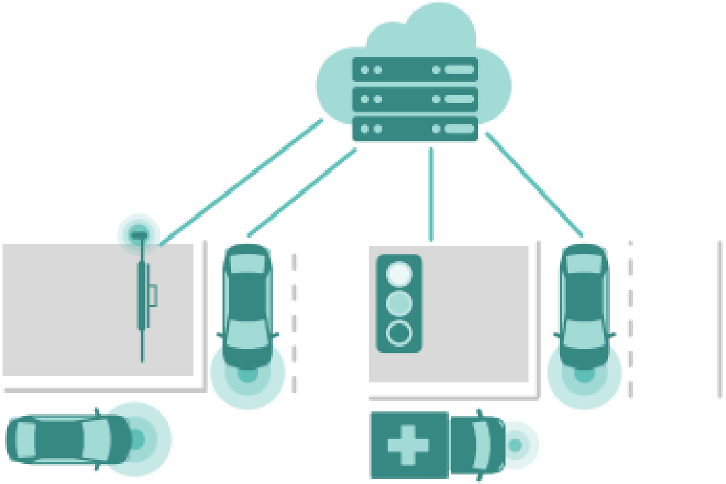
V2X-Cellular for Latency-Tolerant Use Cases



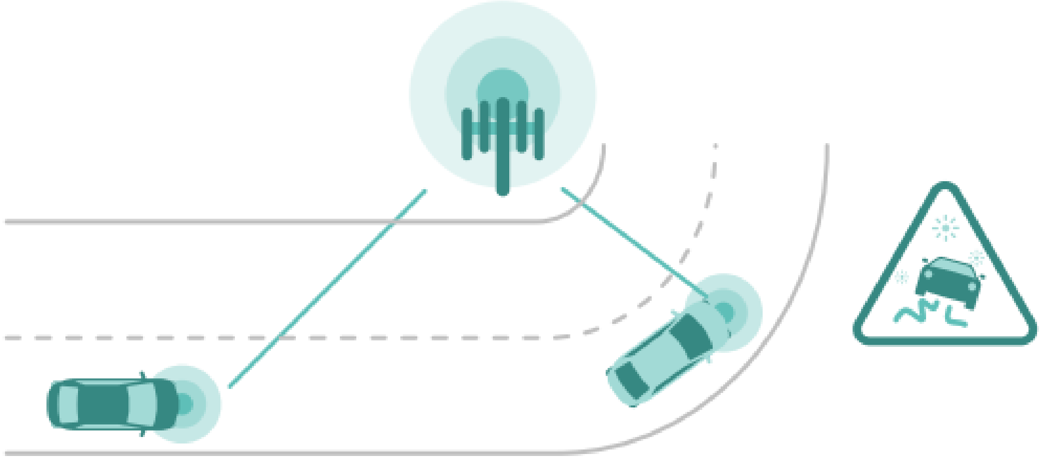
Discover parking
and charging



Traffic flow control/
Queue warning



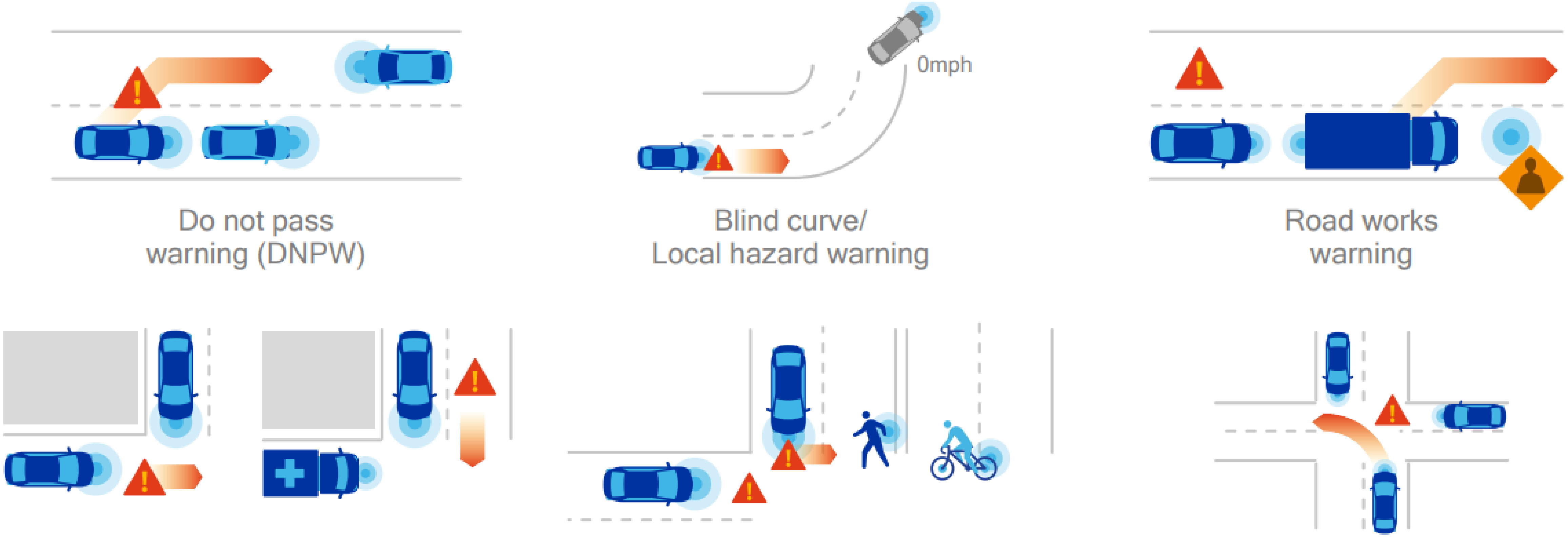
Cloud-based sensor sharing



Road hazard warning 1 km ahead

V2X-Direct for Latency-Sensitive Active Safety Use Cases

- Useful for NLOS (Non-Line-of-Sight) scenarios



Do not pass warning (DNPW)

Blind curve/ Local hazard warning

Road works warning

Intersection movement assist (IMA) at a blind intersection

Vulnerable road user (VRU) alerts at a blind intersection

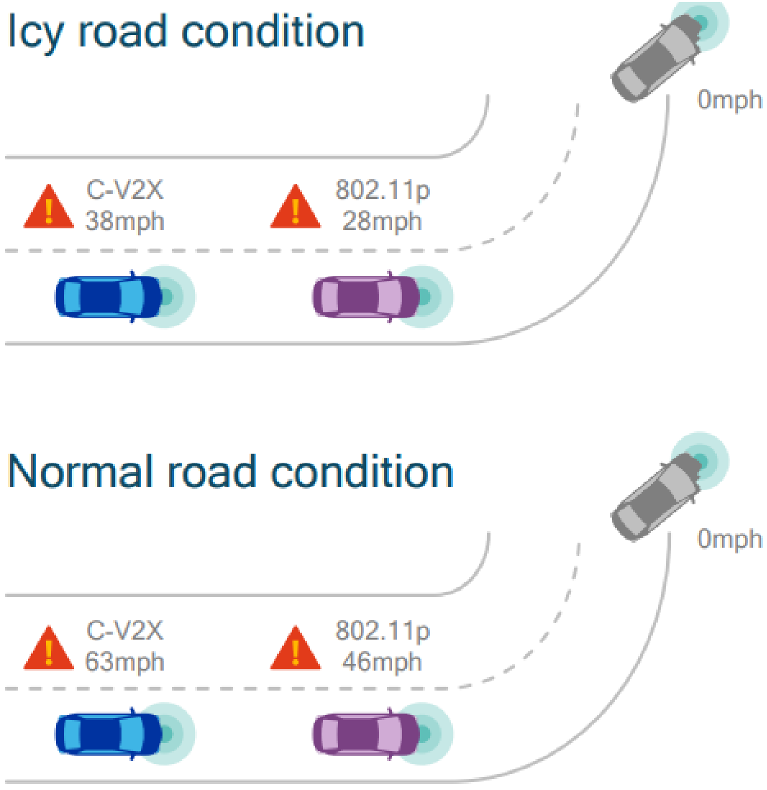
Left turn assist (LTA)

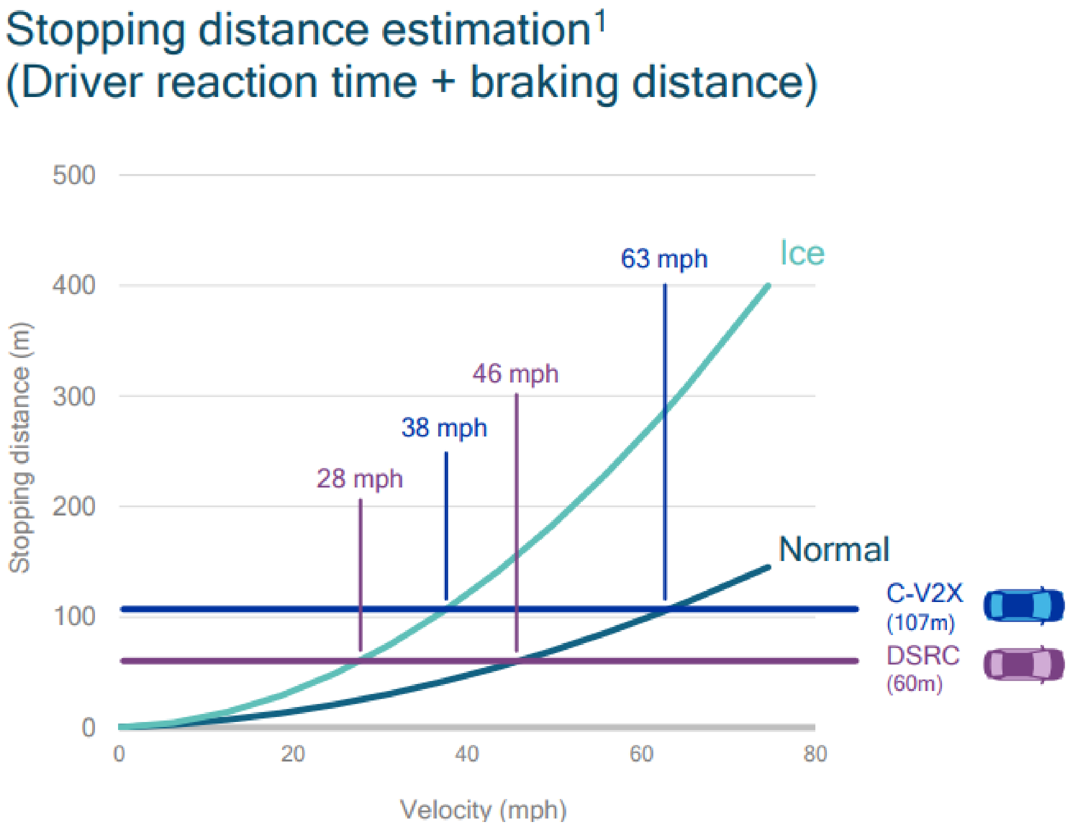
C-V2X Deployment

- Combined RSUs (Road-Side Units) with direct link (PC5) interface for V2X-Direct, and 4G/5G base stations for V2X-Cellular, benefiting from cellular network densification in 5G (smaller and denser cells)

Use Case: Disabled Vehicle after Blind Curve

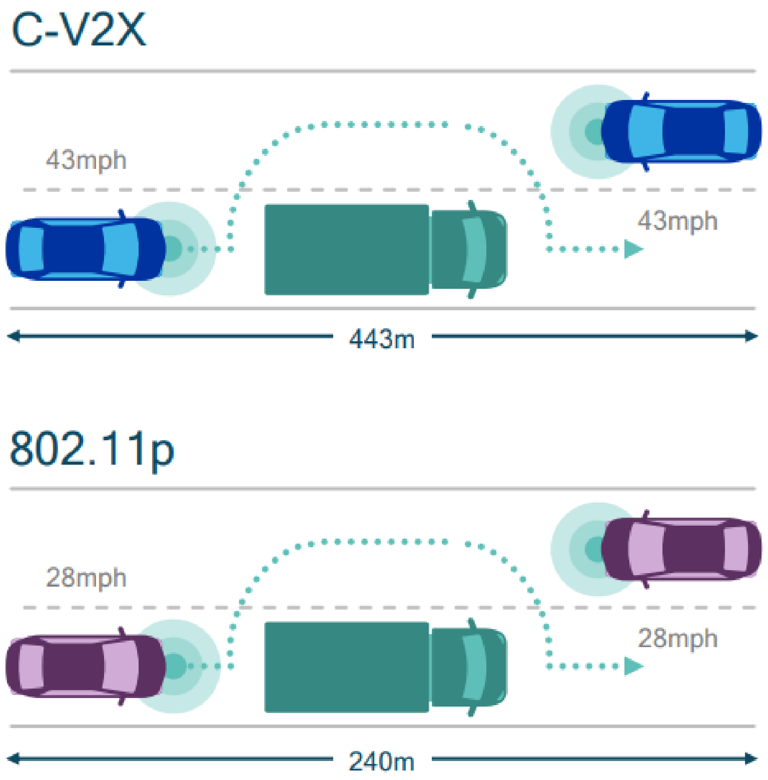
- C-V2X has (at least 2x) longer range than DSRC/802.11p, which enables the ego-vehicle to get warning message earlier, hence travel at higher speed while avoiding collision with the disabled vehicle

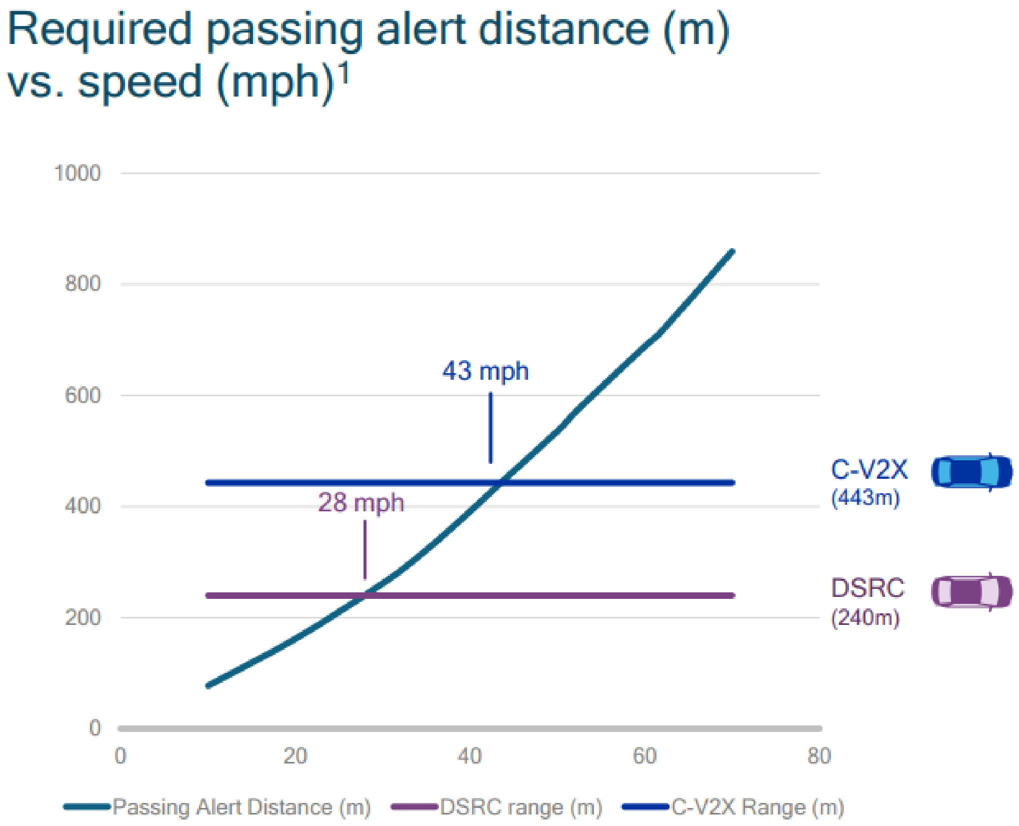




Use Case: Do Not Pass Warning

- C-V2X's longer range enables the ego-vehicle to get warning message earlier, hence travel at higher speed while avoiding collision with the disabled vehicle





Industry Consortium

- 5GAA is a cross-industry consortium that defines 5G V2X communications

Analog Devices AT&T Audi BAIC BMW Bosch CAICT CETECOM China Mobile Continental Daimler

Danlaw Denso Ericsson FEV Ficosa Ford Gemalto Hirschmann Car Communication Huawei Infineon

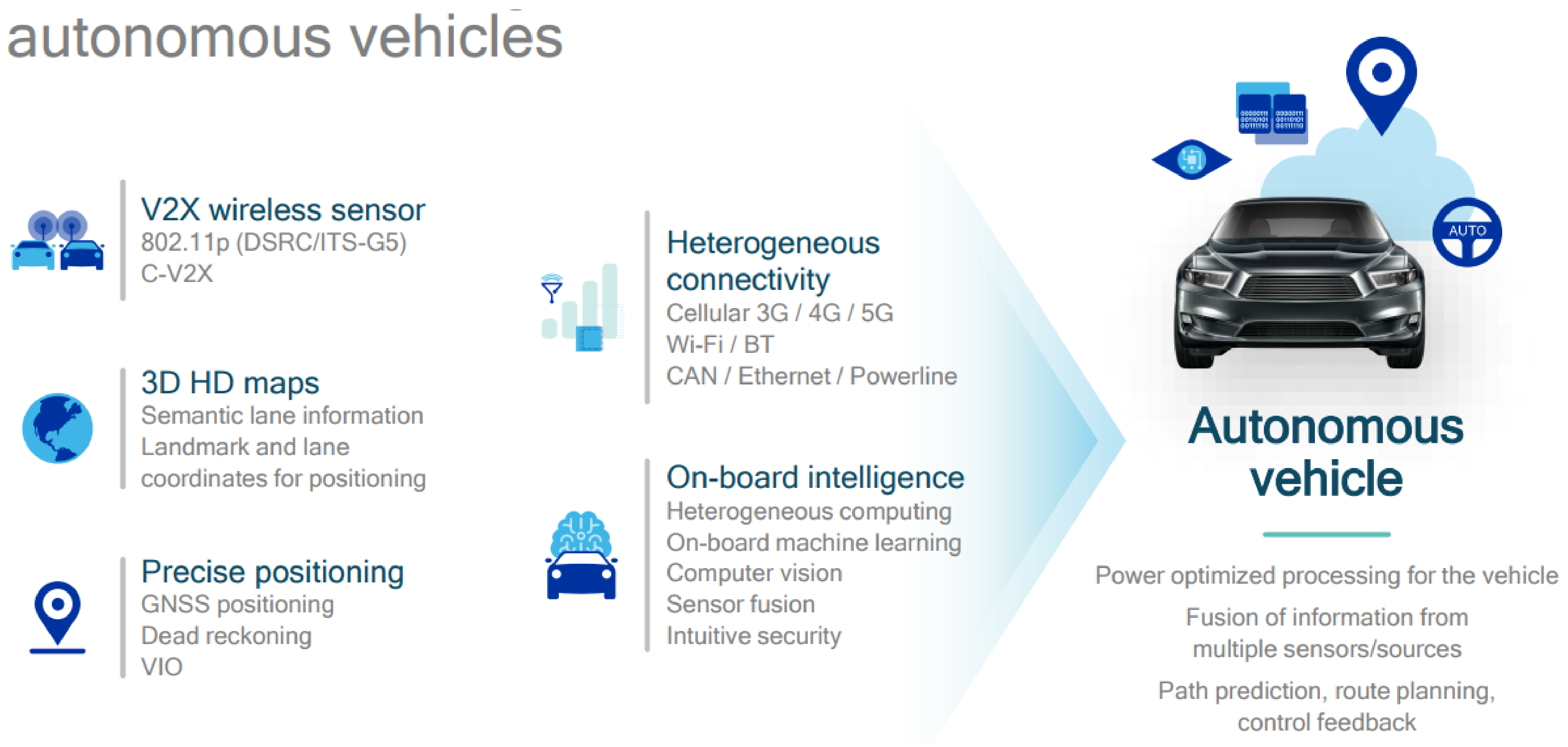
Intel Interdigital Jaguar KDDI Keysight Technologies KT Laird Land Rover LG MINI muRata Nokia

NTT DoCoMo P3 Panasonic Qualcomm Rohde & Schwarz ROHM Rolls-Royce SAIC Motor Samsung Savari

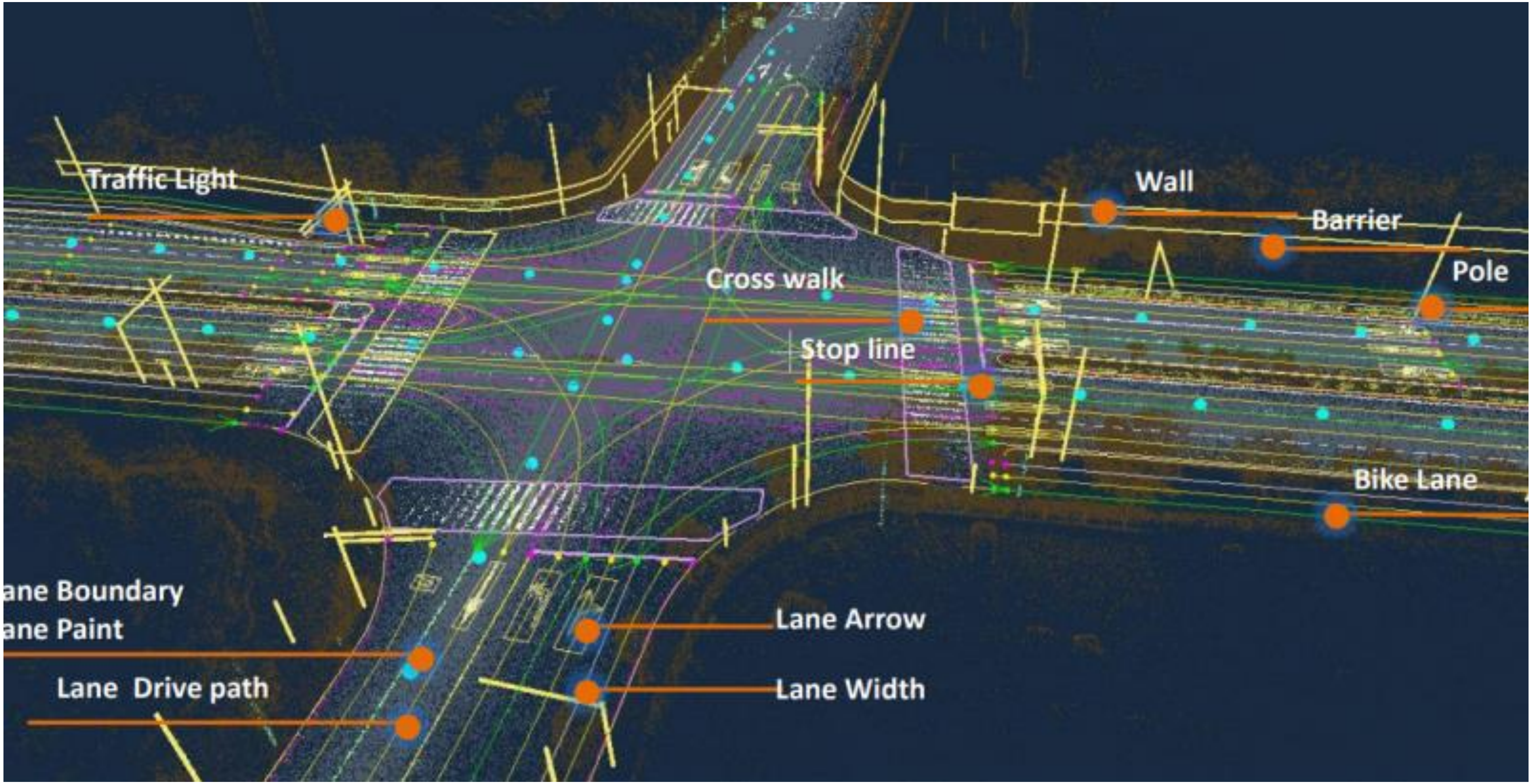
SK Telecom SoftBank T-Mobile Telefonica Telstra TÜV Rheinland Valeo Verizon VLAVI Vodafone ZF ZTE

5G Accelerates AVs

- Massive deployment of V2X is necessary for AVs to benefit from V2X; It is a promising technology, but current AV players are not replying on V2X

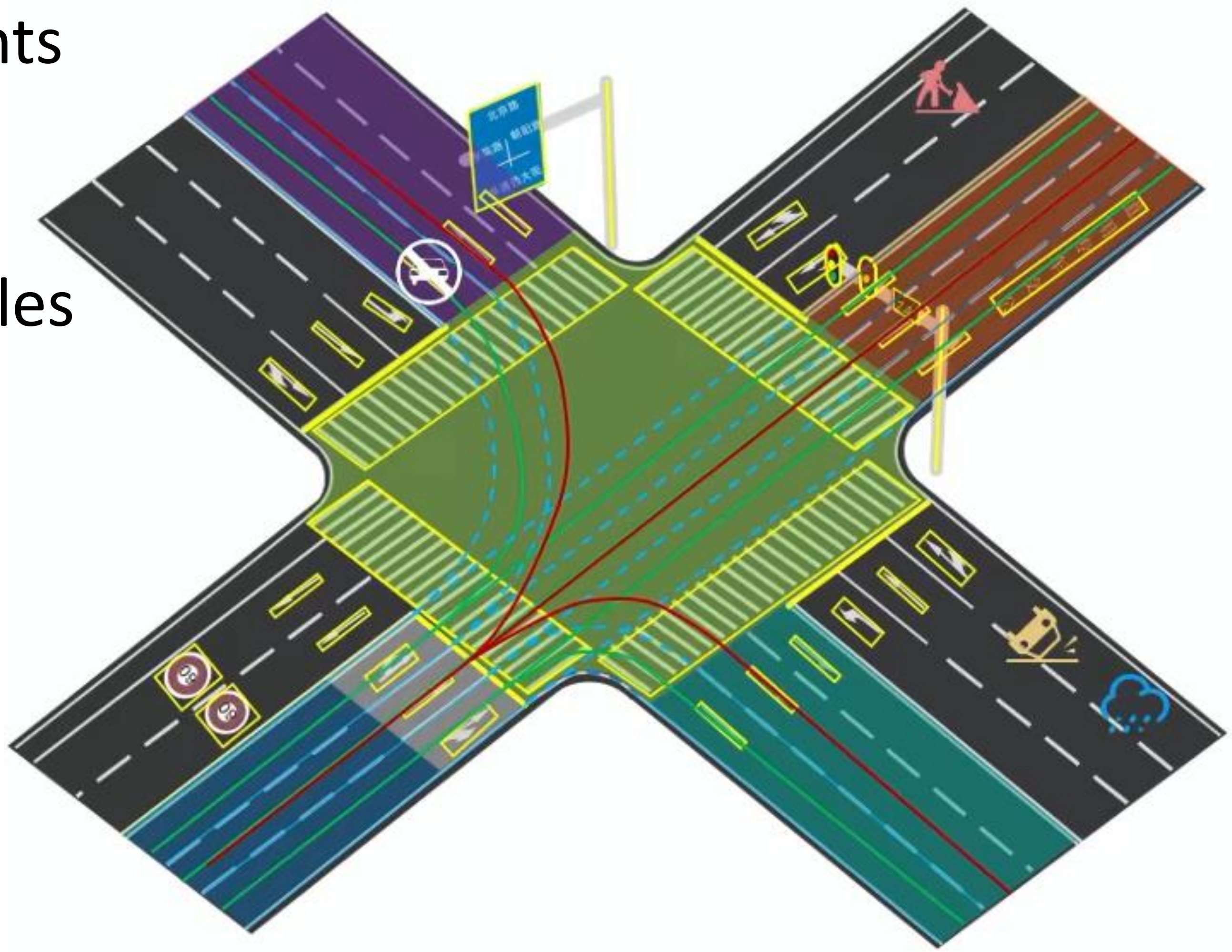


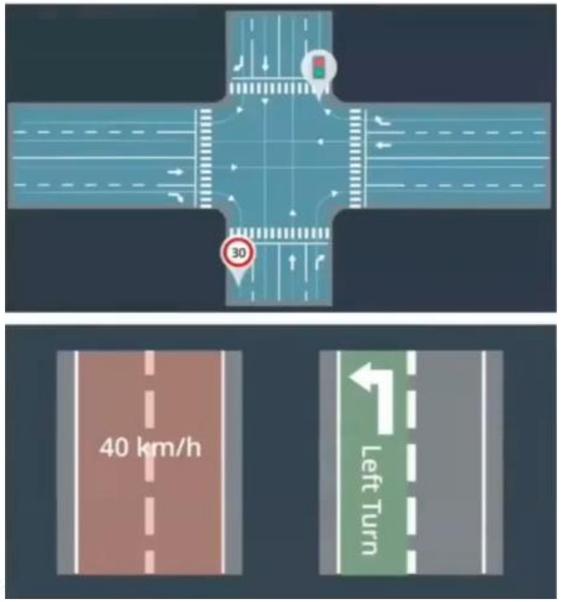
High-Definition (HD) Maps



HD Maps: 4 Layers

- Dynamic layer
  - Traffic + incidents
- Localization objects
  - Traffic signs/poles
- Lane layer
  - Geometry + topology
- Road layer
  - Geometry + topology





HD Maps

- Different from navigation maps (e.g., Google Maps), HD maps are designed for processing by computers
  - Highly-accurate (cm-level) 3D representation of the road network, e.g., cross section layout; locations of traffic lights/signs; semantic information on certain road segments (speed limits…)
- Pros:
  - Helps with lane detection, and localization based on known object positions, esp. under adverse weather conditions such as snow, rain and fog
  - Reduces computational workload of on-board sensing, e.g., by reducing Region-of-Interest (ROI) for detection of traffic elements
  - The more that has already been mapped out, the easier it is for the on-board system to focus on the moving parts; mapless systems must figure out everything on-the-fly with no prior knowledge of the environment
- Cons:
  - High cost of acquisition; low update freq (1-2 times/yr) leads to out-of-date maps
  - Limits area of operation (typically large cities); mapless systems allow universal operation anywhere (small cities, rural areas)
- Currently, higher levels (L3+) of automation rely on HD maps (e.g., Waymo); lower levels may work without them (e.g., Tesla)