

RWR 4015

Traffic Simulation for Planning Applications

Dr. Ahmad Mohammadi

Week 6 | Lecture:
Mixed Traffic Planning:
AVs and Manual Vehicles

Fall 2026

RoadwayVR



2D VISUALIZATION



3D VISUALIZATION



Agenda

Autonomous Vehicle (AVs)

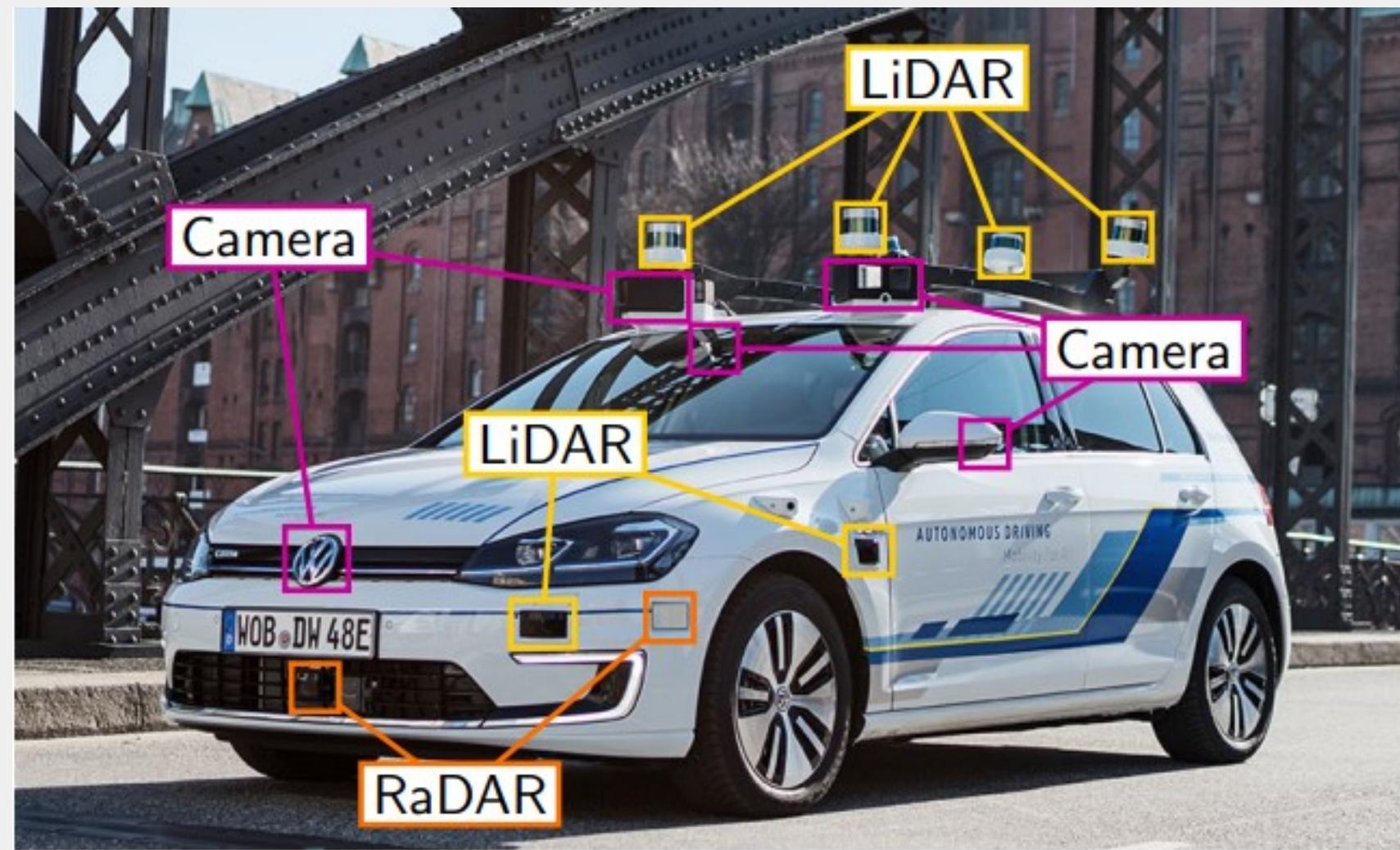
- Fundamental of Connected and Autonomous Vehicles (CAVs)
- Automation Levels
- Simulation Tools for CAVs CARLA, OMNET++/Vein, and SUMO
- Developing Mixed CAVs and Normal Traffic Environment in SUMO

<https://www.transportation.gov/sites/dot.gov/files/docs/policy-initiatives/automated-vehicles/320711/preparing-future-transportation-automated-vehicle-30.pdf>



Autonomous Vehicle

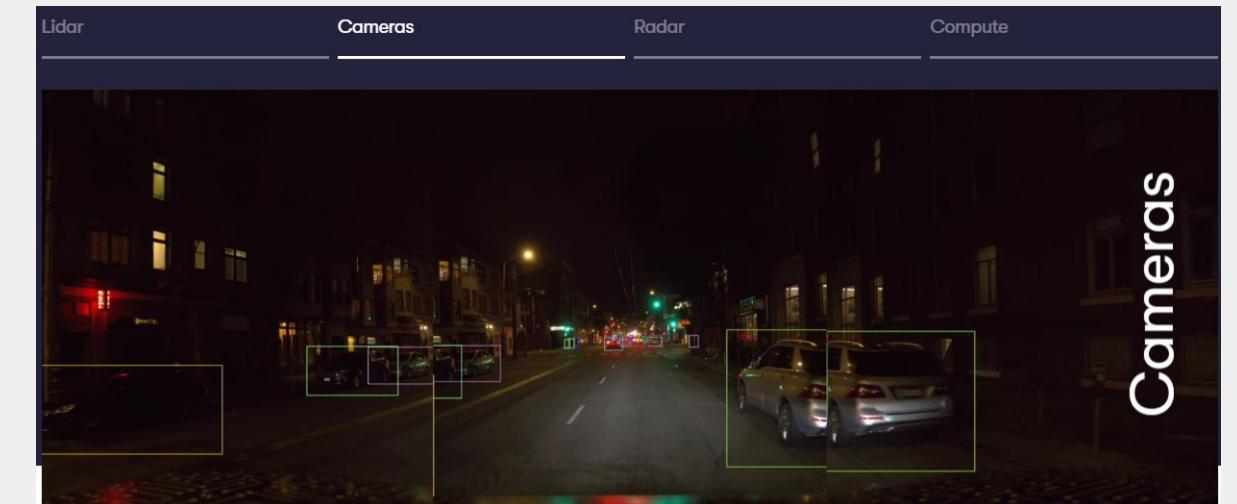
□ **Autonomous Vehicle (AV) Without Connectivity:** Vehicles rely purely on their onboard sensors (for example, radar, Lidar, camera) and artificial intelligence algorithms to handle tasks like steering, braking/acceleration etc.



Autonomous Vehicle

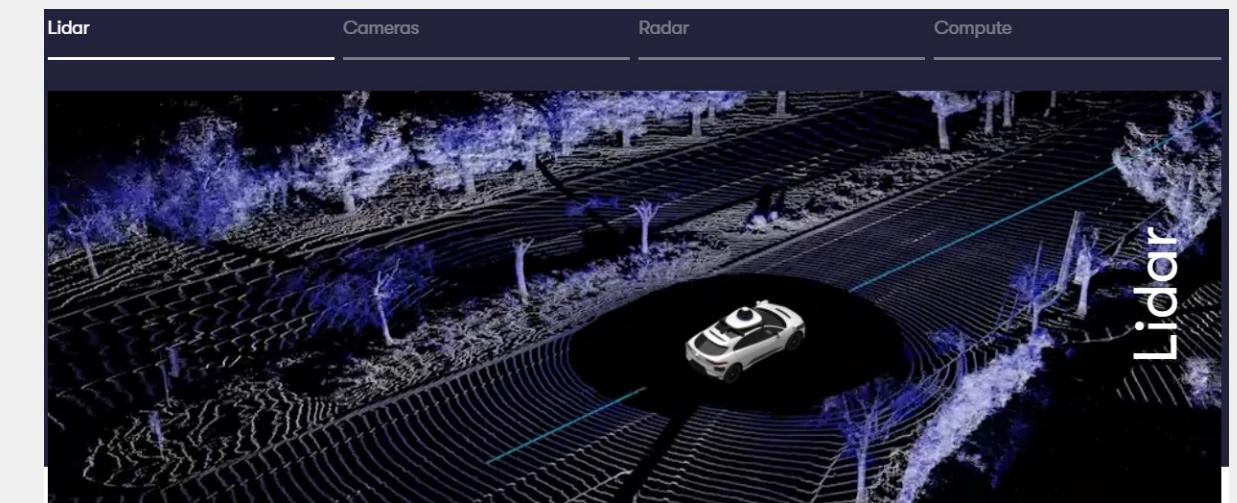
Camera:

- ❑ Recognize lane markings, traffic signals, road signs, and obstacles like pedestrians or other vehicles.



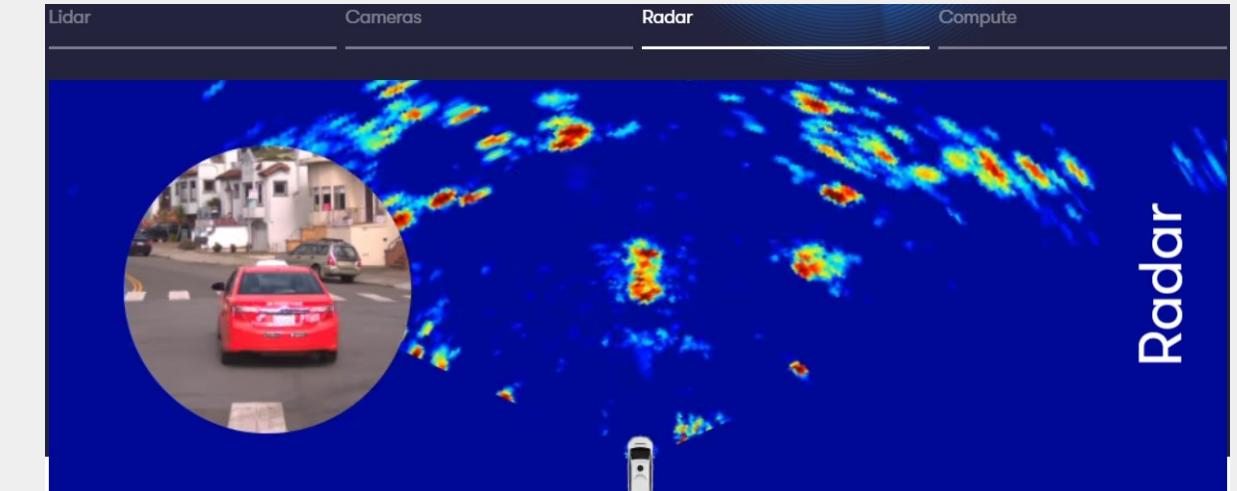
Lidar (light detection and ranging):

- ❑ Measures exact distances to objects and maps the geometry of the scene.



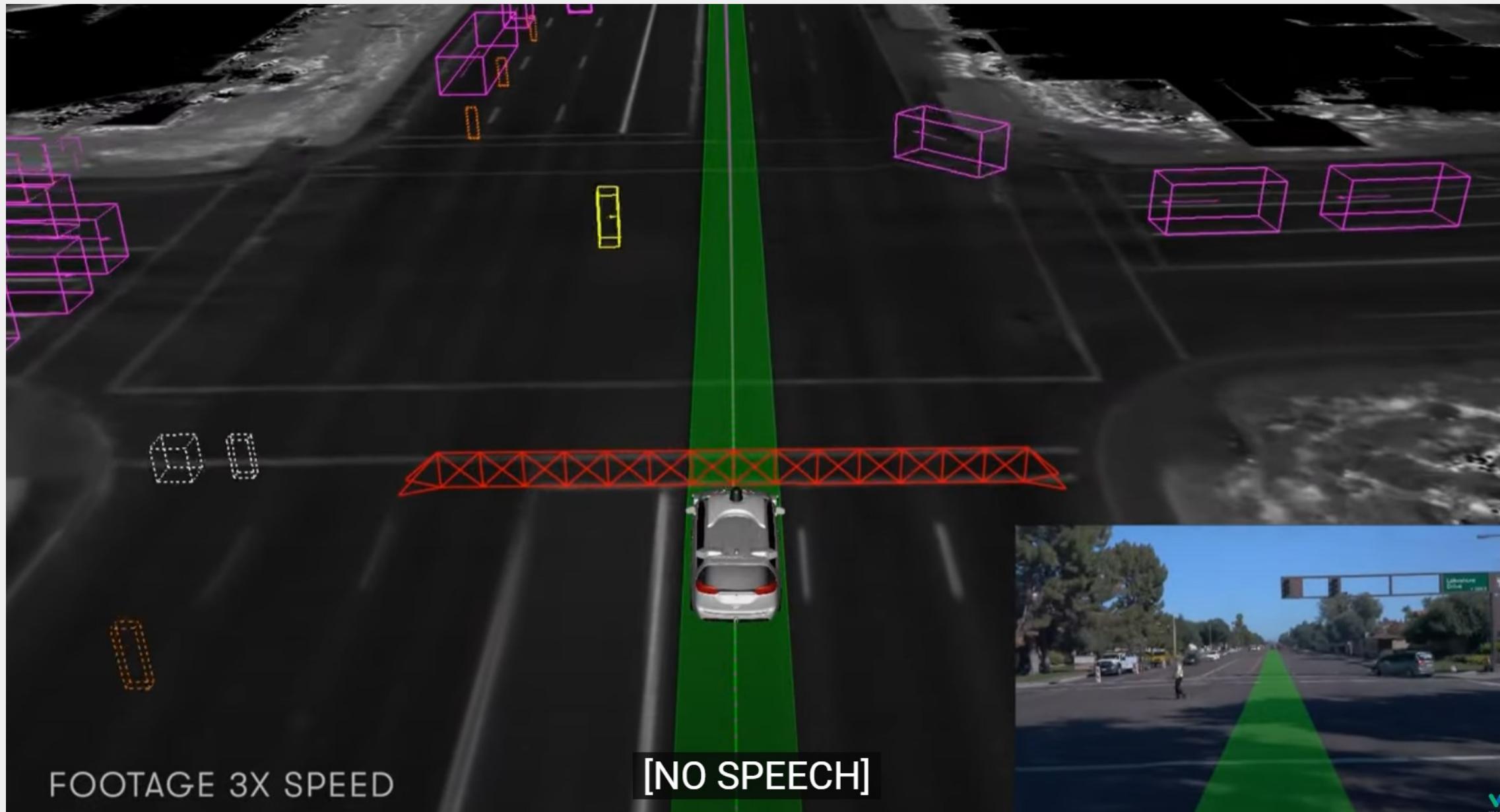
Radar:

- ❑ Measuring exact distances to objects and their relative speeds. It works well in adverse weather conditions (fog, rain, snow) where cameras and lidar may struggle.



What an AV Sees

□ Pause and watch the following video clip: <https://www.youtube.com/watch?v=OopTOjnD3qY>



Society of Automotive Engineers (SAE) Automation Levels

Level #	Functions	Hands / Feet / Eyes
Level 0 (No Automation)	Steering, accelerating, braking, monitoring environment are handled by drivers	Hands on wheel, foot on pedals, eyes on road at all times
Level 1 (Driver Assistance)	Either steering or accelerating/braking is handled by Driver Assistance Systems	Hands on wheel, foot on pedals, eyes on road at all times
Level 2 (Partial Automation)	Steering and accelerating/braking are handled by Driver Assistance Systems	Hands on wheel, foot on pedals, eyes on road at all times (system assists both steering & acceleration, but driver must stay vigilant)
Level 3 (Conditional Automation)	Steering, accelerating, braking, and monitoring are handled by the automated driving system	Hands/feet/eyes can be off under certain conditions, but driver must be ready to intervene upon system request
Level 4 (High Automation)	Steering, accelerating, braking, monitoring are handled by the automated driving system	Hands/feet/eyes off in the system's operational domain; no driver input needed unless outside that domain (for example, well-mapped urban areas or highways in good weather)
Level 5 (Full Automation)	Steering, accelerating, braking, monitoring are handled by the automated driving system	Hands/feet/eyes off in the system's operational domain

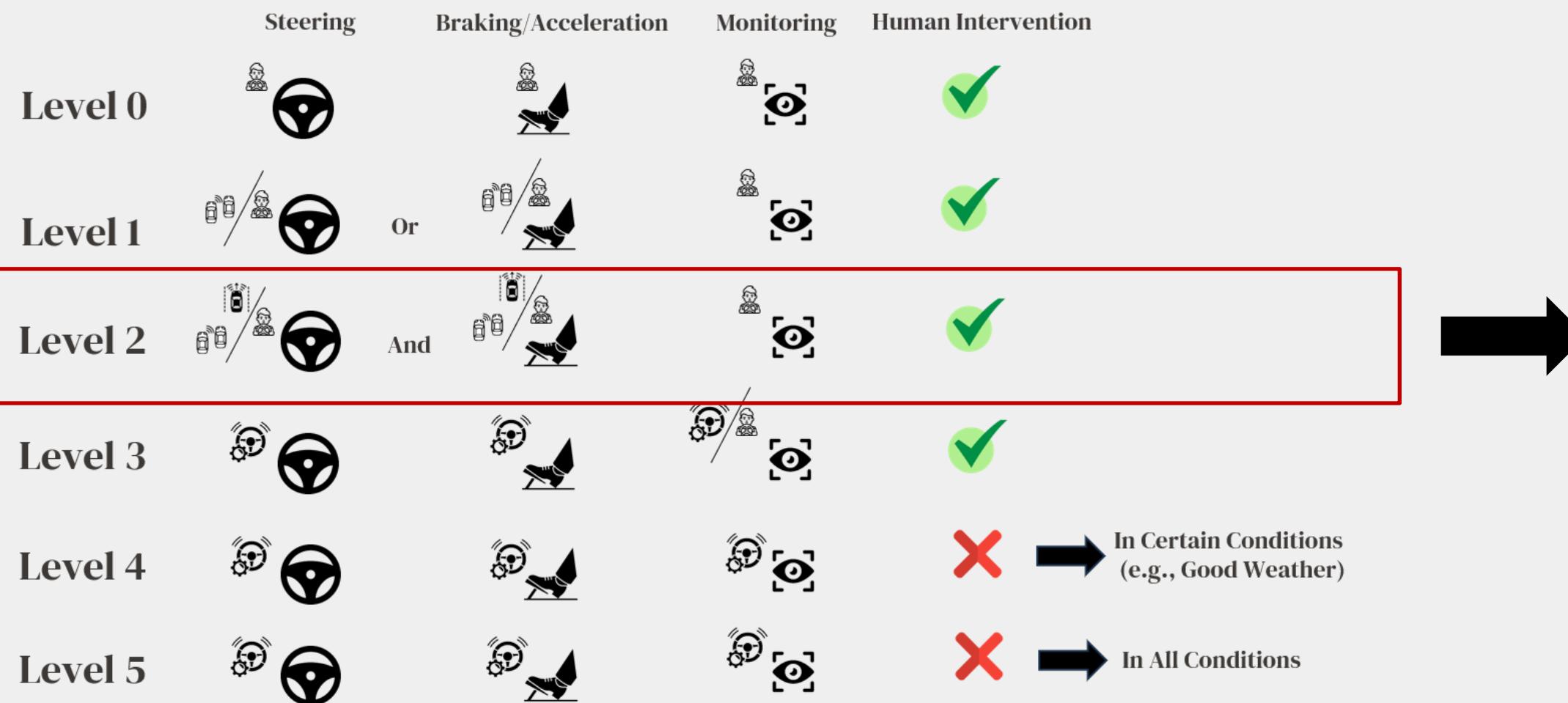
Reference

SAE International. J3016_201806: Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles. Warrendale, PA: SAE International, 15 June 2018. https://www.sae.org/standards/content/j3016_201806/

Society of Automotive Engineers (SAE) Automation Levels

	Steering	Braking/Acceleration	Monitoring	Human Intervention
Level 0				
Level 1				
Level 2	And			
Level 3			Or	
Level 4			Or	→ In Certain Pilot Areas
Level 5			Or	→ In All Conditions

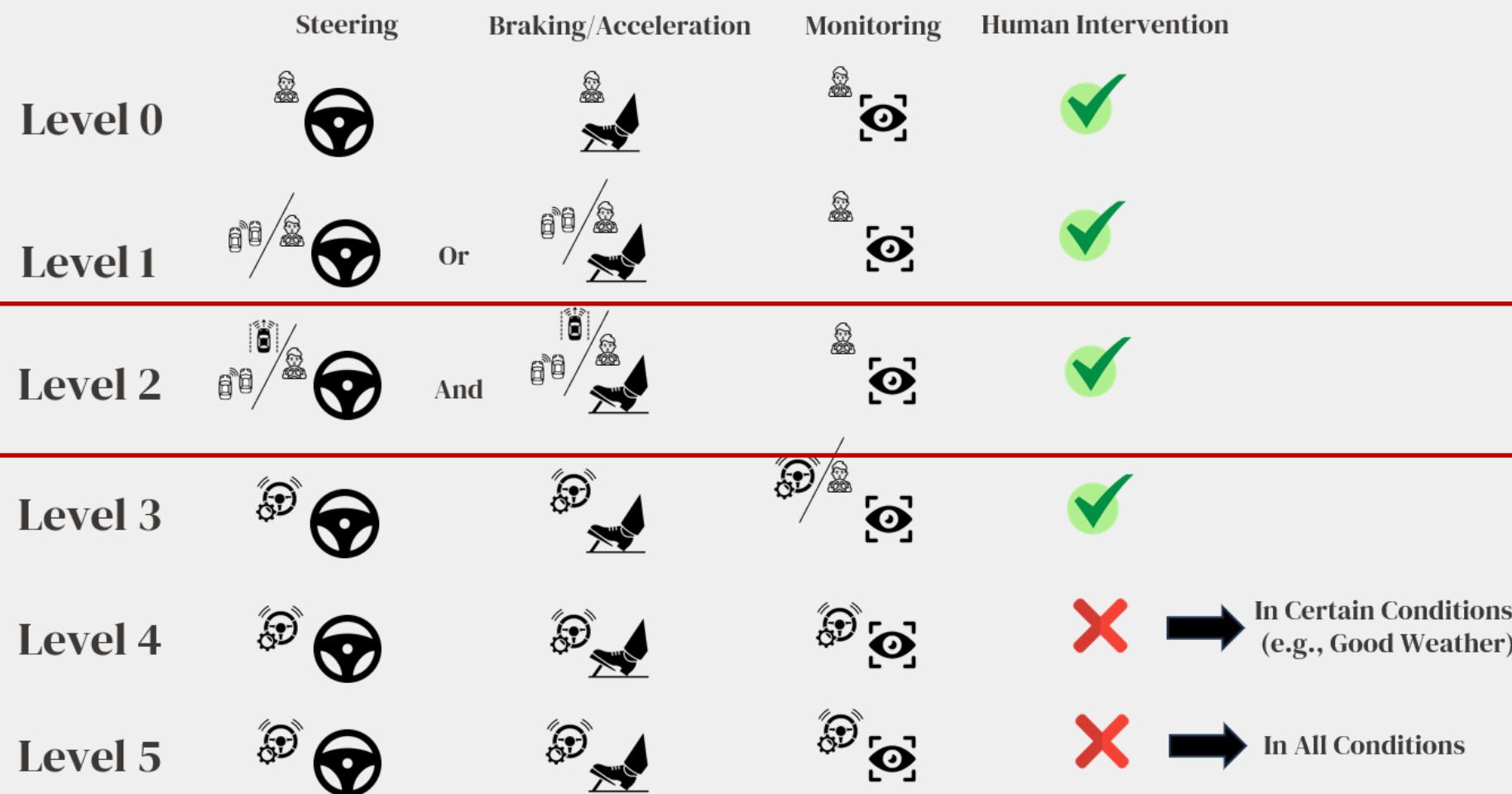
Society of Automotive Engineers (SAE) Automation Levels



**CACC Car Following Models for Acceleration and Braking in SUMO
Only Consider Longitude Movement**

Li, H., Li, H., Hu, Y., Xia, T., Miao, Q., & Chu, J. (2023). Evaluation of fuel consumption and emissions benefits of connected and automated vehicles in mixed traffic flow. *Frontiers in Energy Research*, 11, 1207449.

Society of Automotive Engineers (SAE) Automation Levels

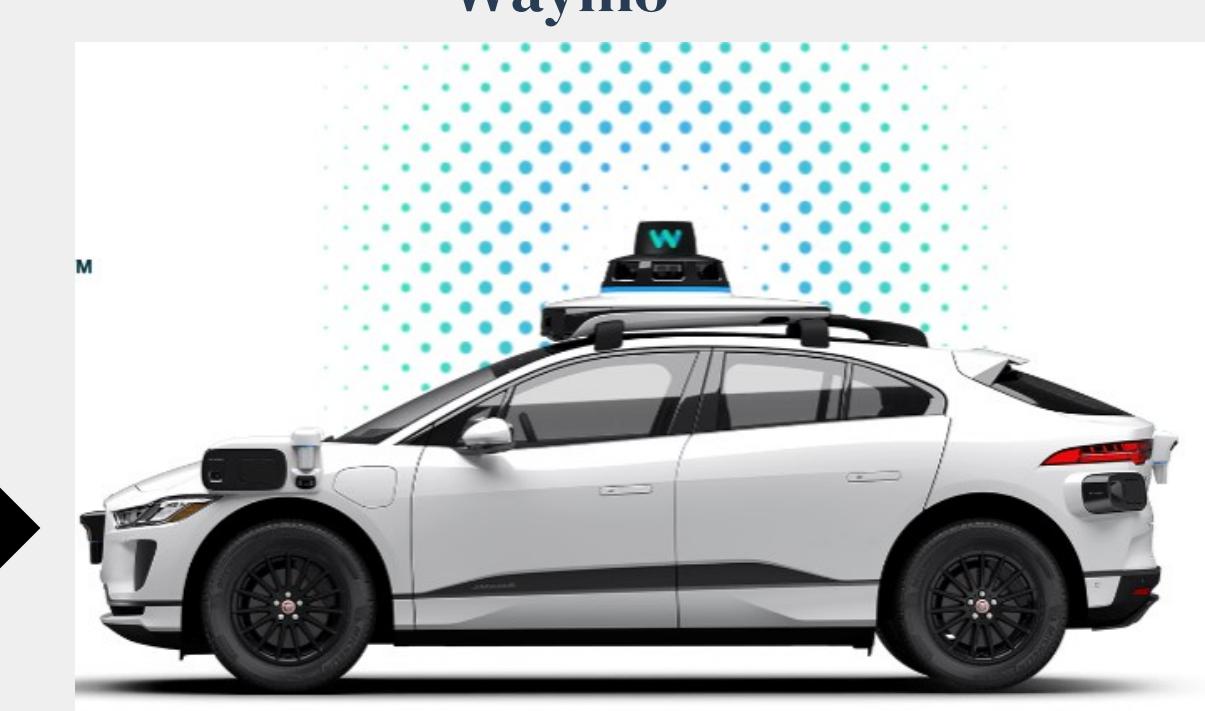
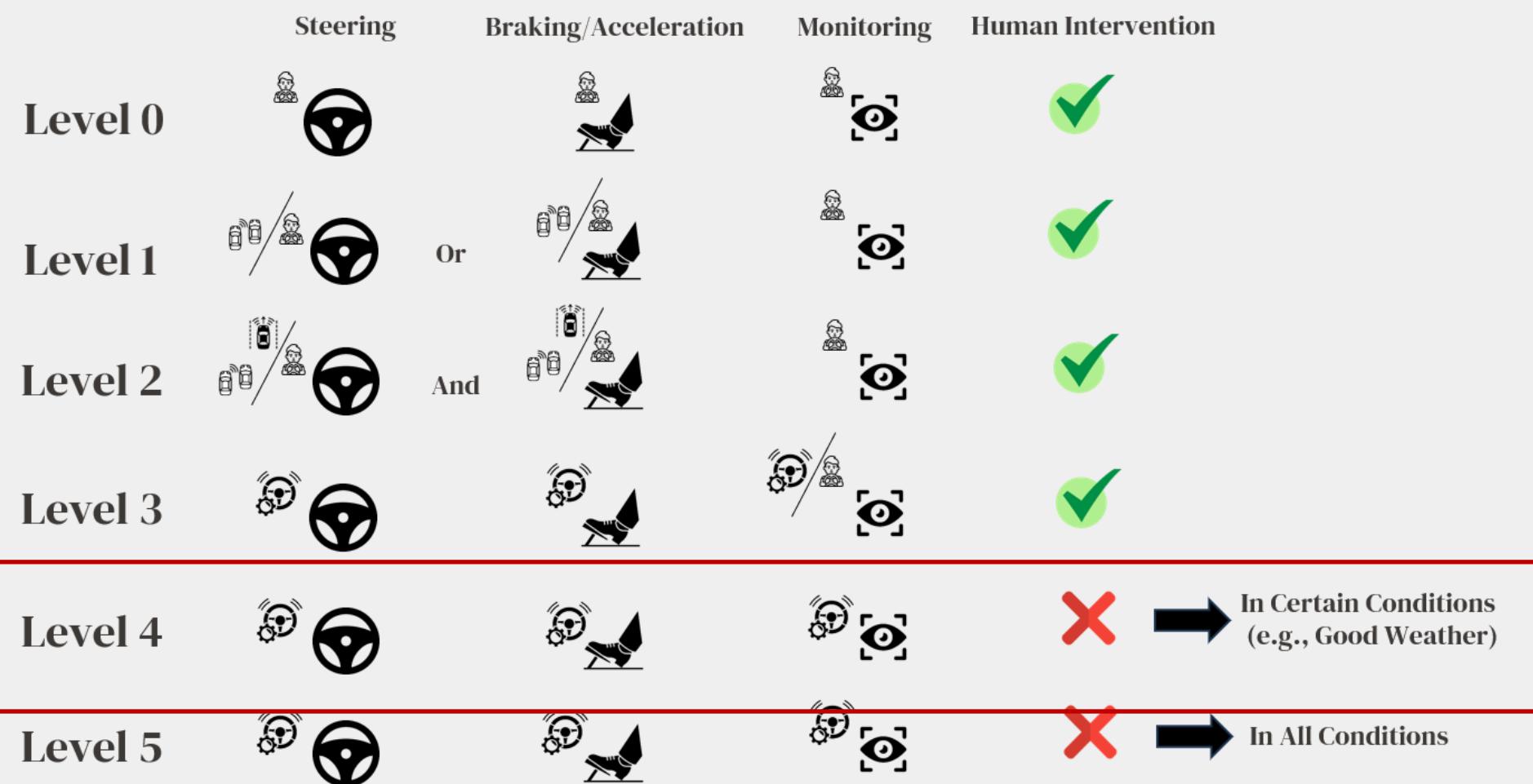


Tesla Autopilot



See video:
<https://vimeo.com/192179726>

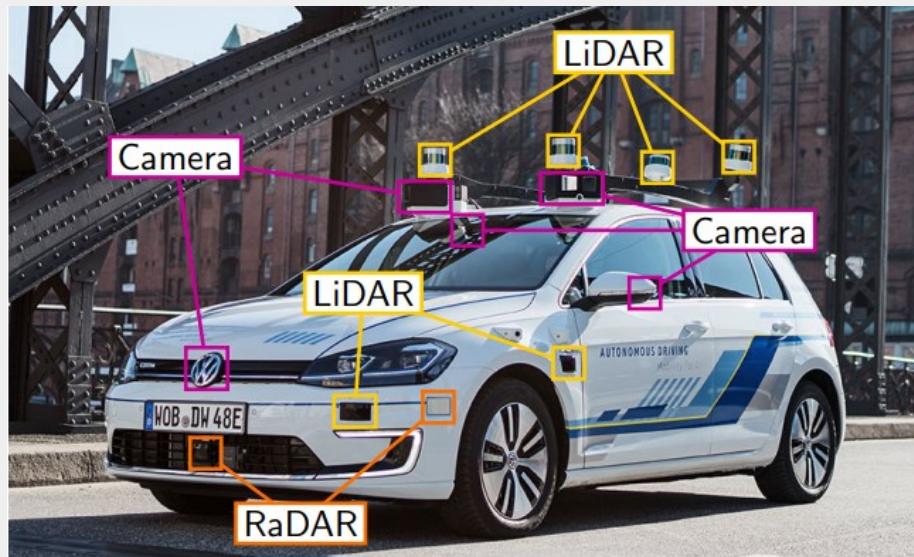
Society of Automotive Engineers (SAE) Automation Levels



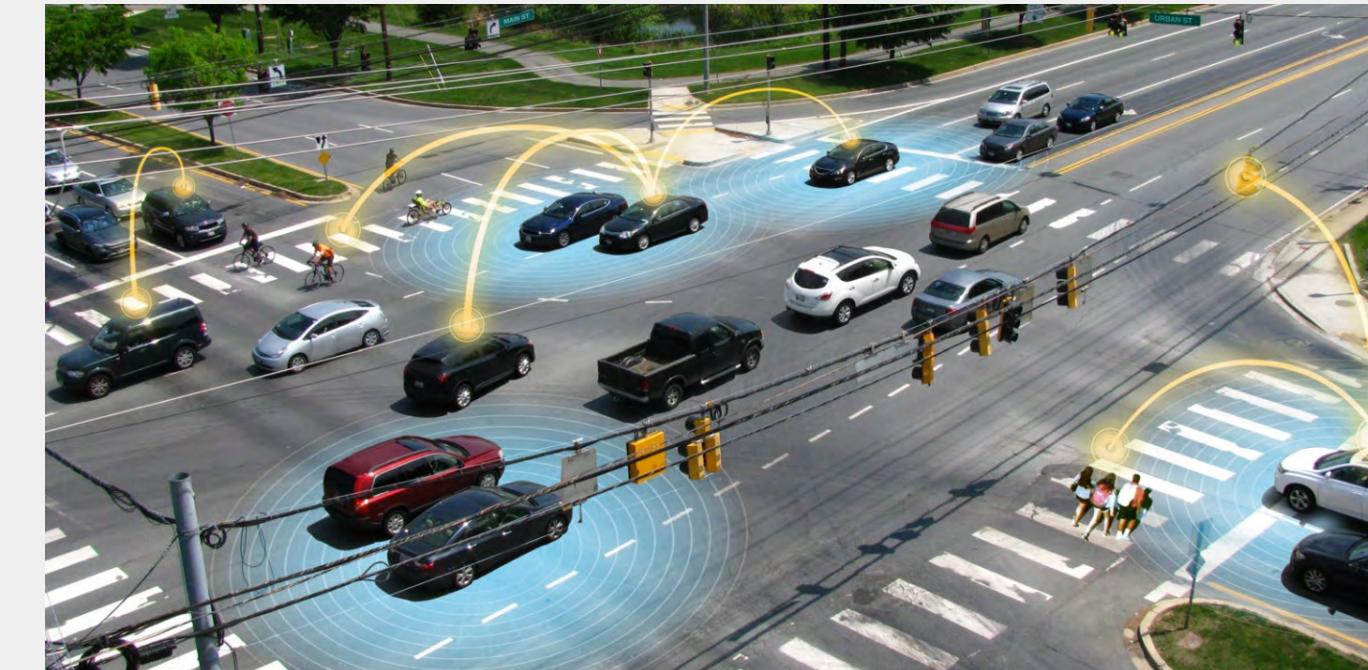
See :
<https://waymo.com/>

Autonomous Vehicle and Connected Vehicles

□ **Autonomous Vehicle (AV):** Vehicles rely purely on their onboard sensors (for example, radar, Lidar, camera) and artificial intelligence algorithms to handle tasks like steering, braking/acceleration etc.

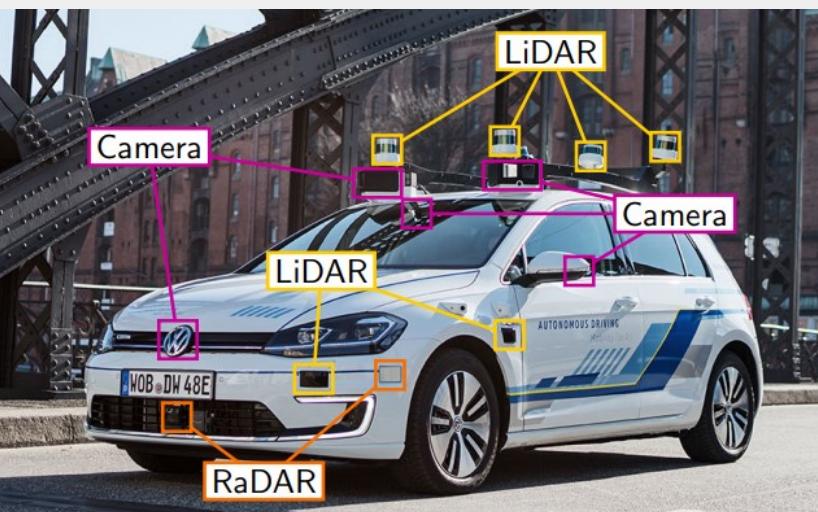


□ **Connected Vehicle (CV):** A vehicle equipped with technology that allows it to communicate with other vehicles, the internet, and external devices, offering features like real-time traffic information, emergency assistance, and remote vehicle control.

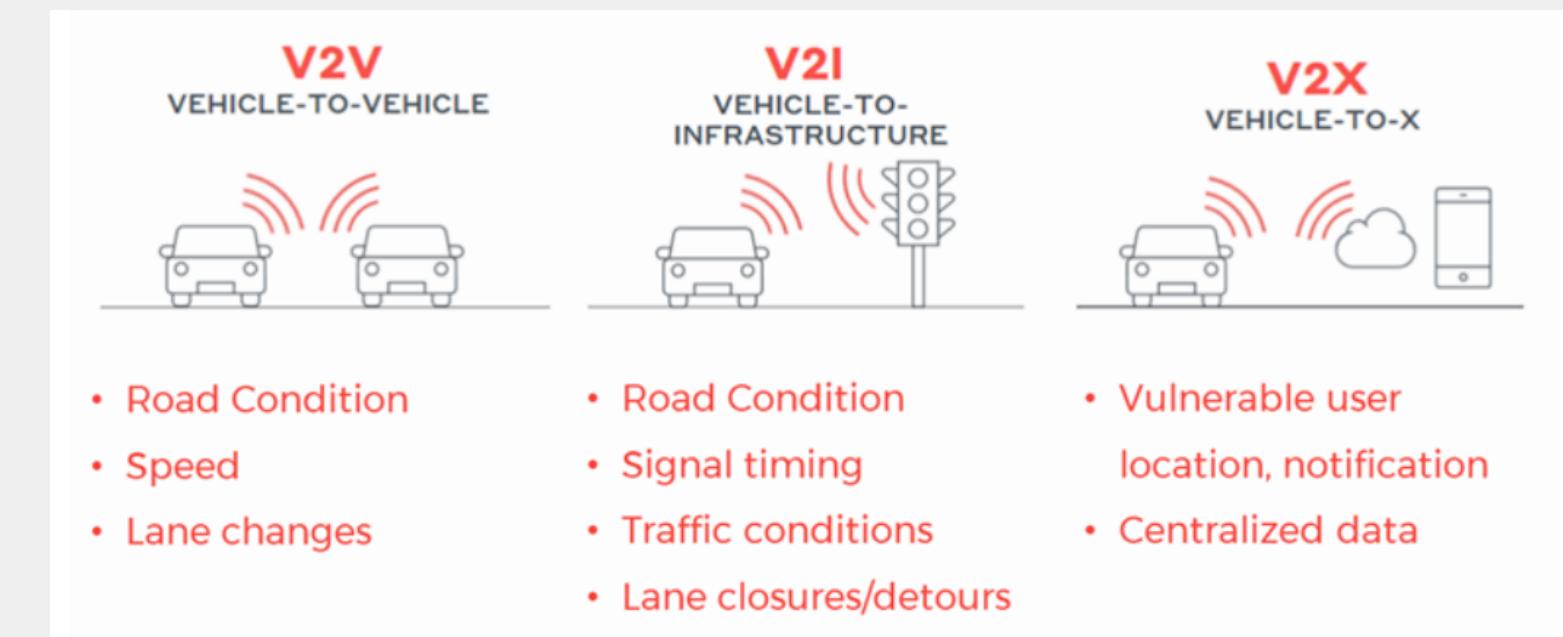


Cooperative and Connected Autonomous Vehicles (CAVs)

- **Connected and Autonomous Vehicles (CAVs):** Vehicles have both onboard sensors and V2X (vehicle-to-everything) capabilities. The vehicle still makes use of local sensor data but also leverages information from other vehicles, and infrastructure such as traffic light information.
- The goal of CAVs: improving traffic flow, safety, and environment (energy and emission)
- V2V: Vehicle-to-Vehicle
- V2I: Vehicle-to-Infrastructure
- V2X: Vehicle-to-Everything (=V2V + V2I)



Reference: Bar, A., Lohdefink, J., Kapoor, N., Varghese, S. J., Huger, F., Schlicht, P., & Fingscheidt, T. (2020). The vulnerability of semantic segmentation networks to adversarial attacks in autonomous driving: Enhancing extensive environment sensing. *IEEE Signal Processing Magazine*, 38(1), 42-52.



Reference: USDOT, <https://www.ovinhub.ca/wp-content/uploads/2020/05/CAV-Readiness-Plan-Final-Report-2020-04-03-1.pdf>

Watch The Following Video Clip



<https://www.youtube.com/watch?v=Q8Cn47L8FRQ>

V2X (Vehicle-to-Everything) Communication

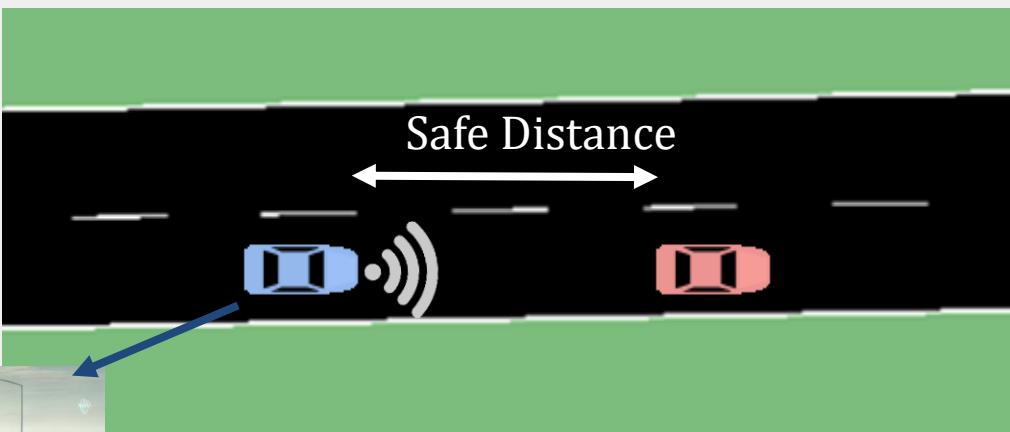
- **V2X:** Lets vehicles exchange data about speed, position, hazards, and more—information that onboard sensors alone might not capture in time.
- **How it Works:**
- **DSRC (Dedicated Short-Range Communications):** uses a Wi-Fi-based protocol (IEEE 802.11p) to send messages directly between vehicles or between a vehicle and roadside units, typically in the 5.9 GHz band.
- **Cellular V2X (4G/5G):** uses mobile networks to enable direct communication (vehicle to vehicle) and/or network-based communication (vehicle to cloud/infrastructure).

AVs – Technologies

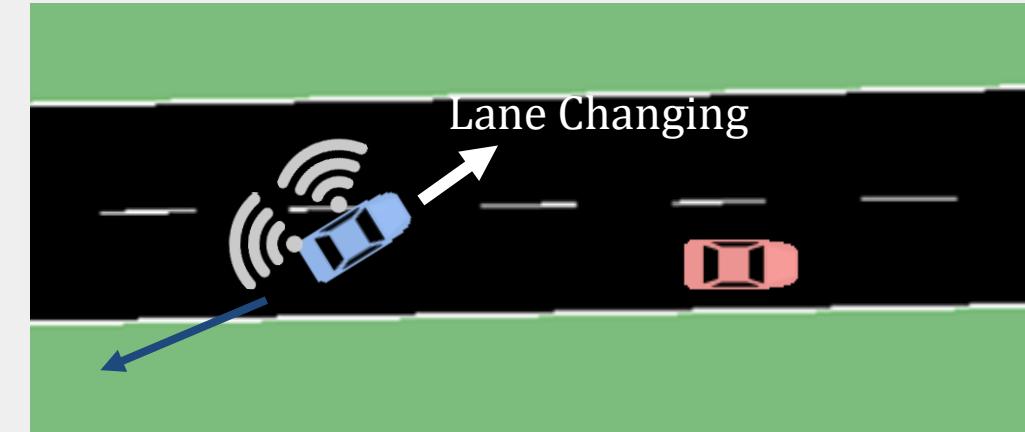
- **Adaptive Cruise Control (ACC):** Each Car use cameras and other sensors to detect surrounding cars and automatically adjusts the vehicle's speed to maintain a safe distance
- ACC is one of the foundational technologies in the progression toward self-driving vehicles.

- **Auto Lane Change (Lane Change Assist):** Each Car uses cameras and other sensors to detect gaps in adjacent lanes and help initiate a safe lane change maneuver when conditions are appropriate.

Longitudinal Movement



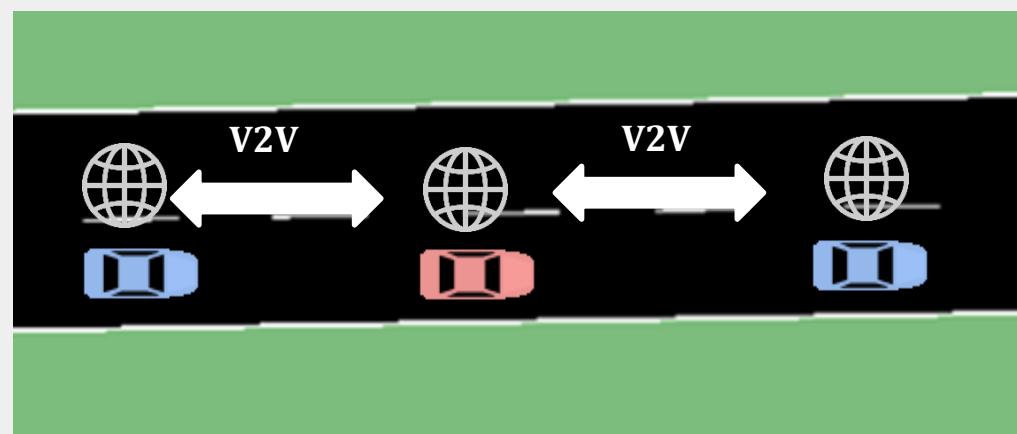
Lateral Movement



CAV - Technology

Cooperative Adaptive Cruise Control (CACC):

Each car has ACC and use vehicle-to-vehicle communication (V2V) to share speed and positioning data.



Benefits Over ACC:

Extended Awareness: Sensors typically have a limited range, so a vehicle might only detect the one directly ahead. V2V communication allows vehicles to receive information about speed and acceleration from multiple vehicles further up the platoon, offering a broader view of traffic conditions.

Reduced Latency: Communication between vehicles can deliver real-time data more quickly than sensors that need to process reflected signals, helping vehicles react faster to changes.

Enhanced Predictability: By knowing the exact speed and intended maneuvers of preceding vehicles, a car can anticipate changes (like deceleration or lane changes) earlier, leading to smoother and safer adjustments.

Autonomous Vehicles (AVs)

- ❑ Fundamental of Connected and Autonomous Vehicles (CAVs)
- ❑ Simulation Tools for CAVs CARLA, OMNET++/Vein, and SUMO
- ❑ Developing Mixed CAVs and Normal Traffic Environment in SUMO

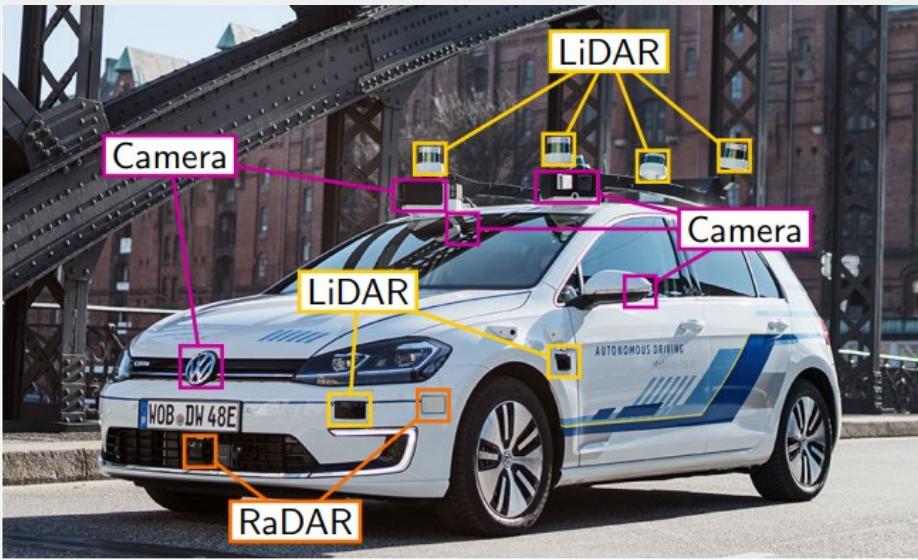
<https://www.transportation.gov/sites/dot.gov/files/docs/policy-initiatives/automated-vehicles/320711/preparing-future-transportation-automated-vehicle-30.pdf>



Difference Of Carla, OMNET ++/Veins, SUMO

Carla Use:

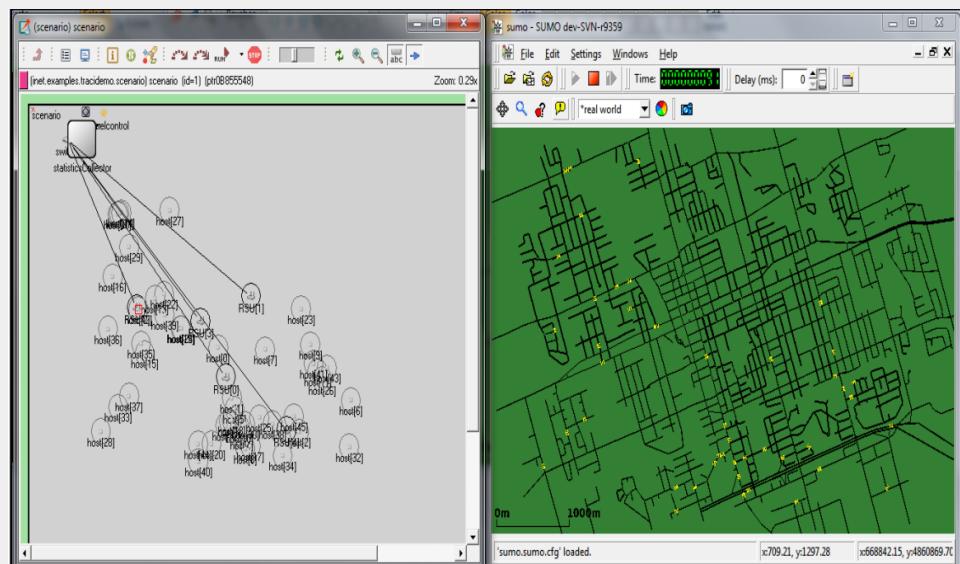
- Computer vision research



Reference: Bar, A., Lohdefink, J., Kapoor, N., Varghese, S. J., Huger, F., Schlicht, P., & Fingscheidt, T. (2020). The vulnerability of semantic segmentation networks to adversarial attacks in autonomous driving: Enhancing extensive environment sensing. *IEEE Signal Processing Magazine*, 38(1), 42-52.

OMNET ++/ Veins Use:

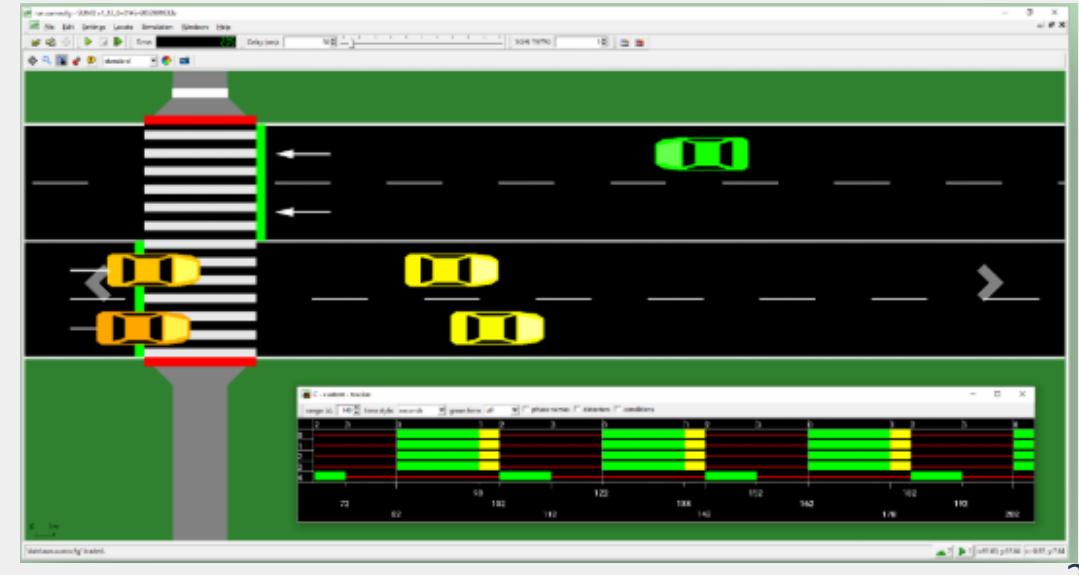
- Communication protocols and networking



Alganas, A. (2011). Social-based trustworthy data forwarding in vehicular delay tolerant networks (Doctoral dissertation, UOIT).

SUMO Use:

- Realistic traffic flows and scenarios, including congestion, traffic lights



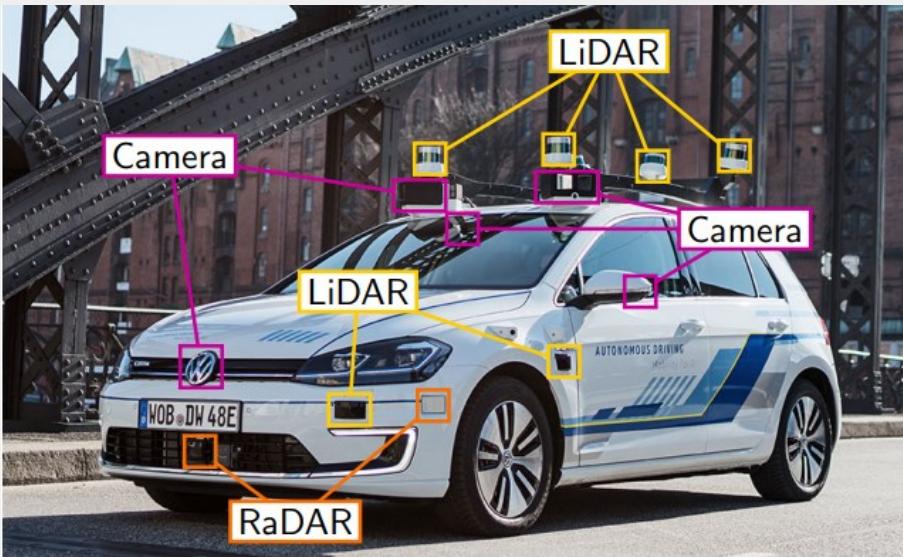
Difference Of Carla, OMNET ++/Veins, SUMO

Carla Use:

Primary Focus: emphasizing sensor data (cameras, LiDAR, radar)

Key Use Cases:

- Computer vision research
- Testing AV control algorithms for sensor fusion, environment perception, and navigation.



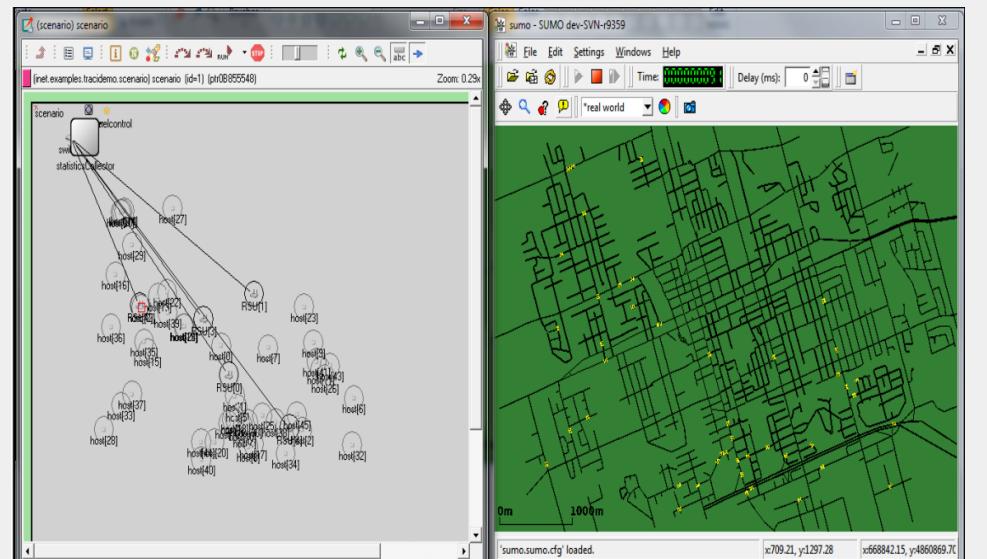
Reference: Bar, A., Lohdefink, J., Kapoor, N., Varghese, S. J., Huger, F., Schlicht, P., & Fingscheidt, T. (2020). The vulnerability of semantic segmentation networks to adversarial attacks in autonomous driving: Enhancing extensive environment sensing. *IEEE Signal Processing Magazine*, 38(1), 42-52.

OMNET ++/ Veins Use:

Primary Focus: Network simulations, specifically for vehicular ad-hoc networks (VANETs) and vehicle-to-everything (V2X) communication.

Key Use Cases:

- Evaluating communication protocols and networking strategies among vehicles (e.g., DSRC, IEEE 802.11p, LTE-V).
- Investigating scalability, latency, and reliability of inter-vehicle communication.
- Integrating with SUMO focusing on the network layers.



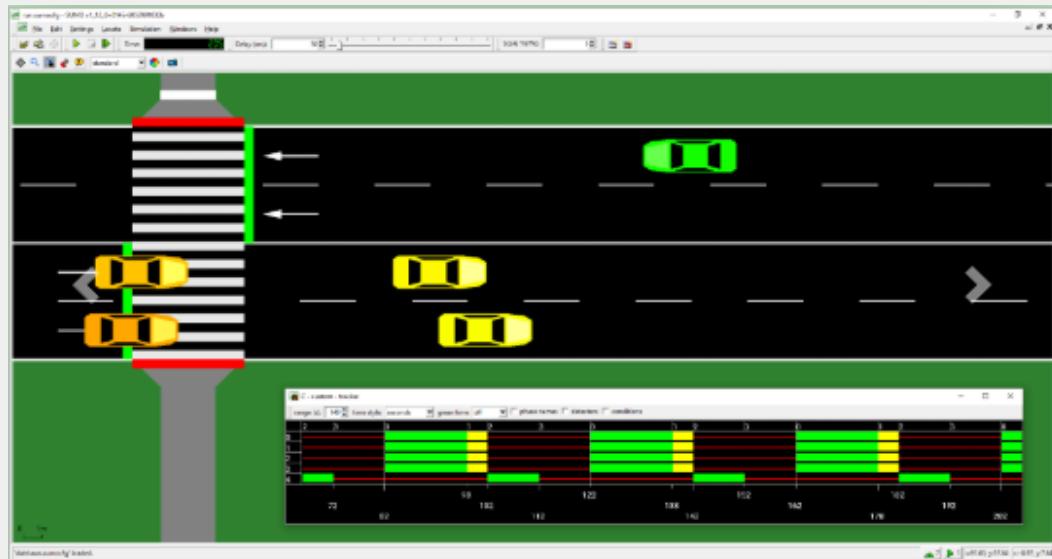
Alganas, A. (2011). *Social-based trustworthy data forwarding in vehicular delay tolerant networks* (Doctoral dissertation, UOIT).

SUMO Use:

Primary Focus: Traffic simulation and modeling of transportation roads, supporting mixed traffic (cars, trucks, buses, bicycles, pedestrians, AVs etc.).

Key Use Cases:

- Generating realistic traffic flows and scenarios, including congestion, traffic lights,
- Studying cooperative and automated driving strategies in a larger traffic environment (e.g., CACC – Cooperative Adaptive Cruise Control).





CARLA in Unreal Engine

Carla for Autonomous Vehicle Simulation and Testing (SAE Levels 0-6)

<https://www.youtube.com/watch?v=u2TxYhv3UKE&t=14s>



Sensors reference

- Collision detector
- Depth camera
- GNSS sensor
- IMU sensor
- Lane invasion detector
- LIDAR sensor
- Obstacle detector
- Radar sensor
- RGB camera
- RSS sensor
- Semantic LIDAR sensor
- Semantic segmentation camera
- Instance segmentation camera
- DVS camera
- Optical Flow camera



AWSIM in Unity

- AWSIM for Autonomous Vehicle Simulation and Testing (SAE Levels 0-6)



A Comprehensive Comparative Analysis of CARLA and AWSIM: Open-Source Autonomous Driving Simulators

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Abstract

The number of open-source autonomous driving simulators has been increasing in recent years, and many papers have surveyed the most popular options. However, there is a lack of in-depth and comprehensive comparison among the most advanced open-source simulators. This article provides a detailed quantitative and qualitative analysis of two of the most promising simulators for end-to-end testing: CARLA and AWSIM. The analysis focuses on various metrics, including the efficiency of simulation, the realism of physics simulation, scenario creation and testing, user-friendliness, and extendability. Based on our findings, we conclude that CARLA remains the best open-source simulator for end-to-end testing, while AWSIM shows advanced performance in specific areas, such as Lidar-based algorithms and Autoware development.

Keywords: Autonomous driving simulator, Unreal engine, Unity, CARLA, AWSIM



Figure 2.5: CARLA Simulator



Figure 2.6: AWSIM

Table 3: CARLA vs. AWSIM Comparison Table

Criteria	Weight	CARLA			AWSIM Unity		
		Raw	Score	Weighted	Raw	Score	Weighted
GPU Utilization	2	32.52%	1.000	2.000	37.85%	0.859	1.718
GPU Used Dedicated Memory	1	30.21%	0.562	0.562	16.98%	1.000	1.000
	3	65.50%	0.655	1.965	100.00%	1.000	3.000
	2	29.56%	1.000	2.000	30.02%	0.985	1.969
	1	22.34%	0.568	0.568	12.68%	1.000	1.000
	1	-	0.300	0.300	-	0.000	0.000
Tire-Road Interaction	1	-	0.300	0.300	-	0.000	0.000
Multi-body Dynamics	1	-	0.300	0.300	-	0.000	0.000
Actuator and Powertrain Modelling	1	-	0.300	0.300	-	0.000	0.000
Integrated Control System Modeling	1	-	0.300	0.300	-	0.000	0.000
Vehicle Parametrization and Customization	1	-	0.300	0.300	-	0.000	0.000
GNSS	3	✓	1.000	3.000	✓	1.000	3.000
IMU	3	✓	1.000	3.000	✓	1.000	3.000
RGB Camera	10	✓	0.850	8.500	✓	0.950	9.500
Depth Camera	2	✓	1.000	2.000	-	0.000	0.000
Event/DVS Camera	2	✓	1.000	2.000	-	0.000	0.000
LiDAR	10	✓	0.500	5.000	✓	0.750	7.500
Radar	2	✓	1.000	2.000	✓	1.000	2.000
V2X	1	✓	1.000	1.000	✓	1.000	1.000
Night	4	✓	1.000	4.000	-	0.300	1.200
Cloudy	4	✓	1.000	4.000	-	0.300	1.200
Rainy	4	✓	0.800	3.200	-	0.200	0.800
Foggy	2	✓	0.800	1.600	-	0.200	0.400
Snowy	1	-	0.100	0.100	-	0.200	0.200
Lighting Conditions	5	✓	1.000	5.000	✓	0.800	4.000
Pedestrian Lights	4	✓	1.000	4.000	✓	1.000	4.000
Classic Traffclights	5	✓	1.000	5.000	✓	1.000	5.000