Introduction and History of Connected and Automated Vehicles

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CAV Introduction + History + Why it matters

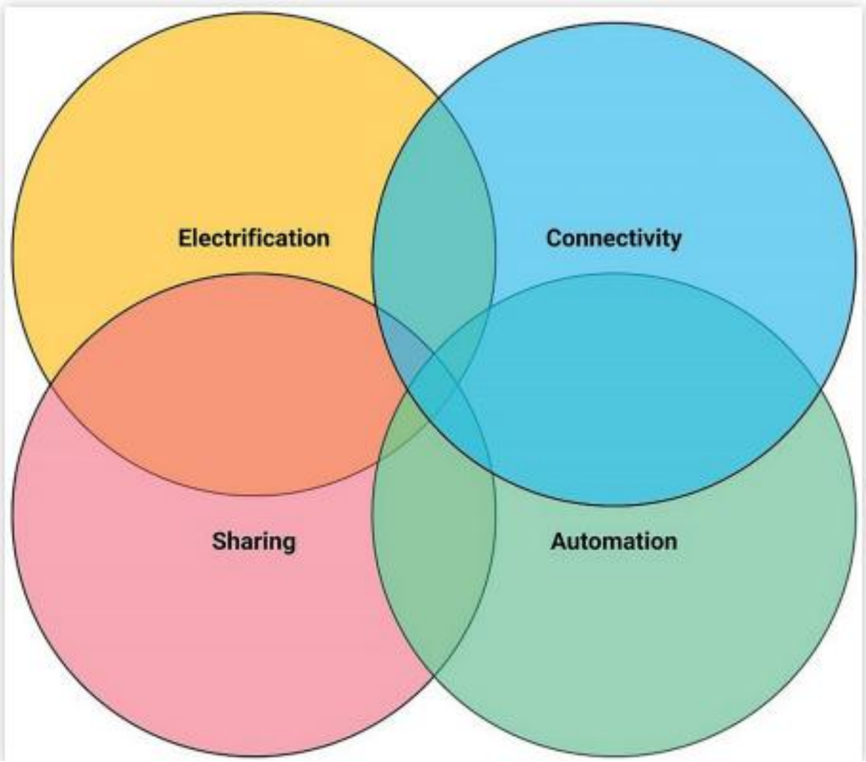
- Why is the automotive industry changing now?
- What exactly are “connected” and “automated” vehicles?
- How did we get here historically?
- And what barriers remain?

The automotive industry is in flux

- Driver-centered paradigm stayed stable for ~100 years
  - Only incremental improvements
  - Human driver controls steering + pedals
  - Minimal communication (turn signals)

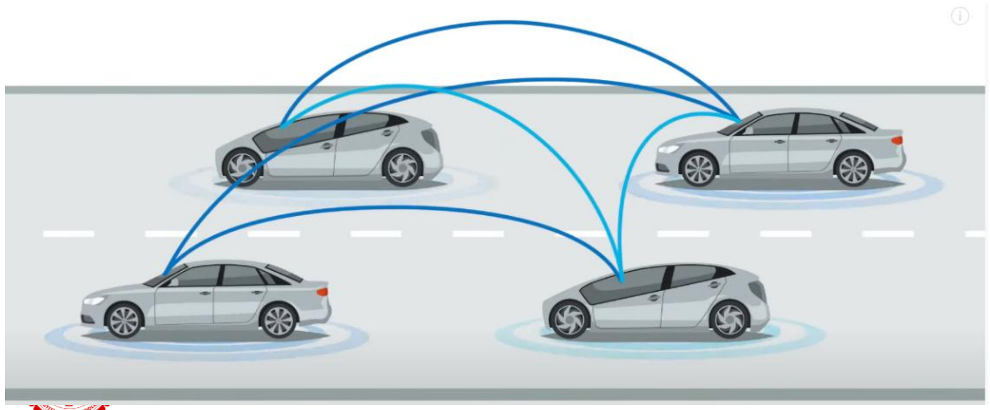
- Automotive industry
  - Improves safety, efficiency, onboard computing

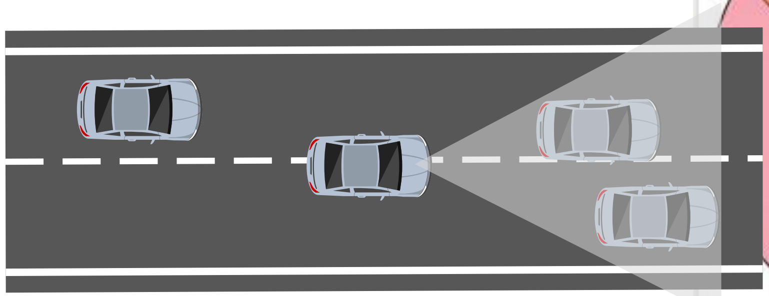
- Electrification
  - Electrification is the most mature of the four trends
  - Powertrain shift from Internal Combustion Engines (ICE) → hybrid/EV (electric motors)
  - R&D work in vehicle electrification is only two decades old
  - Norway, the percentage was 54% in 2020
  - More efficient at converting energy to vehicle motion
  - Fewer moving, mechanical parts → lower maintenance
  - Drastically reduce emissions

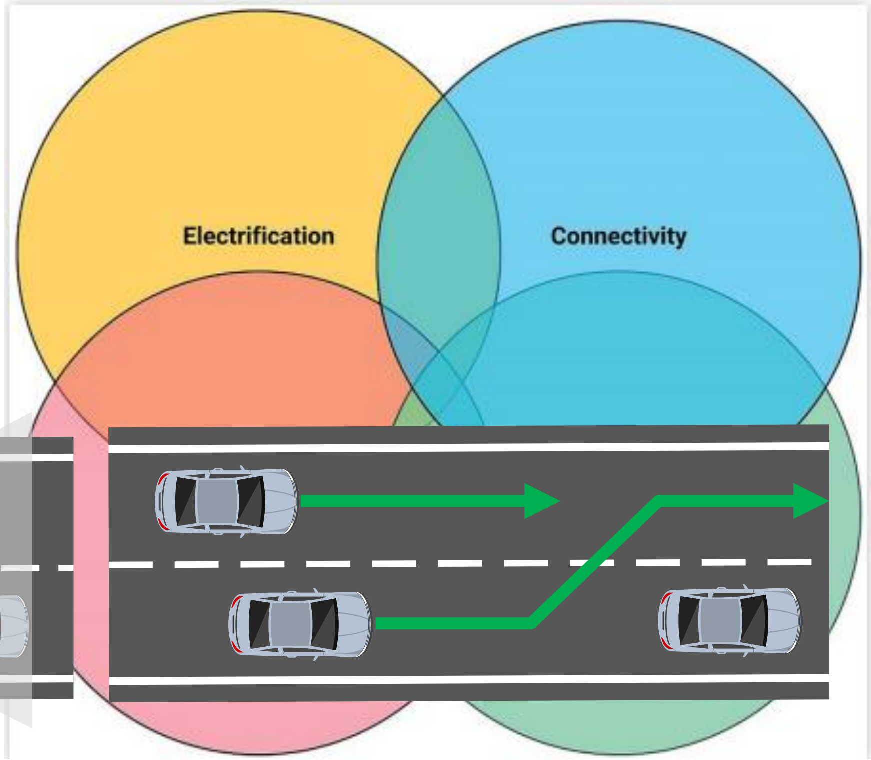


CASE: Electrification + Connectivity + Automation + Sharing

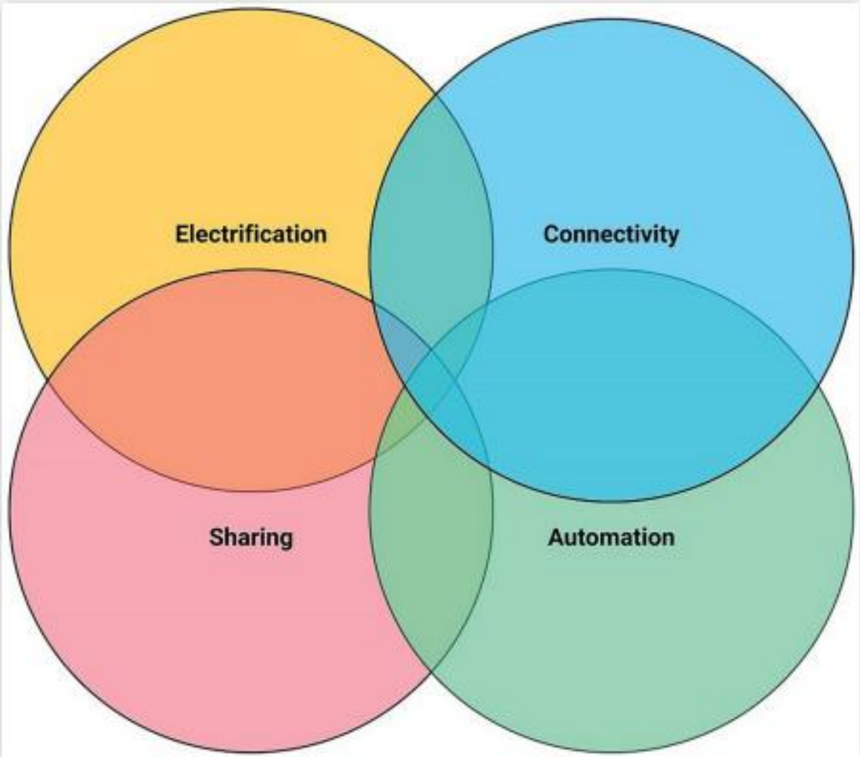
- Connectivity
  - Connectivity is the next mature trend
  - GPS-equipped vehicles were introduced by Oldsmobile ciera 1994
  - Early vehicles can receive Signal Phase and Timing (SPaT) information from traffic signals
    - Provide information on the traffic light sequence and timing
- Possible information exchanged between vehicles
  - Own dynamic properties: position, speed, acceleration
  - Sensor detected object: position, speed, acceleration
  - Driving intentions: future trajectories and waypoints
  - Traffic management procedures and guidelines





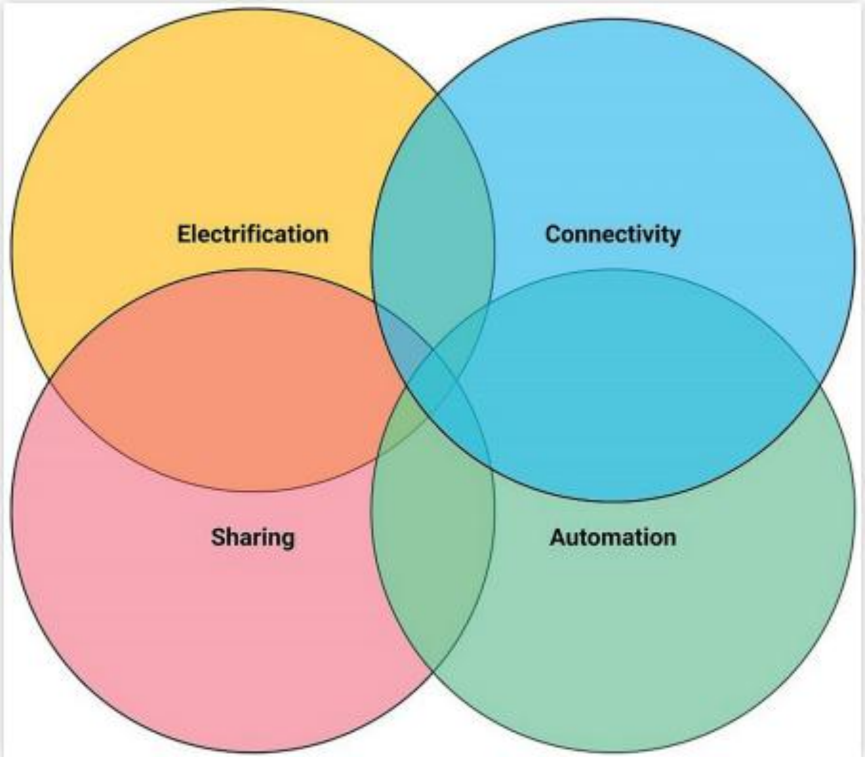


- Sharing
  - Sharing is the second-least mature trend
  - Sharing includes ride hailing (Uber) and car sharing (AutoShare)
  - Sharing is also known as multi-modal transportation
    - From scooters to bicycles to cars to buses and trains
  - Sharing provide enhanced mobility for individuals including
    - disabled persons, seniors, children, etc.
  - Sharing allows for lower levels of vehicle ownership



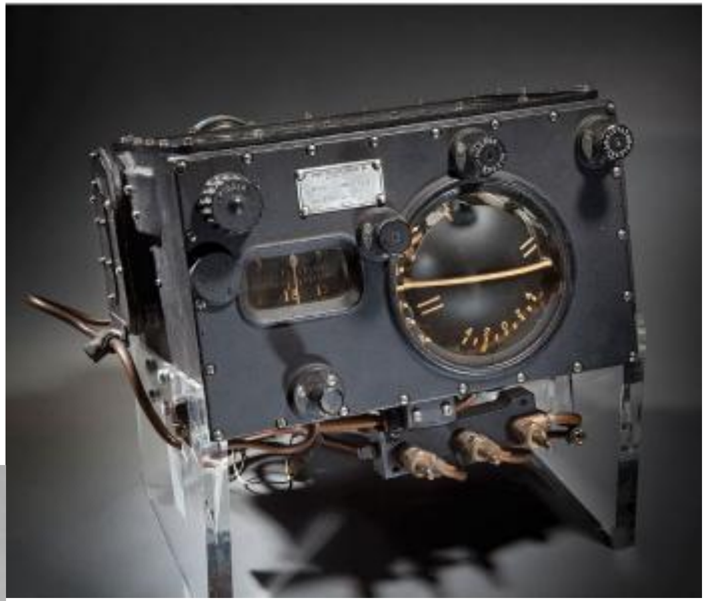
CASE: Electrification + Connectivity + Automation + Sharing

- Automation
  - Automation = vehicles with **Automated Driving Systems (ADS)**
  - **Automation Spectrum (SAE J3016):**
    - Low Level: Driver Assistance (e.g., Adaptive Cruise Control)
    - High Level: Full Automation (No human supervision required)
  - Automation helps humans to focus on other tasks
  - Automation reduce accidents by removing human error
  - Automation helps for those who cannot drive themselves
  - Automation is the **biggest change** in the vehicle industry
    - Since the invention of the automobile itself
  - Automation is the "last in maturity" compared to other trends
    - Holds the highest potential for total sector disruption



HISTORY AND ORIGINS

- Airplane autopilot enabled flying + navigation simultaneously
  - Example: Sperry Gyroscope Autopilot (1930s)
  - Automatically maintain a desired compass heading and altitude
- Early torpedoes: maintain course + depth (1860s)
  - Later: added sonar targeting by WWII
- German V2 rocket: gyroscope-based guidance
  - Early human-made object into outer space



HISTORY AND ORIGINS

- Cockroach-like motion: Sensing → Processing → Reacting
  - Sensing and reacting were possible
  - Hardest part historically: **processing (machine intelligence)**

- 1980s–1990s: High-Speed Autonomy
  - The Mercedes Van (1980): Travel on highways using a primitive automated driving version
  - VaMoRs Van (1997): Third generation of advanced vision systems for autonomous navigation

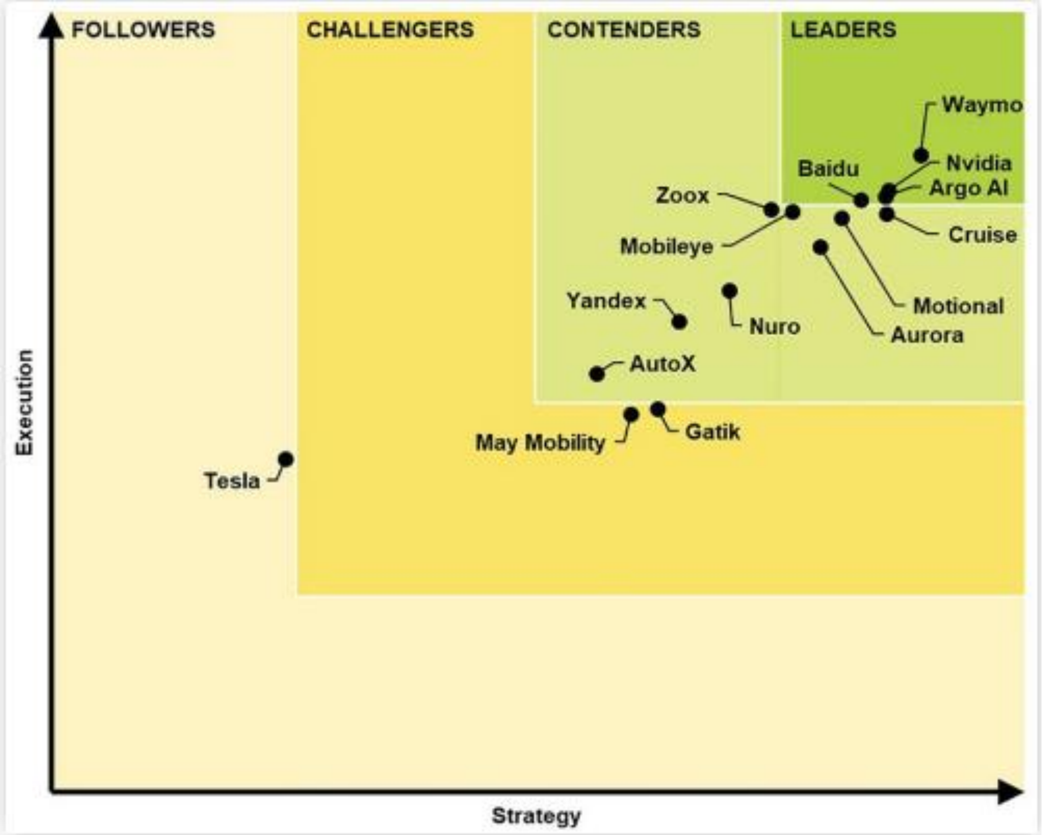
HISTORY AND ORIGINS

- DARPA Challenge (2004–2007)
  - First long distance competition for driverless cars in the world
  - Stanley (2005) and Boss (2007) winners
    - Used machine learning and sensor fusion (LiDAR/Radar) for automation
  - Modern AV industry born
    - Creating companies like Waymo, Tesla, and Uber

GuideHouse report on market analysis 2021

- CAV industry rankings criteria
  - Vision, Go-to market strategy, Partners, Production strategy, Technology, marketing, and distribution, Product capability, Product quality and reliability, Product portfolio, Staying power

- CAV industry leaders
  - Waymo, Nvidia, Argo AI, and Baidu
  - Tesla low in both strategy and execution
    - Public perception may differ



The Reality Check: 2026 CAV Industry Status

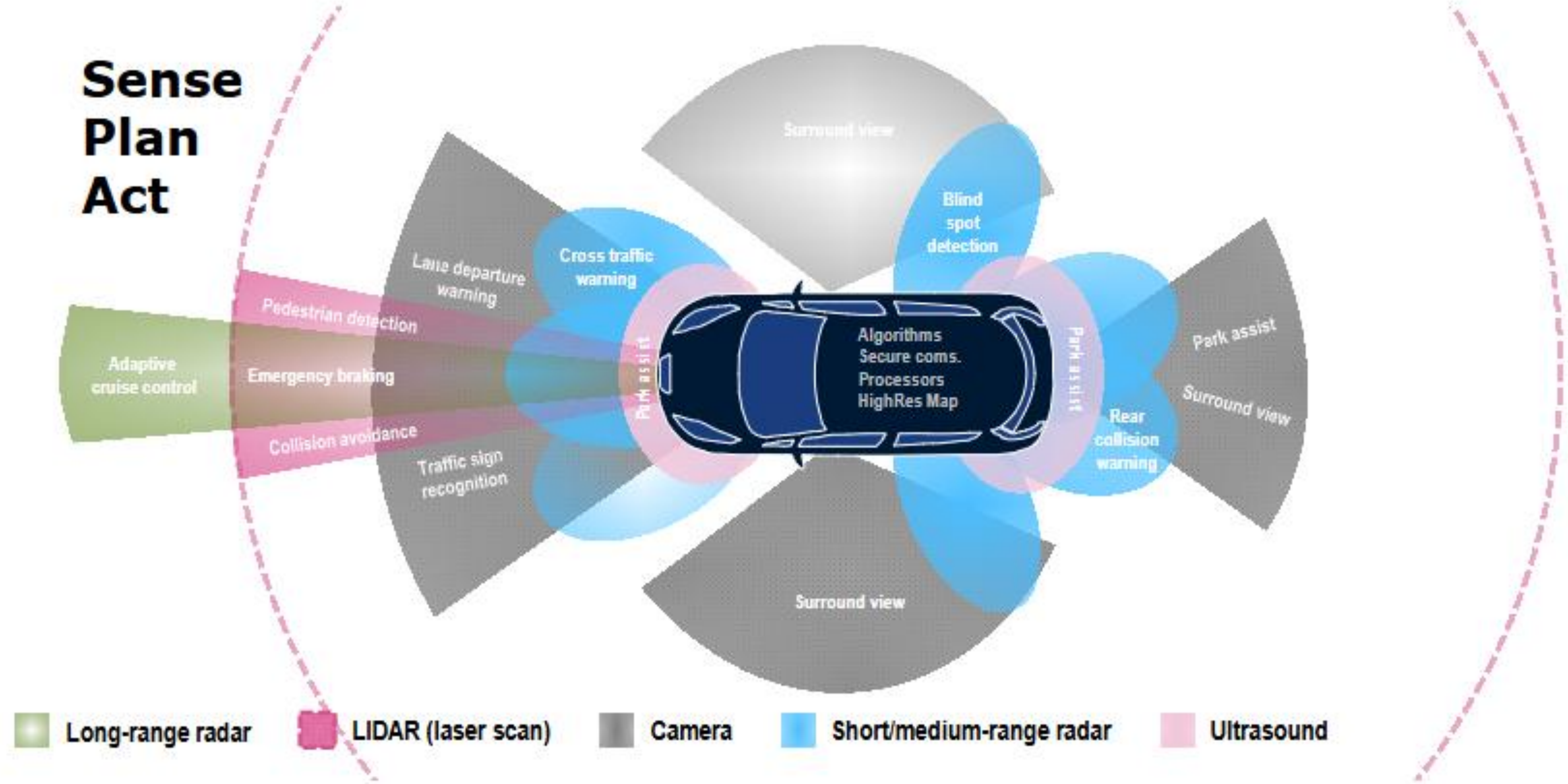
- Strong excitement from industry/government/public in 2020
  - But widespread deployment is not near-term

- **The 80/20 Rule:** The industry has mastered roughly 80–90% of driving tasks,
  - But the final 10–20% (corner cases) is proving exponentially more difficult
  - Perception must handle difficult scenarios:
    - Weather, temporary obstacles/restrictions, parking lots, heavy pedestrian/cyclist traffic, non-mapped areas

- **Timeline Debate:** Opinions are split
  - Some see mass commercialization by 2030, while others predict it is still decades away

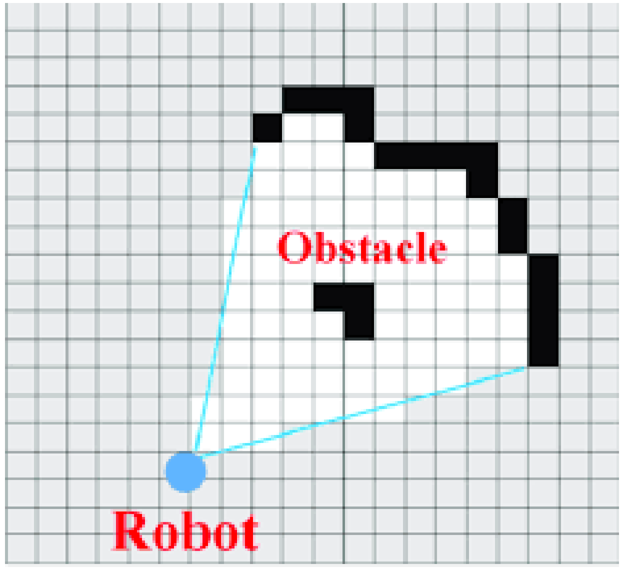
Three Pillars of CAV Intelligence

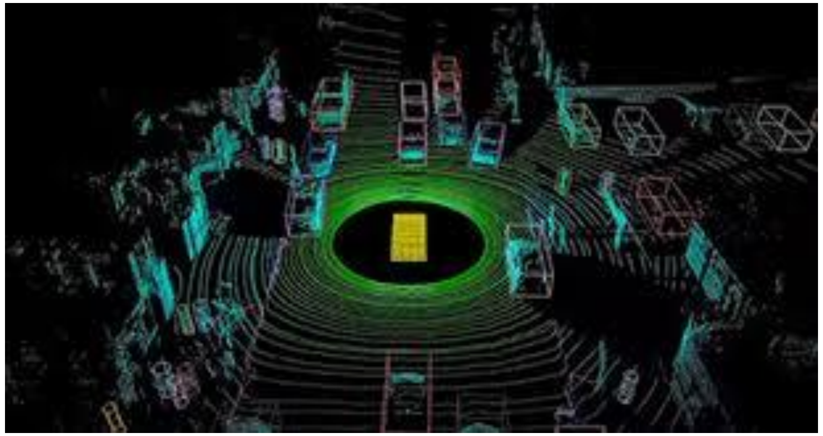
- A CAV works
  - Perception: Understanding the world
  - Planning: Deciding what to do
  - Actuation/Control: Executing safely

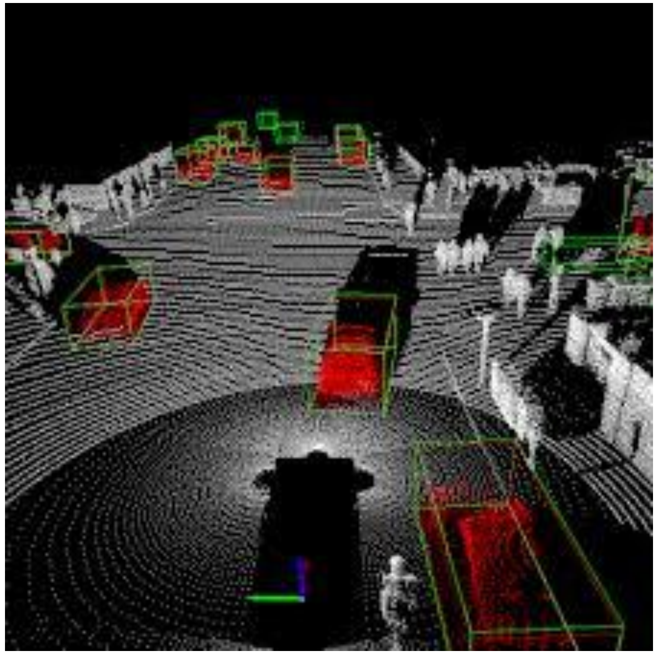


System 1: Perception

- Perception must produce a machine-readable scene of the environment
  - Ego-state: position, velocity, yaw rate, acceleration (vehicle's own motion)
  - Objects: detection + classification (car, truck, pedestrian, cyclist…)
  - Tracking: position/velocity/direction over time of objects
  - Free space: drivable area, boundaries, curbs, road edges
  - Traffic controls: signals, signs, lane markings, right-of-way cues
- **Outputs:** occupancy grid, tracked objects list







How perception is built

- Sensors (typical):
  - **Cameras:** rich semantics (lanes, signs), weak in glare/rain/night
  - **Radar:** strong range/velocity, weaker shape/class semantics
  - **LiDAR:** accurate geometry, cost/packaging concerns
  - **GNSS/IMU/Wheel odometry:** ego motion + localization backbone

- Fusion levels:
  - **Raw-data fusion** (hard, heavy compute)
  - **Feature-level fusion**
  - **Object-level fusion** (common, robust)

System 2: Planning

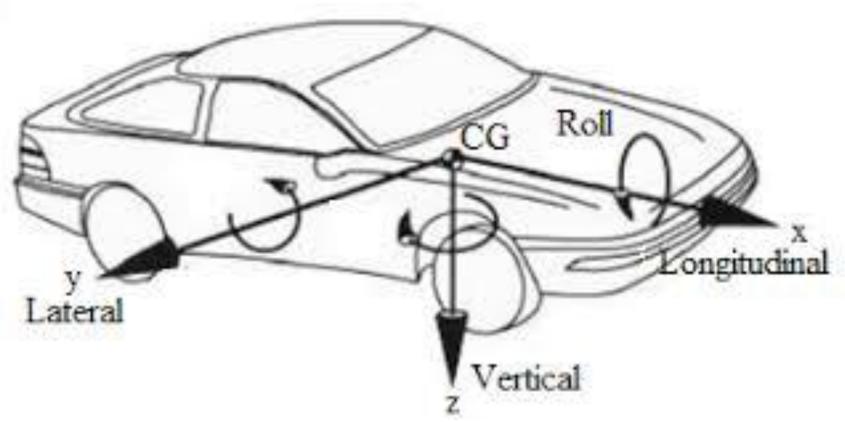
- Planning converts world model + mission into actions:
  - **Mission / Route planning:** where to go
  - **Behavior planning:** what maneuver (keep lane, yield, overtake, stop)
  - **Motion planning:** exact trajectory (path + speed profile) within constraints

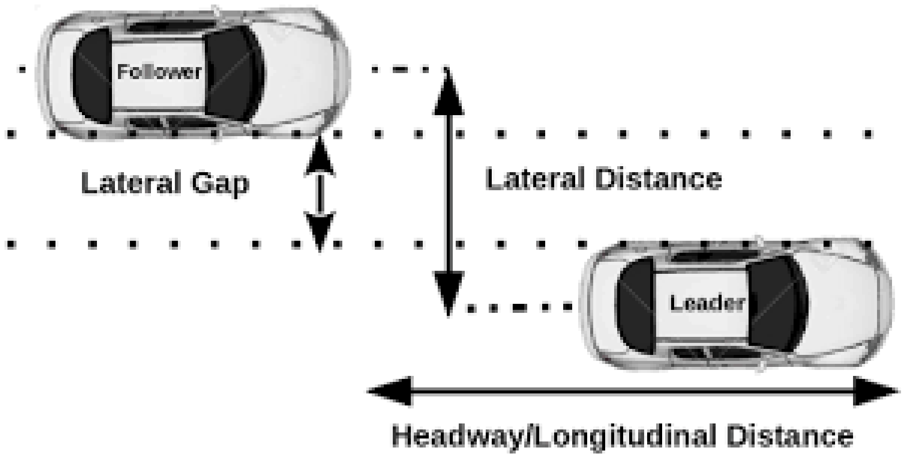
- **Output:** a trajectory: $x(t), y(t), v(t)$ over next few seconds

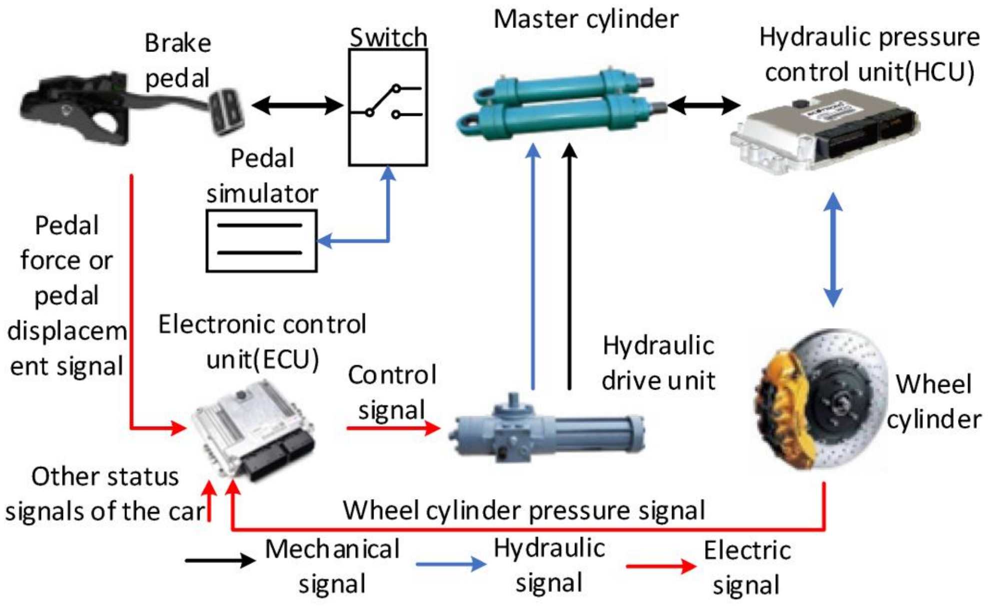
- **Prediction**
  - Forecast trajectories of vehicles/pedestrians/cyclists
  - Estimate maneuver (will cut-in? will cross? will stop?)
- **Prediction Approaches:**
  - Physics-based (constant velocity/acceleration)
  - Rule-based (yielding, lane following)
  - Learning-based (data-driven intent + interaction)

System 3: Actuation/Control

- Control turns planned trajectory into commands:
  - **Lateral control:** steering to follow path
  - **Longitudinal control:** throttle/brake to follow speed profile
- Vehicle actuators:
  - Steering actuator, brake-by-wire, throttle, gear, etc.
  - Safety monitoring: actuator faults, degraded modes
- **Output:** steering angle + throttle/brake commands at high rate







SAE J3016 automation level

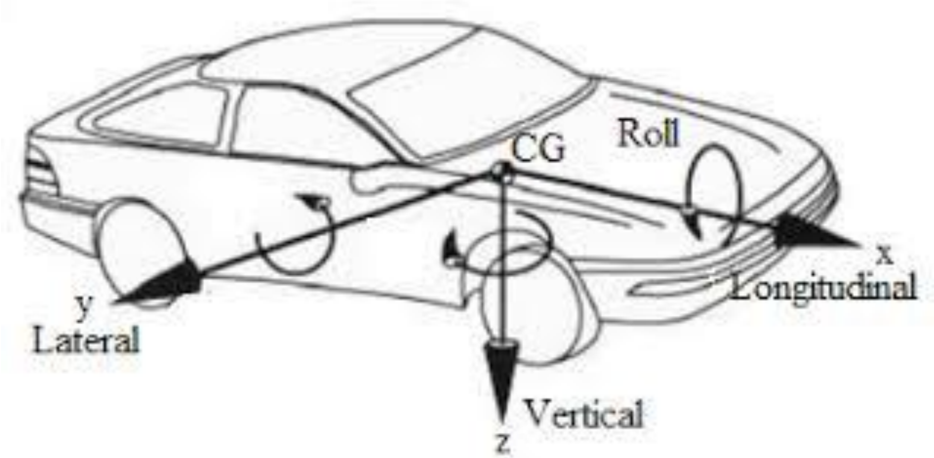
- What is SAE J3016?
  - Defines a **taxonomy** with **six levels of driving automation (0–5)** for on-road vehicles
  - Levels apply to **features**, not necessarily the whole vehicle
    - Car might have a Level 2 highway feature and a Level 4 parking feature

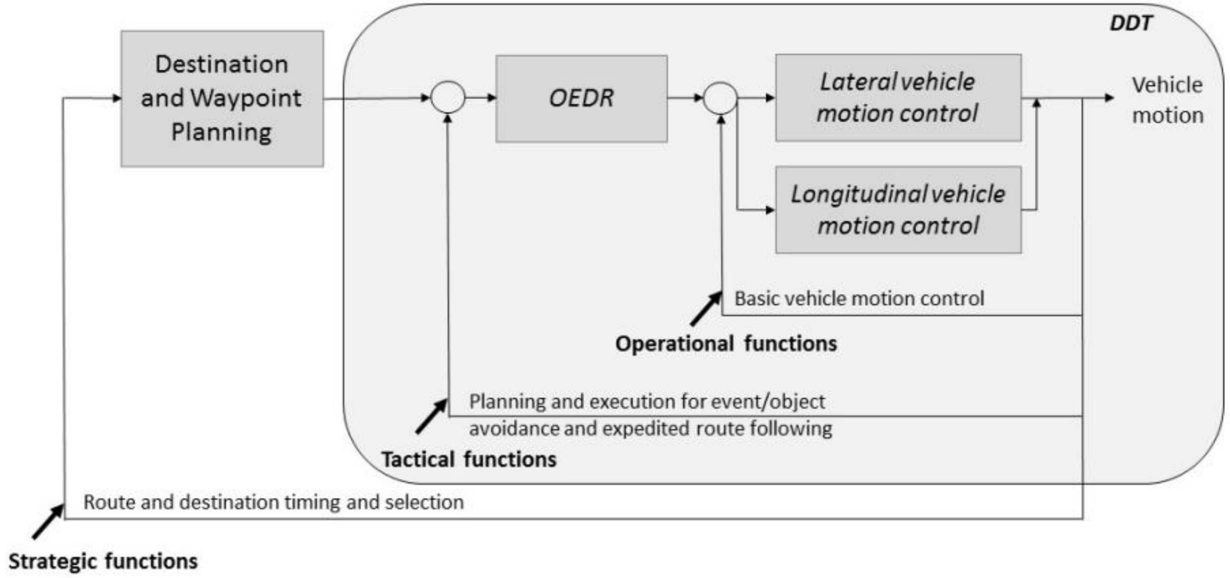
- Three actors model involved
  - **The (Human) User**: Can be a driver, passenger, or remote assistant.
  - **The Driving Automation System**: The hardware/software performing the task.
  - **Other Vehicle Systems**: Brakes, steering, lights (the "conventional" parts of the car)

- Active Safety is **not** driving automation because it is momentary, not sustained
  - Anti-lock Braking System (**ABS**), Electronic Stability Control (**ESC**), Automatic Emergency Braking (**AEB**)

Dynamic Driving Task (DDT)

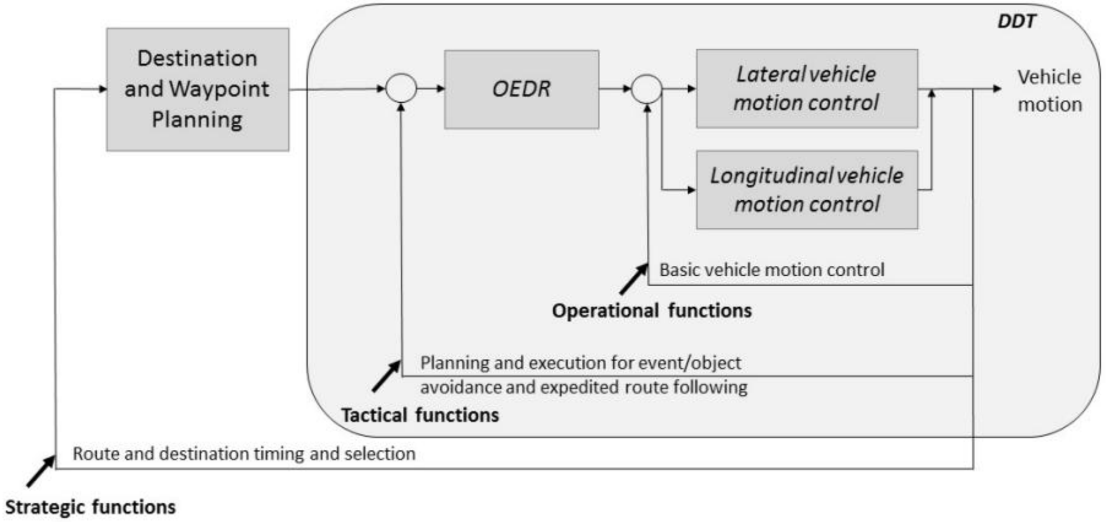
- Dynamic Driving Task **(DDT)**
  - System performs **real-time operational + tactical** driving functions, excluding **strategic** trip planning
- **Strategic**: Trip planning (Destination, Waypoints)
  - This is outside the scope of DDT
- **Tactical**: Maneuver planning (changing lanes, signaling)
- **Operational**: Split-second micro-adjustments (steering, braking)





Important Terms: ODD and OEDR

- **ODD (Operational Design Domain)**
  - Set of operating conditions under which the driving automation feature is designed to function
    - e.g., road type, speed range, geography, weather/visibility, traffic conditions, time-of-day
- **OEDR (Object and Event Detection and Response)**
  - Monitoring the driving environment (detect/recognize/classify objects and events)
  - Responding appropriately to complete the DDT and/or support fallback
- **Key:**
  - ODD = What conditions is this feature supposed to operate
  - OEDR = What it must perceive and how it responds within those conditions



Dynamic Driving Task (DDT) Fallback

- DDT fallback triggered by either
  - **DDT performance-relevant system failure**
    - Malfunction that prevents the automation system to perform DDT
    - Eg: sensor outage (camera/radar), steering/brake actuator fault, compute failure
  - **ODD (Operational Design Domain) exit**
    - Vehicle/feature is no longer operating within ODD
    - Eg: road type changes (highway → city), speed out of range, heavy fog/rain, construction zone

- DDT fallback outcome
  - **Driver takeover**: Human performs the DDT (lateral + longitudinal control)
  - **Minimal Risk Maneuver**: Automated Driving System (ADS) move to a safe minimal-risk state
    - Move to a safe location and stop
    - Reduces crash risk

Level 0: No Driving Automation

- **Definition:** Driver performs the entire **Dynamic Driving Task (DDT)** at all times
- **Key points:**
  - Warnings / momentary interventions do **not** count as automation (not sustained DDT control)
  - Driver is always responsible for steering, speed control, and environment monitoring
- **Examples:** Anti-lock Braking System (ABS), Electronic Stability Control (ESC), Automatic Emergency Braking (AEB), Forward Collision Warning (FCW), Lane Departure Warning (LDW)
- **Roles at Level 0:**
  - Dynamic Driving Task (**DDT**): Driver
  - Object and Event Detection and Response (**OEDR**): Driver
  - **DDT** fallback: Driver
  - Operational Design Domain (**ODD**): Not applicable (no driving automation feature)

Level 1: Driver Assistance

- **Definition:** System performs sustained **either lateral OR longitudinal** motion control (not both)
- **Key points:**
  - Driver performs OEDR (continuous supervision and environment monitoring)
  - Driver controls the other axis not controlled by the system
- **Examples:**
  - Adaptive Cruise Control (ACC): controls speed + gap (longitudinal only); driver steers
  - Cruise Control (CC): controls speed (longitudinal only); driver steers
  - Lane Keeping Assist (LKA): controls steering (lateral only); driver controls speed/brake
- **Roles at Level 1:**
  - Dynamic Driving Task (DDT): Driver + System (system controls one axis)
  - Object and Event Detection and Response (OEDR): Driver
  - DDT fallback: Driver
  - Operational Design Domain (ODD): Feature-specific

Level 2: Partial Driving Automation

- **Definition:** System perfroms sustained **both** lateral **and** longitudinal motion control simultaneous.
- **Key points:**
  - Driver performs OEDR and must supervise continuously.
  - Driver must be ready to intervene immediately at any time.
- **Examples:**
  - Highway Assist / Pilot Assist: controls steering + speed at the same time; driver still monitors
  - Traffic Jam Assist: low-speed stop-and-go and lane centering simultaneously; driver supervises.
  - Traffic-Aware Cruise Control: steering + speed control; driver performs OEDR and fallback.
- **Roles at Level 2:**
  - Dynamic Driving Task (DDT): Driver + System (system controls lateral + longitudinal)
  - Object and Event Detection and Response (OEDR): Driver
  - DDT fallback: Driver
  - Operational Design Domain (ODD): Feature-specific

Level 3: Conditional Driving Automation

- **Definition:**
  - **Automated Driving System (ADS)** performs the entire **DDT including OEDR** within its **ODD**; human is **fallback-ready** and must respond to a **request to intervene**
- **Key points:**
  - User is not required to supervise continuously while ADS is engaged
  - When ADS requests takeover, the user performs fallback (takes over DDT)
- **Examples:** Traffic jam ADS within defined conditions (limited-access roads, speed range, etc.)
- **Roles at Level 3:**
  - Dynamic Driving Task (DDT): ADS
  - Object and Event Detection and Response (OEDR): ADS
  - DDT fallback: Fallback-ready user (upon request)
  - Operational Design Domain (ODD): Required and must be stated

Level 4: High Driving Automation

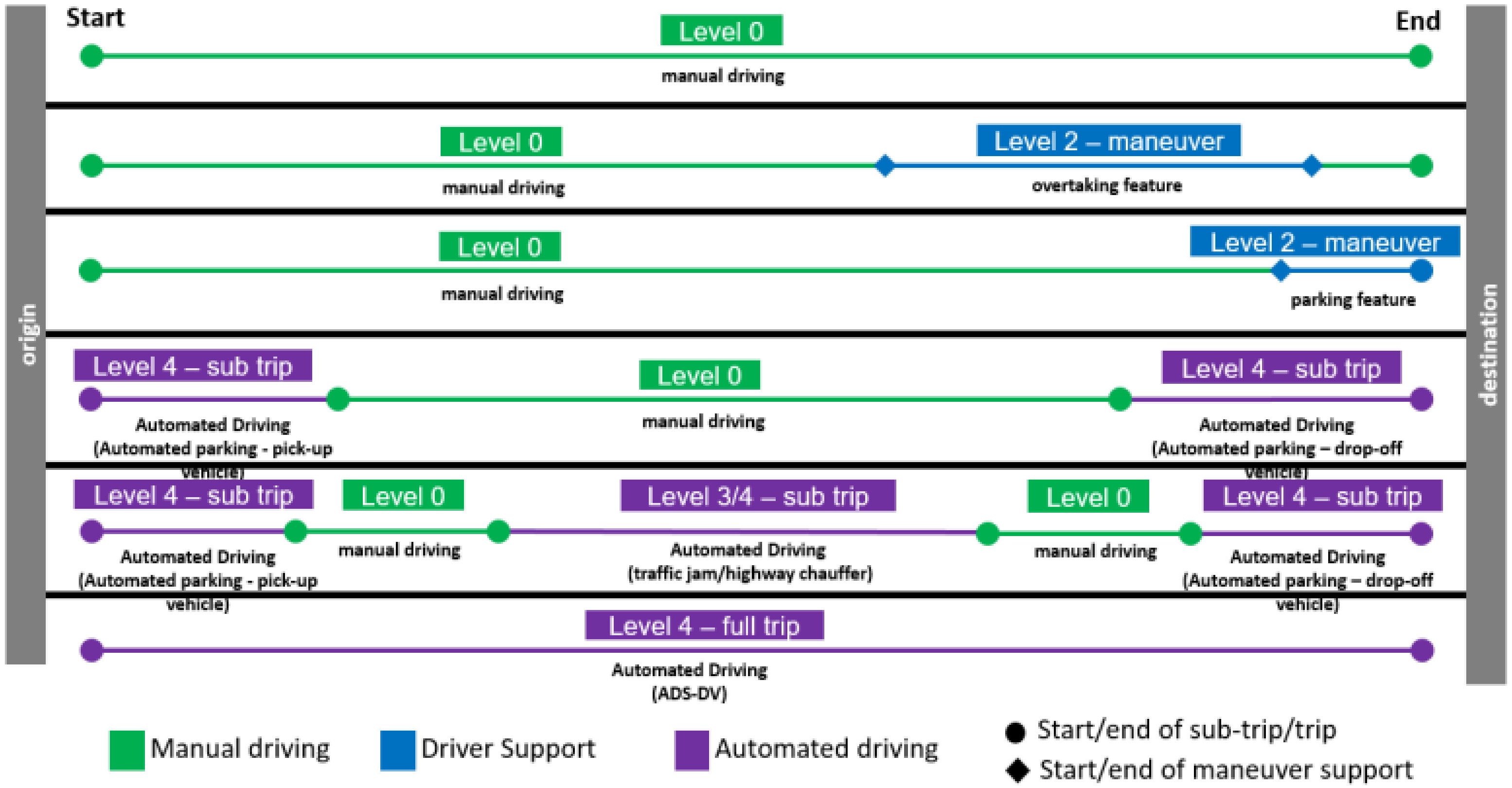
- **Definition:** ADS performs **DDT + OEDR + DDT fallback** within its **ODD** (no expectation of human takeover).
- **Key points:**
  - If a failure occurs or ODD is reached/exceeded, ADS handles fallback (e.g., achieves minimal risk condition).
  - Operation is limited to its ODD (geo-fenced area, specific roads, conditions, etc.).
- **Examples:**
  - Geo-fenced robotaxi, automated shuttle on fixed routes, driverless valet parking in controlled areas
- **Roles at Level 4:**
  - Dynamic Driving Task (DDT): ADS
  - Object and Event Detection and Response (OEDR): ADS
  - DDT fallback: ADS
  - Operational Design Domain (ODD): Required and must be stated

Level 5: Full Driving Automation

- **Definition:** ADS performs **DDT + OEDR + fallback** under **all conditions a human driver could manage**.
- **Key points:**
  - No operational limitation by ODD (conceptually “anywhere a human can drive”).
  - No human driver needed at any time.
- **Examples:**
  - Concept level; no broadly deployed unrestricted Level 5 systems today
- **Roles at Level 5:**
  - Dynamic Driving Task (DDT): ADS
  - Object and Event Detection and Response (OEDR): ADS
  - DDT fallback: ADS
  - Operational Design Domain (ODD): Not limited (no defined constraints)

SAE J3016: sub-trip vs full-trip

- Sub-trip feature:
  - Requires a human driver for at least part of every trip
- Full-trip feature:
  - Automated Driving System (ADS) features that can operate throughout complete trips



Classifying a feature using SAE J3016

- Step 1: Sustained automation of the Dynamic Driving Task (DDT)?
  - Ask: Does the system perform any part of the DDT on a sustained basis (not just warnings or brief interventions)?
  - **If No → Level 0**

- Step 2: How many motion-control axes are automated (when engaged)?
  - One axis only (either lateral steering OR longitudinal accel/brake) → Level 1
  - **Both axes simultaneously (lateral + longitudinal together) → Level 2**

- Step 3: Who performs Object and Event Detection and Response (OEDR)?
  - If the driver must continuously monitor the environment and respond → Level 1 / Level 2
  - **If the system performs OEDR as part of driving → it is an Automated Driving System (ADS) → Level 3+**

Classifying a feature using SAE J3016

- **Step 4: Who performs DDT fallback when needed (system failure or ODD exit)?**
  - If the feature expects a **human takeover** after a request to intervene → **Level 3**
  - If the **ADS performs fallback** and can reach a **minimal risk condition** without expecting human takeover → **Level 4 / Level 5**

- **Step 5: Is the ADS limited to a defined Operational Design Domain (ODD)?**
  - **Yes (ODD-limited: specific roads/area/speeds/weather conditions, etc.)** → **Level 4**
  - **No ODD limitation** (can drive under all conditions a human driver could manage) → **Level 5**

- **Important:**
  - Assign levels using **design intent + specified user role + stated ODD**, not "what it looked like" in a demo.

SAE J3016 automation level

- ACC — Adaptive cruise control
- ADAS — Advanced driver assistance system
- ADS — Automated driving system
- ADS-DV — Automated driving system-dedicated vehicle
- AEB — Automatic emergency braking
- DDT — Dynamic driving task
- ESC — Electronic stability control
- LKA — Lane keeping assistance
- ODD — Operational design domain
- OEDR — Object and event detection and response