Infrastructure for Automated Vehicles: It's a System, Not Just Vehicles

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Transportation Systems

- Railroad: Trains + track + signal control system (+ electric power supply)
- Air: Aircraft + Air traffic control + Ground control at airports + Terminal support
- Marine: Ships + vessel traffic control + ports
- Why should road transport be any different?
  - Vehicles + roadway physical infrastructure + traffic control infrastructure + signage + supporting information infrastructure

Automating Road Transport

- Already far behind other modes in replacement of human labor by machine labor
  - Many more vehicles and human operators
  - Significantly cheaper and smaller vehicles
  - Far more complicated operating environment

→ Infrastructure support could help overcome the complexity challenge, and lack of such support could delay resolving it.

Great Diversity of Road Vehicle Automation Systems

- **Connected (V2V, I2V, V2I) or autonomous (unconnected)**
- **Division of roles between human and machine (levels of automation)**
- **Operational Design Domain (ODD), including:**
  - ***Roadway type***
  - ***Availability of necessary supporting infrastructure features***
  - ***Condition of pavement markings and signage***
  - ***Geographic location (boundaries)***
  - **Traffic conditions and speed range**
  - **Weather and lighting conditions**
  - **(and potentially more…)**

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Taxonomy of Levels of Automation

Driving automation systems **are categorized into levels based on:**

1. **Whether the driving automation system performs *either* longitudinal *or* lateral vehicle motion control → L1**
2. **Whether the driving automation system performs *both* longitudinal and lateral vehicle motion control simultaneously → L2 +**
3. **Whether the driving automation system *also* performs object and event detection and response → L3 +**
4. **Whether the driving automation system *also* performs fallback (fault detection and recovery) → L4 +**
5. **Whether the driving automation system can drive everywhere (L5) or is limited by an operational design domain (ODD) → L4**

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SAE J3016 Definitions – Levels of Automation

SAE Level	Name	Narrative Definition	Execution of Steering/ Acceleration/ Deceleration	*Monitoring* of Driving Environment	Fallback Performance of *Dynamic Driving Task*	System Capability *(Driving Modes)*
Human driver monitors the driving environment						
0	No Automation	the full-time performance by the *human driver* of all aspects of the *dynamic driving task*, even when enhanced by warning or intervention systems	Human driver	Human driver	Human driver	n/a
1	Driver Assistance	the *driving mode*-specific execution by a driver assistance system of either steering or acceleration/deceleration using information about the driving environment and with the expectation that the *human driver* perform all remaining aspects of the *dynamic driving task*	Human driver and system	Human driver	Human driver	Some driving modes
2	Partial Automation	the *driving mode*-specific execution by one or more driver assistance systems of both steering and acceleration/deceleration using information about the driving environment and with the expectation that the *human driver* perform all remaining aspects of the *dynamic driving task*	**System**	Human driver	Human driver	Some driving modes
Automated driving system ("system") monitors the driving environment						
3	Conditional Automation	the *driving mode*-specific performance by an *automated driving system* of all aspects of the *dynamic driving task* with the expectation that the *human driver* will respond appropriately to a *request to intervene*	System	**System**	Human driver	Some driving modes
4	High Automation	the *driving mode*-specific performance by an *automated driving system* of all aspects of the *dynamic driving task*, even if a *human driver* does not respond appropriately to a *request to intervene*	System	System	**System**	Some driving modes
5	Full Automation	the full-time performance by an *automated driving system* of all aspects of the *dynamic driving task* under all roadway and environmental conditions that can be managed by a *human driver*	System	System	System	**All driving modes**

Example Systems at Each Automation Level

(based on SAE J3016 - http://standards.sae.org/j3016_201609/)

Level	Example Systems	Driver Roles
1	Adaptive Cruise Control OR Lane Keeping Assistance	Must drive other function and monitor driving environment
2	Adaptive Cruise Control AND Lane Centering Traffic Jam Assist (Mercedes, Tesla, Volvo, Infiniti, GM SuperCruise…) Parking with external supervision	Must monitor driving environment (system may nag driver to try to ensure it)
3	Traffic Jam Pilot	May read a book, text, or web surf, but be prepared to intervene when needed
4	Highway driving pilot Closed campus “driverless” shuttle “Driverless” valet parking in garage	May sleep, and system can revert to minimum risk condition if needed
5	Ubiquitous automated taxi Ubiquitous car-share repositioning	Can operate anywhere with no drivers needed

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Possibility of Analogous Classifications for Infrastructure?

- Convenient to have, but very difficult to define *a priori*
- What dimensions to classify?
  - Readiness for specific levels of vehicle automation?
  - Physical infrastructure adherence to specific technical standards or condition of repair?
  - Availability of additional physical infrastructure support elements (curbs, barriers, special markers…)?
  - Digital infrastructure (Local Dynamic Map layers)?
  - Wireless communication infrastructure capabilities (I2V, V2I)?
  - Back-office information support functionality?
  - Remote human supervisors, with varying capabilities?
  - Traffic management and control functions?

Challenges to Infrastructure Classification

- Too many dimensions that vary independently – cannot distill to a manageable number of distinct infrastructure “types”
- Too much diversity of existing infrastructure characteristics within any one city, province/state or nation
- Infrastructure support *needs* depend too strongly on vehicle parameters:
  - Sensing capabilities
  - Communication capabilities
  - Operating speeds
  - Price sensitivity
  - Mission requirements (passengers or freight, schedule flexibility,…)

How Infrastructure Can Help (1/3)

- I2V communications
  - Real-time traffic signal phase and timing (SPaT)
  - Trajectories of potential hazards (other road users) detected by infrastructure-based sensors (outside AV line of sight)
  - Active coordination of vehicle maneuvers (merge junctions)
  - Traffic management guidance to improve system efficiency
- Physical segregation of AVs from other road users
  - Simplifying the hazard environment to reduce sensor specs
  - Enabling higher speed AV operations for same sensor suite
  - Restricting access to potential conflict zones with gates or signals (crossings at intersections)

How Infrastructure Can Help (2/3)

- **Partial separation of AVs from other road users**
  - Separate AV lanes with markings to deter other vehicles, pedestrians and bicyclists from interfering with AV motions
  - Curbs to slow down bicyclists crossing the AV path so the AV has enough time to detect and avoid hitting the bicyclist
  - Restricted zones only for AV operations (maybe) at certain times
- **Enhanced conspicuity of traffic control devices**
  - Enhanced visibility of signage and lane markings to improve detection by AV sensors
  - Standardization of signage and markings to ease recognition
  - Maintenance to prevent occlusions (dirt, foliage,…)

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How Infrastructure Can Help (3/3)

- **Positioning and localization support**
  - DGPS corrections and pseudolites for problem locations
  - High-precision local dynamic maps and deliberate roadside landmarks to aid AV localization
- **Off-board fleet and traffic management support**
  - Remote supervisor to diagnose and resolve complicated situations the AV does not understand
  - Traffic management center to provide real-time data about problems beyond line of sight (objects in road, traffic jams, road surface condition problems…)
  - Back-office data storage for support functions

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How Important is Infrastructure Support for AVs?

- **For the next few decades, absolutely essential to compensate for perception system limitations (AVs must be *cooperative* rather than *autonomous*).**

- **In the distant future, when perception systems are much better, it will still be highly beneficial to augment perception systems.**

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