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

Steven E. Shladover, Sc.D.
California PATH Program
University of California, Berkeley
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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...)
**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 $\rightarrow$ L1
2. Whether the driving automation system performs *both* longitudinal and lateral vehicle motion control simultaneously $\rightarrow$ L2 +
3. Whether the driving automation system *also* performs object and event detection and response $\rightarrow$ L3 +
4. Whether the driving automation system *also* performs fallback (fault detection and recovery) $\rightarrow$ L4 +
5. Whether the driving automation system can drive everywhere (L5) or is limited by an operational design domain (ODD) $\rightarrow$ L4
<table>
<thead>
<tr>
<th>SAE Level</th>
<th>Name</th>
<th>Narrative Definition</th>
<th>Execution of Steering/Acceleration/Deceleration</th>
<th>Monitoring of Driving Environment</th>
<th>Fallback Performance of Dynamic Driving Task</th>
<th>System Capability (Driving Modes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>No Automation</td>
<td>the full-time performance by the human driver of all aspects of the dynamic driving task, even when enhanced by warning or intervention systems</td>
<td>Human driver</td>
<td>Human driver</td>
<td>Human driver</td>
<td>n/a</td>
</tr>
<tr>
<td>1</td>
<td>Driver Assistance</td>
<td>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</td>
<td>Human driver and system</td>
<td>Human driver</td>
<td>Human driver</td>
<td>Some driving modes</td>
</tr>
<tr>
<td>2</td>
<td>Partial Automation</td>
<td>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</td>
<td>System</td>
<td>Human driver</td>
<td>Human driver</td>
<td>Some driving modes</td>
</tr>
<tr>
<td>3</td>
<td>Conditional Automation</td>
<td>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</td>
<td>System</td>
<td>System</td>
<td>Human driver</td>
<td>Some driving modes</td>
</tr>
<tr>
<td>4</td>
<td>High Automation</td>
<td>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</td>
<td>System</td>
<td>System</td>
<td>System</td>
<td>Some driving modes</td>
</tr>
<tr>
<td>5</td>
<td>Full Automation</td>
<td>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</td>
<td>System</td>
<td>System</td>
<td>System</td>
<td>All driving modes</td>
</tr>
</tbody>
</table>
## Example Systems at Each Automation Level
*(based on SAE J3016 - http://standards.sae.org/j3016_201609/)*

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