Connected and Automated Vehicle (CAV) Systems: Potential Impacts on Future Interstate Highway System

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Outline

• CAV Systems – categories and examples
  – Diversity of automation systems
  – Gradual pace of market penetration growth for new automotive technologies
• Dominance of uncertainty
• Regional diversity
• Passenger demand implications
• Freight demand implications
• Supply side implications
• Looking ahead 10, 20 and 50 years
Connected Vehicle (CV) Systems (without automation)

- **V2V:**
  - *Cooperative collision warning, mitigation, or avoidance*
  - Automated maneuver negotiation
  - Transit bus connection protection

- **I2V:**
  - Traffic signal status information
  - Traffic and weather condition information
  - Fleet management
  - Variable speed limits and advisories
  - End of queue warnings

- **V2I:**
  - Vehicle probe data collection
  - Electronic toll collection
  - Vehicle status information for fleet management
  - Mayday and concierge services
Driving Automation System Categories

• Levels of automation (relative roles of driver and “the system”)
• Cooperative (connected) vs. autonomous (unconnected)
• Operational design domain (ODD) restrictions
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.
2. Whether the driving automation system performs both longitudinal and lateral vehicle motion control simultaneously.
3. Whether the driving automation system also performs object and event detection and response.
4. Whether the driving automation system also performs dynamic driving task (DDT) fallback.
5. Whether the driving automation system can drive everywhere or is limited by an operational design domain (ODD).
# 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>
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<tbody>
<tr>
<td>1</td>
<td>Adaptive Cruise Control OR Lane Keeping Assistance</td>
<td>Must drive other function and monitor driving environment</td>
</tr>
<tr>
<td>2</td>
<td>Adaptive Cruise Control AND Lane Keeping Assistance Traffic Jam Assist (Mercedes, Tesla, Infiniti, Volvo…) Parking with external supervision</td>
<td>Must monitor driving environment (system nags 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>
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</tbody>
</table>
Operational Design Domain (ODD)

- The specific conditions under which a given driving automation system is designed to function, including:
  - Roadway type
  - Traffic conditions and speed range
  - Geographic location (boundaries)
  - Weather and lighting conditions
  - Availability of necessary supporting infrastructure features
  - Condition of pavement markings and signage
  - (and potentially more...)
Fastest changes in automotive market: Regulatory mandate

Source: Gargett, Cregan and Cosgrove, Australian Transport Research Forum 2011

Figure 1: US seat belt adoption curves

90% 6 years (22 years)
Historical Market Growth Curves for Popular Automotive Features (35 years)

Percent of NEW vehicles equipped each year

Figure 3.3.10. Diffusion of new technologies in the US car industry (in percent of car output). (Source: Jutila and Jutila, 1986.)
Dominance of Uncertainty

- Fusion of elements from IT, vehicle and infrastructure industries, with radically different cultures and time scales
- CV deployment governed by fate of NHTSA’s FMVSS 150 rulemaking
- AV development uncertainties
  - Rate of advancement of technologies, costs
  - User rate of market uptake
  - Rate of development of new greenfield cities or roadway infrastructure
- Decisions must be robust to uncertainties
CAV Industries

• Information technology
  – Product life cycles of months
  – Low-capital cost products and developments
  – Customer does beta testing for speed and cost saving

• Motor vehicle technology
  – Product life cycles of years
  – High capital cost products and developments
  – Safety-criticality requires extensive testing before release

• Roadway infrastructure technology
  – Product life cycles of decades
  – Very high capital cost products and developments
  – Safety-critical, and long time to plan and construct
Regional Diversity of Impacts

- Coastal/inland, sun belt/rust belt, urban/rural

Differences in:
- Affinity for new technologies
- Resources available to be early adopters
- Financial and human resources available to local governments
- Digital divide
- Availability and costs of right of way for infrastructure expansions
Passenger Travel Demand Effects (1/2)

- Reducing number of vehicle trips:
  - Telecommuting (work at home)
  - Remote work centers
  - Teleconferencing and virtual reality
  - Online retailing
  - Ride-share matching and TNCs

- Changing character of trips:
  - Traffic and route guidance information
  - Parking information
  - Decline of shopping malls and office parks
  - Growing importance of special event trips
Passenger Travel Demand Effects (2/2)

- Increasing number and length of trips:
  - Empty backhaul trips repositioning shared-use vehicles
  - High automation freeing up driver time to do other things (reduced “value of time”)
  - Mobility for older and younger travelers
  - Remote “driverless” valet parking at low-cost peripheral sites
  - Zero-occupancy roving billboards
Freight Travel Demand Effects

- Dominant influences are larger economic forces, international trade, etc.
- CAV can improve price and service quality of trucking relative to competing modes:
  - Better routing information to improve reliability, reduce travel times, save money
  - CACC/platooning improving traffic flow reliability, reducing delays, saving fuel costs
  - L3/L4 automation relieving driver shortage
  - L3/L4 automation enabling hours of service reforms, enhancing long-haul competitiveness
  - L4 automation eventually limiting need for drivers
- Different importance for long-haul vs. drayage trips
- Dedicated truck lanes could offer strong synergy
Supply Side: Traffic Improvements

- Collision warning and avoidance
- Enhanced traffic, incident and weather management by CV
- Variable speed limits and coordinated ramp metering
- Integrated corridor management
- Advance reservations for highway trips/peak spreading
- Enhanced ETTM with dynamic pricing
- Right-sized shared use automated transit vehicles
- Automated truck platoons (+ dedicated truck lanes)
- Automated urban freight distribution
- CACC and automated merge coordination
- L4 freeway automation (+ dedicated lanes)
Notes on Supply Side Improvements

• At high market penetrations, lane capacity improvements could be substantial:
  + 50 % for CACC
  + 100% for CACC + lane change coordination
  + 200% for L4 automation in dedicated lanes

• Improved connectivity, conspicuity and system management are low capital cost, but need substantial O&M support

• Funding formulas need to incentivize proper consideration of life cycle costs
10 - Year Horizon

- Dominated by inertia, with limited uncertainty
  - Many unequipped vehicles still on the road
  - Roadside IT improvements depend on public sector funding availability
  - Very limited physical infrastructure changes
- Significant V2V connectivity (if FMVSS 150 proceeds)
- I2V/V2I connectivity in more advanced regions
- Limited L1/L2 AV vehicle population, with limited traffic impacts
- Truck CACC/platooning possible for major fleets and corridors
20 - Year Horizon

• Vehicle connectivity should be virtually ubiquitous
  – Information to make travelers and traffic managers more efficient
• Substantial uncertainties on vehicle automation technology maturity and market penetration
  – Truck platooning commonly available
  – CACC and platooning of transit vehicles and private cars could improve urban interstate operations
  – Cooperative L4 automation could offer dramatic improvements if implemented in dedicated lanes
  – Prospects for L4 automation in mixed traffic depend on technological uncertainty
  – Market/user acceptance of L4 automation?
50 - Year Horizon

• Massive uncertainty about both societal and technological changes.
  – Changes in other domains affecting road travel needs (virtual reality, Hyperloop, …)
• Expect high levels of cooperative automation on Interstate network, maybe enough to dedicate lanes or sections for automation
  – Energy and emissions savings per VMT
  – Throughput and safety increases
  – Potential for realizing latent and induced demand, with locational changes
Cautionary Notes on AV Technology

- Beware of media hype on AV technology state of development
  - Most of what you see is wrong.
- Recognize the safety challenges involved if the driver is to be replaced by software
  - “perfect” software is a phantom
- Recognize hazard detection challenges for sensor systems
- Recognize differences in time scales for IT, vehicle and infrastructure industries (pacing by slowest)
- Remember how slowly the vehicle fleet turns over
The Safety Challenge

• Current U.S. traffic safety sets a very high bar:
  – 3.4 M vehicle hours between fatal crashes (390 years of non-stop 24/7 driving)
  – 61,400 vehicle hours between injury crashes (7 years of non-stop 24/7 driving)

• How does that compare with your laptop, tablet or “smart” phone?
• How much testing would you have to do to show that an automated system is equally safe?
  – RAND study – multiple factors longer times
• How many times safer does it need to be?
Evidence from Recent Testing

- California DMV testing rules require annual reports on safety-related disengagements
- Waymo (Google) far ahead of others:
  - All disengagements reconstructed in detailed simulations (what if allowed to continue?)
  - Simulations predicted ~5000 miles between critical events based on 2016 data (2.5 factor improvement over 2015)
- Human drivers in U.S. traffic safety statistics:
  - ~2 million miles per injury crash
  - 100 million miles per fatal crash
How to certify “safe enough”?

- What input conditions to assess?
- What combination of closed track testing, public road testing, and simulation?
  - How much of each is needed?
  - How to validate the simulation?
- What time and cost?
  - Aerospace experience shows software V&V representing 50% of new aircraft development cost (for much simpler software with continuous expert oversight)
Traffic Safety Challenges for High and Full Automation

• Extreme external conditions arising without advance warning (failure of another vehicle, dropped load, lightning, …)

• NEW CRASHES caused by automation:
  – Strange circumstances the system designer could not anticipate
  – Software bugs not exercised in testing
  – Undiagnosed faults in the vehicle
  – Catastrophic failures of vital vehicle systems (loss of electrical power, …)

• Driver not available to act as the fall-back
Dynamic External Hazards (Examples)

- Behaviors of other vehicles:
  - Entering from blind driveways
  - Violating traffic laws
  - Moving erratically following crashes with other vehicles
  - Law enforcement (sirens and flashing lights)
- Pedestrians (especially small children)
- Bicyclists
- Officers directing traffic
- Animals (domestic pets to large wildlife)
- Opening doors of parked cars
- Unsecured loads falling off trucks
- Debris from previous crashes
- Landslide debris (sand, gravel, rocks)
- Any object that can disrupt vehicle motion
Environmental Conditions (Examples)

- Electromagnetic pulse disturbance (lightning)
- Precipitation (rain, snow, mist, sleet, hail, fog,…)
- Other atmospheric obscurants (dust, smoke,…)
- Night conditions without illumination
- Low sun angle glare
- Glare off snowy and icy surfaces
- Reduced road surface friction (rain, snow, ice, oil…)
- High and gusty winds
- Road surface markings and signs obscured by snow/ice
- Road surface markings obscured by reflections off wet surfaces
- Signs obscured by foliage or displaced by vehicle crashes
Internal Faults – Functional Safety Challenges

Solvable with a lot of hard work:

• Mechanical and electrical component failures
• Computer hardware and operating system glitches
• Sensor condition or calibration faults

Requiring more fundamental breakthroughs:

• System design errors
• System specification errors
• Software coding bugs
Needed Breakthroughs

• Software safety design, verification and validation methods to overcome limitations of:
  – Formal methods
  – Brute-force testing
  – Non-deterministic learning systems

• Robust threat assessment sensing and signal processing to reach zero false negatives and near-zero false positives

• Robust control system fault detection, identification and accommodation, within 0.1 s response

• Ethical decision making for robotics

• Cyber-security protection
## Much Harder than Commercial Aircraft Autopilot Automation

<table>
<thead>
<tr>
<th>Measure of Difficulty – Orders of Magnitude</th>
<th>Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of targets each vehicle needs to track (~10)</td>
<td>1</td>
</tr>
<tr>
<td>Number of vehicles the region needs to monitor (~10^6)</td>
<td>4</td>
</tr>
<tr>
<td>Accuracy of range measurements needed to each target (~10 cm)</td>
<td>3</td>
</tr>
<tr>
<td>Accuracy of speed difference measurements needed to each target (~1 m/s)</td>
<td>1</td>
</tr>
<tr>
<td>Time available to respond to an emergency while cruising (~0.1 s)</td>
<td>2</td>
</tr>
<tr>
<td>Acceptable cost to equip each vehicle (~$3000)</td>
<td>3</td>
</tr>
<tr>
<td>Annual production volume of automation systems (~10^6)</td>
<td>-4</td>
</tr>
<tr>
<td><strong>Sum total of orders of magnitude</strong></td>
<td><strong>10</strong></td>
</tr>
</tbody>
</table>
Backup Slides on Automation Developments
No Automation and Driver Assistance (Levels 0, 1)

• Primary safety advancements likely at these levels, adding machine vigilance to driver vigilance
  – Safety warnings based on ranging sensors
  – Automation of one function facilitating driver focus on other functions

• Driving comfort and convenience from assistance systems (ACC)

• Traffic, energy, environmental benefits depend on V2V, I2V cooperation

• Widely available on cars and trucks now
Partial Automation (Level 2) Impacts

- Probably only on limited-access highways
- Somewhat increased driving comfort and convenience (but driver still needs to be actively engaged)
- Possible safety increase, depending on effectiveness of driver engagement
  - Safety concerns if driver tunes out
- (only if V2V cooperative) Increases in energy efficiency and traffic throughput
- When? Now (Mercedes, Infiniti, Volvo, Tesla)
Intentional Mis-Uses of Level 2 Systems by ordinary drivers

Mercedes S-Class

Infiniti Q50

Let's see how well the Active Lane Control works on the new Infiniti Q50S
Conditional Automation (Level 3) Impacts

• Driving comfort and convenience increase
  – Driver can do other things while driving, so disutility of travel time is reduced
  – Limited by requirement to be able to re-take control of vehicle in a few seconds when alerted

• Safety uncertain, depending on ability to re-take control in emergency conditions

• (only if V2V cooperative) Increases in efficiency and traffic throughput

• When? Unclear – safety concerns could impede introduction
High Automation (Level 4) Impacts – General-purpose light duty vehicles

• Only usable in some places (limited-access highways, maybe only in managed lanes)
• Large gain in driving comfort and convenience on available parts of trip (driver can sleep)
  – Significantly reduced value of time
• Safety improvement, based on automatic transition to minimal risk condition
• (only if V2V cooperative) Significant increases in energy efficiency and traffic throughput from close-coupled platooning
• When? Starting 2020 – 2025?
PATH Automated Platoon – 1997 Demo (Level 4 automation in protected lane)
High Automation (Level 4) Impacts – Special applications

- Buses on separate transitways
  - Narrow right of way – easier to fit in corridors
  - Rail-like quality of service at lower cost
- Heavy trucks on dedicated truck lanes
  - (cooperative) Platooning for energy and emission savings, higher capacity
- Automated (driverless) valet parking
  - More compact parking garages
- Driverless shuttles within campuses or pedestrian zones at low speeds
  - Facilitating new urban designs, first mile/last mile
- When? Could be just a few years away
CityMobil2 La Rochelle Demo 2015
Level 4 Urban Shuttle, Infrastructure Protection
Limited Pace of Change in Transportation

• Consider useful lifetimes of investments in:
  – Roadway infrastructure – decades
  – Vehicles – years
  – Personal electronics – months

• Essential differences:
  – Capital intensity
  – Safety criticality
  – Cost of making a mistake
Big Unresolved Questions (1/2)

• How safe is “safe enough”?
• How can an AV be reliably determined to meet any specific target safety level?
• What roles should national and regional/state governments play in determining whether a specific AV is “safe enough” for public use?
• Should AVs be required to inhibit abuse and misuse by drivers?
• How long will it take to achieve the fundamental technological breakthroughs needed for higher levels of automation?
Big Unresolved Questions (2/2)

• How much support and cooperation do AVs need from roadway infrastructure and other vehicles?
• What should the public sector role be in providing infrastructure support?
• Are new public-private business models needed for higher levels of automation?
• How will AVs change public transport services, and to what extent will societal goals for mobility be enhanced or degraded?
• What will be the net impacts of AVs on vehicle miles traveled, energy and environment?
How should we prepare?

- Install cooperative infrastructure for I2V communication (5.9 GHz DSRC) at traffic signals
- Support regulations that balance public safety and encouraging innovation
- Seek early deployment opportunities for first generation systems (automated shuttles in well protected environments)
- Support infrastructure investments to segregate automated vehicles from other road users
- Local governments identify their point persons for vehicle automation (cutting across traditional agency stove-pipes)