Opportunities and Challenges for Implementation of Automation in Road Transportation

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Outline

- Levels of road vehicle automation
- Impacts of each level of automation on travel (and when?)
- Safety and technical challenges
- Broader deployment challenges
- What to do now?

Terminology Problems

- **Common misleading, vague to wrong terms:**
  - **"driverless" – but generally they're not!**
  - **"self-driving"**
  - **"autonomous" – 4 common usages, but different in meaning (and 3 are wrong!)**
- **Central issues to clarify:**
  - **Roles of driver and "the system"**
  - **Degree of connectedness and cooperation**
  - **Operational Design Domain (ODD)**

Definitions
(per Oxford English Dictionary)

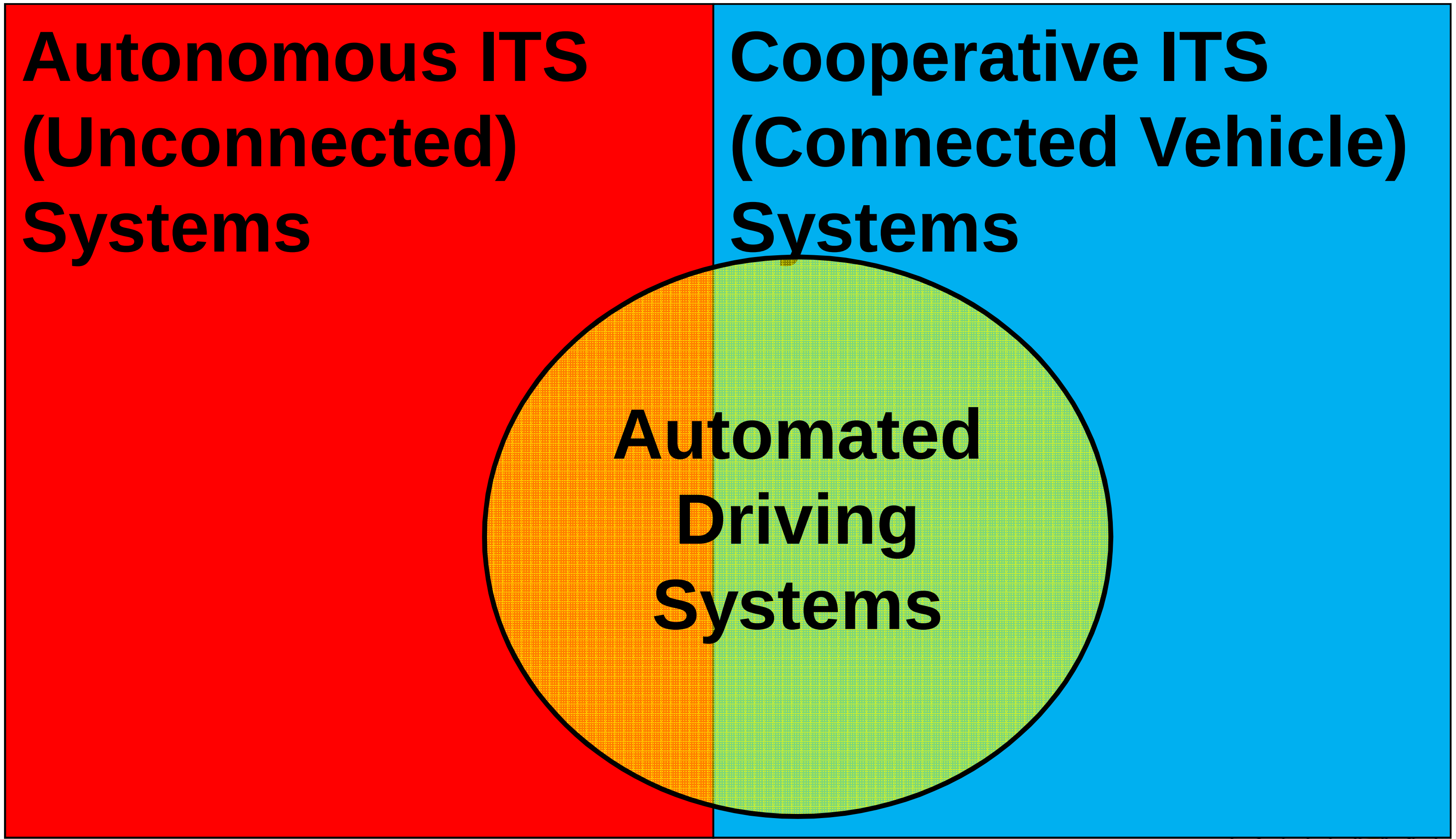
- **autonomy:**
  1. *(of a state, institution, etc.)* the right of self-government, of making its own laws and administering its own affairs
  2. *(biological)* (a) the condition of being controlled only by its own laws, and not subject to any higher one; (b) organic independence
  3. a self-governing community.

  autonomous:
  1. of or pertaining to an autonomy
  2. possessed of autonomy, self governing, independent
  3. *(biological)* (a) conforming to its own laws only, and not subject to higher ones; (b) independent, i.e., not a mere form or state of some other organism.

- **automate: to apply automation to; to convert to largely automatic operation**

  automation: automatic control of the manufacture of a product through a number of successive stages; the application of automatic control to any branch of industry or science; by extension, the use of electronic or mechanical devices to replace human labour

Autonomous and Cooperative ITS



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 more…)**

Other Important SAE J3016 Terms

- **DYNAMIC DRIVING TASK (DDT) - All of the real-time operational and tactical functions required to operate a vehicle in on-road traffic, excluding the strategic functions such as trip scheduling and selection of destinations and waypoints.**
- **OBJECT AND EVENT DETECTION AND RESPONSE (OEDR) - The subtasks of the DDT that include monitoring the driving environment (detecting, recognizing, and classifying objects and events and preparing to respond as needed) and executing an appropriate response to such objects and events (i.e., as needed to complete the DDT and/or DDT fallback).**
- **SAE J3016 definitions document available free at: http://standards.sae.org/j3016_201609/**

Taxonomy of Levels of Automation

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

1. Whether the driving automation system performs *either* the longitudinal *or* the lateral vehicle motion control subtask of the DDT.

2. Whether the driving automation system performs *both* the longitudinal and the lateral vehicle motion control subtasks of the DDT simultaneously.

3. Whether the driving automation system *also* performs the OEDR subtask of the DDT.

4. Whether the driving automation system *also* performs DDT fallback.

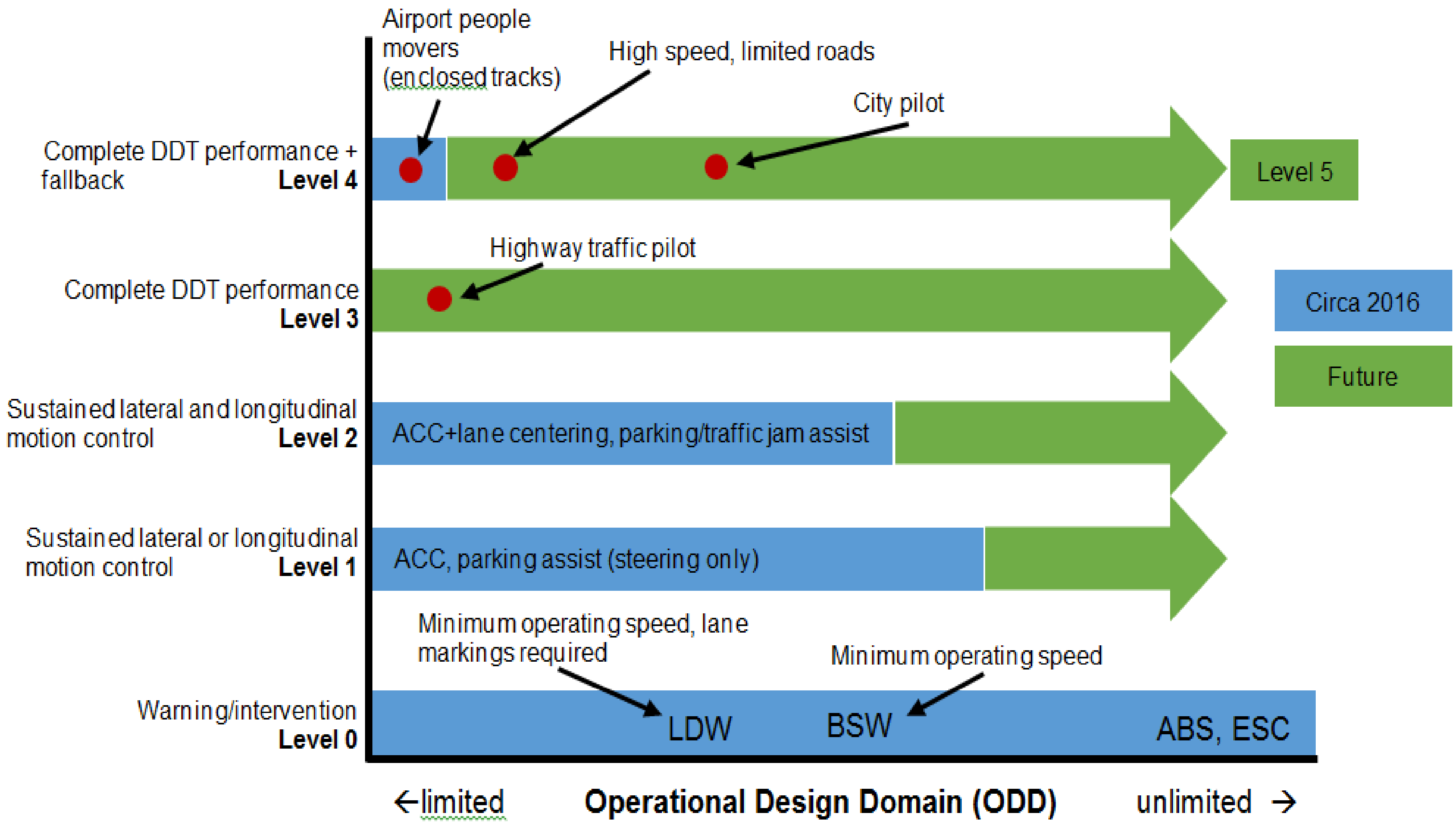
5. Whether the driving automation system is limited by an ODD.

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

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 Keeping Assistance Traffic Jam Assist (Mercedes, Tesla, Infiniti, Volvo…) Parking with external supervision	Must monitor driving environment (system nags 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	No drivers needed


Airport people movers (enclosed tracks)
High speed, limited roads
City pilot
Complete DDT performance + fallback Level 4
Level 5
Highway traffic pilot
Complete DDT performance Level 3
Circa 2016
Future
Sustained lateral and longitudinal motion control Level 2
ACC+lane centering, parking/traffic jam assist
Sustained lateral or longitudinal motion control Level 1
ACC, parking assist (steering only)
Minimum operating speed, lane markings required
Minimum operating speed
Warning/intervention Level 0
LDW
BSW
ABS, ESC
←limited
Operational Design Domain (ODD)
unlimited →

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Automation Is a Tool for Solving Transportation Problems

- **Alleviating congestion**
  - **Increase capacity of roadway infrastructure**
  - **Improve traffic flow dynamics**
- **Reducing energy use and emissions**
  - **Aerodynamic “drafting”**
  - **Improve traffic flow dynamics**
- **Improving safety**
  - **Reduce and mitigate crashes**

…BUT the vehicles need to be connected

Alleviating Congestion

- **Typical U.S. highway capacity is up to 2200 vehicles/hr/lane (or 750 trucks/hr/lane)**
  - **Governed by drivers' car following and lane changing gap acceptance needs**
  - **Vehicles occupy only 5% of road surface at maximum capacity**
- **Stop and go disturbances (shock waves) result from drivers' response delays**
- **<u>V2V Cooperative</u> automation provides shorter gaps, faster responses, and more consistency**
- **<u>I2V Cooperation</u> maximizes bottleneck capacity by setting most appropriate target speed**

→ Significantly higher throughput per lane

→ Smooth out transient disturbances

Reducing Energy and Emissions

- **At highway speeds, half of energy is used to overcome aerodynamic drag**
  - **Close-formation automated platoons can save 10% to 20% of total energy use**
- **Accelerate/decelerate cycles waste energy and produce excess emissions**
  - **Automation can eliminate stop-and-go disturbances, producing smoother and cleaner driving cycles**
- **BUT, this only happens with V2V cooperation**

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Improving Safety

- **95% of crashes in the U.S. are caused by driver behavior problems (perception, judgment, response, inattention) and environment (low visibility or road surface friction)**
- **Automation avoids driver behavior problems**
- **Appropriate sensors and communications are not vulnerable to weather problems**
  - **Automation systems can detect and compensate for poor road surface friction**
- **BUT, current traffic safety sets a very high bar:**
  - **3.3 M vehicle <u>hours</u> between fatal crashes (375 years of non-stop 24/7 driving)**
  - **65,000 vehicle <u>hours</u> between injury crashes (7+ years of non-stop 24/7 driving)**

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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 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 cooperative) Increases in energy efficiency and traffic throughput**
- **When? Now (Mercedes, Infiniti, Volvo, Tesla)**

Intentional Mis-Uses of Level 2 Systems

Mercedes S-Class

Infiniti Q50

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 cooperative) Increases in efficiency and traffic throughput**
- **When? Unclear – safety concerns could impede introduction**

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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 cooperative) Significant increases in energy efficiency and traffic throughput from close-coupled platooning**
- **When? Starting 2020 – 2025?**

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**
  - Facilitating new urban designs
- **When? Could be just a few years away**

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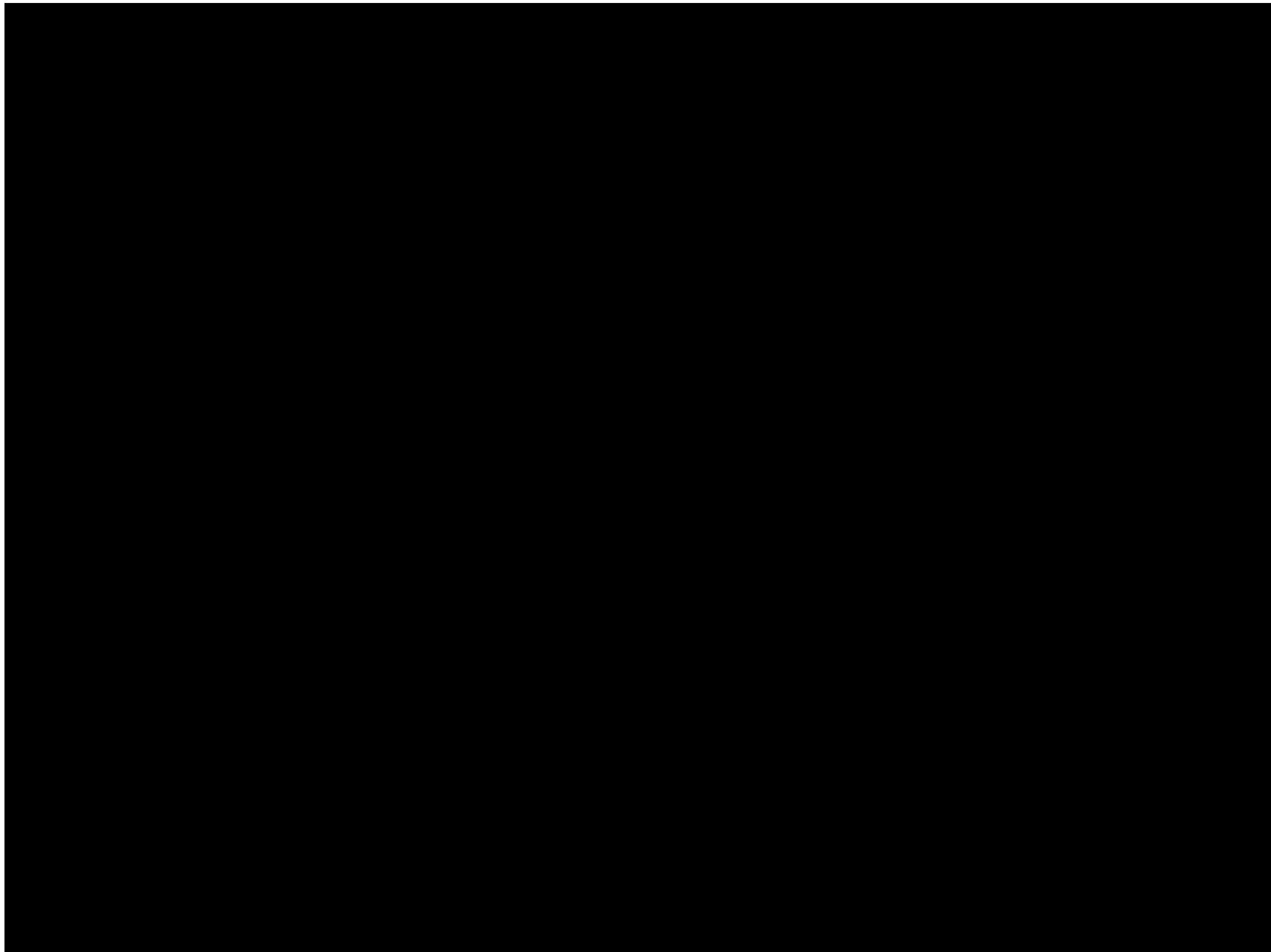
Low-Speed Shuttle in La Rochelle – Vehicle and Infrastructure Combined

Vehicle-Infrastructure Protection for L4



Potential for Shared-Use Vehicles at L4?

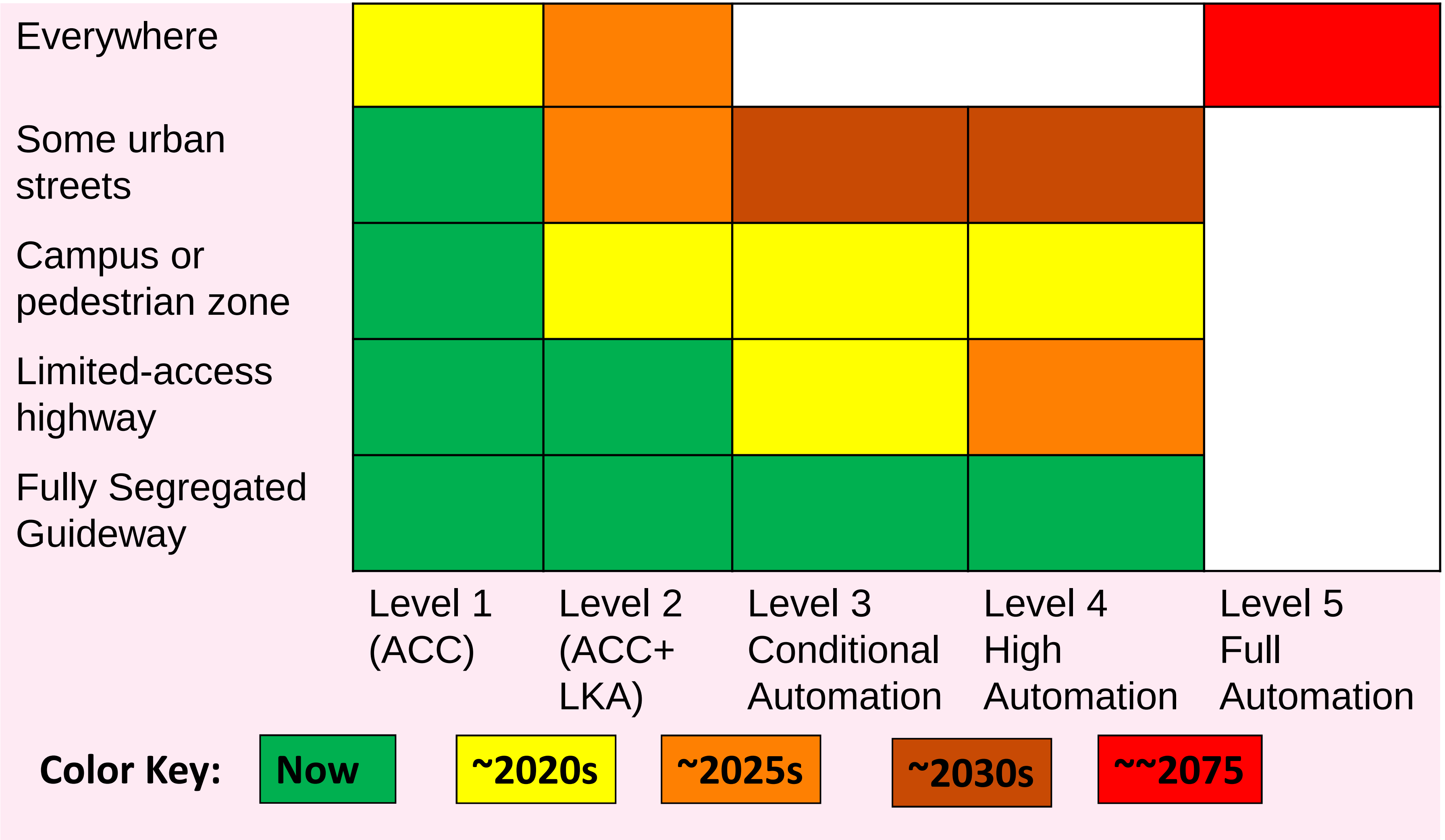
- **Specialized low-speed shuttles for first and last mile access, on protected fixed routes - yes**
- **"Driverless" taxi or car-share repositioning services? – Only under severely constrained ODD conditions for the foreseeable future:**
  - **Strict geo-fencing to carefully mapped and physically protected zones**
  - **Low speed operations only**
  - **Fair weather only**
  - **Close supervision by dispatch center**

Full Automation (Level 5) Impacts

- **Ubiquitous electronic taxi service for mobility-challenged travelers (young, old, impaired)**
- **Ubiquitous shared vehicle fleet repositioning (driverless)**
- **Ubiquitous "driverless" urban goods pickup/delivery**
- **Full "electronic chauffeur" service**

- **Ultimate comfort and convenience**
  - **Travel time disutility plunge**
- ***(if cooperative)* Large energy efficiency and road capacity gains**
- **When? Many decades… (Ubiquitous operation without driver is a huge technical challenge)**

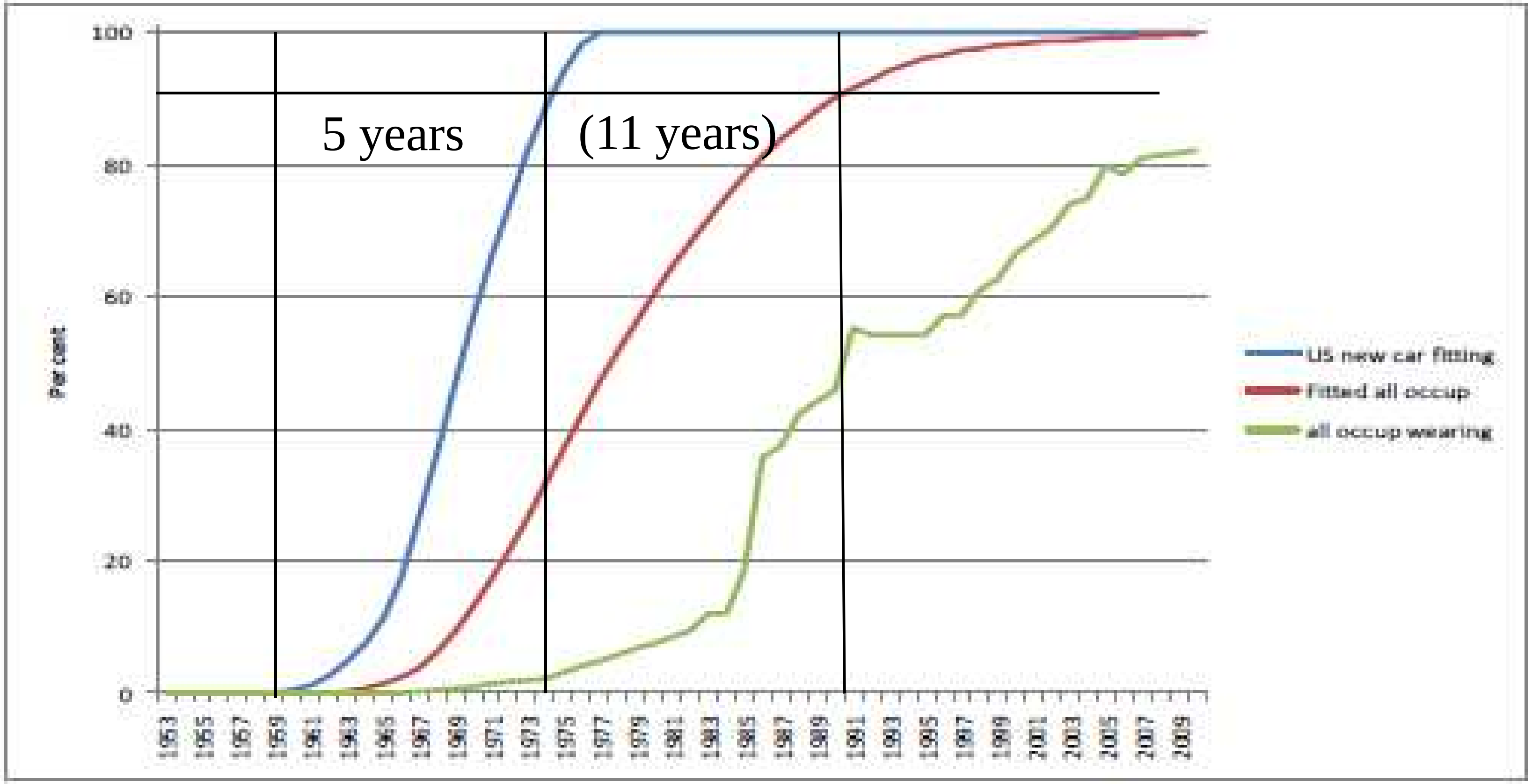
Personal Estimates of Market Introductions
** based on technological feasibility **



Example Market Growth for Seat Belts After Mandate

Figure 1: US seat belt adoption curves

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



Fastest possible adoption, required by law in U.S.

Historical Market Growth Curves for Popular Automotive Features

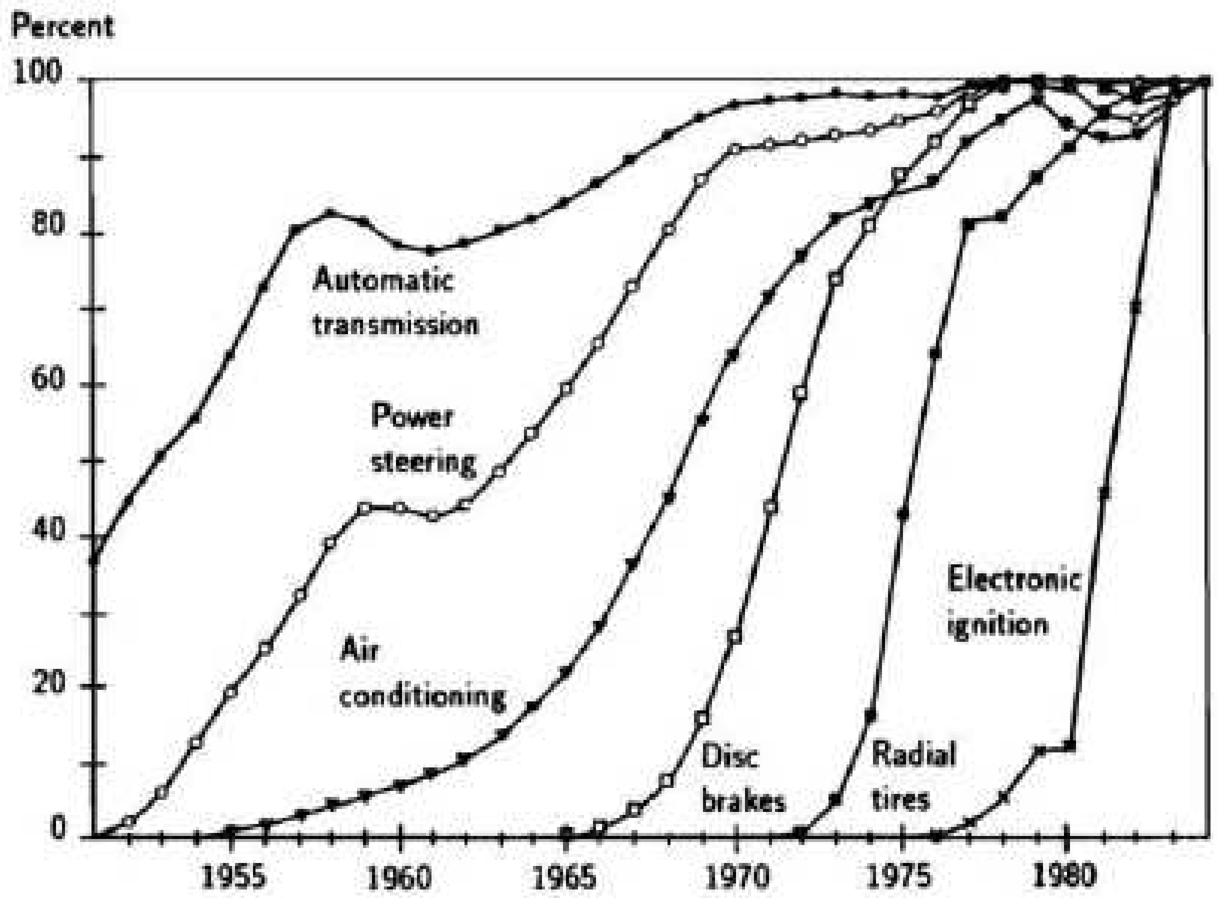


Figure 3.3.10. Diffusion of new technologies in the US car industry (in percent of car output). (Source: Jutila and Jutila, 1986.)

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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**

Why this is a super-hard problem

- **Software intensive system (no technology available to verify or validate its safety under its full range of operating conditions)**
- **Electro-mechanical elements don't benefit from Moore's Law improvements**
  - **Cannot afford extensive hardware redundancy for protection from failures**
- **Harsh and unpredictable hazard environment**
- **Non-professional vehicle owners and operators cannot ensure proper maintenance and training**

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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

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Much Harder than Commercial Aircraft Autopilot Automation

Measure of Difficulty – Orders of Magnitude	Factor
Number of targets each vehicle needs to track (~10)	1
Number of vehicles the region needs to monitor (~10^6)	4
Accuracy of range measurements needed to each target (~10 cm)	3
Accuracy of speed difference measurements needed to each target (~1 m/s)	1
Time available to respond to an emergency while cruising (~0.1 s)	2
Acceptable cost to equip each vehicle (~$3000)	3
Annual production volume of automation systems (~10^6)	- 4
Sum total of orders of magnitude	**10**

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Human Interactions with Technology

- **Fundamental changes in the nature of the driving task**
- **Driver capabilities and preferences are extremely diverse, across <u>and</u> within drivers**
- **Unclear how to “train” drivers to acquire correct mental models of capabilities and limitations of automation systems**
- **Drivers will “push the envelope” beyond system capabilities, which could become extremely dangerous**
- **No viable experimental protocols to safely test drivers’ usage of higher automation levels**

Public and Private Sector Interactions

- **Public road infrastructure and private vehicles**
- **Must cooperate to deploy an integrated system to be able to provide societal benefits**
- **Radically different investment planning horizons**
  - **Decades for roadway infrastructure**
  - **Years for vehicles**
  - **Months for information technology**
- **Potentially conflicting priorities**
- **Mutual suspicion and mistrust**

Public Policy Considerations

- **Need business models for funding supporting infrastructure deployment**
- **Identify public policy actions to facilitate automation implementation**
- **Harmonization of goals and regulations (federal/state and among states)**
- **Lessons learned from other transportation technology rollouts (e.g. air traffic control)**
- **Voters, journalists and politicians are generally technological illiterates**
- **Many aspects of motor vehicle usage will change, invalidating assumptions behind existing rules**

Fundamental Challenges in Defining Automation Regulations

- **Balancing need to protect public safety (due diligence) with desire to encourage technological innovation**
- **Blurred boundaries between regulating new vehicle equipment and regulating how vehicles are operated**
- **Lack of technical standards to provide baseline references for performance, safety or testing protocols**
- **Trying to ensure that general public really understands limitations of their vehicles**
- **Detecting unsafe systems as early as possible**
- **Cultural differences between automotive and information technology industries**
- **Self-certification vs. third-party certification**

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NHTSA Policy Guidance

- Released for public comment and review Sept. 20, 2016
  - 112-page report with 123 footnotes
- Broad statement of balanced approach in four areas:
  - Vehicle performance guidance
  - Model state policy
  - NHTSA's current regulatory tools
  - Modern (future) regulatory tools
- Applies to "highly automated vehicles", HAV (SAE Levels 3-5)
- Extensive outreach in progress

U.S. Department of Transportation

NHTSA

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NHTSA “Safety Assessment Letter”

- Data recording and sharing
- Privacy
- System safety
- Vehicle cybersecurity
- Human-machine interface
- Crashworthiness
- Consumer education and training
- Registration and certification
- Post-crash behavior
- Federal, state and local laws
- Ethical considerations
- Operational design domain
- Object and event detection and response
- Fallback (minimal risk condition)
- Validation methods

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NHTSA’s Model State Policy

- **Developed in coordination with AAMVA**
- **Defines boundaries between federal and state**
- **Main elements:**
  - **Define administrative framework by state**
  - **Specify application for testing on public roads**
  - **Local jurisdictions to grant permission for testing**
  - **Minimum rules for testing, test drivers**
  - **Re-examine rules for drivers**
  - **Code HAV on registration**
  - **Study law enforcement changes needed**
  - **Re-examine liability and insurance regulations**
- **Planned cross-border engagement with Canada, Mexico**

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?

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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?

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NCHRP Projects to Help State and Local Governments Prepare for AVs

- **Research Roadmap from NCHRP 20-24(98) published, covering connected vehicles (CV), automated vehicles (AV) and connected automated vehicles (CAV)**
- **Projects identified in Roadmap being funded as separate tasks in NCHRP 20-102 or through other DOT mechanisms**

NCHRP Roadmap: Institutional and Policy Issues

- **Business models for infrastructure deployment**
- **Public policy actions to facilitate implementation**
- ***Implications of AV for motor vehicle codes – 20-102(07)***
- **Harmonization of state goals and regulations**
- **Federal/state/local responsibilities**
- **Lessons learned from Safety Pilot and CV Pilots**
- **Lessons learned from other tech rollouts (e.g. 511, Next Gen air traffic control)**

NCHRP Roadmap: Infrastructure Design and Operations Issues

- ***Road infrastructure design – 20-102(06)***
- **Tools for CV/AV impact assessment**
- **CV/AV maintenance fleet applications**
- **Relationships of CV to AV**
- **Traffic control strategies**
- ***Dedicated lanes for CV/AV – 20-102(08)***
- **Roadway geometric design**
- ***Cybersecurity for states and locals – 20-102(10)***
- **Workforce capability strategies**
- **Management of "Big" Data**

NCHRP Roadmap: Transportation Planning

- ***AVs and regional long-term planning models – 20-102(09)***
- **Assessing impacts of CV/AV (applying tools to test cases)**
- **Modeling long-term effects of AV/CV on land use and travel demand**

NCHRP Roadmap: Modal Applications

- ***Impacts of transit regulations on AV/CV tech introduction - 20-102(02)***
- ***Next steps for AV/CV applications to long-haul freight – 20-102(03)***
- **Benefit/cost analysis of AV transit systems**

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What to do now?

- **Focus first on connected vehicle capabilities to provide technology for cooperation**
- **For earliest public benefits from automation, focus on transit and trucking applications in protected rights of way**
  - **Professional drivers and maintenance**
  - **Direct economic benefits to users**
- **Capitalize on managed lanes to concentrate equipped vehicles together**
- **Develop enabling technologies for Level 5 automation (software verification and safety, real-time fault identification and management, hazard detection sensing,…)**

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