# 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/)

| Level | Example Systems | Driver Roles |
| --- | --- | --- |
| 1 | Adaptive Cruise Control OR<br>Lane Keeping Assistance | Must drive <u>other</u> function and monitor driving environment |
| 2 | Adaptive Cruise Control AND Lane Keeping Assistance<br>Traffic Jam Assist (Mercedes, Tesla, Infiniti, Volvo…)<br>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<br>Closed campus “driverless” shuttle<br>“Driverless” valet parking in garage | May sleep, and system can revert to minimum risk condition if needed |
| 5 | Ubiquitous automated taxi<br>Ubiquitous car-share repositioning | Can operate anywhere with no drivers needed |

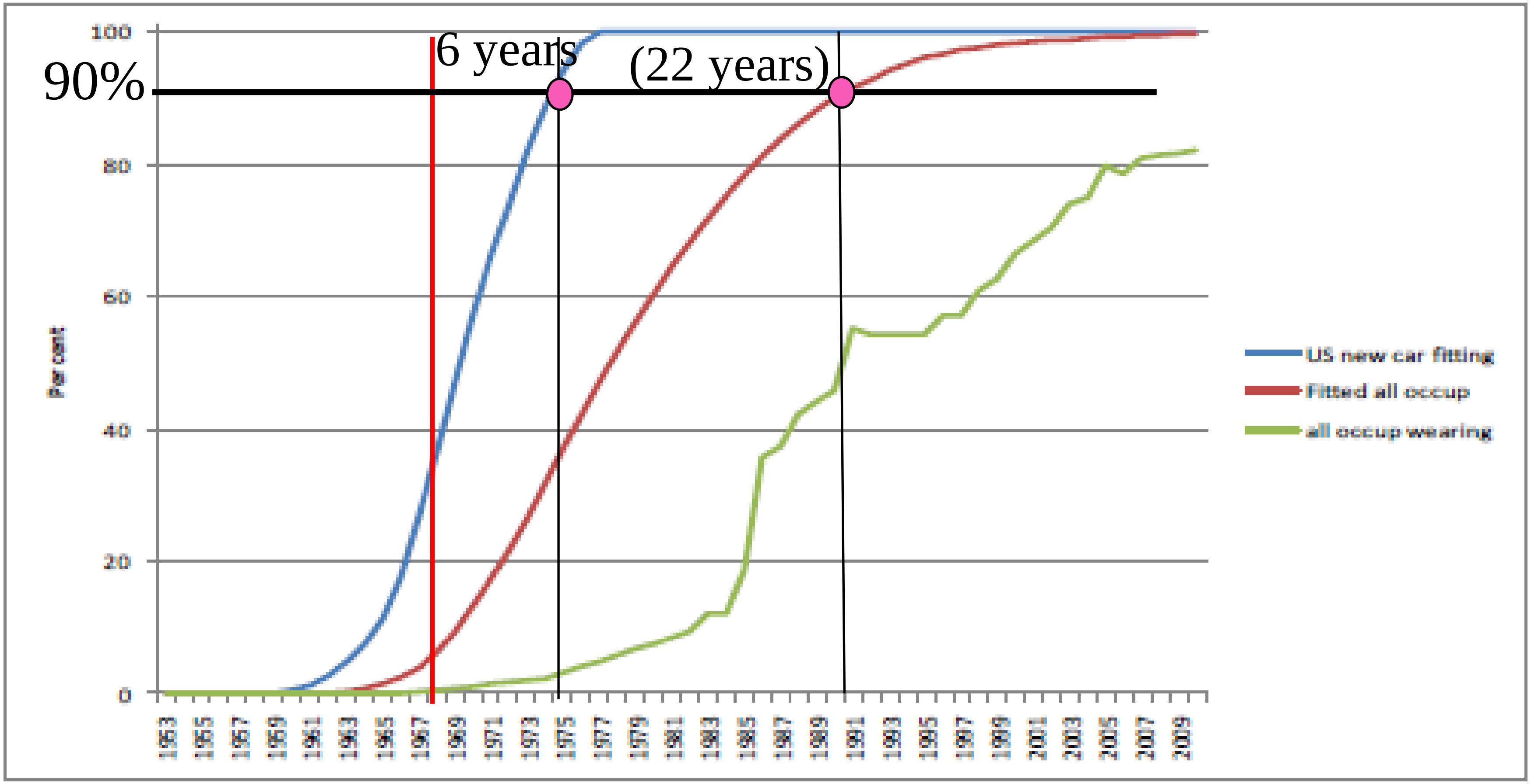
# Operational Design Domain (ODD)

- **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

**Figure 1: US seat belt adoption curves**

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



# Historical Market Growth Curves for Popular Automotive Features (35 years)

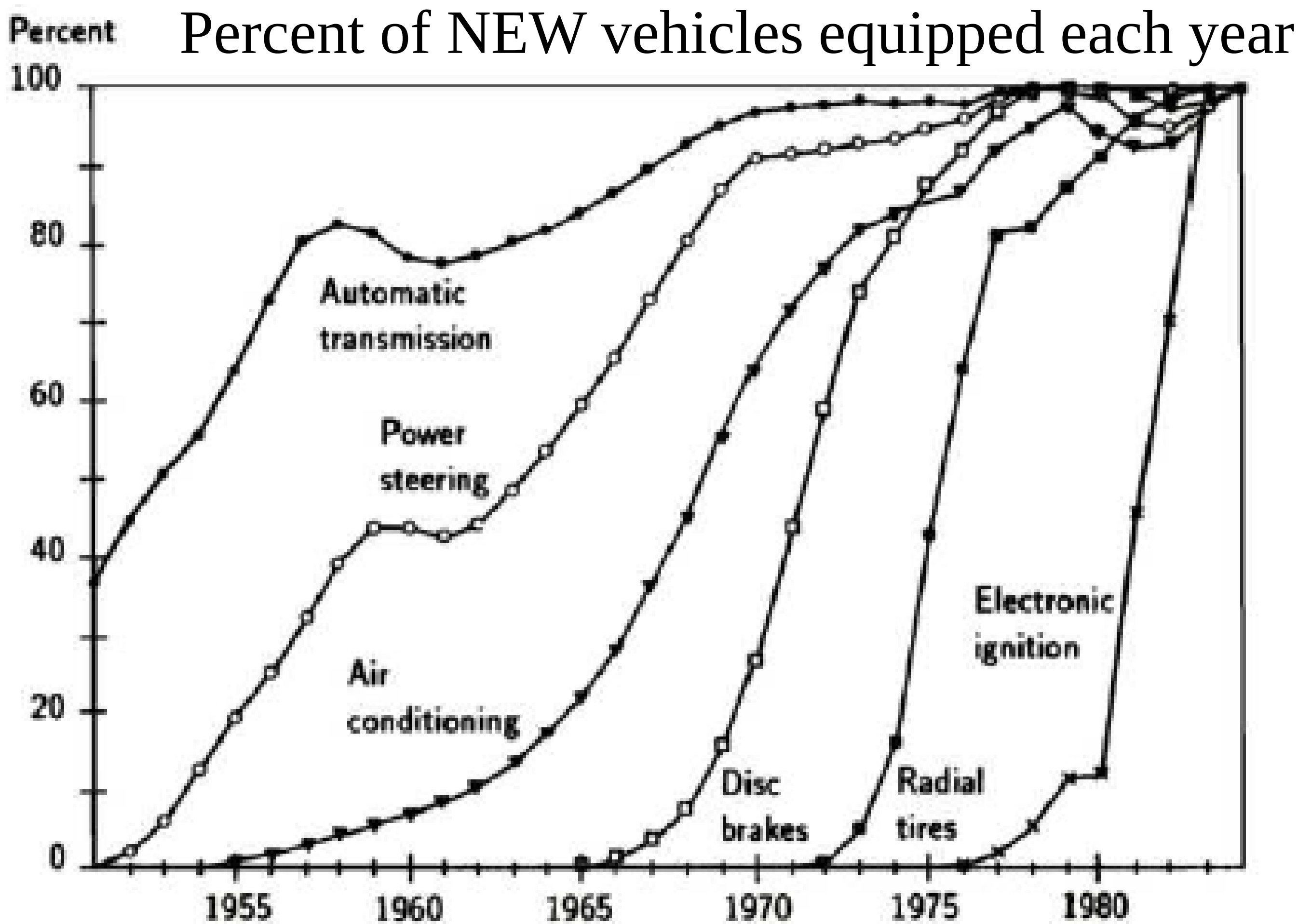



**Figure 3.3.10.** Diffusion of new technologies in the US car industry (in percent of car output). (Source: Jutila and Jutila, 1986.)

# 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 <u>months</u>
  - Low-capital cost products and developments
  - Customer does beta testing for speed and cost saving
- **Motor vehicle technology**
  - Product life cycles of <u>years</u>
  - High capital cost products and developments
  - Safety-criticality requires extensive testing before release
- **Roadway infrastructure technology**
  - Product life cycles of <u>decades</u>
  - 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 <u>hours</u> between fatal crashes (390 years of non-stop 24/7 driving)**
  - **61,400 vehicle <u>hours</u> 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

| 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** |

# 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**

# 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 <u>net</u> 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)