Road Vehicle Automation History, Opportunities and Challenges

Steven E. Shladover, Sc.D.
California PATH Program
Institute of Transportation Studies
University of California, Berkeley

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Outline

- Historical development of automation
- Levels of road vehicle automation
- Benefits to be gained from automation
- Why cooperation (*not autonomy*) is needed
- Impacts of each level of automation on travel (and when?)
- Challenges (technical and non-technical)
- What to do now?

History of Automated Driving (pre-Google)

- **1939 – General Motors “Futurama” exhibit**
- **1949 – RCA technical explorations begin**
- **1950s – GM/RCA collaborative research**
- **1950s – GM “Firebird II” concept car**
- **1964 – GM “Futurama II” exhibit**
- **1964-80 – Research by Fenton at OSU**
- **1960s – Tsugawa wire following in Japan**
- **1970s – Tsugawa vision guidance in Japan**
- **1986 – California PATH and PROMETHEUS programs start**
- **1980s – Dickmanns vision guidance in Germany**
- **1994 – PROMETHEUS demo in Paris**
- **1994-98 – National AHS Consortium (Demo ‘97)**
- **2003 – PATH automated bus and truck demos**
- ***(2004 - 2007 – DARPA Challenges)***

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General Motors 1939 Futurama

GM Firebird II Publicity Video

GM Technology in 1960

General Motors 1964 Futurama II

Robert Fenton’s OSU Research

Pioneering Automated Driving in Japan
(courtesy of Prof. Tsugawa, formerly at MITI)

1960s – Wire following
Kikuchi and Matsumoto

1970s – Vision Guidance
(Tsugawa)

Pioneering Automated Driving in Germany (1988 - courtesy Prof. Ernst Dickmanns, UniBWM)

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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**

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

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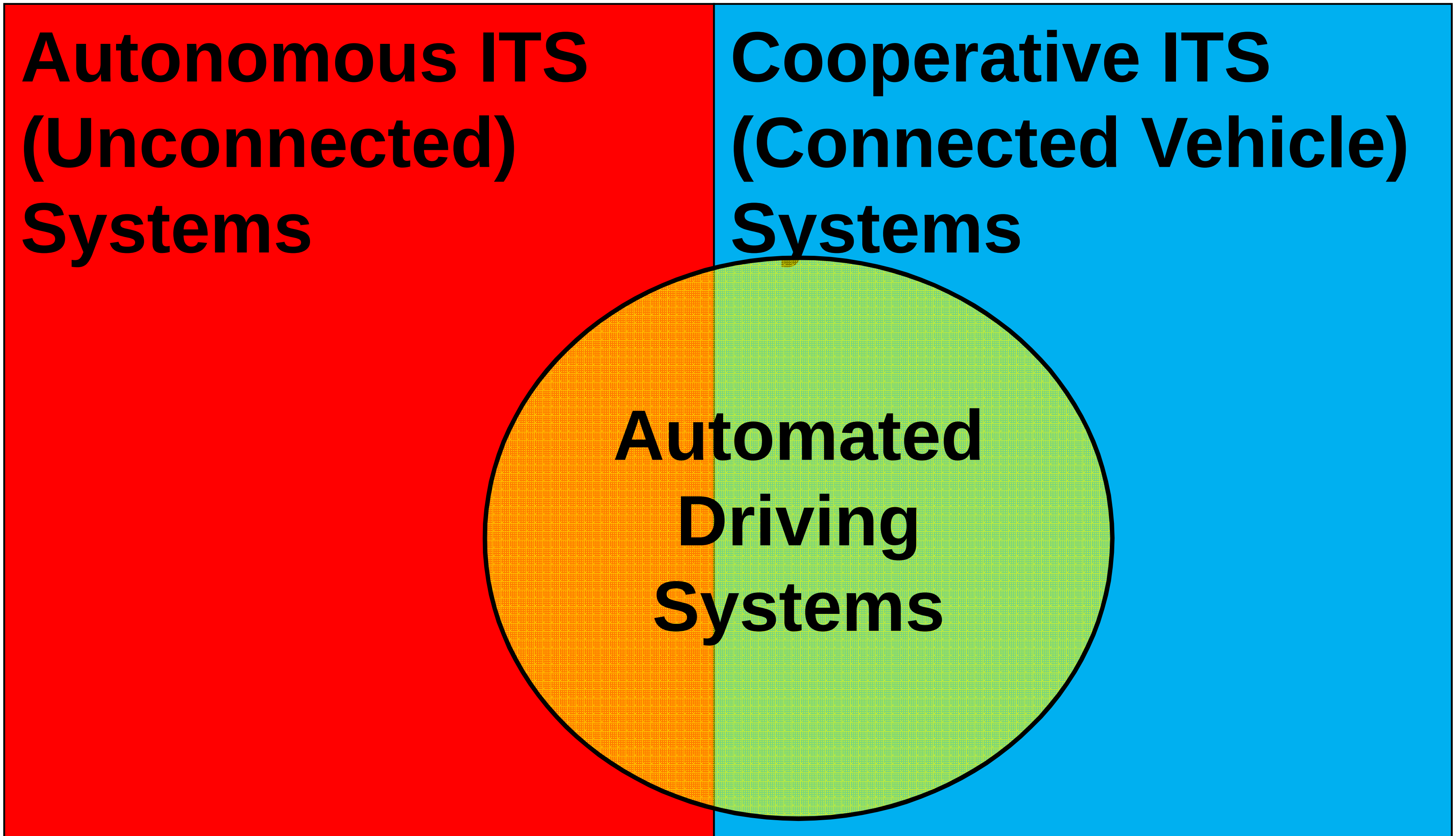
Autonomous and Cooperative ITS



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 <u>other</u> function and monitor driving environment
2	Adaptive Cruise Control AND Lane Keeping Assistance Traffic Jam Assist (Mercedes)	Must monitor driving environment (system nags driver to try to ensure it)
3	Traffic Jam Pilot Automated parking with supervision	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	Automated taxi (even for children) Car-share repositioning system	No driver needed

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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 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

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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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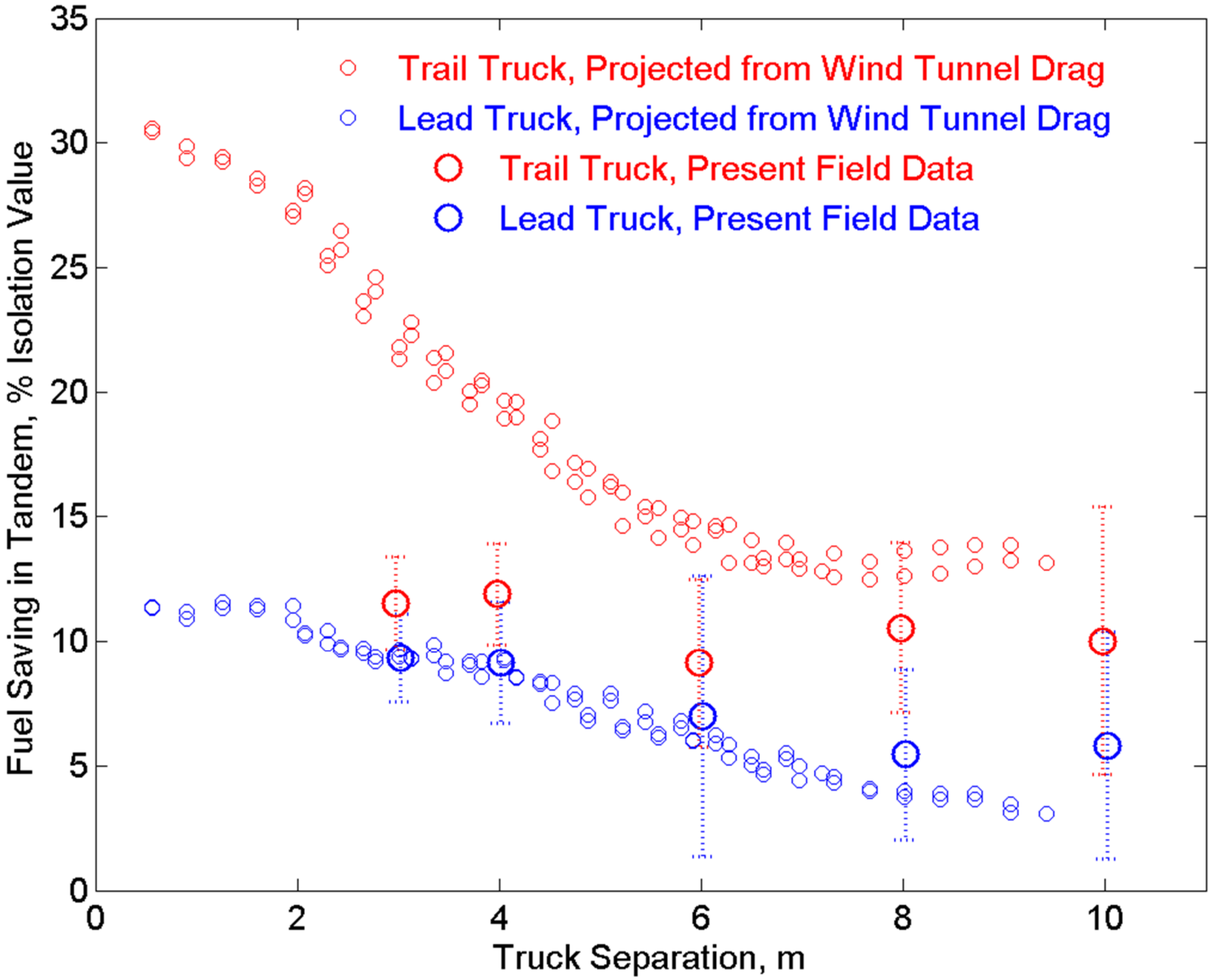
Heavy Truck Energy Savings from Close-Formation Platoon Driving



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 U.S. 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 driving)**

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Cooperation Augments Sensing

- Autonomous vehicles are "deaf-mute"
- Cooperative vehicles can "talk" and "listen" as well as "seeing" (using 5.9 GHz DSRC comm.)
  - NHTSA regulatory mandate in process in U.S.
- Communicate vehicle performance and condition directly rather than sensing indirectly
  - Faster, richer and more accurate information
  - Longer range
- Cooperative decision making for system benefits
- Enables closer separations between vehicles
- Expands performance envelope – safety, capacity, efficiency and ride quality

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Challenges to Achieving Cooperation

- "Chicken and egg" problem – who equips first?
  - May need regulatory "push" to seed the market
- Benefits scale strongly with market penetration
  - Need to concentrate equipped vehicles in proximity to each other
- Deployment opportunity using managed lanes
  - Economic incentives
  - Productivity increases

Examples of Performance That is <u>Only</u> Achievable Through Cooperation

- **Vehicle-Vehicle Cooperation**
  - **Cooperative adaptive cruise control (CACC) to eliminate shock waves**
  - **Automated merging of vehicles, starting beyond line of sight, to smooth traffic**
  - **Multiple-vehicle automated platoons at short separations, to increase capacity**
  - **Truck platoons at short enough spacings to reduce drag and save energy**
- **Vehicle-Infrastructure Cooperation**
  - **Speed harmonization to maximize flow**
  - **Speed reduction approaching queue for safety**
  - **Precision docking of transit buses**
  - **Precision snowplow control**

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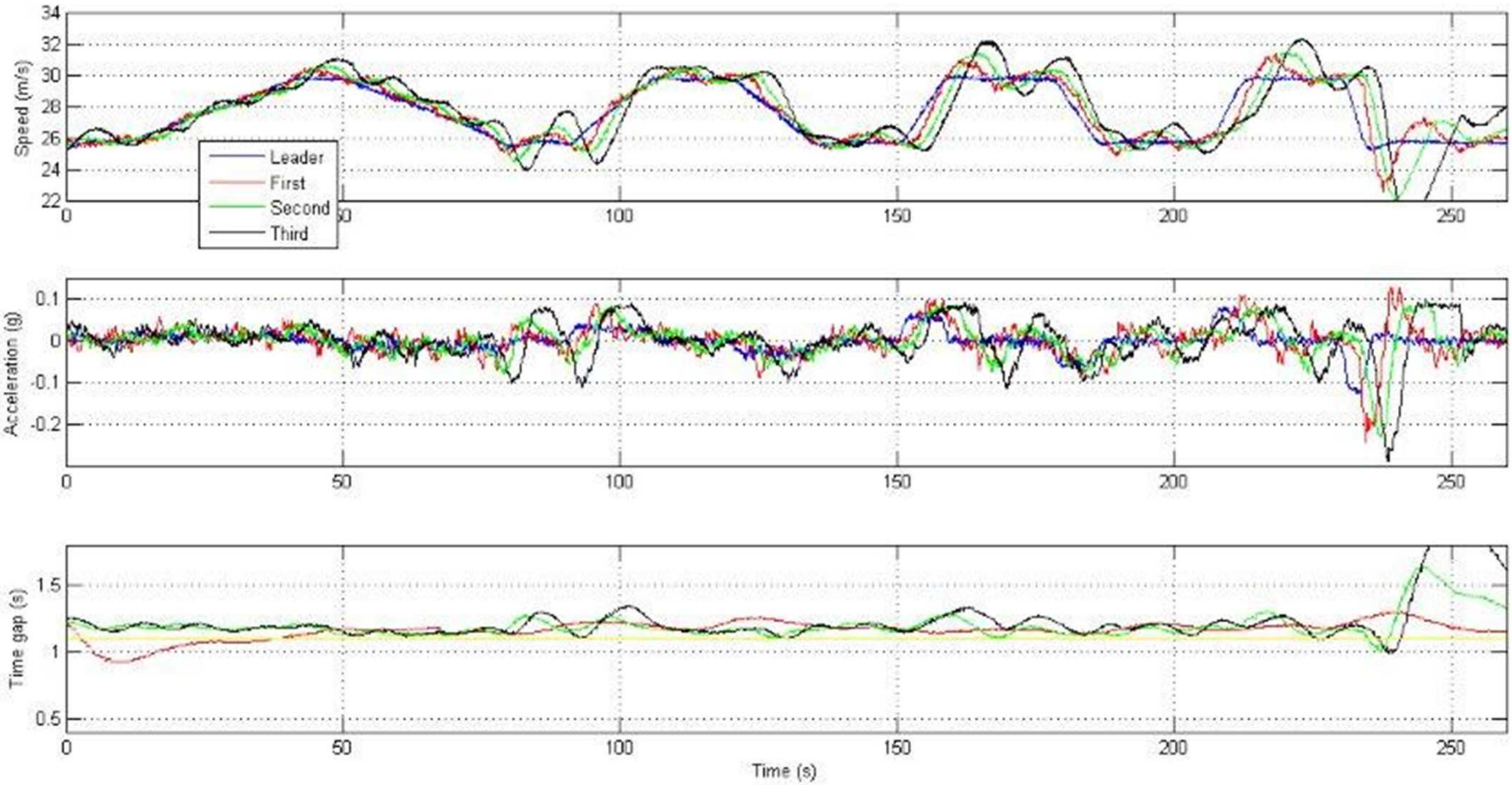
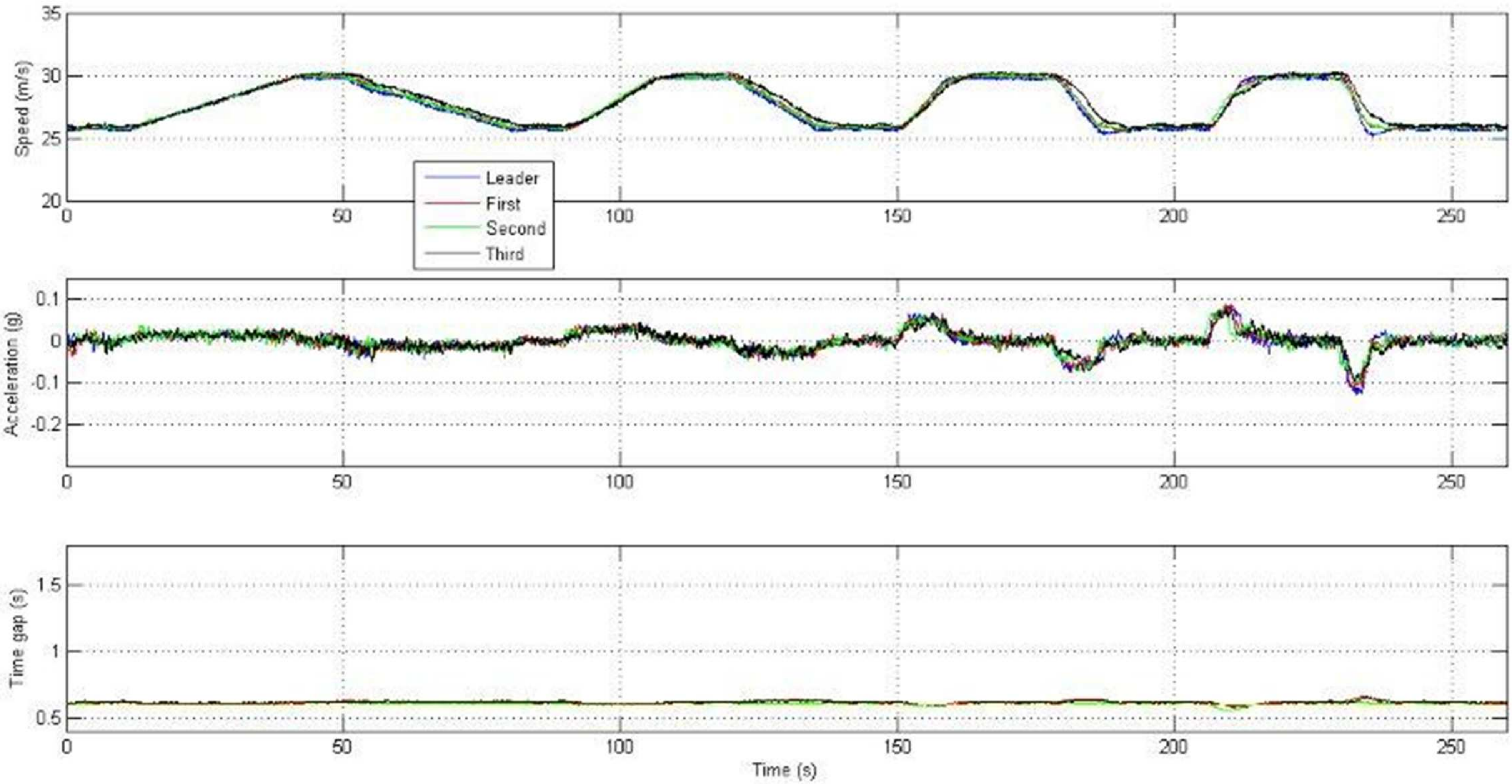
Example 1 – Production Autonomous ACC (at minimum gap 1.1 s)

Response of Production ACC Cars



Example 2 – V2V Cooperative ACC (at minimum gap 0.6 s)

V2V CACC Responses (3 followers)



PATH Automated Platoon Longitudinal Control and Merging (V2V)

2000

1997

PATH V2V Truck Platoons (2003, 2010)

2 trucks, 3 to 10 m gaps

3 trucks, 4 to 10 m gaps
(6 m in video)

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PATH Magnetic Bus Guidance in Eugene, OR

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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)

Intentional Mis-Uses of Level 2

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?**

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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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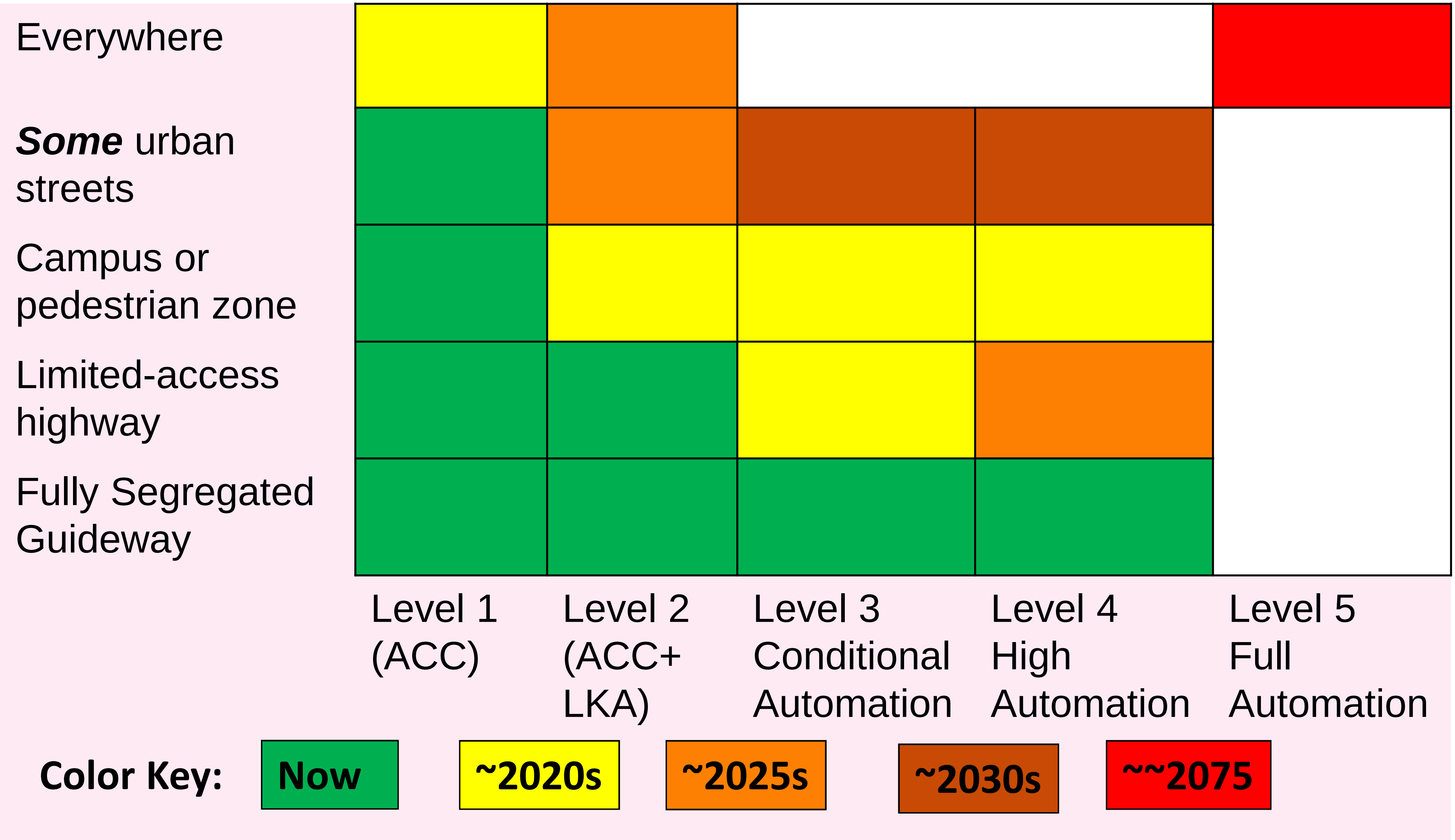
Full Automation (Level 5) Impacts

- **Electronic taxi service for mobility-challenged travelers (young, old, impaired)**
- **Shared vehicle fleet repositioning (driverless)**
- **Driverless urban goods pickup and 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)*



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Traffic Safety Challenges for 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 to rely on 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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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

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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**

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Safety Challenges for Full Automation

- Must be "significantly" safer than today's driving baseline (2X? 5X? 10X?)
  - Fatal crash MTBF > 3.3 million vehicle hours
  - Injury crash MTBF > 65,000 vehicle hours
- Cannot <u>prove</u> safety of software for safety-critical applications
- Complexity – cannot <u>test</u> all possible combinations of input conditions and their timing
- How many hours of testing are needed to demonstrate safety better than this?
- How many hours of <u>continuous, unassisted</u> automated driving have been achieved in real traffic under diverse conditions?

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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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Threat Assessment Challenge

- Detect and respond to every hazard, including those that are hard to see:
  - Negative obstacles (deep potholes)
  - Inconspicuous threats (brick in tire track)
- Ignore conspicuous but innocuous targets
  - Metallized balloon
  - Paper bag
- Serious challenges to sensor technologies
- How to set detection threshold sensitivity to reach zero false negatives (missed hazards) and near-zero false positives?

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Much Harder than Commercial Aircraft 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**

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 (in U.S.)

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

California DMV Regulatory Issues

- **Due diligence in protecting general public while unproven systems are being tested among them**
- **Trying to ensure that general public really understands limitations of their vehicles**
- **Detecting unsafe systems as early as possible (earlier than NHTSA?)**
- **Adapting or re-interpreting existing codes:**
  - **Responding to law enforcement officer commands**
  - **Exchanging insurance information after crashes**
  - **Restrictions on driver behaviors (DUI, open alcohol containers, cell phones, texting, distraction, recklessness…)**
  - **Protection of unattended children…**

Testing on Public Roads (Published)

- **Legislative:**
  - **$5 M bond/proof of self-insurance**
  - **Test driver must be designated by manufacturer**
  - **"The driver shall be seated in the driver's seat, monitoring the safe operation of the AV, and capable of taking over immediate manual control…"**
- **Administrative:**
  - **Application to test covers specific vehicles and test drivers**
  - **Many test driver qualifications (driving record, training)**
  - **No motorcycle, commercial or heavy vehicle testing**
  - **Prior "controlled testing" under comparable conditions**
  - **Report total amount of test driving and all disengagements associated with failures or driving hazards**
  - **(no provision for naturalistic testing with naïve drivers)**

Deployment for Public Operation

- **Legislative highlights in CA Vehicle Code:**
  - **"The AV shall allow the operator to take control in multiple manners, including, without limitation, through the use of the brake, the accelerator pedal, or the steering wheel…"**
  - **Separate EDR for "autonomous technology sensor data" for at least 30 seconds**
  - **"The department [DMV] shall notify the Legislature of the receipt of an application from a manufacturer seeking approval to operate an AV capable of operating without the presence of a driver inside the vehicle…"**
  - **$5 M bond/proof of self-insurance**

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Deployment for Public Operation

- **Potential administrative regulation topics:**
  - Identification as AV on registration
  - Specify valid types of driving environments ("areas of operation")
  - Evidence of minimum behavioral competency for operation in these areas
  - Safety monitoring plan
  - Consumer education plan
  - Information privacy disclosure
  - Vehicle external labeling
  - Operator responsibility for traffic law violations
  - No special driver training or licensing

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Additional Issues for Driverless Operation

- **Special license plate**
- **Emergency stop mechanisms for occupants**
- **Communication to owner/operator for emergency conditions**
- **Owner/operator information available for post-incident data exchanges**
- **Legislature must be notified of application, with 120-day hold period to decide on need for any additional legislation**

What next for California regulations?

- Further updates of California regulations based on public input, experience in the field, new technology developments
- Uncertain prospects for additional state legislation (Google backed off lobbying)
- Industry standards development proceeding, but very slowly
- Everybody waiting for NHTSA to act (but not expected in foreseeable future)
  - Their May 2013 policy statement advised states to hold off on authorizing public use of Level 3 or above

Broader Public Policy Considerations

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

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What to do now?

- **Focus 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**
- **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,…)**