Road Vehicle Automation History, Opportunities and Challenges

Steven E. Shladover, Sc.D.

California PATH Program

Institute of Transportation Studies

University of California, Berkeley

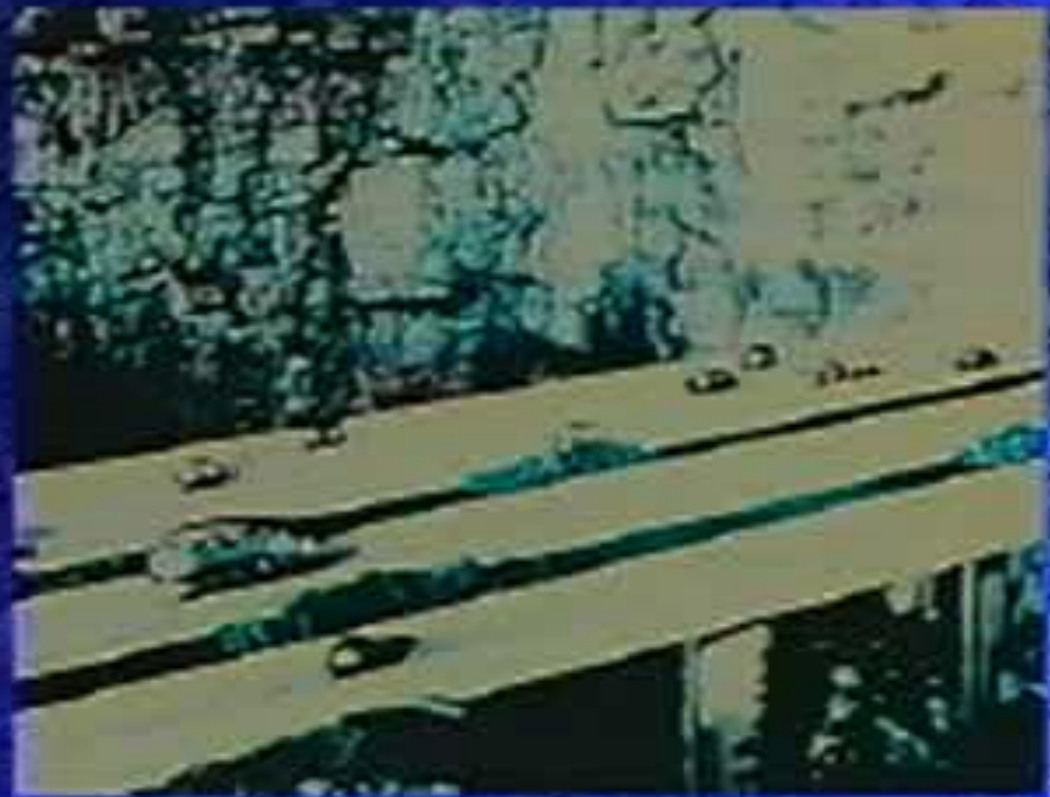**May 2015**

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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

General Motors' Futurama
1939 New York World's Fair

GM Firebird II Publicity Video

1954-55

GM Technology in 1960

General Motors 1964 Futurama II

1964-65

Robert Fenton's OSU Research

Automatically Controlled
1965 Plymouth at
Transportation Research Center of Ohio
The Ohio State University (OSU)
1977

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

1960s

1970s – Vision Guidance

Inductive Cable and A Pair of Pickups

Intelligent Vehicle

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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 <u>self-government</u>, 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 <u>independence</u>
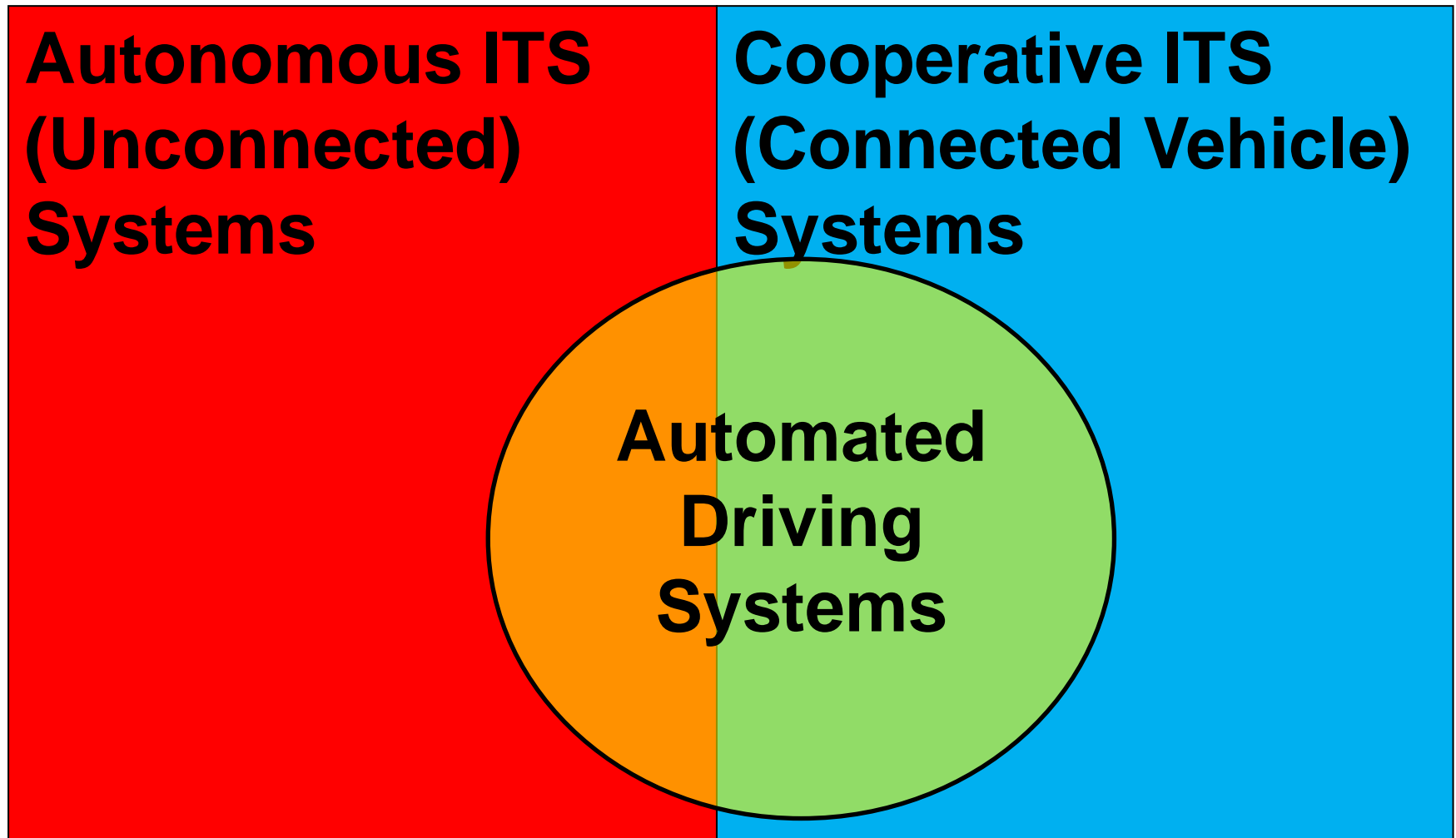 3. a <u>self-governing</u> community.

  autonomous:
  1. of or pertaining to an autonomy
  2. possessed of autonomy, <u>self governing, independent</u>
  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, <u>the use of electronic or mechanical devices to replace human labour</u>

Autonomous and Cooperative ITS

Autonomous ITS (Unconnected) Systems

Cooperative ITS (Connected Vehicle) Systems

Automated Driving Systems

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)**	**Must monitor driving environment (system nags driver to try to ensure it)**
3	**Traffic Jam Pilot** **Automated parking**	**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**

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
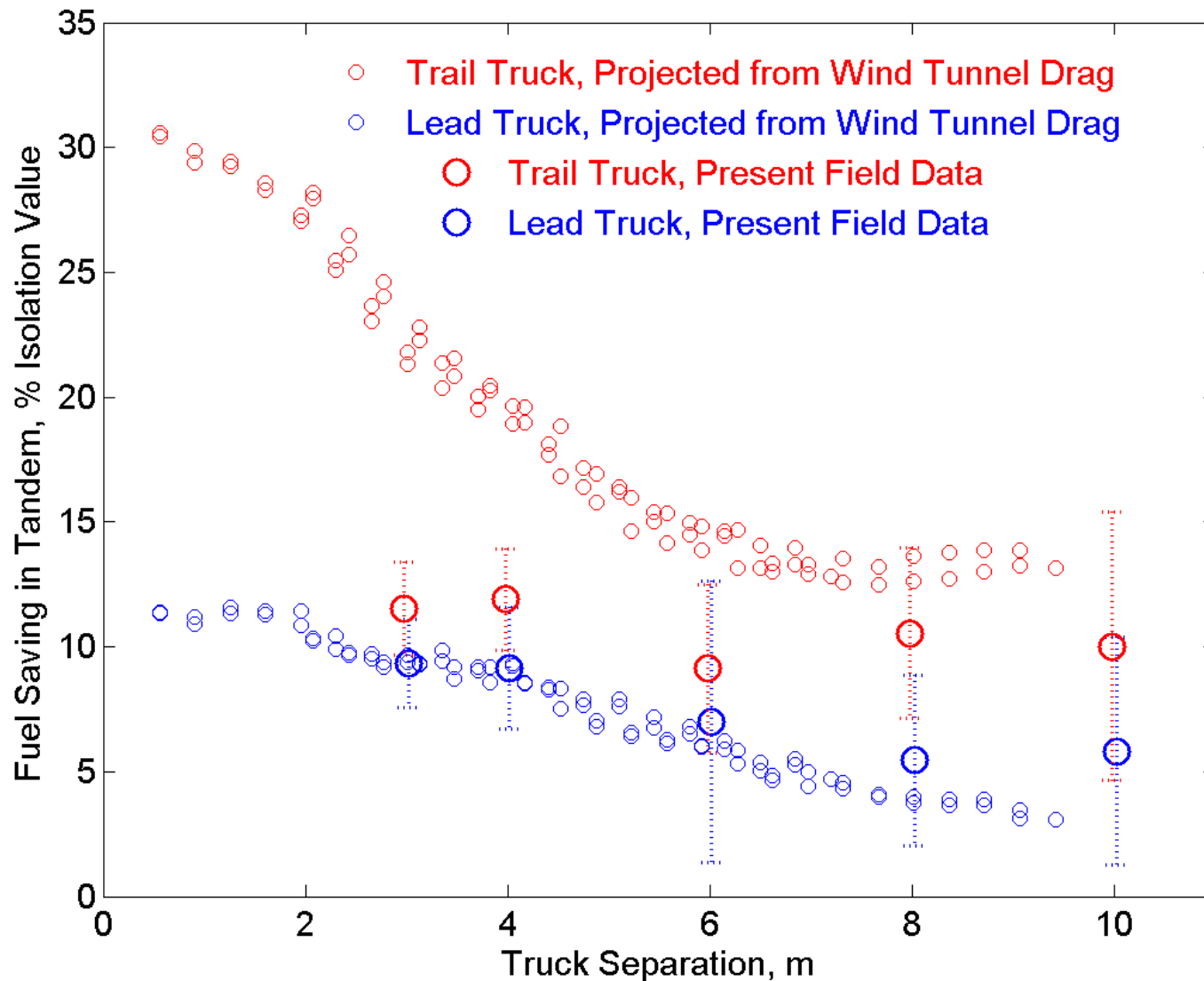
Improving Safety

- **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 traffic safety sets a very high bar:**
    - **3.3 M vehicle <u>hours</u> between fatal crashes**
    - **65,000 vehicle <u>hours</u> between injury crashes**

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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

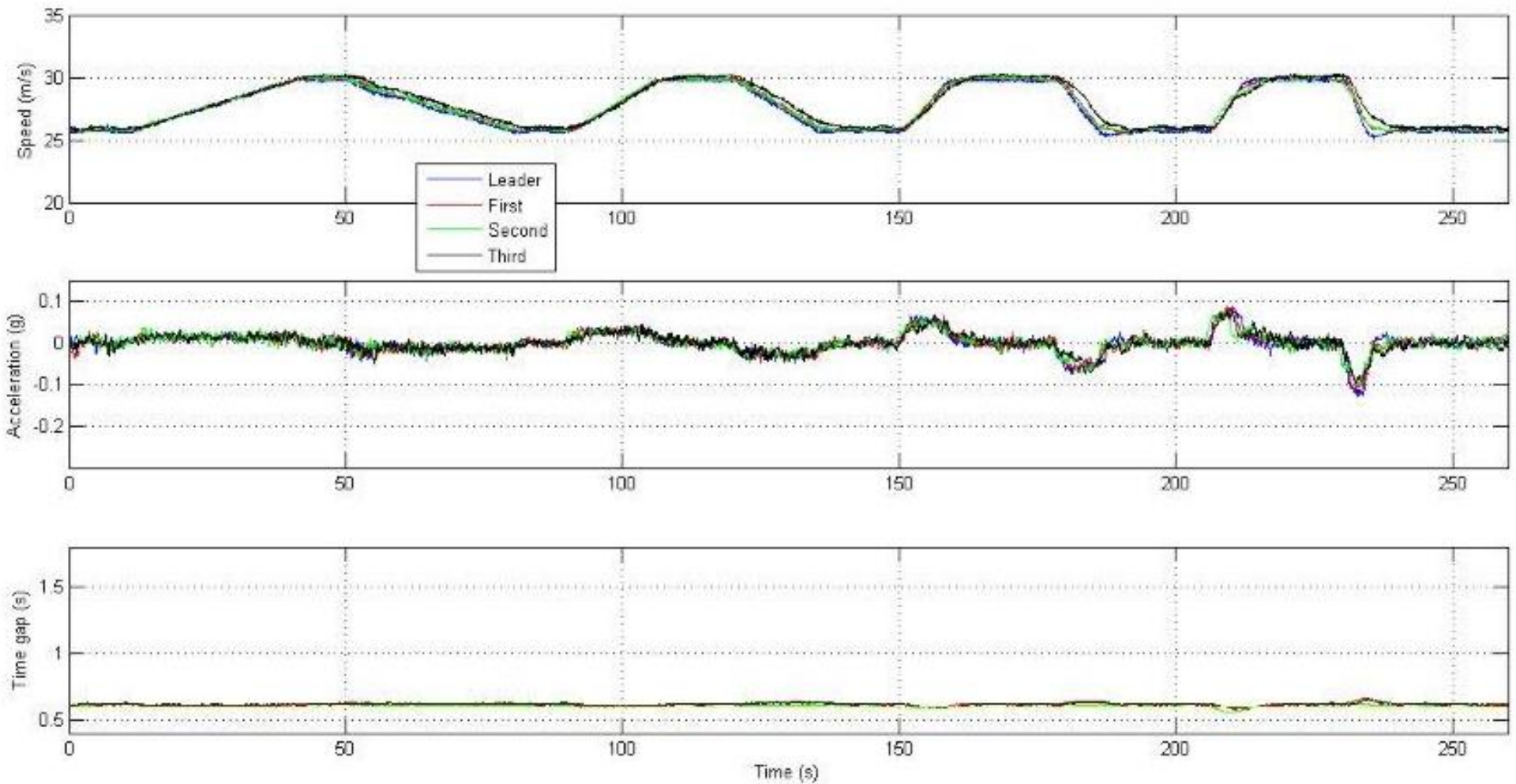# Example 1 – Production Autonomous ACC (at minimum gap 1.1 s)

Response of Production ACC Cars
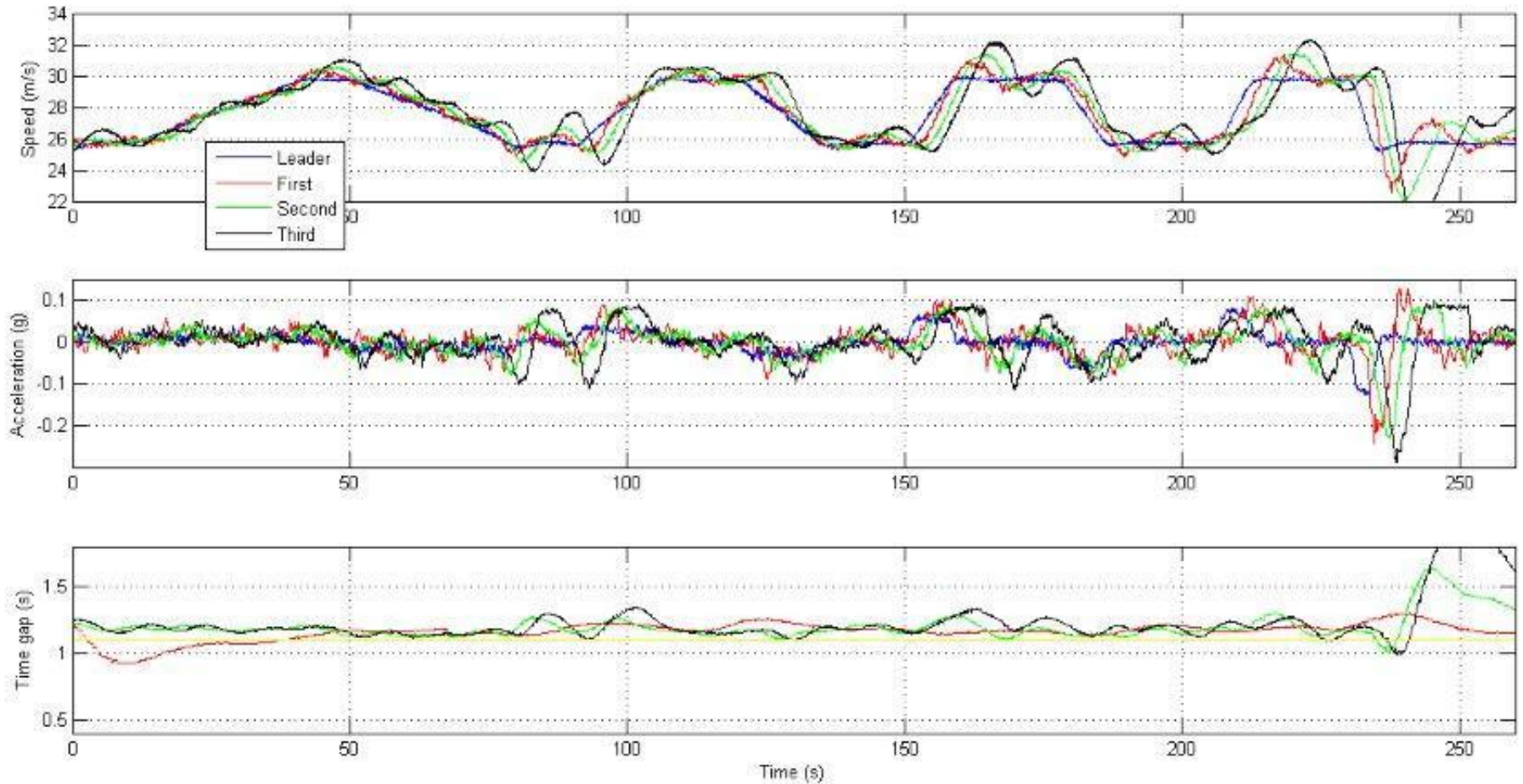
Example 2 – V2V Cooperative ACC (at minimum gap 0.6 s)

V2V CACC Responses (3 followers)

PATH Automated Platoon Longitudinal Control and Merging (V2V)

1997

2000

# PATH 3-Truck V2V Platoon (2011)

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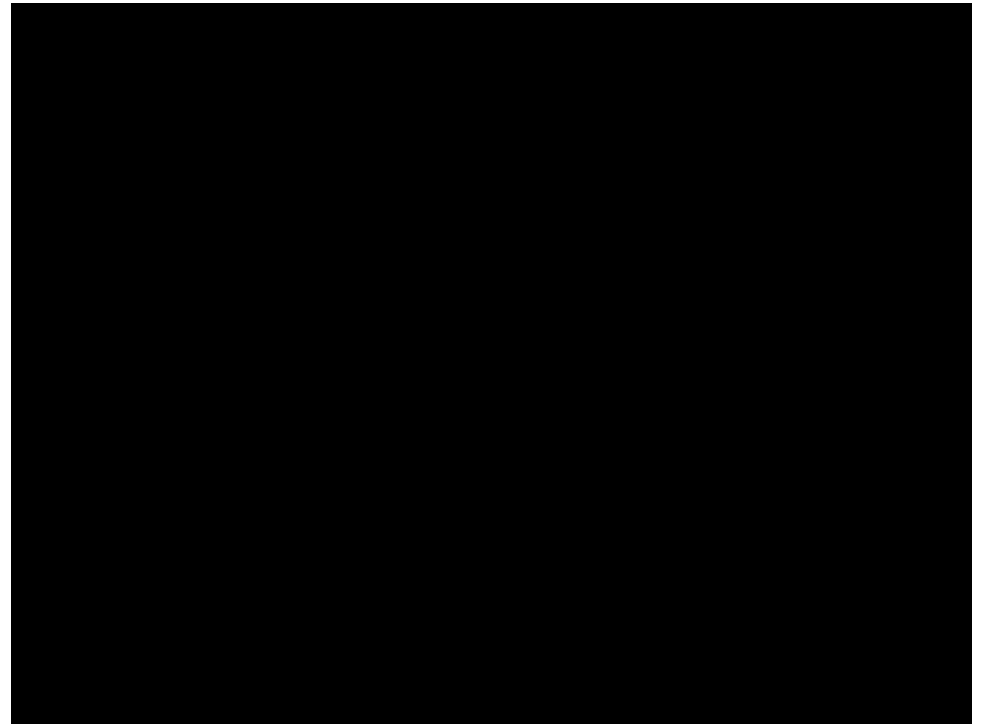
Partial Automation (Level 2) Impacts

- **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? Starting this year (Mercedes S-class)**

Intentional Mis-Uses of Level 2

Mercedes S-Class
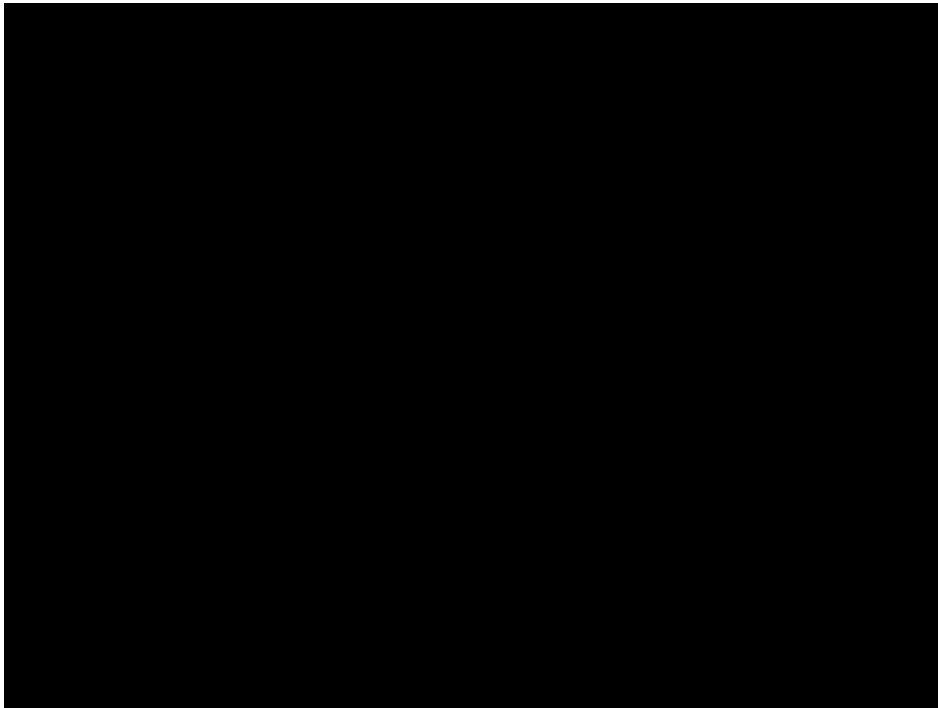
Infiniti Q50

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**

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?**

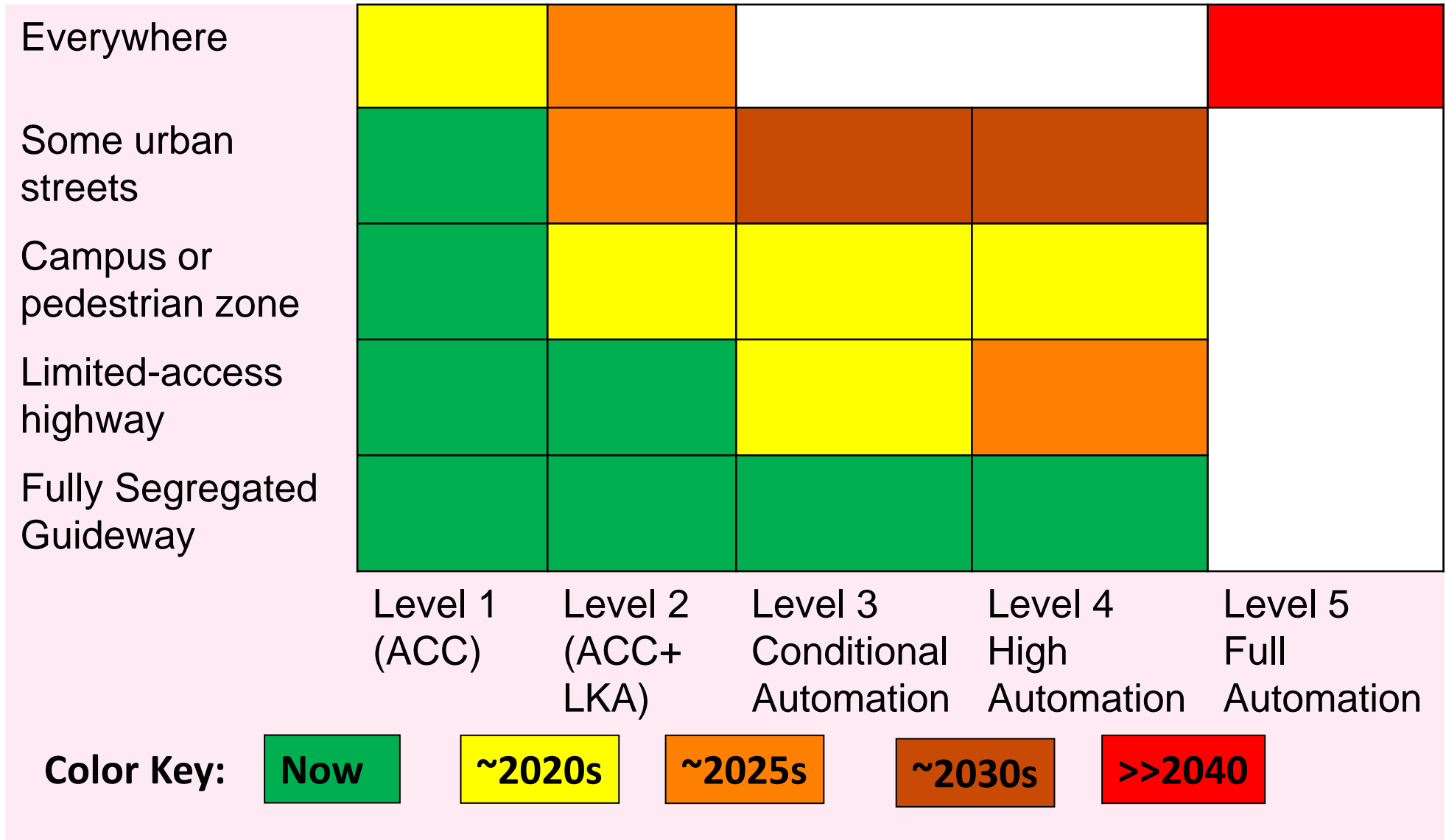# High Automation (Level 4) Impacts – Special applications

- **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**

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)*

	Level 1 (ACC)	Level 2 (ACC+ LKA)	Level 3 Conditional Automation	Level 4 High Automation	Level 5 Full Automation
Everywhere	~2020s	~2025s			>>2040
Some urban streets	Now	~2025s	~2030s	~2030s	
Campus or pedestrian zone	Now	~2020s	~2020s	~2020s	
Limited-access highway	Now	Now	~2020s	~2025s	
Fully Segregated Guideway	Now	Now	Now	Now	

Color Key: Now | ~2020s | ~2025s | ~2030s | >>2040

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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

- **Harsh and unpredictable hazard environment**
- **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**
- **Non-professional vehicle owners and operators cannot ensure proper maintenance and training**

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**
- **How many hours of testing are needed to demonstrate safety better than this?**
- **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 <u>continuous, unassisted</u> automated driving have been achieved in real traffic under diverse conditions?**

Unmet Technical Requirements

- **Real-time software safety/verification**
- **On-line fault detection, identification and accommodation**
  - **"Zero" missed detections (false negatives)**
  - **"Near-zero" false alarms (false positives)**
  - **"Instant" ability to switch to and operate in safe degraded mode (~0.1 s)**
- **Comprehensive general obstacle detection**
  - **Any object large enough to cause harm**
  - **Ignore innocuous "soft" targets**
  - **All weather conditions**
- **Cyber security**

Technological Limitations

- **Remote sensing and threat assessments…**
- **Designers cannot anticipate every hazard scenario in advance, but learning systems are non-deterministic (unpredictable)**
  - **Safety cannot be ascertained**
- **Problems incorporating ethical decisions into software (life or death value judgments)**
- **No efficient formal methods for verifying safety of complicated software logic**
- **Cannot test for all possible input conditions**

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

Needed Breakthroughs

- **Affordable sensors and signal processing to discriminate benign from hazardous targets**

- **Methods for specifying algorithms that are verifiable for completeness, correctness and safety**

- **Methods for verifying software safety under highly diverse operating conditions**

- **Cost-effective methods for rapidly detecting, identifying and accommodating failures in a complicated mechatronic system**

- **Methods of proving safety, durability and availability of a complicated mechatronic system without exhaustive testing**

Safety and the Driver

- **If maximum safety is indeed the goal…**
  - **ADD the system's vigilance to the driver's vigilance instead of bypassing the driver's vigilance**
  - **Comprehensive hazard warnings plus some control assistance (e.g., ACC)**
- **If the driver is out of the control loop (texting, sleeping, incapable, or not present), the system has to handle EVERYTHING…**
  - **Bad scenarios none of us can imagine**
  - **Ethically untenable scenarios**

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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**

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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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,…)**