Road Vehicle Automation History, Opportunities and Challenges

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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 – Kikuchi and Matsumoto 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

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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)

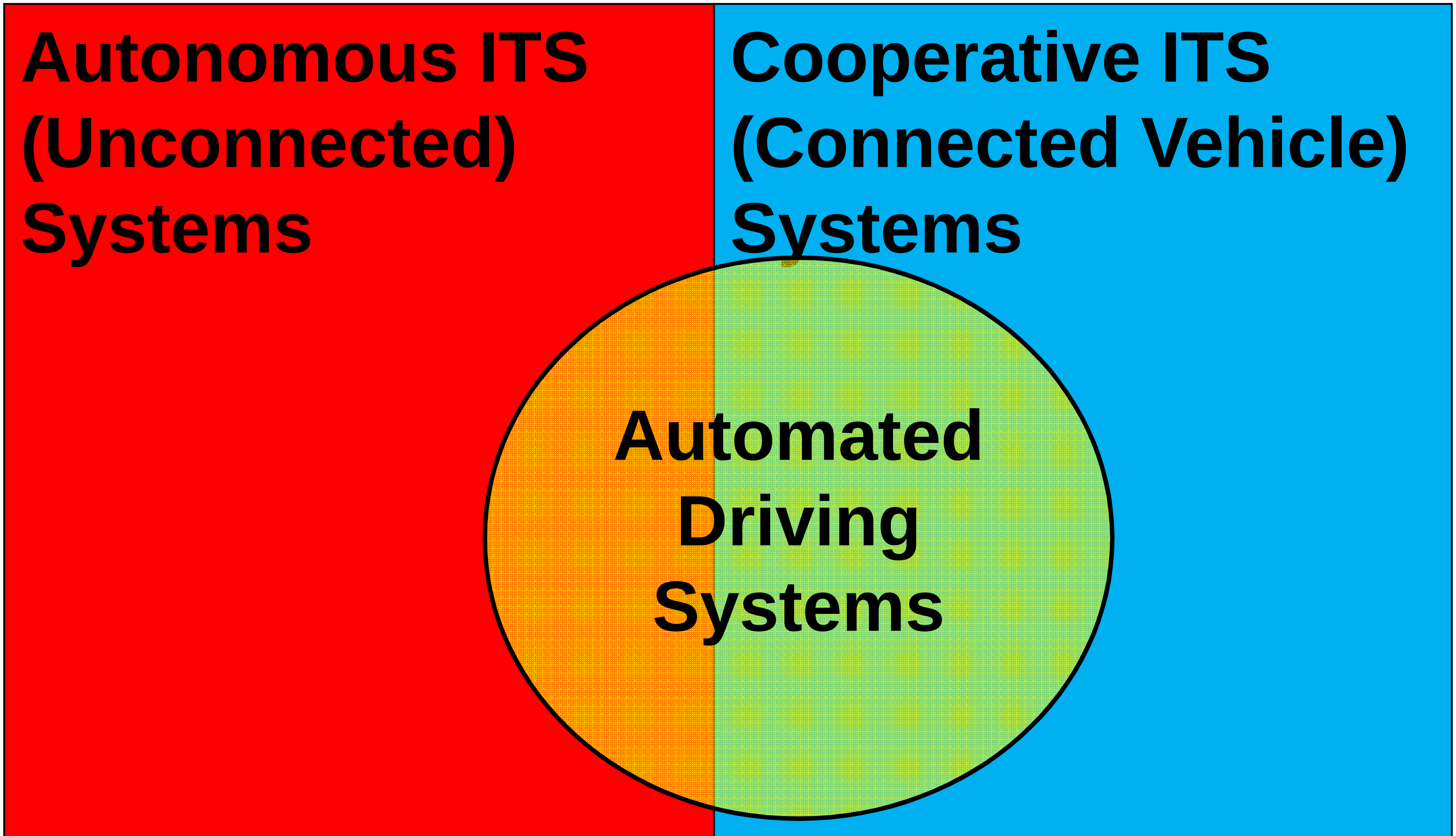
- **<u>autonomy</u>:**
  1. *(of a state, institution, etc.)* the right of <u>self-government</u>, of making its own laws and administering its own affairs
  2. *(biological)* (a) the condition of being controlled only by its own laws, and not subject to any higher one; (b) organic <u>independence</u>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

  <u>autonomous</u>:
  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.

- **<u>automate</u>: to apply automation to; to convert to largely automatic operation**

  <u>automation</u>: 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



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, Volvo, Infiniti)	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

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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**

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 hours between fatal crashes (375 years of non-stop driving)
  - 65,000 vehicle hours 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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Examples of Performance That is Only 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 and reduce drag (especially for trucks)
- **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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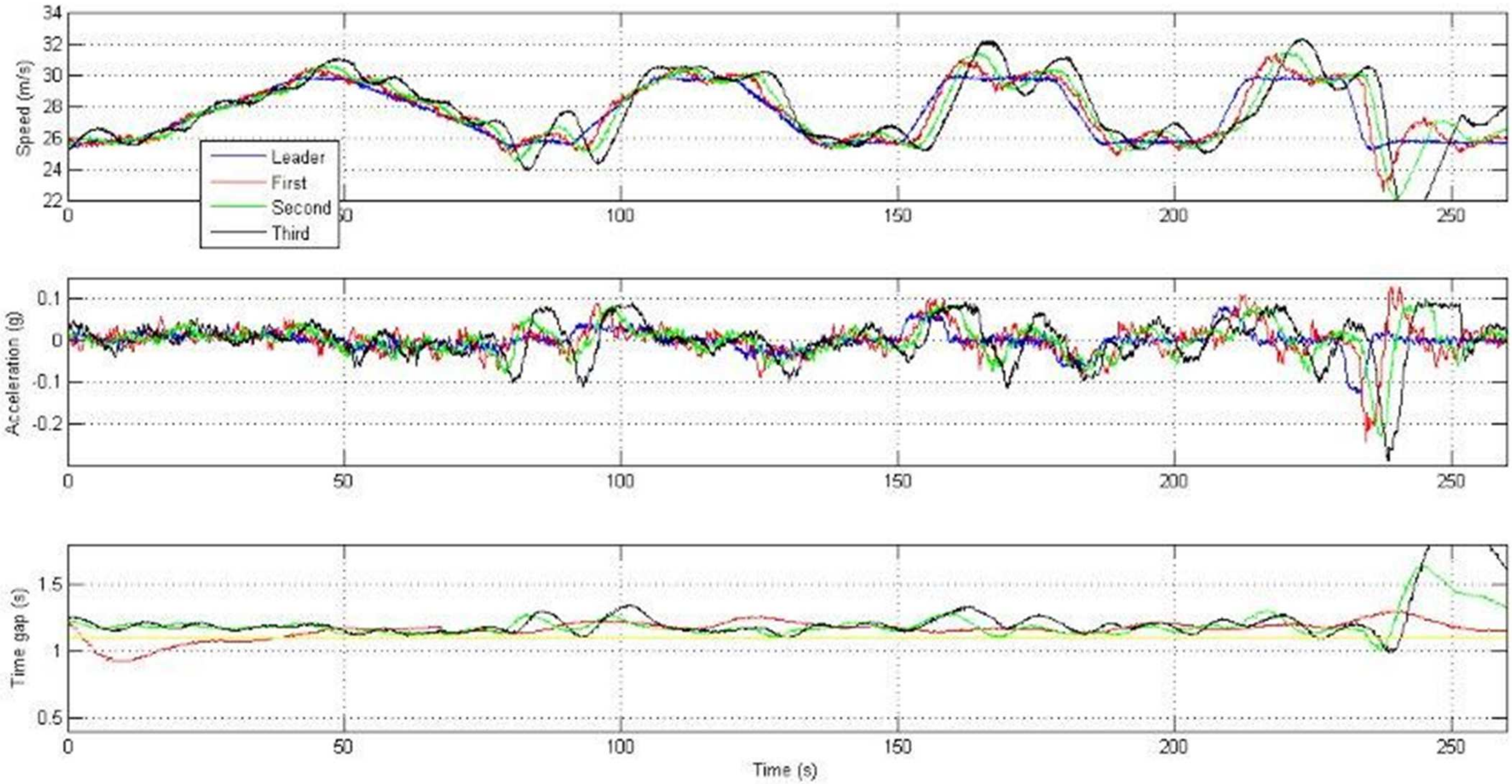
Example 1 – Production Autonomous ACC (at minimum gap 1.1 s)

Response of Production ACC Cars



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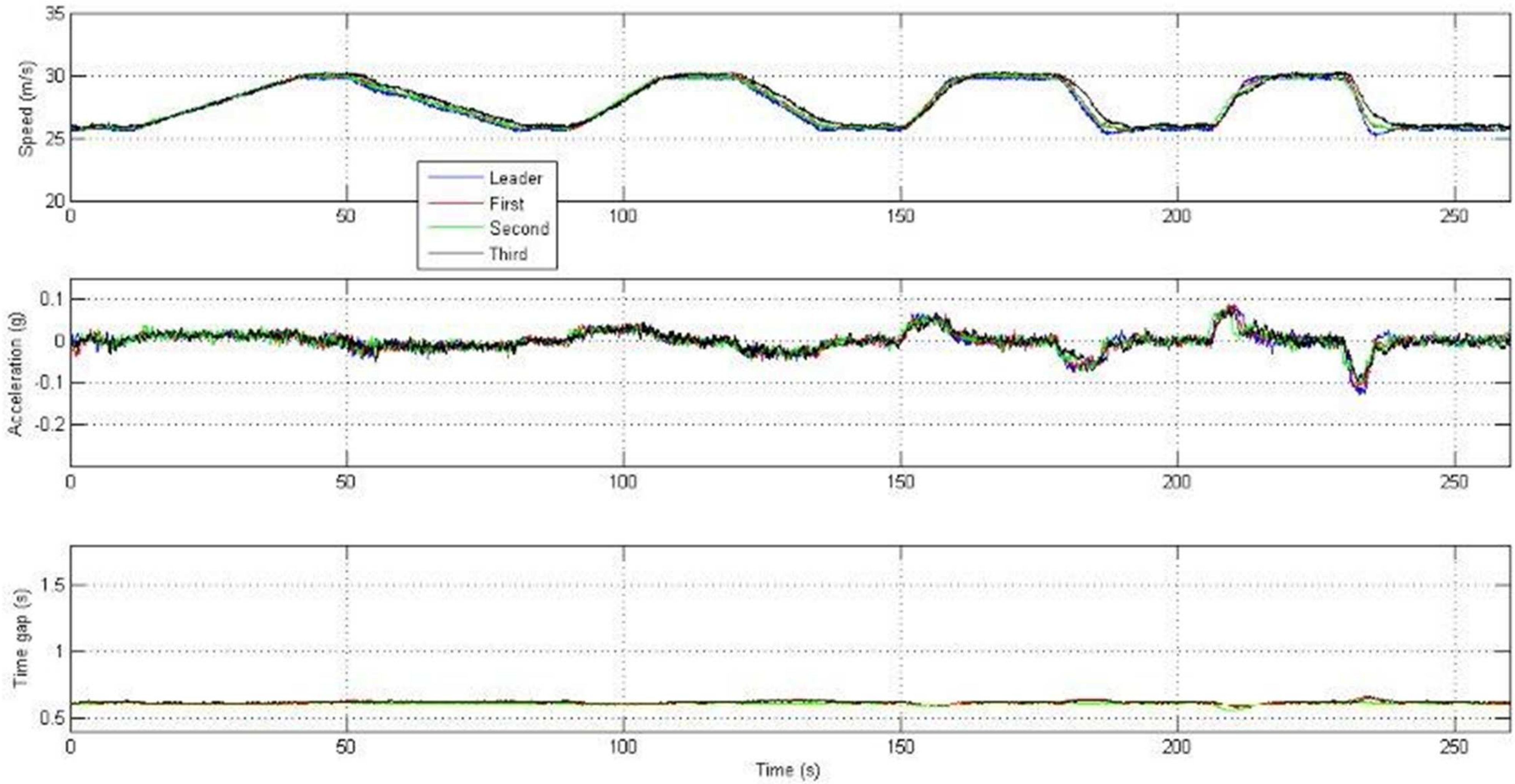
Example 2 – V2V Cooperative ACC (at minimum gap 0.6 s)

V2V CACC Responses (3 followers)



PATH Automated Platoon Longitudinal Control and Merging (V2V)

2000

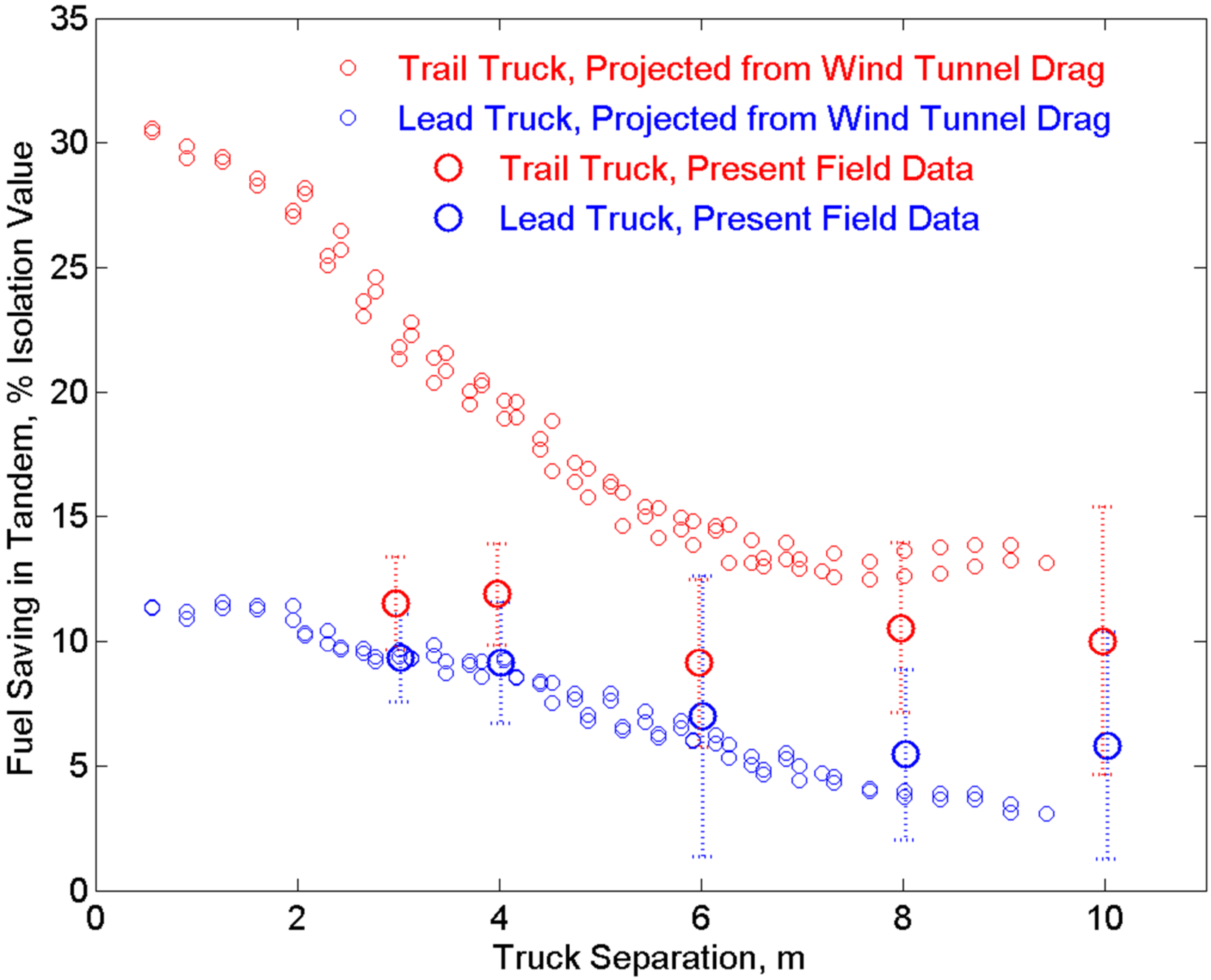
1997

PATH V2V Truck Platoons (2003, 2010)

2 trucks, 3 to 10 m gaps

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

Heavy Truck Energy Savings from Close-Formation Platoon Driving



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**

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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? Now (Mercedes, Infiniti, Volvo)**

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?**

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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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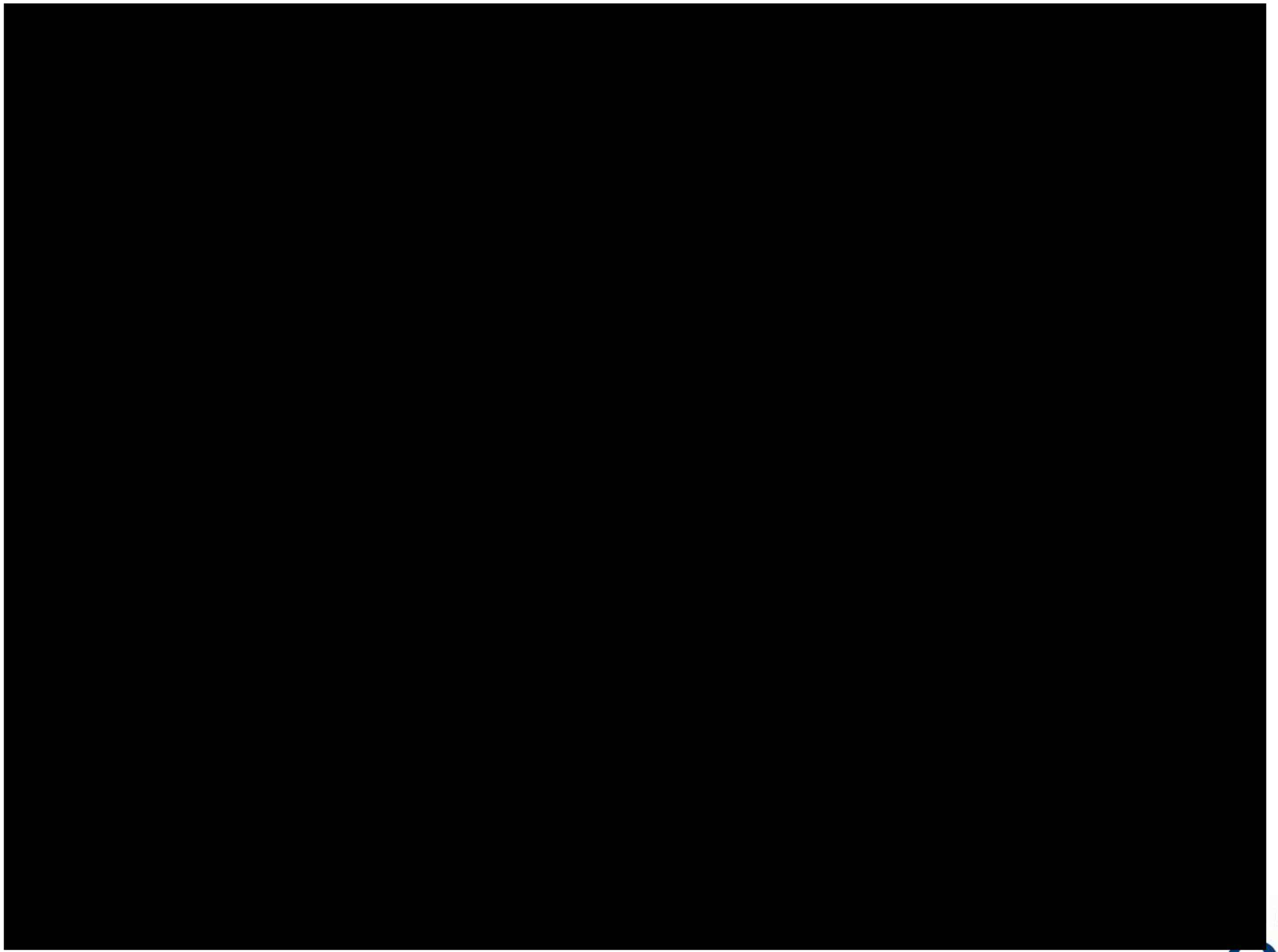
Low-Speed Shuttle in La Rochelle – Vehicle and Infrastructure

Vehicle-Infrastructure Protection



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)**

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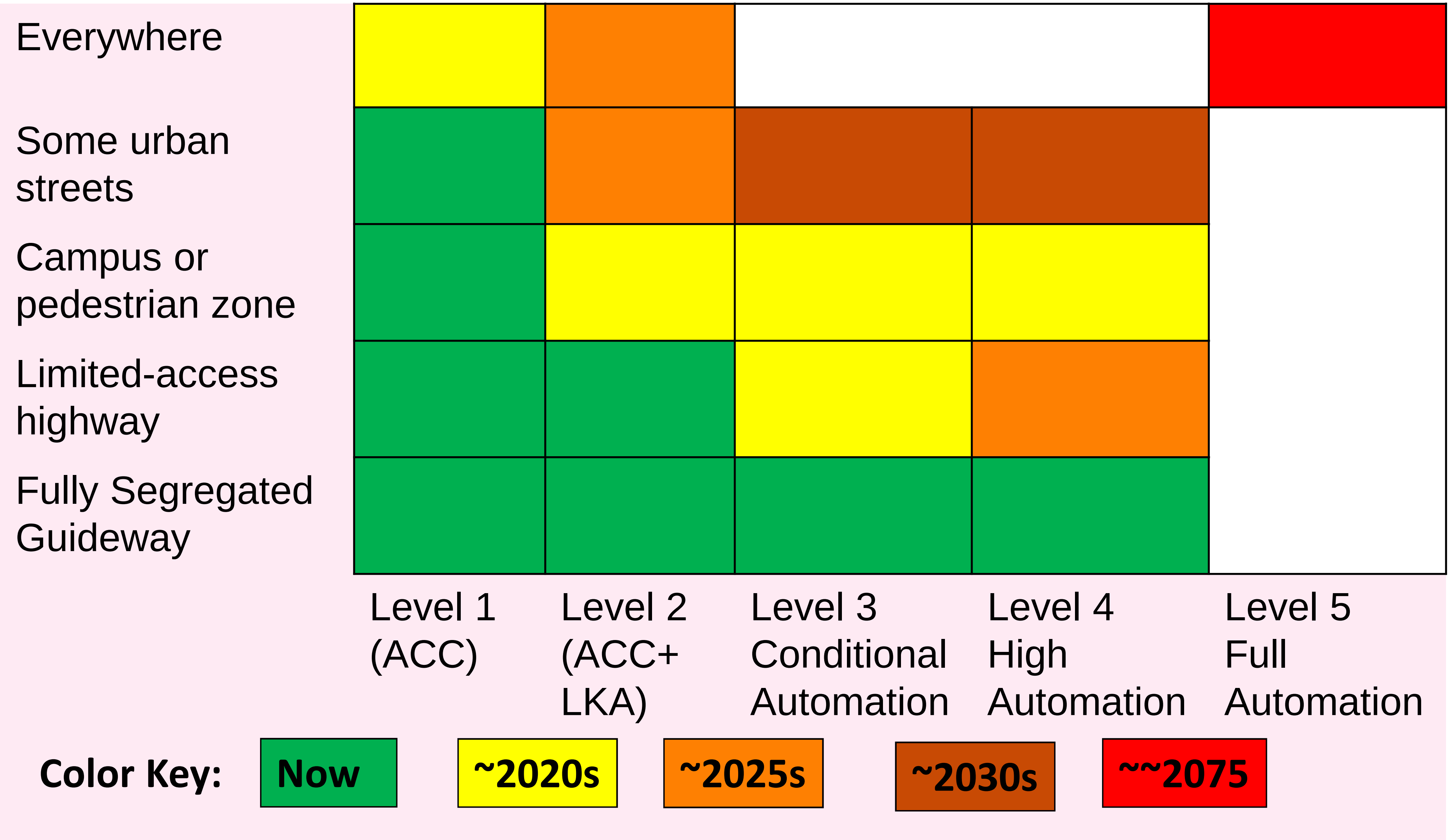
Personal Estimates of Market Introductions
** based on technological feasibility **



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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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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

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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**

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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 would be needed to demonstrate safety better than today?
- 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 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**

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**

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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,…)**