Road Vehicle Automation: History, Opportunities and Challenges

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

April 2017

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

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

1960s – Wire following
Kikuchi and Matsumoto

1970s – Vision Guidance
(Tsugawa)

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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**
  - **Operational design domain**

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Definitions
(per Oxford English Dictionary)

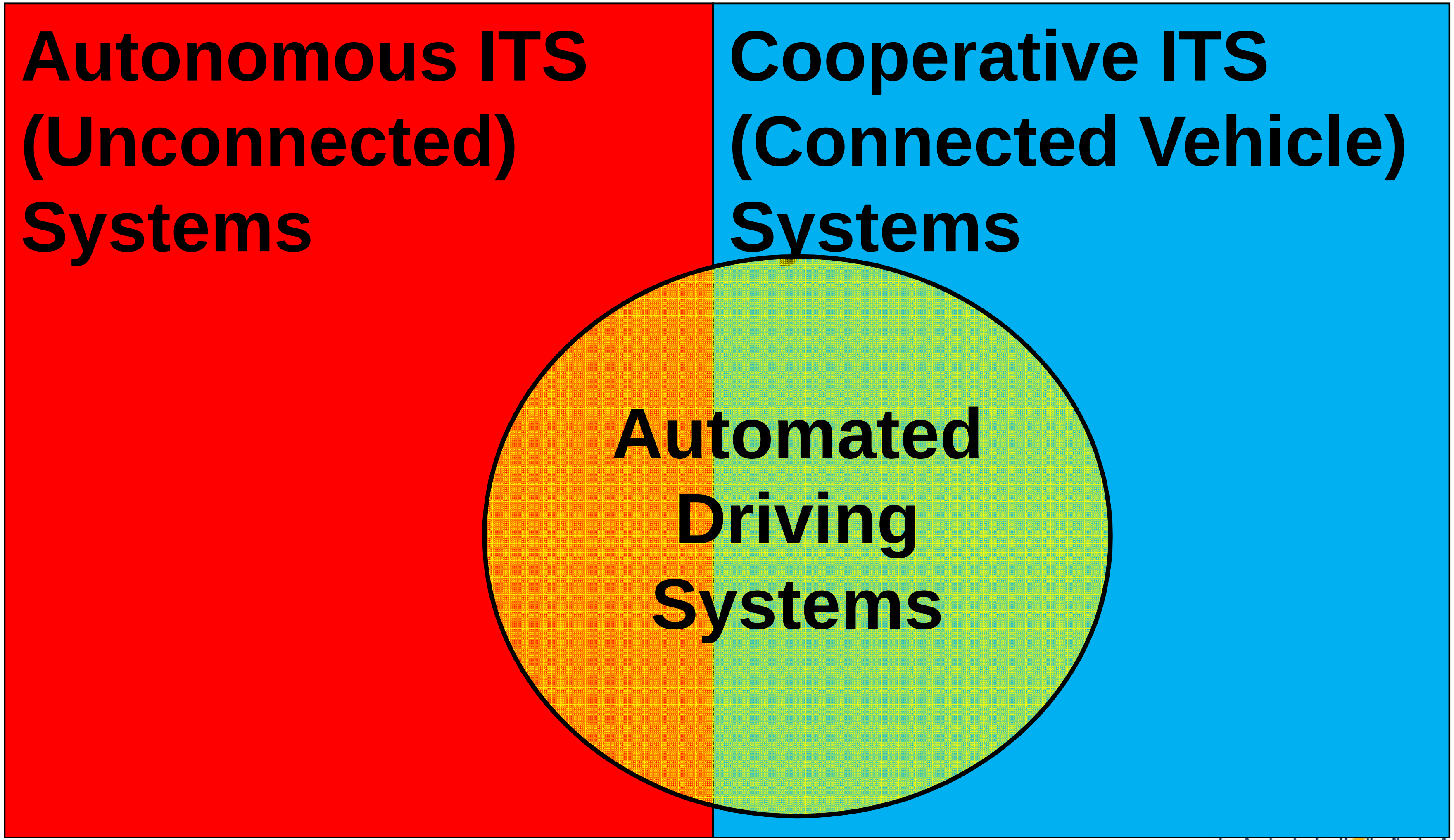
- **autonomy:**
  1. *(of a state, institution, etc.)* the right of self-government, of making its own laws and administering its own affairs
  2. *(biological)* (a) the condition of being controlled only by its own laws, and not subject to any higher one; (b) organic independence
  3. a self-governing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



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 dynamic driving task (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 object and event detection and response.**
4. **Whether the driving automation system *also* performs DDT fallback.**
5. **Whether the driving automation system can drive everywhere or is limited by an operational design domain (ODD).**

Operational Design Domain (ODD)

- **The specific conditions under which a given driving automation system or feature thereof is designed to function, including, but not limited to, driving modes.**
  - **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…)**

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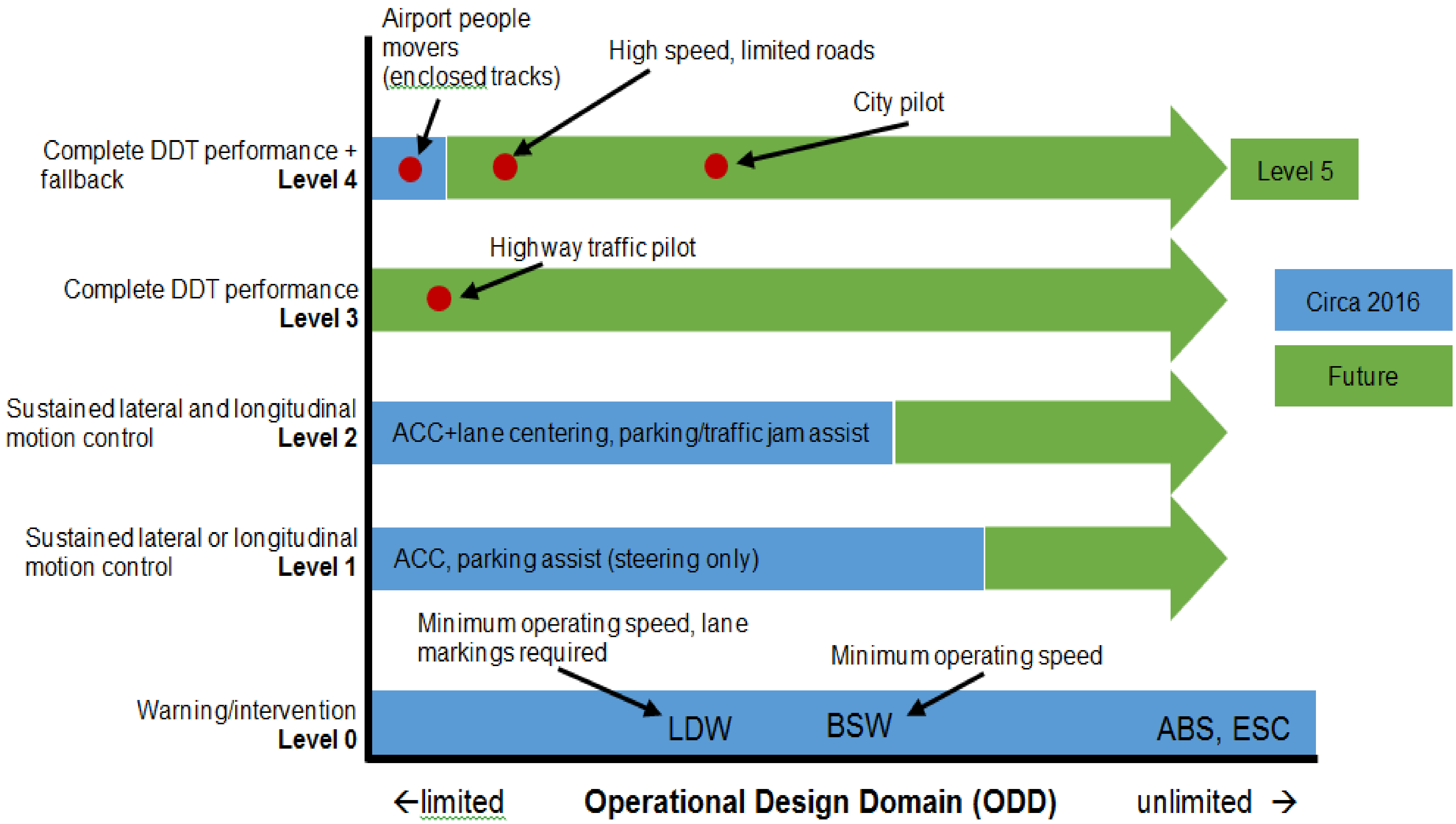
SAE J3016 Definitions – Levels of Automation

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**



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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 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	Can operate anywhere with no drivers 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**
- **V2V Cooperative automation provides shorter gaps, faster responses, and more consistency**
- **I2V Cooperation 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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Improving Safety

- 94% 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:
  - 3.4 M vehicle hours between fatal crashes (390 years of non-stop driving)
  - 61,400 vehicle hours between injury crashes (7 years of non-stop driving)

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Cooperation Augments Sensing

- Autonomous vehicles are "deaf-mute" drivers
- 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
  - 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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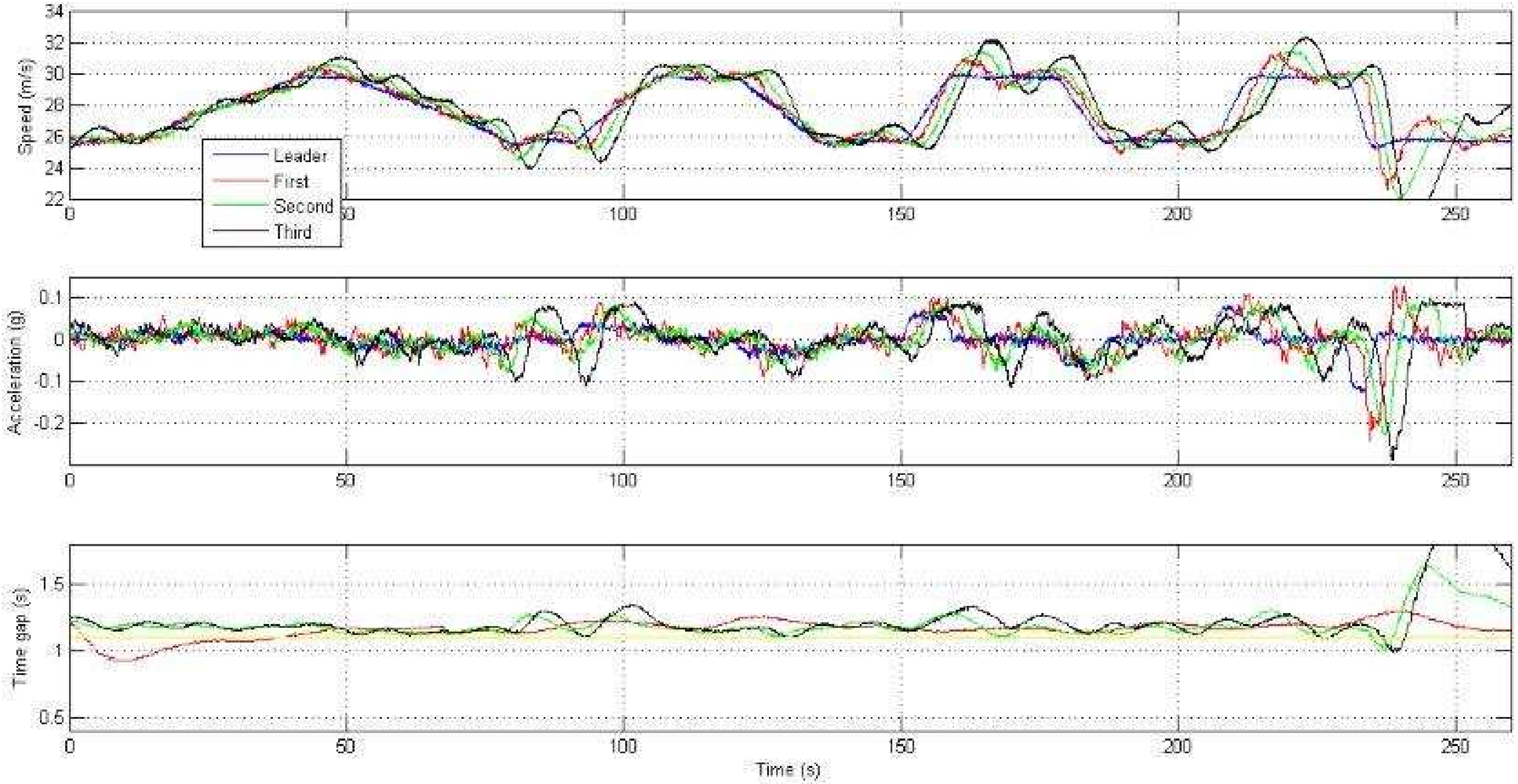
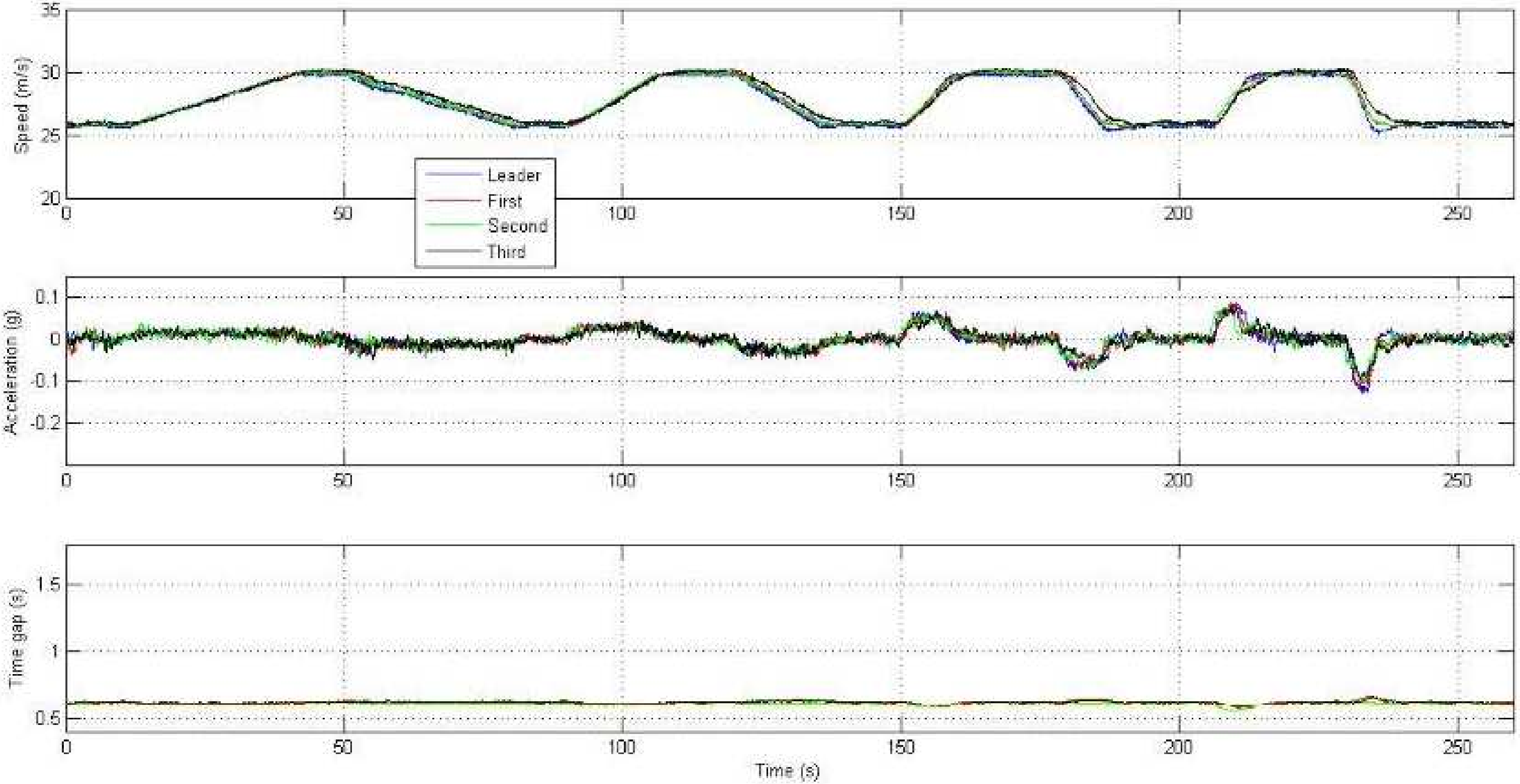
Example 1 – Production Autonomous ACC (at minimum gap 1.1 s)

Response of Production ACC Cars



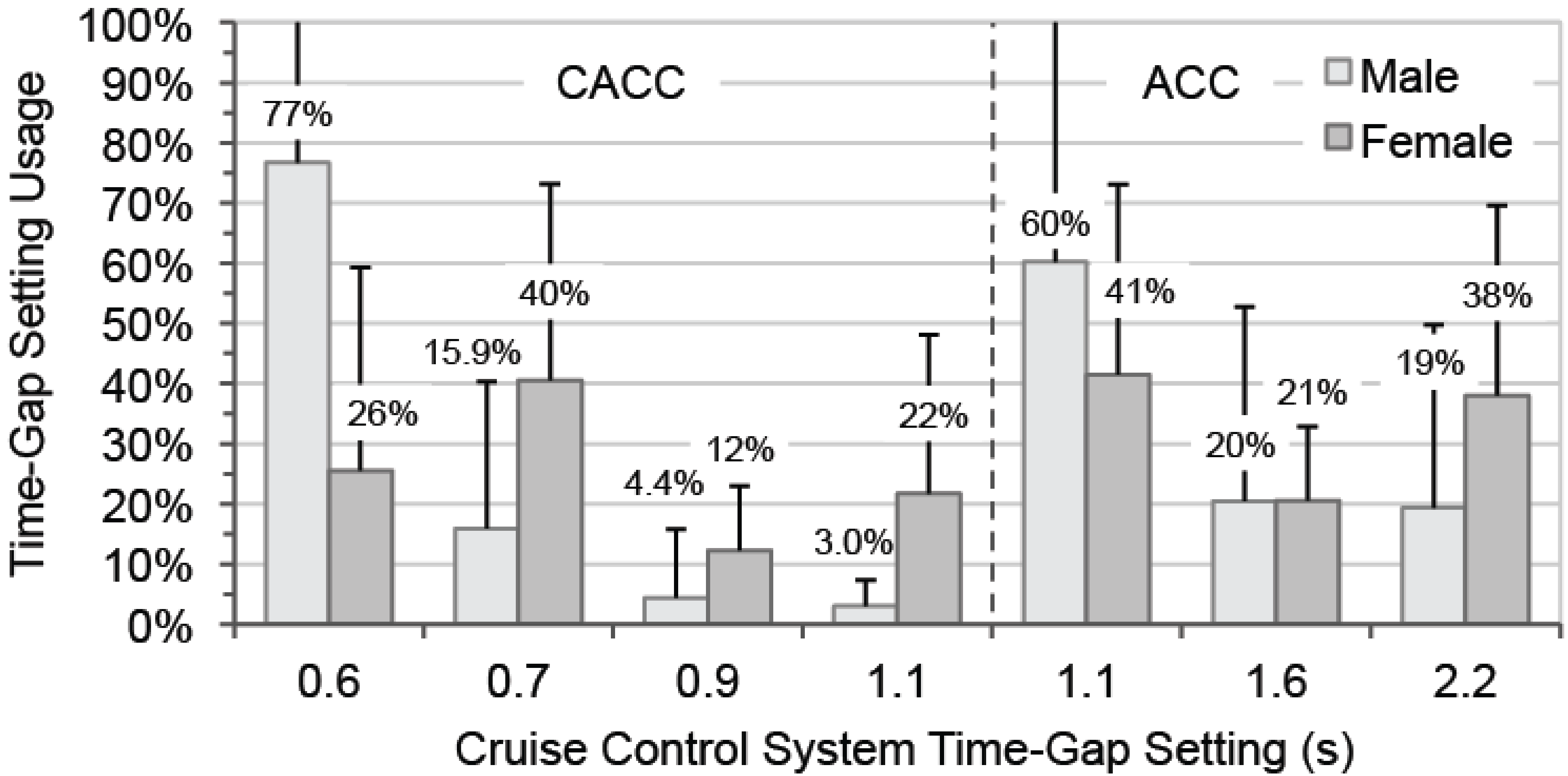
Example 2 – V2V Cooperative ACC (at minimum gap 0.6 s)

V2V CACC Responses (3 followers)

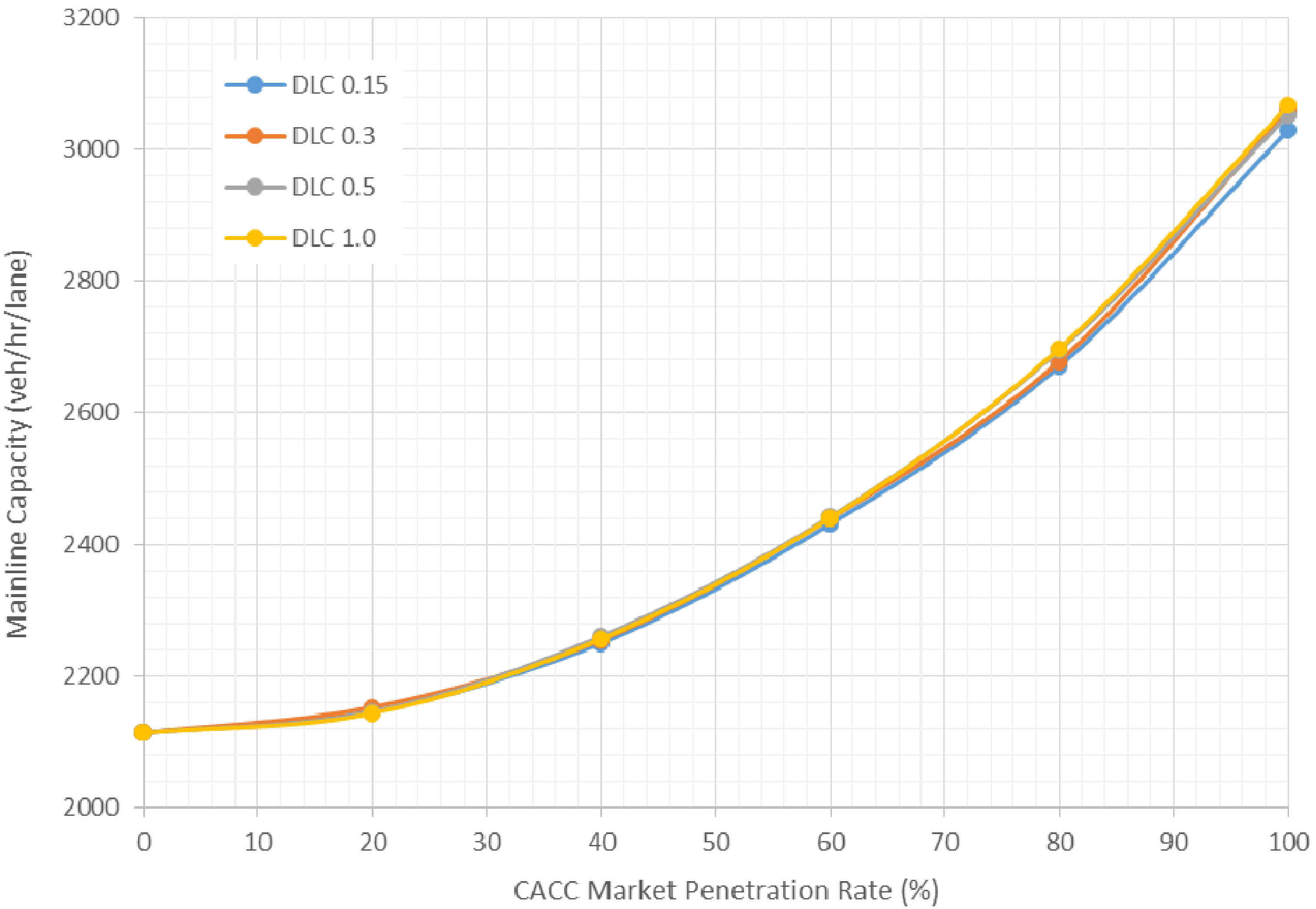


Distribution of Time Gap Selections by General Public Drivers of CACC

Results from PATH experiment with 16 drivers in 2009



Lane Capacity vs. CACC Market Pen. Based on Gaps Chosen by Drivers

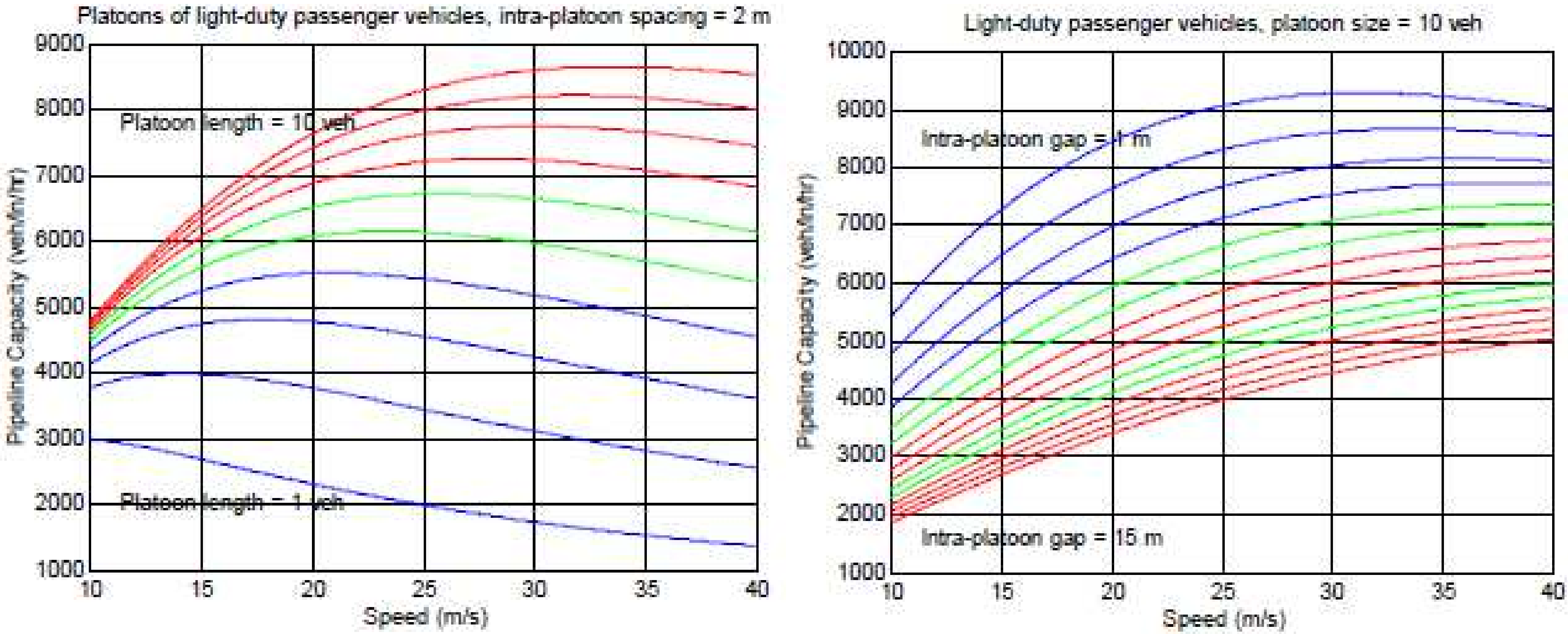


PATH Automated Platoon Longitudinal Control and Merging (V2V)

2000

1997

Significant Lane Capacity Increases From Close-Formation Platoons



- Results from analysis with 100% market penetration of cars in platoons
- Idealized analysis without including lane changing and merging, so achievable results will be about 75% of this

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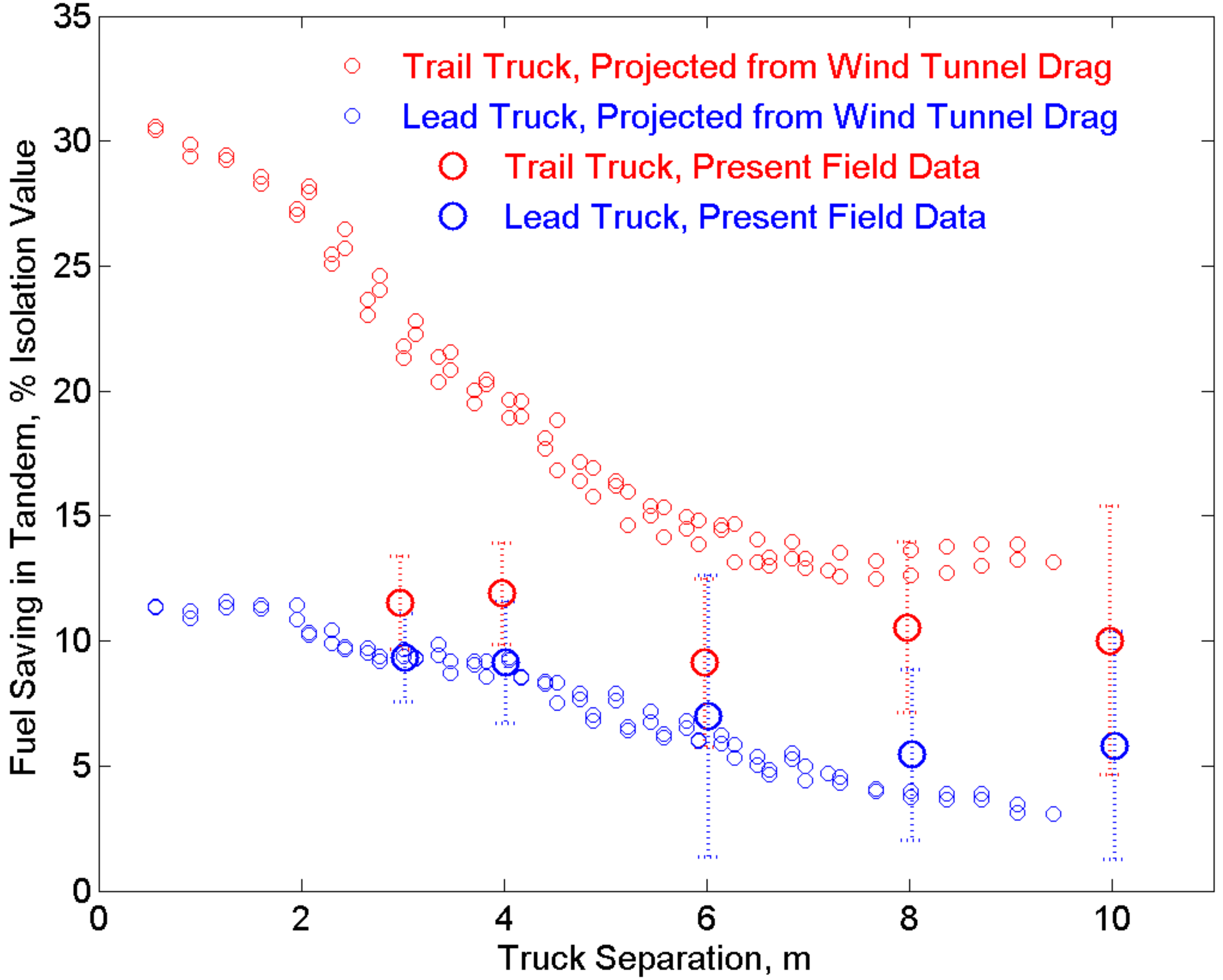
PATH V2V Truck Platoons (2003, 2010)

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



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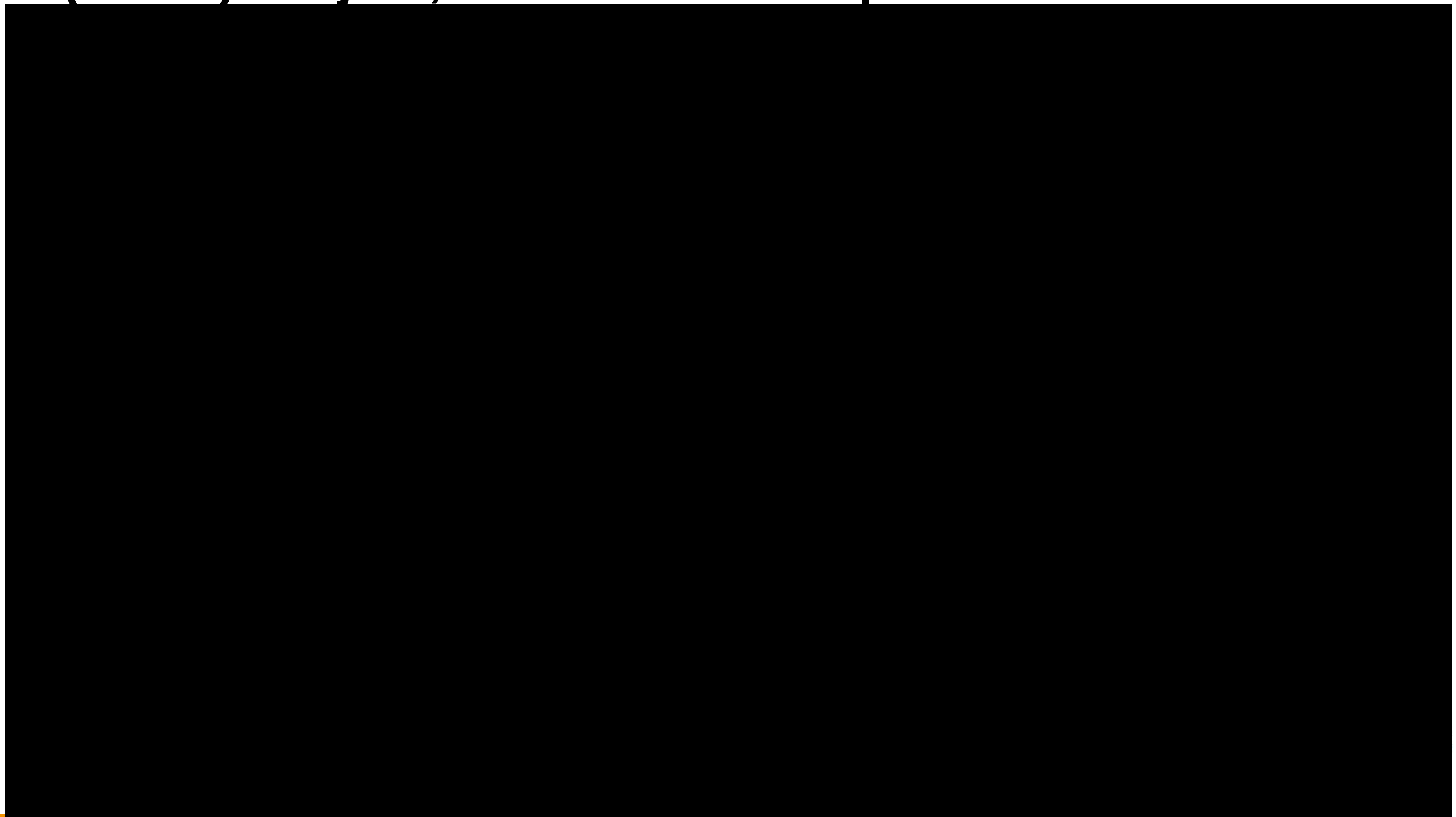
2016 - CACC on 3 Class-8 Trucks

- **FHWA EARP "Partially Automated Truck Platooning" (PATP) Project, with Volvo Group**



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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, Tesla, 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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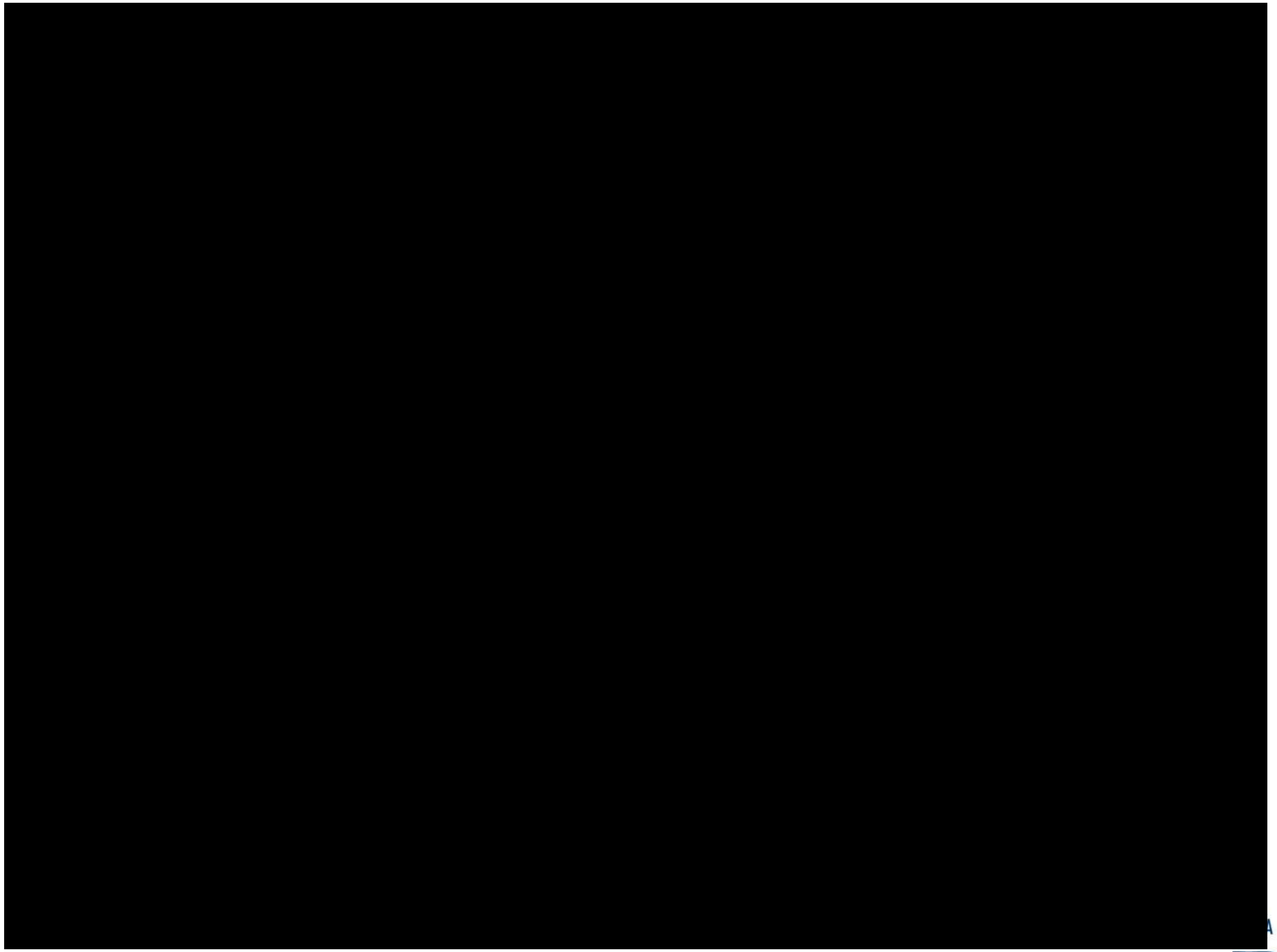
Low-Speed Shuttle in La Rochelle – Vehicle and Infrastructure

Vehicle-Infrastructure Protection for L4

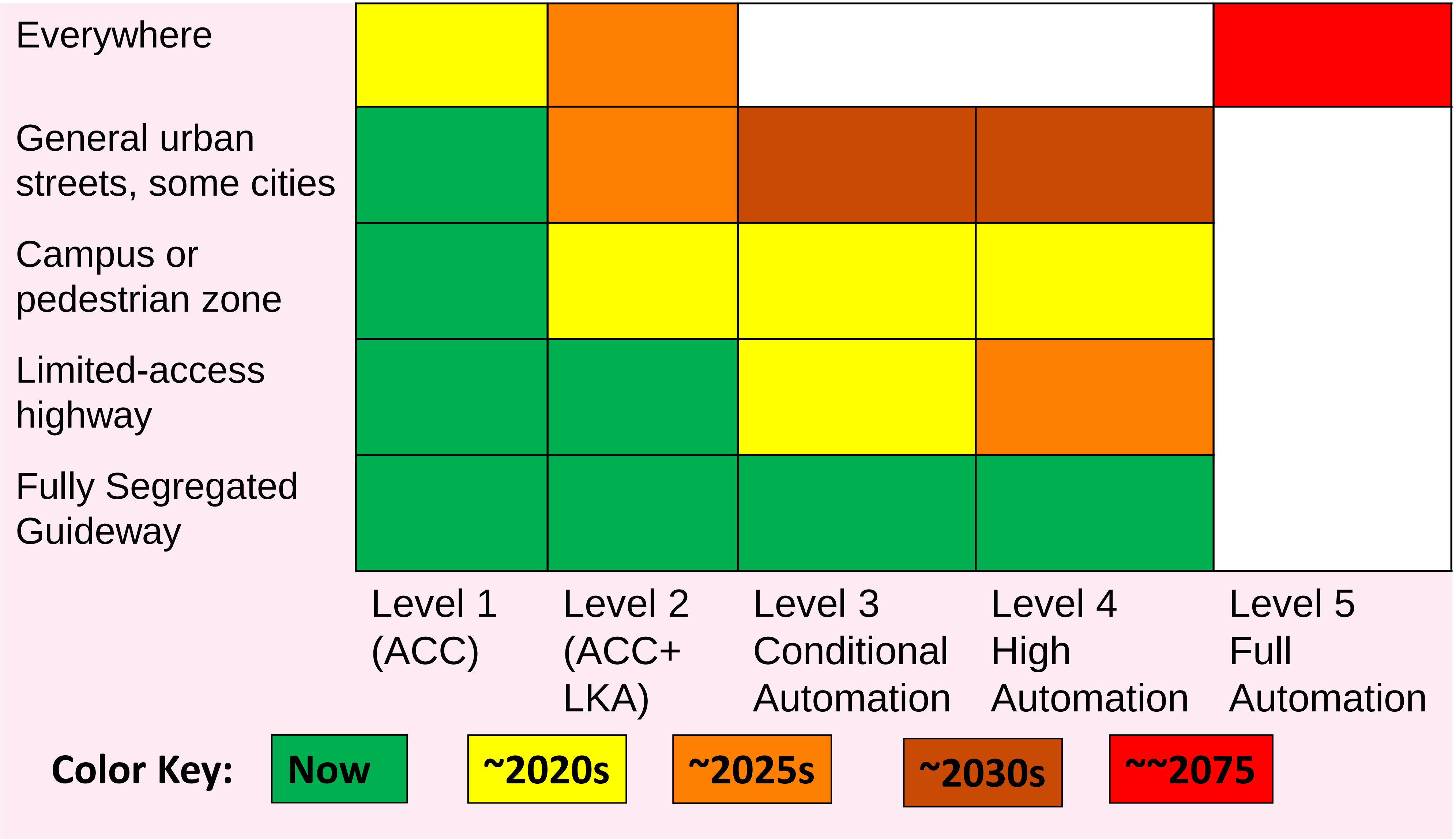


Full Automation (Level 5) Impacts

- **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)**

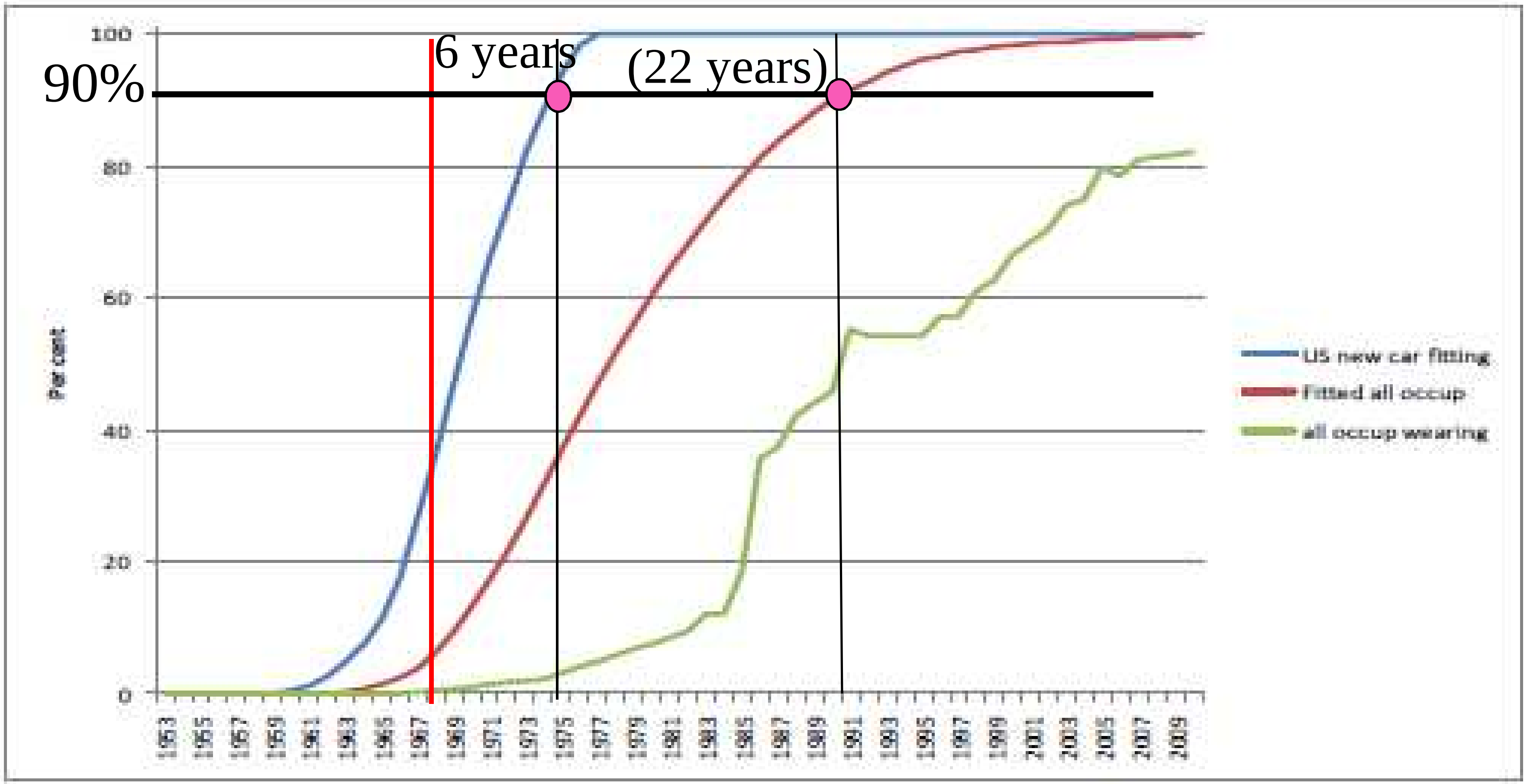
Personal Estimates of Market Introductions ** based on technological feasibility **



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)

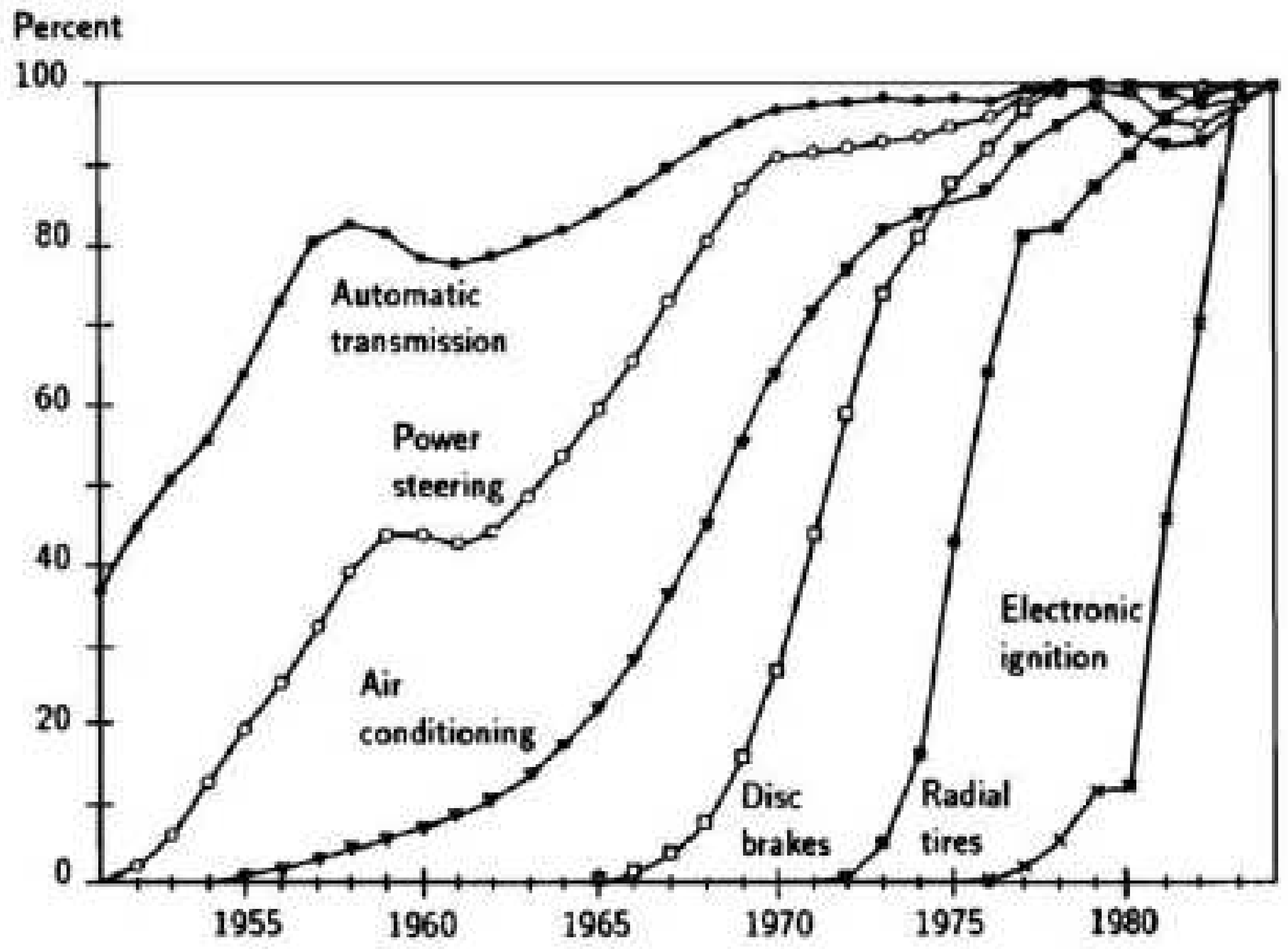


Figure 3.3.10. Diffusion of new technologies in the US car industry (in percent of car output). (Source: Jutila and Jutila, 1986.)

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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**

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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

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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 > 3.4 million vehicle hours**
  - **Injury crash MTBF > 61,400 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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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 showed ~5000 miles between critical events in 2016 (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

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 ($\sim 10^6$)	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 (~$3000)	3
Annual production volume of automation systems ($\sim 10^6$)	- 4
Sum total of orders of magnitude	**10**

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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,…)

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