
Practical Challenges to Deploying Highly Automated Vehicles

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**Drive Sweden
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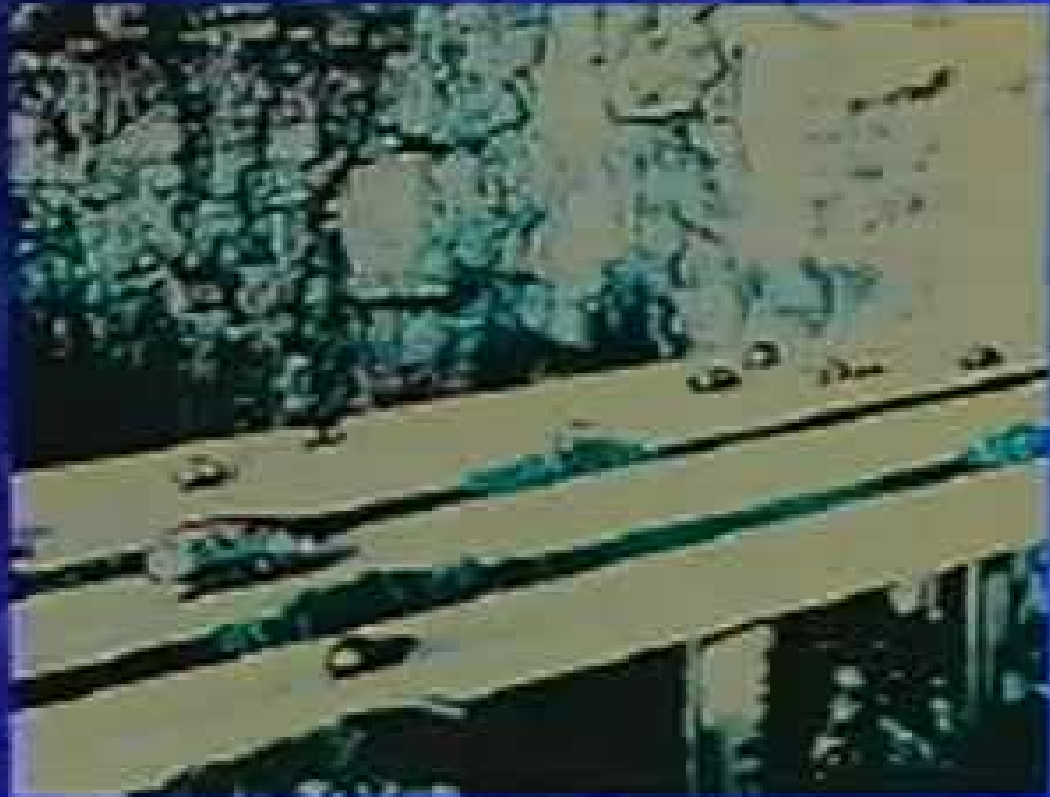


Outline

- **Historical overview**
- **Road vehicle automation terminology**
- **Importance of connectivity for automation**
- **Perception technology challenges**
- **Safety assurance challenges**
- **Market introduction and growth – how slow?**

General Motors 1939 Futurama

General Motors' Futurama
1939 New York World's Fair



GM Firebird II Publicity Video



GM Technology in 1960



General Motors 1964 Futurama II



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 Germany (1988 - courtesy Prof. Ernst Dickmanns, UniBWM)



PATH's 1997 Automated Highway System Platoon Demo



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Terminology Inhibiting Understanding

- **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!)
 - “robotic”
- **Central issues to clarify:**
 - Roles of driver and “the system”
 - Degree of connectedness and cooperation
 - Operational design domain

SAE Taxonomy of Levels of Automation

Driving automation systems are categorized into levels based on:

1. Whether the driving automation system performs *either* longitudinal *or* lateral vehicle motion control.
2. Whether the driving automation system performs *both* longitudinal and lateral vehicle motion control simultaneously.
3. Whether the driving automation system *also* performs object and event detection and response.
4. Whether the driving automation system *also* performs fallback (complete fault management).
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 is designed to function, including:
 - Roadway type
 - Traffic conditions and speed range
 - Geographic location (geofenced boundaries)
 - Weather and lighting conditions
 - Availability of necessary supporting infrastructure features
 - Condition of pavement markings and signage
 - (and potentially more...)
- Will be different for every system

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 <u>other</u> function and monitor driving environment
2	Adaptive Cruise Control AND Lane Keeping Assistance Highway driving assist systems (Mercedes, Tesla, Infiniti, Volvo...) Parking with external supervision	Must monitor driving environment (system nags driver to try to ensure it)
3	Freeway 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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Cooperation Augments Sensing

- Autonomous vehicles are “deaf-mute” drivers
 - Automation *without* connectivity will be bad for traffic flow, efficiency and probably safety
- Cooperative vehicles can “talk” and “listen” as well as “seeing” (using 5.9 GHz DSRC – ITS-G5)
- 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

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

What are the V2V wireless needs?

- Frequent enough state updates to not impede vehicle dynamic responses (50 – 100 ms)
 - Enough data to represent vehicle motions smoothly and safely for platooning (BSM +)
 - Emergency flags and maneuver commands
- Additional messages:
 - External hazard alerts
 - Negotiating cooperative maneuvers
- Well-suited to 5.9 GHz DSRC

What are the I2V/V2I needs?

- **I2V:**
 - Traffic signal status (SPaT) – 100 ms period
 - Variable speed advisories
 - Medium to long-range hazard alerts or traffic condition updates
 - Emergency software updates
- **V2I:**
 - Traffic and road condition (probe) information
 - Signal priority requests
- **Most could be satisfied by 3G/4G cellular, or all by DSRC (locally)**

Needed advances

- **5.9 GHz DSRC:**
 - Prove congestion management in highest-density traffic environments
 - Define BSM extensions to support V2V cooperative control/platooning (and gain access to safety channel for them)
- **5G cellular:**
 - Show that it can scale to support these applications in high-density traffic, while everybody is using their 5G mobile devices too
 - Show an acceptable cost/business model for vehicle users

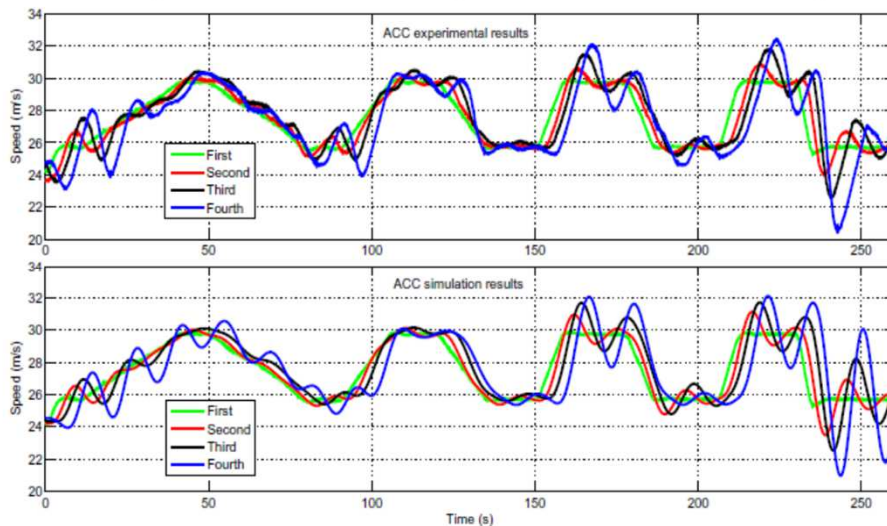
Traffic Simulations to Estimate Impacts of Connected Automated Vehicles (CAV)

- High-fidelity representations of human driver car following and lane changing
 - Calibrate human driver model to traffic data from a real freeway corridor
- Model ACC and CACC car following based on full-scale vehicle experimental data
- Model traffic management strategies for taking advantage of CAV capabilities
- Analyze simulated vehicle speed profiles to estimate energy consumption
- *Results for Level 1 automation are relevant for higher levels of automation*

AACC Car-Following Model Predictions Compared to Calibration Test Results

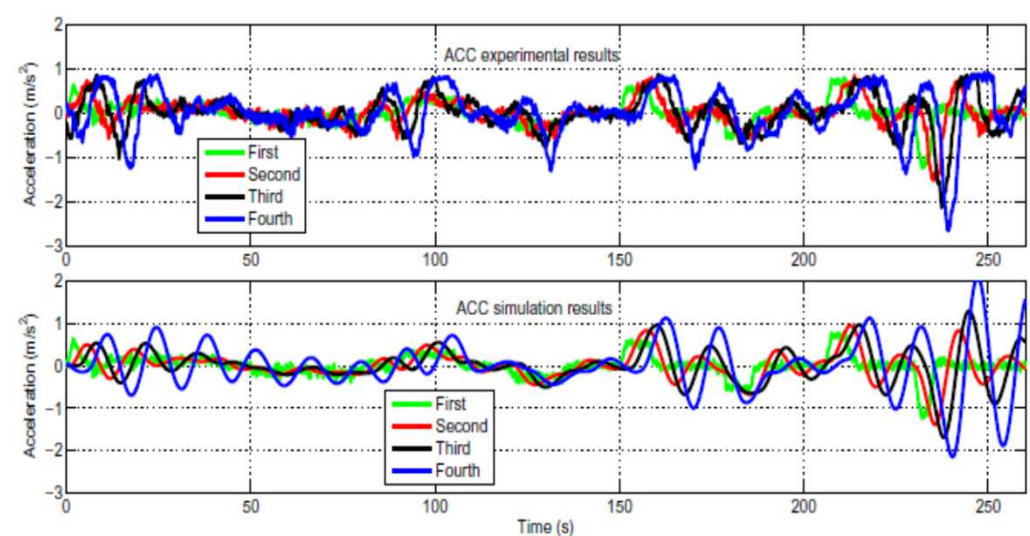
Speeds

(Test above, model below)



Accelerations

(Test above, model below)

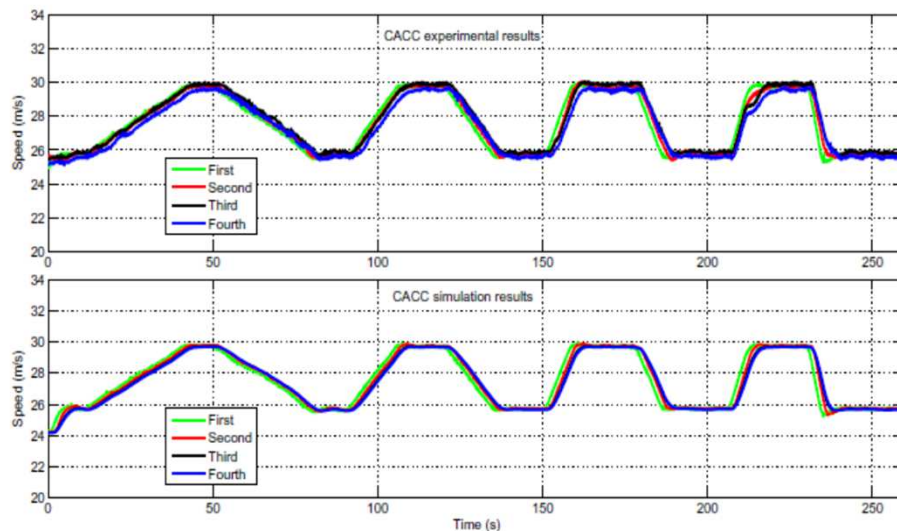


Note string instability (amplification of disturbance)
without connectivity/cooperation

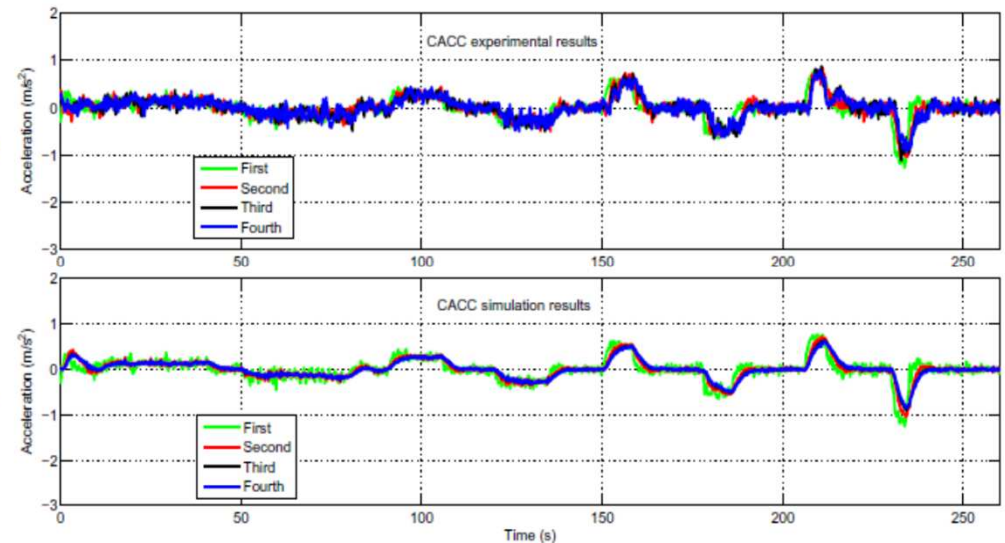
Ref. Milanes and Shladover, Transportation Research Part C, Vol. 48, 2014)

CACC Car-Following Model Predictions Compared to Calibration Test Results

Speeds
(Test above, model below)



Accelerations
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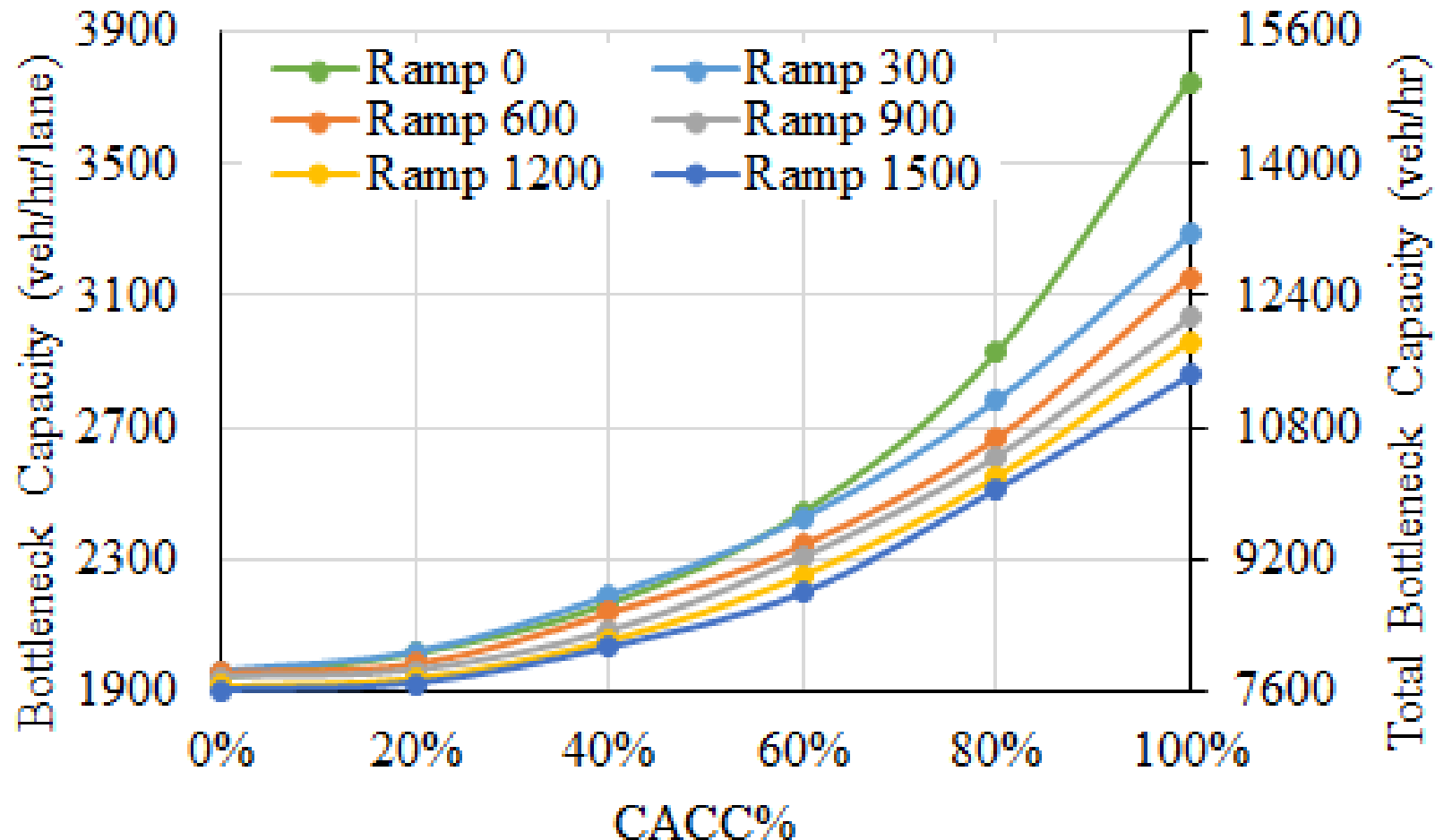
Note stable response **with** cooperation

Ref. Milanes and Shladover, Transportation Research Part C,
Vol. 48, 2014)

CACC Throughput with Varying On-Ramp Volumes

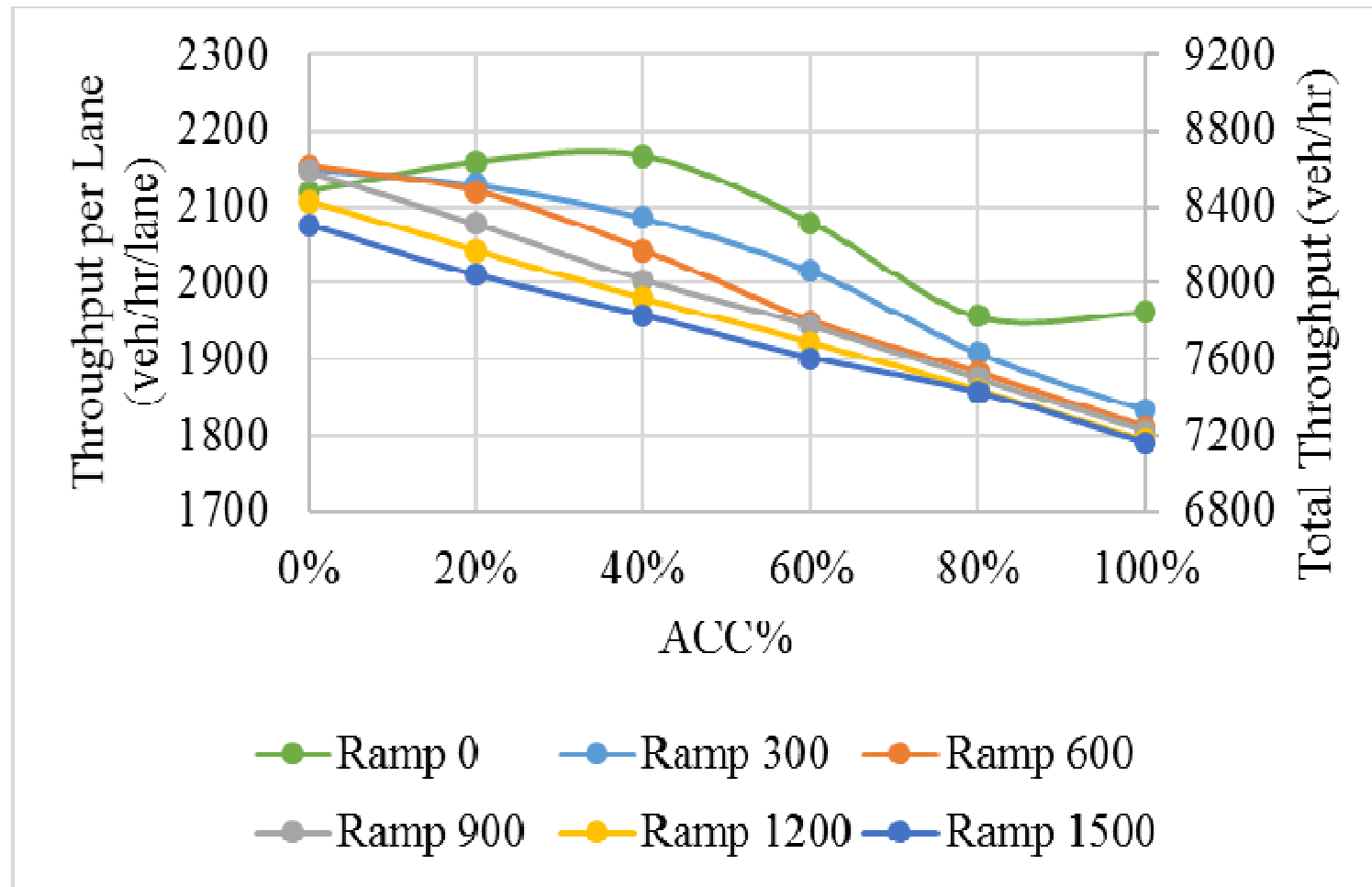
Ramp traffic entering in veh/hr

Mainline input traffic volume is at pipeline capacity for that market penetration



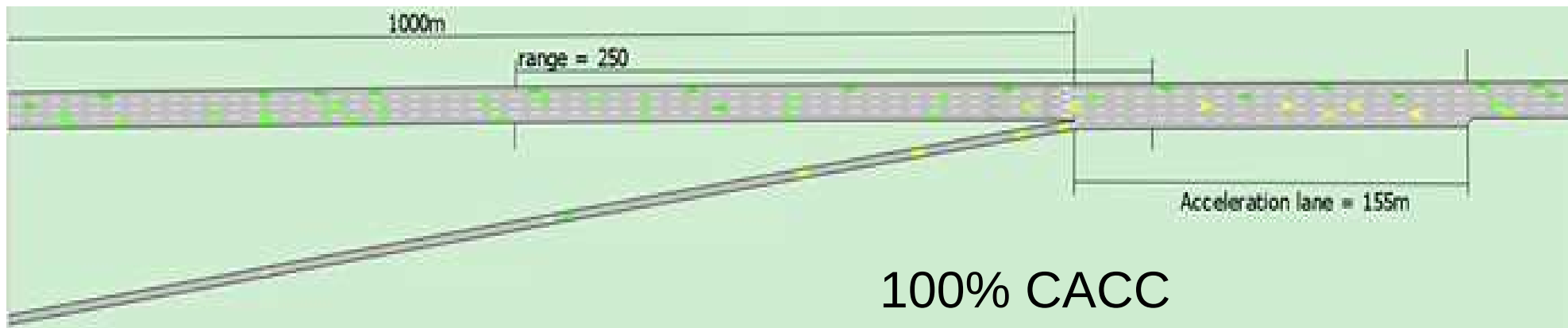
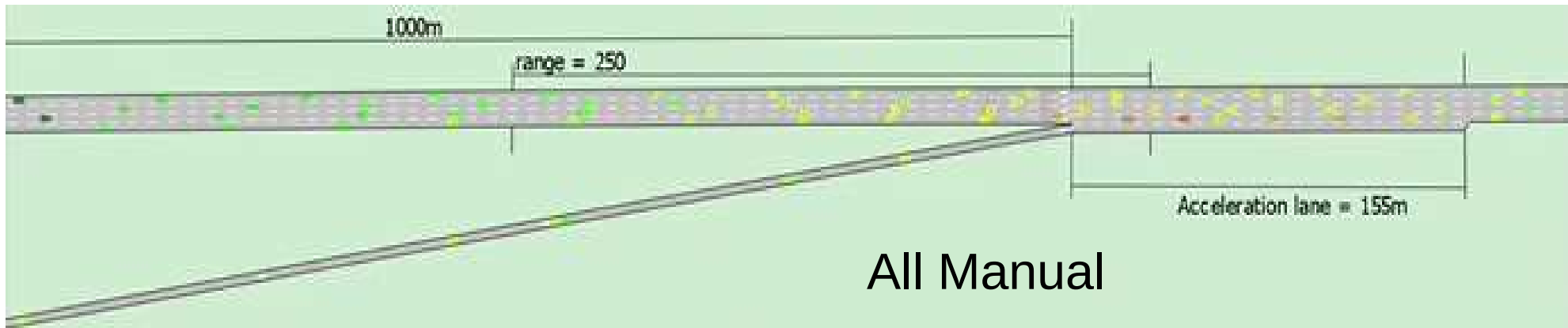
Downstream throughput reduces as on-ramp traffic increases

AACC Throughput with Varying On-Ramp Volumes



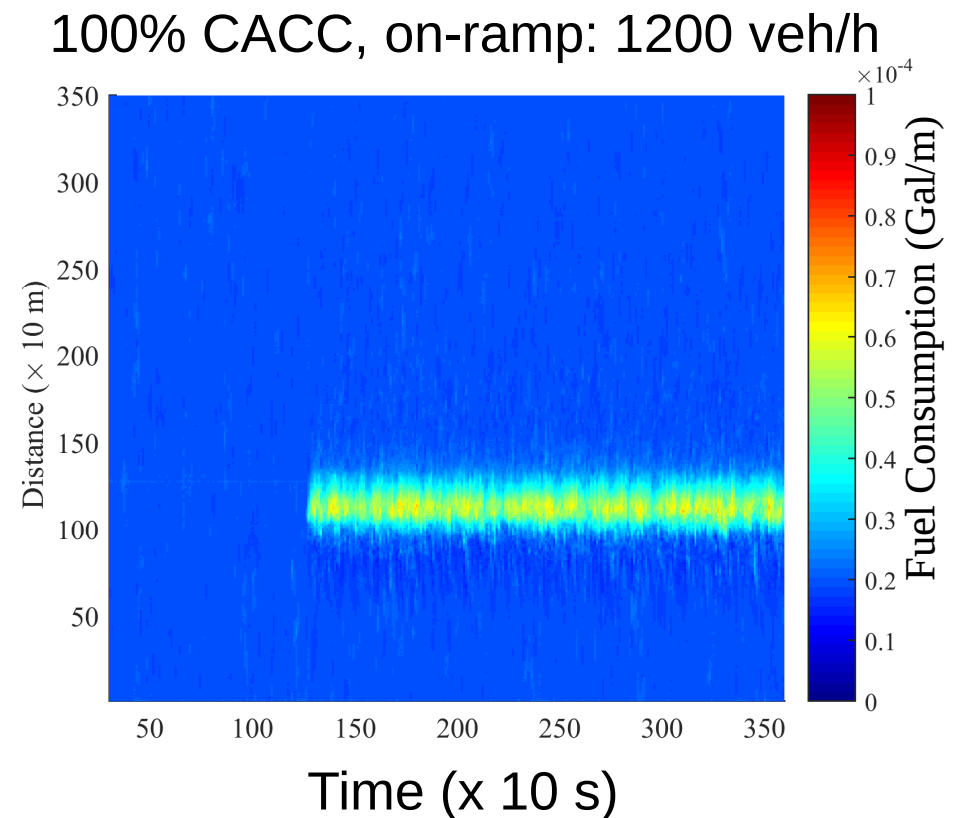
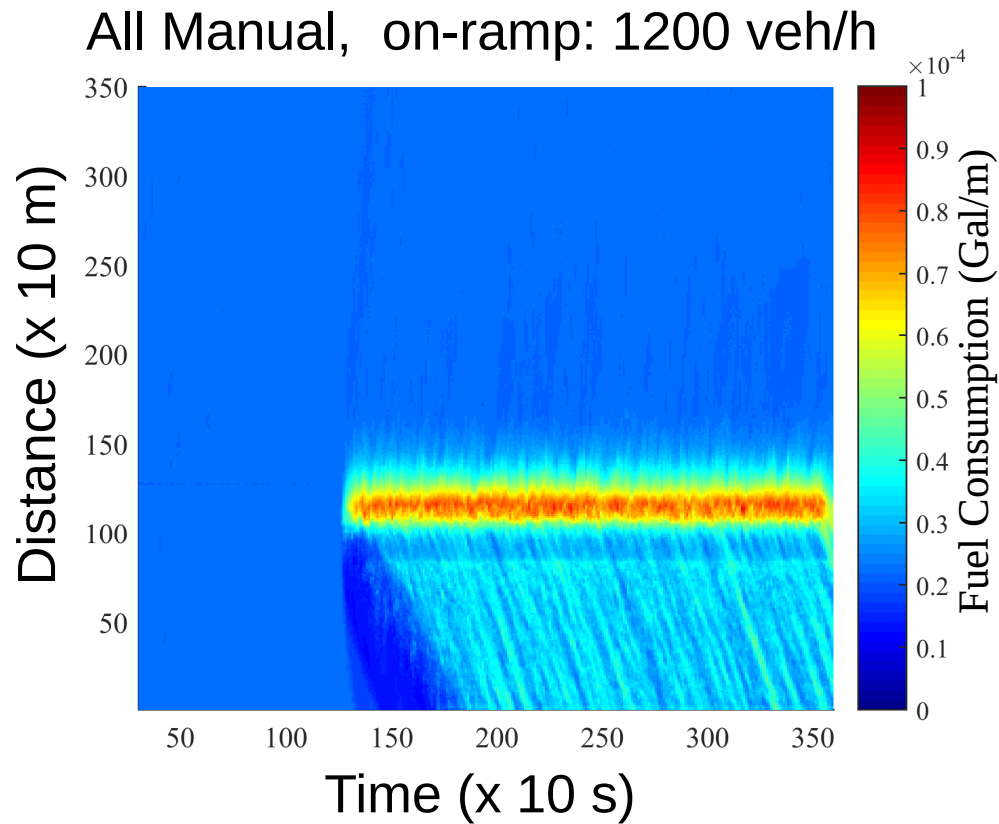
Traffic flow instability with more AACC (lacking V2V communication capability)

Animations Comparing Manual and CACC Driving at a Merge Junction for the Same Traffic Volume



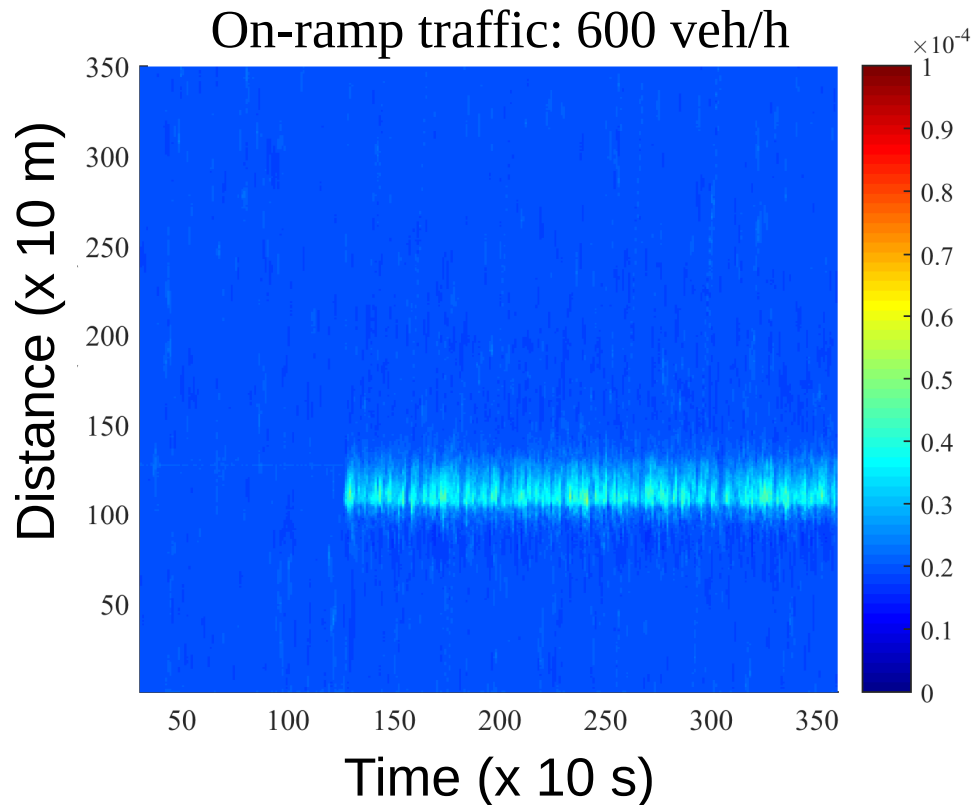
Mainline input: 7500 veh/hr On-ramp input: 900 veh/hr

Fuel Consumption: Spatiotemporal Pattern for Manual and CACC (Same traffic volume)

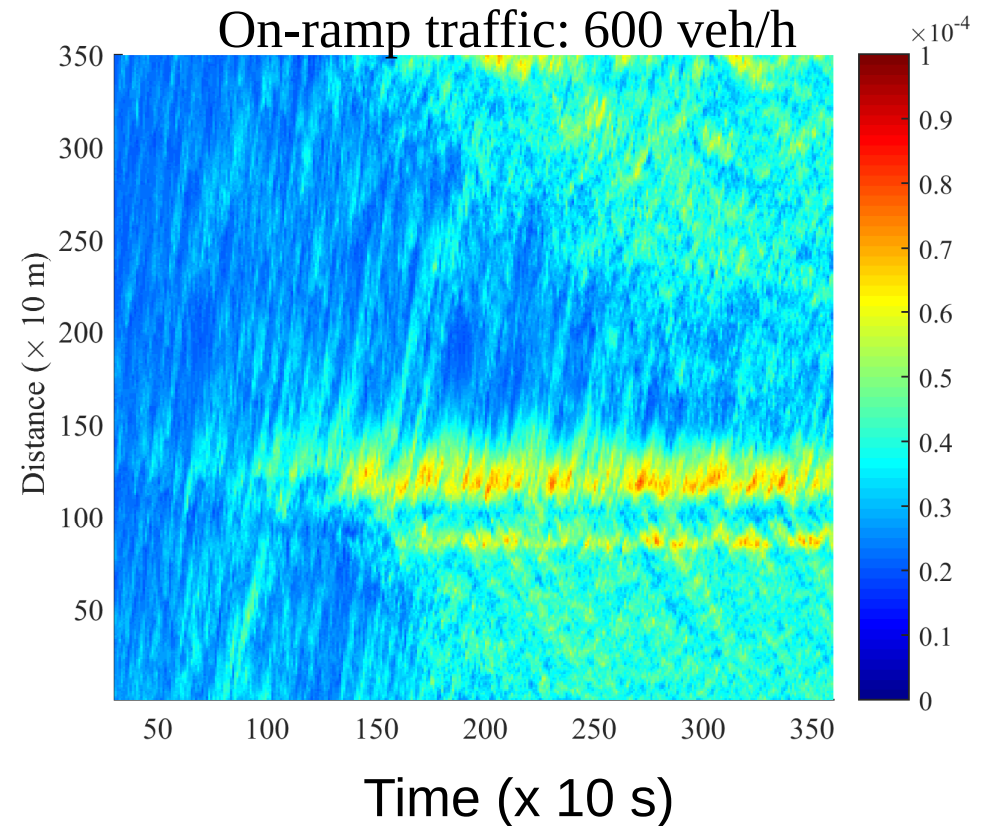


Fuel Consumption: CACC vs. ACC

100% CACC

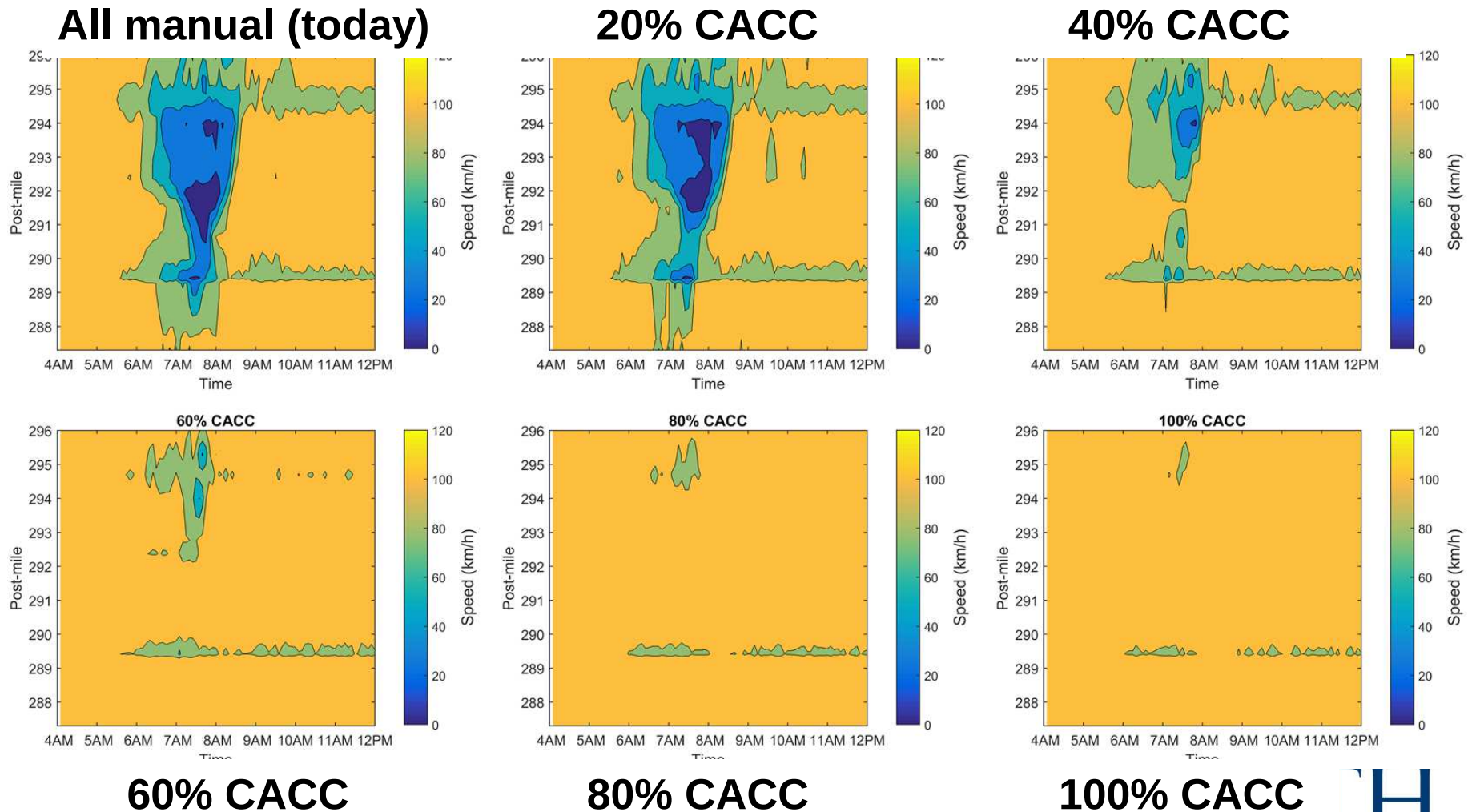


100% ACC



Effects of CACC Market Penetration on SR-99 Freeway Corridor Traffic

Traffic speeds from 4 am to 12 noon at current traffic volume



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Environment Perception (Sensing) Challenges for Highly Automated Driving

- Recognizing all relevant objects within vehicle path
- Predicting future motions of mobile objects (vehicles, pedestrians, bicyclists, animals...)
- Must at least match perception capabilities of experienced human drivers under all environmental conditions within ODD
- No “silver bullet” sensor; will need:
 - Radar AND
 - Lidar AND
 - High-precision digital mapping/localization AND
 - Video imaging AND
 - Wireless communication

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?
-

Safety – Functionality Trade-offs

- False positive vs. false negative hazard detection
- Safety requires virtually zero false negatives (always detect real hazards)
 - Limit speed to improve sensor discrimination capability
 - When in doubt, stop
- Functionality requires very low false positives
 - Avoid spurious emergency braking
 - Maintain high enough speed to provide useful transportation service

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

Simplifying the Environment through Cooperative Infrastructure



The Safety Challenge

- Current U.S. traffic safety sets a very high bar:
 - 3.4 M vehicle hours between fatal crashes (390 years of non-stop 24/7 driving)
 - 61,400 vehicle hours between injury crashes (7 years of non-stop 24/7 driving)
- This will improve with growing use of collision warning and avoidance systems
- Sweden's values about twice as large as U.S.
- How does that compare with your laptop, tablet or “smart” phone?
- How much testing do you have to do to show that an automated system is equally safe?
 - RAND study – multiple factors longer

Evidence from Recent AV Testing

- California DMV testing rules require annual reports on safety-related disengagements
- Waymo (Google) far ahead of the others:
 - 2017 report is ambiguous about their approach, but it appears to be based on reconstruction of disengagement cases in simulations (what if allowed to continue?)
 - Estimated ~5600 miles between critical events based on 2017 data (9% improvement over 2016)
- Human drivers in U.S. traffic safety statistics:
 - ~ 2 million miles per injury crash
(maybe ~ 300,000 miles for any kind of crash)
 - 100 million miles per fatal crash

Learning Systems?

- 90% success recognizing objects in a fairly complex environment is considered very good
- What's needed for highly automated driving?
 - Moderate density highway driving – estimate 1 object per second (3600 per hour)
 - 3.4 M hours = 12.2×10^9 objects $\sim 10^{10}$
 - Missing one for a fatal crash $\rightarrow$ 99.999999999% success rate
 - High density urban driving – estimate 10 objects per second
 - Missing one for a fatal crash $\rightarrow$ 99.99999999999% success rate

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Traffic Safety Challenges for Highly Automated Driving

- 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

How to certify “safe enough”?

- What combinations of input conditions to assess?
- What combination of closed track testing, public road testing, and simulation?
 - How much of each is needed?
 - How to validate simulations?
- What time and cost?
 - Aerospace experience shows software V&V representing 50% of new aircraft development cost (for much simpler software, with continuous expert oversight)

Internal Faults – Functional Safety Challenges

Solvable with a lot of hard work:

- Mechanical and electrical component failures
- Computer hardware and operating system glitches
- Sensor condition or calibration faults

Requiring more fundamental breakthroughs:

- System design errors
- System specification errors
- Software coding bugs

Needed Breakthroughs

- **Software safety design, verification and validation methods to overcome limitations of:**
 - **Formal methods**
 - **Brute-force testing**
 - **Non-deterministic learning systems**
- **Robust threat assessment sensing and signal processing to reach zero false negatives and near-zero false positives**
- **Robust control system fault detection, identification and accommodation, within 0.1 s response**
- **Ethical decision making for robotics**
- **Cyber-security protection**

Much Harder than Commercial Aircraft Autopilot Automation

Measure of Difficulty – Orders of Magnitude	Factor
Number of targets each vehicle needs to track (~ 10)	1
Number of vehicles the region needs to monitor ($\sim 10^6$)	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 ($\sim \$3000$)	3
Annual production volume of automation systems ($\sim 10^6$)	- 4
Sum total of orders of magnitude	10

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This is like climbing Mt. Everest...

Automated Driving System	Climbing Mt. Everest
My system handles 90% of the scenarios it will encounter on the road	I flew from San Francisco to New Delhi, covering 90% of the distance to Everest
My system handles 99% of the scenarios it will encounter on the road	I flew from New Delhi to Katmandu, so I'm 99% of the way to Everest
My system handles 99.9% of the scenarios it will encounter on the road	I flew to the airport closest to Everest Base Camp
My system handles 99.99% of the scenarios it will encounter on the road	I hiked up to Everest Base Camp
And now comes the really hard work!	
My system handles 99.99999999% of the scenarios it will encounter, so it's comparable to an average skilled driver	I made it to the summit of Mt. Everest

Personal Estimates of Market Introductions

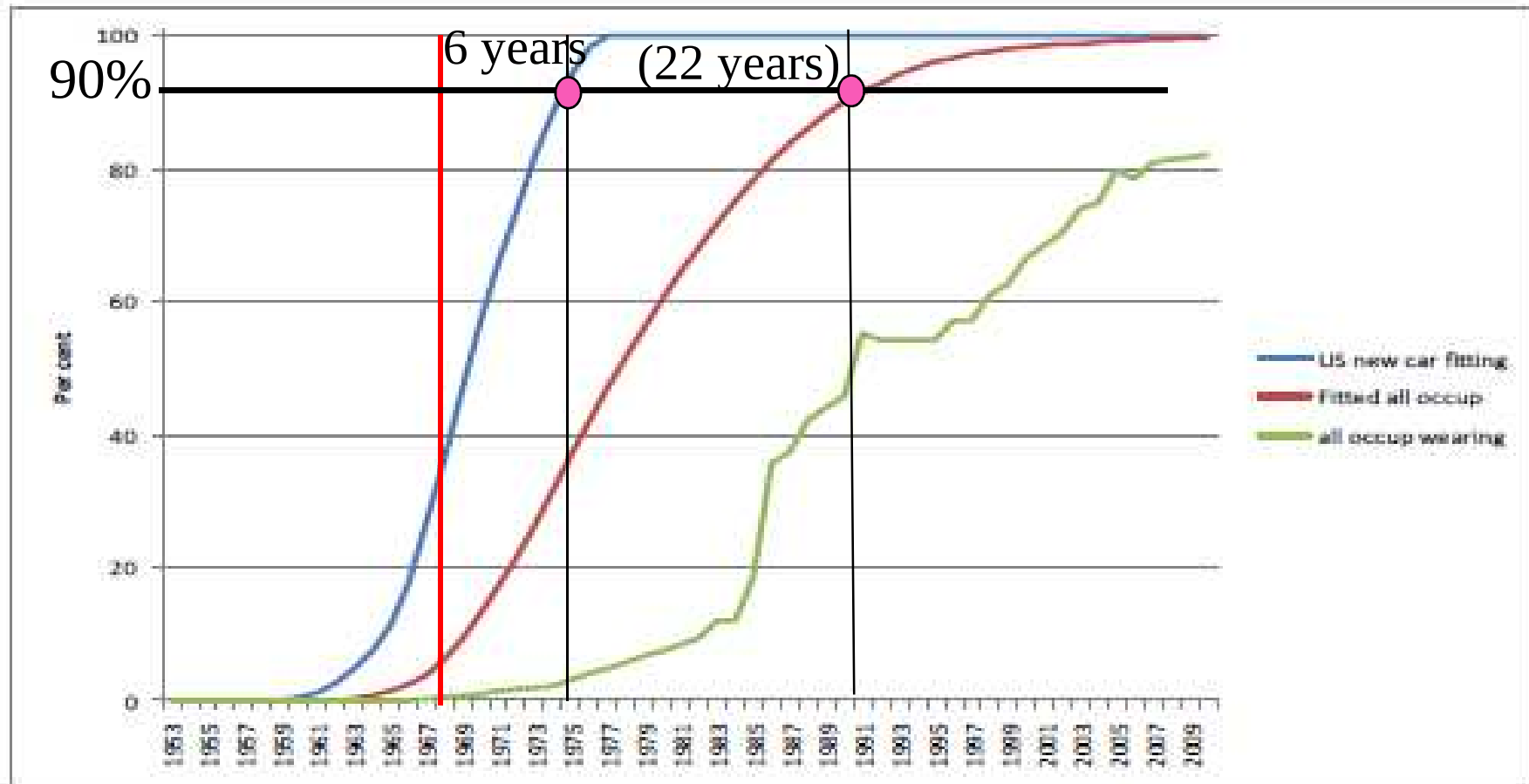
**** based on technological feasibility ****

Everywhere					
General urban streets, some cities					
Closed campus or pedestrian zone					
Limited-access highway					
Fully Segregated Guideway					
	Level 1 (ACC)	Level 2 (ACC+ LKA)	Level 3 Conditional Automation	Level 4 High Automation	Level 5 Full Automation
Color Key:	Now	~2020s	~2025s	~2030s	~~2075

Fastest changes in automotive market: Regulatory mandate forcing them

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)

Percentages of NEW vehicles sold each year

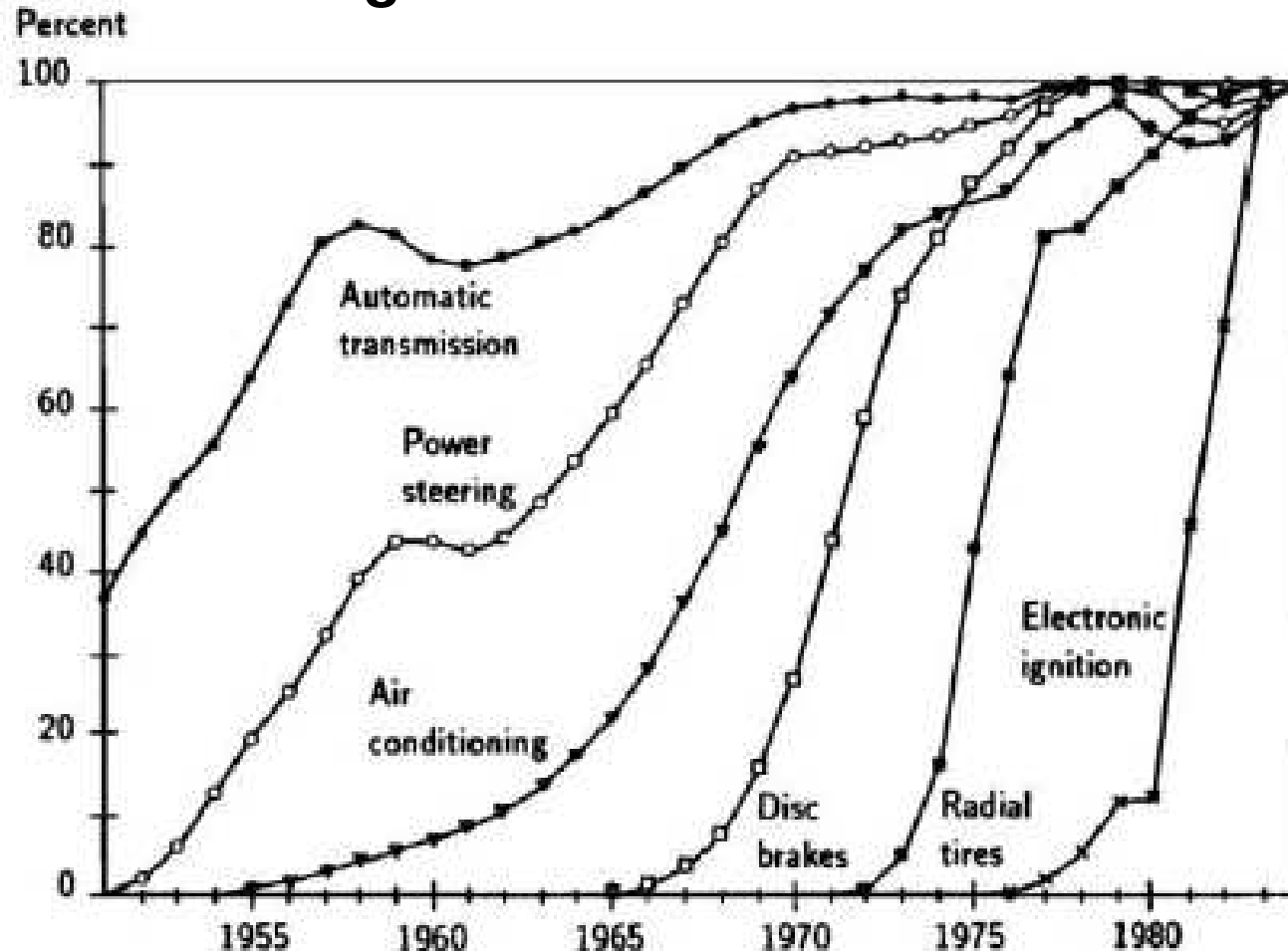


Figure 3.3.10. Diffusion of new technologies in the US car industry (in percent of car output). (Source: Jutilla and Jutilla, 1986.)

How to Reconcile This With the Optimism You See in the Media?

- Public is eager to gain the benefits of automation
- Media are eager to satisfy public hunger, and science fiction is sexier than science fact
- Industry is in “fear of missing out” (FOMO) on the next big thing
- Each company seeks image of technology leader, so they exaggerate their claims
 - Journalists lack technical insight to ask the right probing questions
- Companies are manipulating media reports
- CEO and marketing claims don't match the reality of what the engineers are actually doing

How to maximize progress now?

- Focus on implementing systems that are technically feasible now to enhance performance and gain public confidence:
 - Level 1, 2 driving automation
 - DSRC communications
- Develop more highly automated systems within well constrained ODDs to ensure safety, then gradually relax ODD constraints as technology improves
- Work toward the fundamental breakthroughs needed for high automation under general (relatively unconstrained) conditions