How Vehicular Networking Can Enable Automated Driving

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Outline

• Vehicle-highway automation
  – Historical development
  – Vision and benefits

• Communication-enabled cooperation
  – Concepts
  – Performance advantages
  – Progress

• Future automation challenges
U.S. History of Driving Automation

- General Motors’ “Futuramas” at 1939/40 and 1964/65 Worlds Fairs in New York
- General Motors/RCA technology development and testing in 1950s-1960s
- Ohio State University experimental work from 1965-1980
- Personal Rapid Transit (PRT) development from ~1970
- PATH Program R&D from 1986 (leading to national IVHS, then ITS programs)
- National AHS Consortium 1994-98
- Limited activities since then
The Highway Capacity Challenge

• Roadway infrastructure is expensive, and will only get more expensive (no Moore’s Law)
• At maximum throughput (2200 veh/hr/lane), vehicles occupy only 5.5% of road surface
  - Half the lane width
  - Average longitudinal gap = 9 car lengths
  - Severely under-utilized because of driver behavior limitations
Highway Capacity with Automation

• Capacity must be defined based on safe responses to serious fault conditions (sudden hard deceleration), and with allowance for maneuvering

• Close-formation communication-coordinated platoons permit gentle impacts between vehicles in fault cases, but large gaps between platoons prevent severe impacts

• Platoons enable lane capacity to be doubled or tripled, while maintaining safety
  – 6000 – 8000 cars/hour in 10-car platoons
  – 1500 heavy trucks/hour in 3-truck platoons
Other Automation Benefits

• Smoother traffic flow, avoiding “stop and go” instabilities caused by driver response lags
  – Energy and emissions savings by constant speed cruising
  – Travel time savings
• Car following at very short gaps
  – Aerodynamic drag reductions, saving up to 15% of energy use at highway speed
• Safety possibilities
  – 95% of current crashes caused by driver errors
  – BUT, need to exceed current crash MTBF levels
• Comfort and convenience
It’s not just vehicles, it’s a system!

People and Goods

Vehicles

Information

Roadway Infrastructure

Information

Information
Vehicle Automation Principles

• Need to increase highway capacity significantly and hopefully improve safety, energy and emissions too
• To do that safely, automated highway systems (AHS) must:
  1. Operate automated vehicles physically separated from non-automated vehicles
  2. Fully automate vehicle driving, removing the driver from the control loop
  3. Use best real-time information about the driving environment, based on communication and coordination among vehicles and infrastructure (NOT autonomous vehicles)
Cooperation Can Augment Sensing

• Autonomous vehicles are “deaf-mute”
• Cooperative vehicles can “talk” and “listen” as well as “seeing”
• Communicate performance and condition data directly rather than sensing it indirectly
  – Reduce uncertainties
  – Reduce filtering lags
  – More sources of information available, including beyond line of sight
• Expand performance envelope – capacity and ride quality
Cooperative System Advantages

- All vehicles sharing status information
  - Current and planned actions
  - Identification of hazards
  - Earlier and safer responses possible
- Information available beyond line of sight
- Vehicles “negotiating” maneuvers for safety and efficiency
- Augmenting remote sensor data with more reliable and cheaper “self” state information
- Safety can be based on definitive “handshakes”
- Higher performance enabled
Autonomous (Non-Cooperative) Automated Vehicles

• Several generations of development work for U.S. Army
  – Unmanned vehicles in dangerous places
  – Typically off-road or in light traffic
• DARPA Challenges (off-road and urban)
• Google’s current automated driving experiments
  – Combining Stanford and CMU DARPA teams
  – Personal interest by one of Google’s founders
  – 260,000 km driven on SF Bay Area roads
  – Sponsored Nevada law to create driver licensing rules
Google’s Cars – A Skeptical View

• Autonomous approach - no cooperation with other vehicles or infrastructure – limits safety and performance potential
• No clear definition of goals or benefits – Safety? Comfort and convenience? Environmental improvement?
• How much emphasis on full automation vs. improved warning and control assistance?
• Highly unlikely to achieve safety comparable to today’s driving in U.S.:
  – 2 million vehicle hours between fatal crashes
  – 50,000 vehicle hours between injury crashes
Examples of Higher Performance through Cooperation

• Vehicle-Vehicle Cooperation
  – Cooperative adaptive cruise control (CACC)
  – Automated merging of vehicles, starting beyond line of sight
  – Multiple-vehicle automated platoons at short separations
  – Truck platoons at short enough spacings to reduce drag

• Vehicle-Infrastructure Cooperation
  – Precision docking of transit buses
  – Precision snowplow control
Cooperative Vehicle-Highway Automation Progress

- AHS architecture and operational concepts
- Automatic longitudinal (platoon) control
- Automatic lateral (steering) control
- Passenger responses
- V2V Cooperative ACC as an early opportunity
- Deployment staging strategies
- Heavy truck automation
- Transit bus automation
PATH’s Hierarchical, Distributed ITS Architecture (Varaiya, 1991)
Automatic Longitudinal (Platoon) Control

- Engines and brakes of conventionally powered vehicles can be controlled accurately enough for precision vehicle following in platoons (20 cm accuracy)
- Precise, stable cooperative vehicle following can be done with smooth ride quality
- Vehicles can be driven in close-formation coordinated platoons (3 – 5 m gaps) without exposing occupants to exhaust gases or impeding cooling air to radiators
- Vehicles can merge into the middle of a passing platoon, using wireless coordination
Automatic Steering (Lateral) Control

- Vehicle lateral position can be measured accurately (cm) under all weather conditions, with cooperative infrastructure reference markings.
- Automatic steering can exceed performance of highly skilled drivers, even up to 0.8 g lateral acceleration.
- Vehicles can be steered very accurately while maintaining smooth ride quality
  - 10 cm at highway speed (up to 170 km/h)
  - 1 cm at low speed (bus docking)
- Lanes only need to be 50 cm wider than vehicles (except on sharp curves).
- With automatic fault management, a car can be kept in lane after a front-tire blowout.
Cooperative Automated Platoon Control and Merging
Driver/Passenger Responses

- After a few minutes of automated driving, passengers relax and become comfortable with it, even at 5.5 m gap at highway speed.
- Smooth ride quality and imperceptible changes in vehicle-following gaps are vital to passenger comfort and acceptance.
- Demonstration riders were extremely positive in post-demo surveys (1997)
- Recent testing proved driver acceptance of short Cooperative Adaptive Cruise Control (CACC) gaps in normal freeway traffic
CACC Driving at Four Gap Settings

1.1 s

0.9 s

0.7 s

0.6 s
Lead Vehicle Braking at 1.1 s Gap
Distribution of Time Gap Selections

Cruise Control System Time-Gap Setting (s)

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Mean Time-Gap Preferences in Vehicle Following
Lane Capacity vs. CACC Market Pen.

With addition of “Here I Am” vehicles ("Vehicle Awareness Devices")
Lane Capacity with ACC and CACC
Automation Deployment Staging

• Need for vehicle-infrastructure cooperation generally indicates need for public-private cooperation, adding complexity

• First applications to Bus Rapid Transit buses and highway maintenance vehicles can be implemented by a single public agency, with limited infrastructure investment

• Heavy trucks on dedicated truck lanes have a strong economic case for automation

• Passenger cars and vanpools likely to come later in managed lanes
Heavy Truck Automation

- Cooperative automated tractor-trailer trucks can be driven at highway speed at a separation of 3 m
  - Saves 10% to 15% of energy use
- Three-truck cooperative automated platoons could double the capacity of a dedicated truck lane, enabling dramatic cost savings in construction of high-capacity truck facilities
Three-truck Automated Platoon (2010)
Comparison of Wind Tunnel and Direct Measurements of Fuel Saved

PATH Experiments by Prof. Fred Browand, USC (2003)

Wind tunnel models were cab-over engine, Field tests were engine-forward trucks
Transit Bus Automation

- Likely to be first adopter based on operational needs, economics and politics
- Precision docking can be done with centimeter accuracy at low speed at bus station
- Smooth automatic steering with accuracy of 10 cm enables operation in narrow lanes (busways on former rail ROW or urban arterials, toll plazas)
- Automation enables buses to provide rail quality of service at much lower cost
- Platoons where higher capacity is needed
Technical Challenges to Implementation of Vehicle Automation Systems

- Sensor performance and cost
- Logic and data processing
- Software complexity and safety
- Human factors and driver roles
- Need for separation from manual traffic to achieve safety and capacity improvements
- (Communication seems to be less of a problem here)
Sensor Challenges for **Autonomous Automation**

- High-performance, costly sensors are needed (accuracy, field of regard, discriminant capability)
- No single sensor technology can satisfy all needs, so fusion of multiple sensors with complementary faults and vulnerabilities is necessary
  - Costly
  - Complex
- Filtering is necessary, but introduces lags
- Remote sensors are slower and more uncertain than onboard sensors (speed, acceleration, driver actions)
- Sensors cannot detect subtle cues from other vehicles and drivers like experienced drivers
Logic and Data Processing Challenges

- Sensor signal processing (e.g., distinguishing hazardous from benign obstacles)
- Predicting future actions of other vehicles
- General driving threat assessment (defensive driving)
- Decision making in ethically ambiguous threat situations (truck vs. motorcycle)
- Learning systems cannot do better than the humans who train them
  - But they **must** do better to provide benefits!
- Moore’s Law does not provide salvation
Software Challenges for Fully Automated Driving

• Complexity – cannot test all combinations of conditions
• Cannot prove safety of software for safety-critical applications

• How many hours of testing are needed to prove safety better than human driving?
  – Fatal crash MTBF = 2 million vehicle hours
  – Injury crash MTBF = 50,000 vehicle hours

• How many hours of continuous, unassisted automated driving has anybody achieved in real traffic?
Human Factors Challenges for Automated Driving

- Earning confidence of drivers willing to cede control to the system
- “Semi automated” operations are questionable
  - Underloading of driver precludes vigilance
  - Forcing driver vigilance negates convenience benefits and likely to be a nuisance
  - Mental model ambiguities lead to errors
- When is driver intervention permitted?
  - Errors could make the situation worse
- Should intervention be required in emergencies?
- Who is responsible for the crash?
Basic Research Needs – Autonomous and Cooperative Automation Systems

• 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 degraded mode
  – General approach first, then applied to specific vehicles and system designs
• General obstacle detection
  – Any object large enough to cause harm
  – BUT, ignore innocuous “soft” targets
From Basic Research Toward Deployment

- Sensing and data fusion for comprehensive vehicle neighborhood state mapping
- Extensive development and testing of fault management, fault tolerant control and software safety
- Infrastructure development case studies, with site-specific costs, benefits and constraints
- Human factors testing to define driver roles with potentially viable partial automation systems
- Long-duration prototype testing under adverse conditions to prove technical viability and sufficient safety for insurance underwriters
Institutional Issues to be Resolved

- How can protected infrastructure be acquired to separate automated vehicles from hazards?
- Legal concerns – possible legislation needed
  - Liability exposure allocation among multiple parties
  - Certification processes needed to start operations
  - Insurability without actuarial data
  - International differences in laws and legal systems
- Risk management – commercial
  - Uncertain benefit/cost before deployment
  - Ability of new suppliers to provide long-term product support