Cooperative Adaptive Cruise Control
A Real-Time Cooperative Driving System

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Outline

- Introduction TNO & current research program
- Introduction & motivation Cooperative Driving
- Cooperative Adaptive Cruise Control (CACC)
  - Nominal control objectives & robustness issues
  - String stability
  - Controller design
- Experiments
- Application in daily traffic situations
- Conclusions
TNO

- Netherlands Organisation for Applied Scientific Research (TNO)
- Statutory, non-profit research organization
- 600 m€ turnover
- 4,100 employees
TNO Transport & Mobility

Safe and sustainable transport
- Business line Clean
- Business line Safe

Reliable mobility
- Business line Reliable
- Business line Logistics
Adaptive Multi-Sensor Networks

- TNO research program (focussing on “enabling technologies”)
- Funded by Netherlands government

Mission

- To understand the fundamental mechanisms for the design of fully scalable and adaptive networks of intelligent sensors along three lines of critical system properties:
  - Time-critical performance
  - Large scale

One of the application areas in AMSN: Cooperative Driving
Introduction – Cooperative Driving

- Influencing the individual vehicles, either through advisory or autonomous actions, so as to optimize the collective behavior with respect to throughput, fuel consumption/emissions and/or safety.

- Main enabler: wireless communications

- Emerging research topic:
  Employing the wireless traffic sensor network for real-time cooperative driving
Cooperative Adaptive Cruise Control (CACC)

- CACC: a use case in real-time cooperative driving

- CACC objectives
  - Increase road capacity by decreasing the time headway
  - Mitigate resulting(!) shockwaves
  - Decrease fuel consumption/emissions (trucks)

- CACC system
  - Adaptive Cruise Control (ACC)
  - Wireless inter-vehicle communication
CACC (cnt’d)

› Control objectives
  › Maintain desired time gap, as small as possible (< 1 s)
  › Comfortable behavior (as in ACC)
  › Attenuation of oscillations in upstream direction: string stability

› Robustness requirements
  › Specific to application in daily traffic situations
    › Non-equipped vehicles
    › Wireless communication and on-board sensor impairments (e.g., latency, fading, packet loss, radar ghosts, ...)
      ⇒ graceful degradation
  › Complex traffic scenarios: cut-in, cut-out, merging at junctions
String Stability – Human Driving Behavior

String Stability – ACC

- Infinite string
- ACC, with time headway $h = 0.5$ s
- Initial velocity 72 km/h
- Initial position error of one vehicle of 2 m
- String unstable $\Rightarrow$ inefficient driving
Controller Design – Communication Topologies

- Ad-hoc platooning: no designated platoon leader
- Realistic solution for everyday traffic
- Least demanding for communication
- Unidirectional communication with directly preceding vehicle
Controller Design

Spacing policy

\[ d_{r,i} = r + h \cdot v_i \quad 2 \leq i \leq m \]

- \( h \): time headway [s]
- \( r \): standstill distance [m]

Spacing policy improves string stability properties!

- Communication of vehicle acceleration (amongst others)
- Controller acts on vehicle acceleration to realize the desired spacing
Controller Design – Simulation Results

- Without communication ($h = 0.5$ s)

- With communication ($h = 0.5$ s)
Experiments

- Test fleet: 6x Toyota Prius, equipped with low-cost instrumentation
  - Prius ex-factory long-range radar
  - Wireless communications (IEEE 802.11p, ETSI Geonet)
  - EGNOS GPS (may be too low-cost :-)
  - CACC control computer
  - Low-level vehicle control computer (interacts with the vehicle CAN bus to automatically accelerate/decelerate)
Experiments – “highway”

- Velocity responses of test fleet

ACC (i.e., no WiFi)  CACC
Experiments – “urban”

- Velocity responses of test fleet

ACC (i.e., no WiFi)  CACC
Application in daily traffic situations

- Communication & sensor impairments
  - Wireless communications: (varying) latency, packet loss
  - Wireless communications: limited scalability in view of the above
  - GPS inaccurate & slow
  - Radar/lidar: ghost detections, sensitivity to environmental conditions
  - Unequipped vehicles

⇒ robustness (dependability) is an important issue!
Application in daily traffic situations (cnt’d)

- Wireless communication improvements
  - Distributed Congestion Control (scalability)
  - Transmission Power Control
  - Transmission Rate Control
  - Multi-hop (within the ETSI Geonetworking scheme)
Application in daily traffic situations (cnt’d)

Flexible/adaptive object tracking
- Estimate/measure position, velocity & acceleration
- Wireless comm. (GPS) / radar / both
- To be extended with (mono-)vision, 3G/LTE

Measurement example
- Real-time implementation
- Prius radar measurements
- 802.11p wireless comm.
- Tracking for CACC
Application in daily traffic situations (cnt’d)

➤ Graceful degradation mechanisms
  ➤ Change controller settings and/or spacing policy depending on (reliability of) data sources
  ➤ Change controllers: multiple- to single-vehicle look ahead
  ➤ If all else fails: smoothly revert from CACC to CC or manual driving
Conclusions

- CACC allows for very small headway times ⇒ increases road capacity, potentially decreases fuel consumption/emissions

- Implementation in daily traffic is feasible
  - CACC can be regarded as add-on to ACC
  - Standardization in wireless communications well under way (IEEE 802.11p, ETSI Geo-routing & CAM content)

- Crucial research topics in real-time cooperative driving
  - Wireless comm. congestion control
  - Robust & adaptive object tracking
  - Graceful degradation mechanisms