

Engineers of the future?

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acknowledgements: Gerrit Naus, Jeroen Ploeg, Sinan Oncu and others

Projects: Connect & Drive, CCC, SPITS, GCDC

CACC: Outline

- **Introduction**
- **Cooperative Adaptive Cruise Control (CACC)**
- **String stability**
- **CACC design¹**
- **Conclusions**

1 Ackn. Gerrit J.L. Naus et al, TU/e

Introduction: societal trends

- **A growing need for mobility, individuality, freedom**
 - **expected growth in mobility 20 – 30%**
 - **total loss of travelling hours will double**
- **Significantly more road space in the living environment is not acceptable**
- **Environmental awareness and climate change will support the demand for clever solutions**
- **Technology innovation offers possibilities**
 - **information technology (generic architectures)**
 - **communication technology (ad hoc wireless networks)**
 - **sensor technology (sensors & fusion)**
 - **electronics (small, light weight, low power)**
 - **vehicle technology (controllability)**



Introduction: ADA trends

- **Advanced Driver Assistance (ADA) systems**
 - “systems that support the driver in his driving task, primarily based on information regarding the environmental traffic conditions”
- autonomous driving



mobility: cooperative driving



safety: collision warning → mitigation → avoidance



comfort: cruise control, advanced cruise control

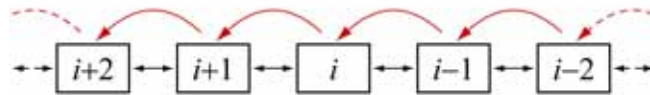
Introduction: Cooperative Driving

- **Cooperative Driving**
 - “influencing the individual vehicles, either through advisory or autonomous actions, so as to optimize the collective behavior with respect to a certain criterion”
 - criterion related to
 - throughput
 - safety (affects throughput)
 - emission/fuel consumption (trucks)

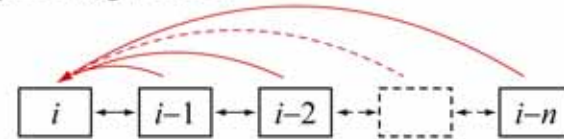
- **Cooperative Adaptive Cruise Control (CACC)**
 - first candidate for (closed-loop) cooperative driving
 - basis: Adaptive Cruise Control (ACC)
 - wireless communication of vehicle info
 - targets throughput and emission/fuel consumption
 - safety as constraint

CACC: communication flows

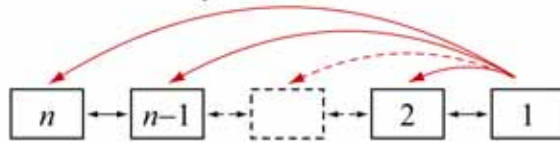
Directly preceding vehicle



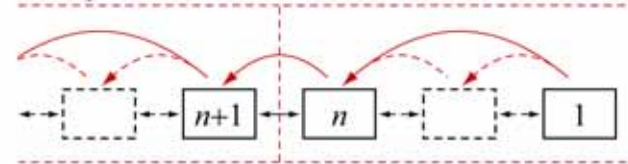
n preceding vehicles



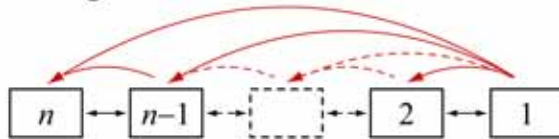
Leader vehicle only



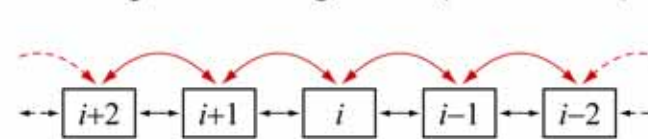
Mini platoons



Preceding and leader vehicle



Preceding and following vehicle (bi-directional)

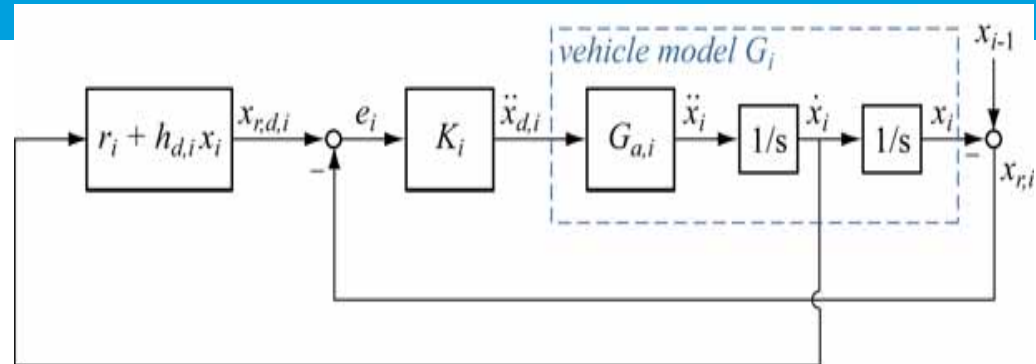


driving direction →

least demanding for communication
no designated platoon leader

CACC: control structure

- Basic Adaptive Cruise Control



- i : host (“ego”) vehicle; $i-1$: preceding vehicle

- Vehicle model:

$$G_i(s) = \frac{G_{a,i}(s)}{s^2} = \frac{k_{G,i}}{s^2(\tau_{G,i}s + 1)} e^{-\theta_{G,i}s}$$

- Spacing policy:

with $h_{d,i}$ the desired time headway

$$x_{r,d,i} = r_i + h_{d,i}\dot{x}_i$$

- ACC feedback controller:

$$K_i(s) = \omega_{K,i}(\omega_{K,i} + s)$$

CACC: necessary hard/-software



CACC: design objectives

- **Stability of individual vehicle**
 - relatively low bandwidth in view of comfort
- **Spacing policy: headway as small as possible**
 - taking safety into account as a constraint
- **Attenuation of oscillations in upstream direction:**
 - **String stability is a platoon performance criterion, not a (Lyapunov) stability criterion**

String stability: definition

- **Various definitions found in literature**
 - error string stability
 - input string stability

- **output string stability:**

$$SS_{x,i}(s) = \frac{X_i}{X_{i-1}}$$

- **Output string stability adopted here**
 - clear interpretation (especially compared to error string stability)
 - direct link to vehicle performance characteristics such as fuel consumption and comfort

String stability: definition

- **String stability conditions**

- **strong string stability:**

$$\|SS_{x,i}(s)\|_{\infty} = \left\| \frac{X_i}{X_{i-1}} \right\|_{\infty} \leq 1$$

- **Strong string stability is a sufficient condition for oscillation attenuation \Rightarrow applied here.**

- **CACC:**

$$SS_{x,i} = \frac{G_i F_i D_i s^2 + G_i K_i}{1 + H_i G_i K_i}, \quad \text{for } i > 1$$

String stability: examples

- Assume ideal vehicle model (double integrator); no time delays
- ACC with constant distance headway: string instable

$$h_{d,i} = 0 \Rightarrow H_i(s) = 1 + h_{d,i}s = 1$$

$$SS_{x,i} = \frac{G_i K_i}{1 + G_i K_i} \Rightarrow \|SS_{x,i}\|_{\infty} > 1$$

ACC with constant time headway: string stable under conditions

$$SS_{x,i} = \frac{G_i K_i}{1 + H_i G_i K_i}$$

$$\Rightarrow \|SS_{x,i}\|_{\infty} \leq 1 \text{ iff } h_{d,i} \omega_{K,i} \geq \sqrt{2}$$

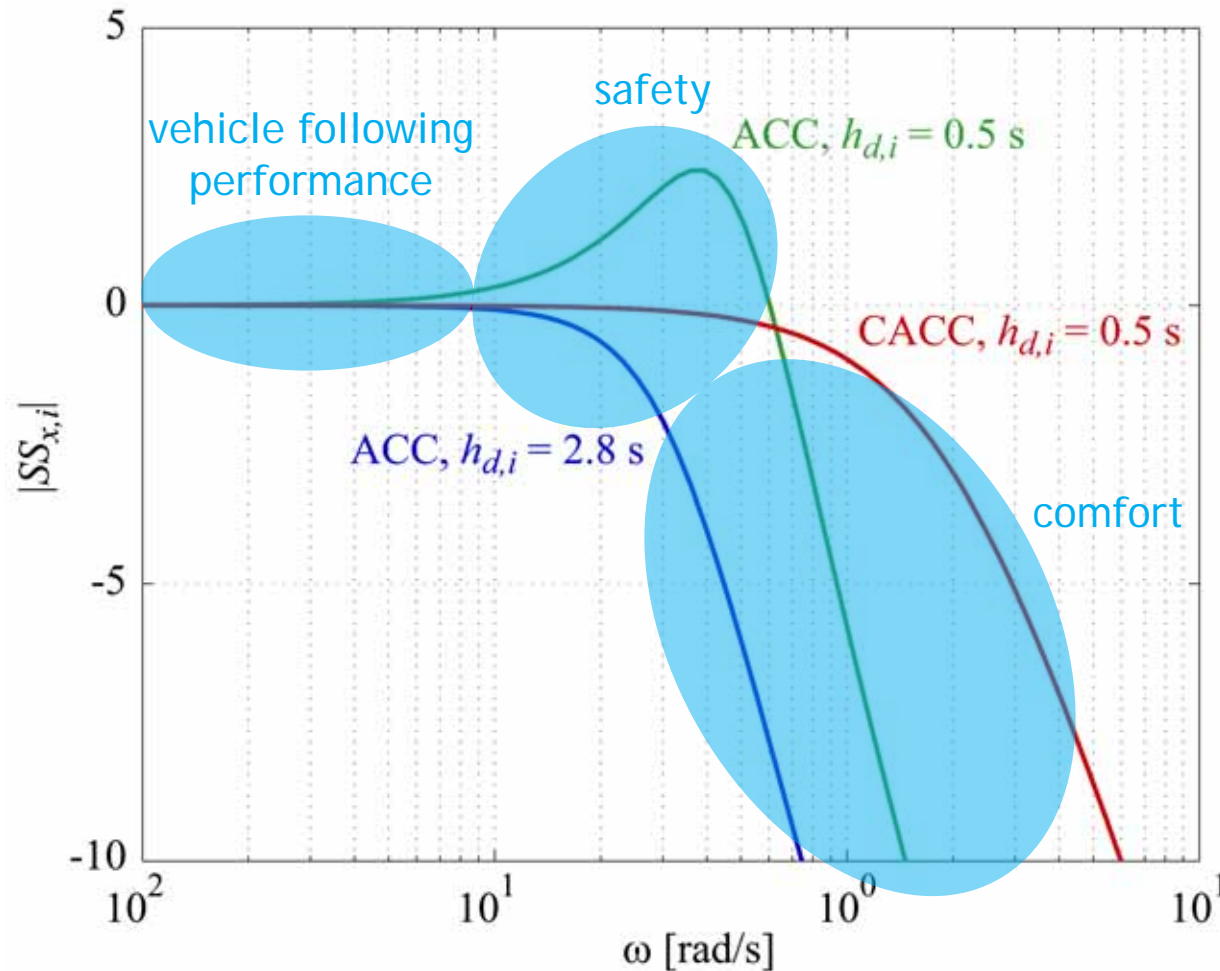
$$\Rightarrow \text{for } \omega_{K,i} = 0.5 \text{ rad/s, } h_{d,i} \geq 2.8 \text{ s}$$

- CACC: string stable

$$\|SS_{x,i}\|_{\infty} \leq 1 \text{ iff } h_{d,i} \geq 0$$

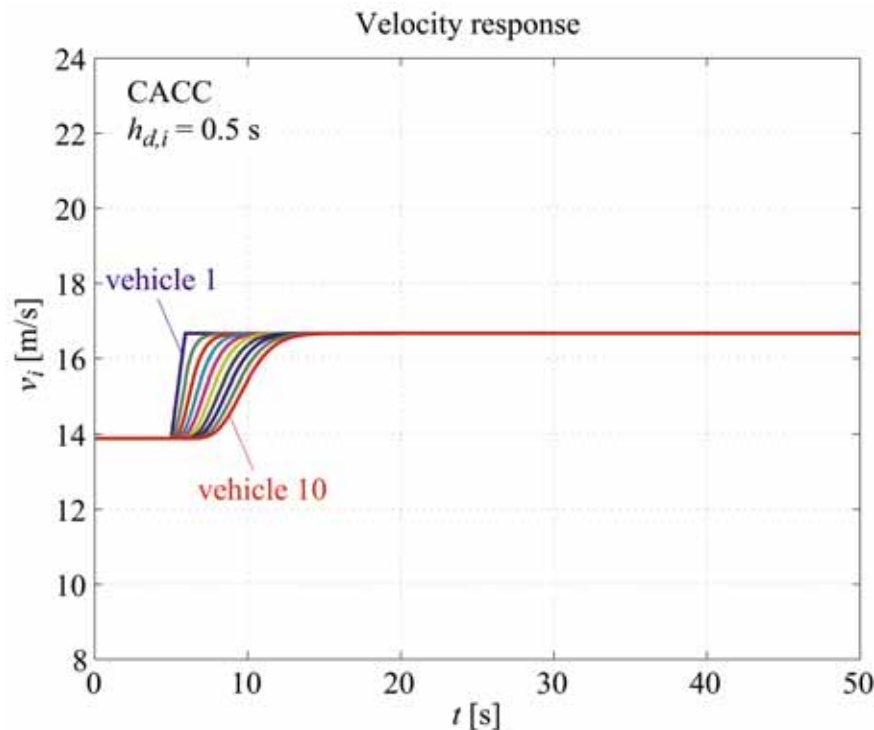
String stability: examples

relation to individual vehicle characteristics



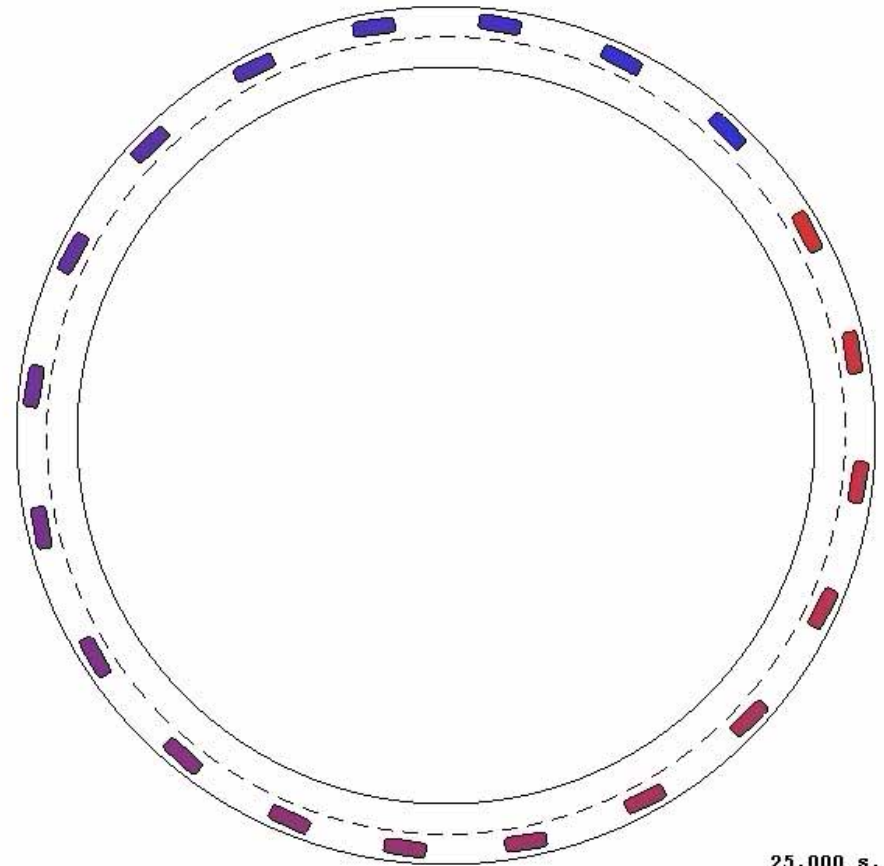
CACC design: simulations

- **Step on acceleration of lead vehicle**
 - [ACC, with $h_{d,i} = 0.5$ s \Rightarrow string unstable]
 - **CACC, with $h_{d,i} = 0.5$ s \Rightarrow string stable**

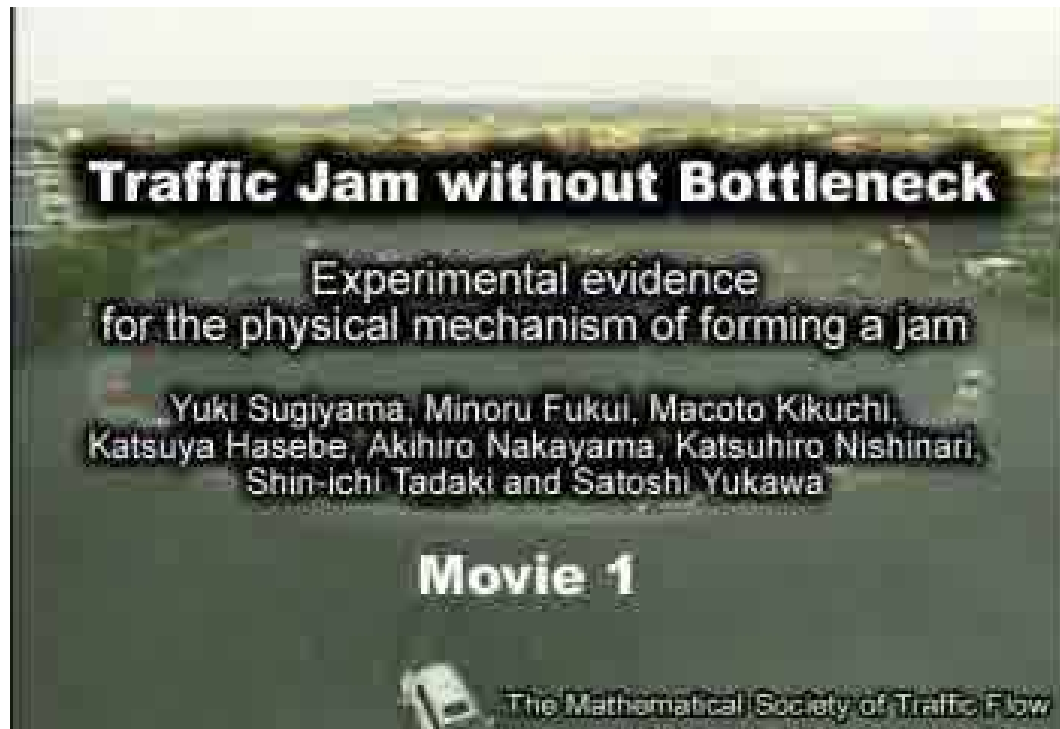


CACC design: simulations

- **Infinite string**
 - ACC, with $h_{d,i} = 0.5$ s
 - initial velocity 50 km/h
 - $x_{r,d,i} = 10.5$ m
 - Initial condition error of lead (red) vehicle of 2 m
 - string unstable \Rightarrow with linear controller, a collision occurs



Intermezzo: human driving behavior



CACC design: practical experiments

TNO & TU/e

- 2 passenger vehicles
 - ACC, with $h_{d,i} = 2.0$ s and $h_{d,i} = 0.5$ s
 - CACC, with $h_{d,i} = 0.5$ s



String stability tests
Ford Lommel Proving Ground
July 23th, 2009

Conclusion and outlook

- **String stability is a valid measure for platoon behavior**
- **CACC allows for very small headway times while maintaining string stability**
- **Design focusing on implementation is feasible**
 - **CACC can be regarded as add-on to ACC**
 - **short distance communication of very limited amount of signals**
- **CACC in fact simplest implementation of Cooperative Driving**

Conclusion and outlook

- **Robustness w.r.t. non-equipped vehicles, wireless communication, ...**
- **Fail safety**
- **Traffic scenarios: cut-in/-out, merging at junctions**
- **Ultimately: 2D-following in a virtual structure (new string stability definition necessary!)**

Questions?

