Intelligent Cars

Improving traffic flow and vehicle safety

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Context and Motivation

Last year, nearly 26,000 people died in traffic accidents in the European Union (EC, 2015). Traffic accidents are one of the leading causes of death and hospital admission.

Every Hamburg citizen spends two days per year on average stuck in a traffic jam (INRIX 2015).

Surely we can improve that situation using modern technology?

Contents

Flow rate and capacity

Flow rate of a lane: number of vehicles n per hour.
Capacity of a (highway) lane: Maximum stable flow rate; without technical enhancements $n_{crit} \approx 2200\, veh/h$.

Assumptions:

- Average velocity of $108\, km/h$, or $30\, m/s$
- Average vehicle length $5\, m$
- Average gap between vehicles $45\, m \mathrel{\widehat{=}} 1.5\, s$

Thus, we get a throughput of $\frac{108\, km/h}{0.05\, km/veh} = 2160\, veh/h$

If more cars enter the highway, increasing the number of cars past $n = n_{crit}$, traffic flow breaks down.

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Intelligent Traffic Management

Intelligent traffic management: Improve performance of the traffic system by making it responsive. Different aspects:

- Throughput
- Safety
- Fuel consumption/Emissions
- Reliability
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- Throughput
- Safety

Here, we focus on these two.

Intelligent Traffic Management

Two different approaches - who regulates the traffic?

- Vehicle controlled-systems
- Infrastructure-controlled systems

Decentralised vs. centralised, mixed approaches are possible.

Intelligent Traffic Management

Two different approaches - who regulates the traffic?

- Vehicle controlled-systems
- Infrastructure-controlled systems

We focus on the former.

Platooning

Increasing throughput means reducing inter-vehicle-spacing!

- A string of vehicles ("platoon") closely spaced, autonomously following the lead of the first car
- Larger inter-platoon-spacing, to allow for additional cars to enter the road (on-ramps!)

A platoon of cars in California's PATH project, source: [rsc]

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We need a device that regulates the behaviour of a car, depending on the behaviour of the car in front: The Adaptive Cruise Control.

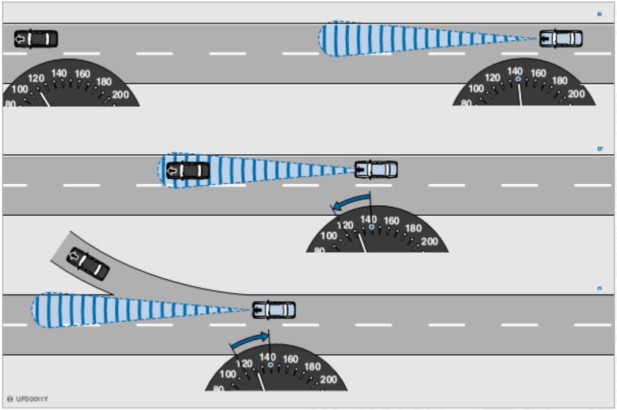
What is an adaptive cruise control?

Cruise control: maintains a set speed (no need to press gas pedal). Introduced as a comfort feature by Chrysler in 1958.

Adaptive cruise control = an "intelligent" cruise control: CC + sensor on the car. Not only maintains constant speed, but also constant *distance*.

Typically microwave radar, sometimes lidar is used for the distance sensor (see lectures).

How does it work?



The principle of ACC, source: [bosch]

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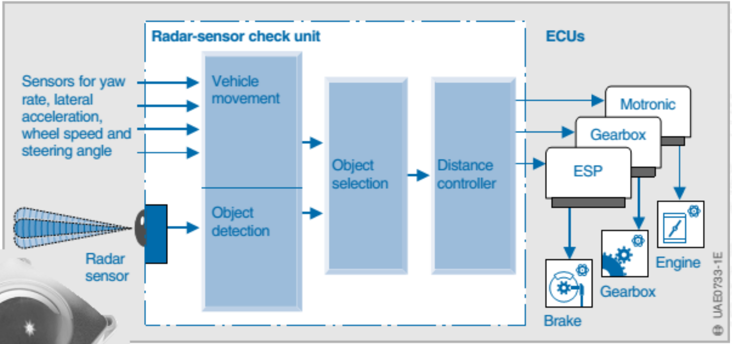

The components of an ACC, source: [bosch]

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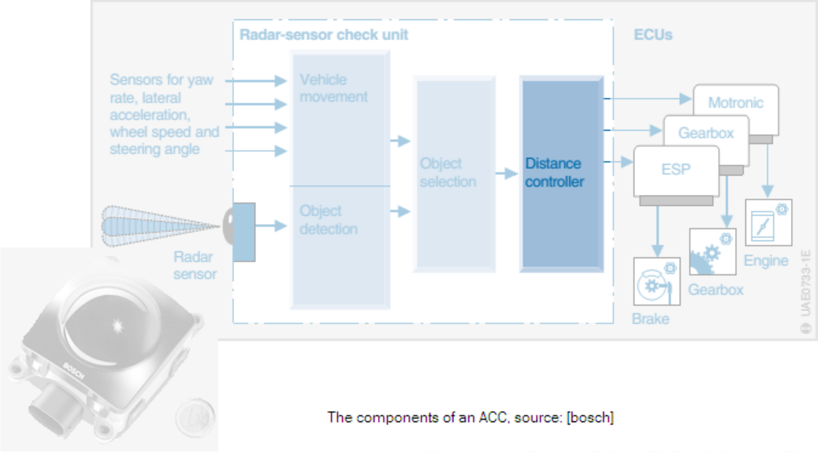

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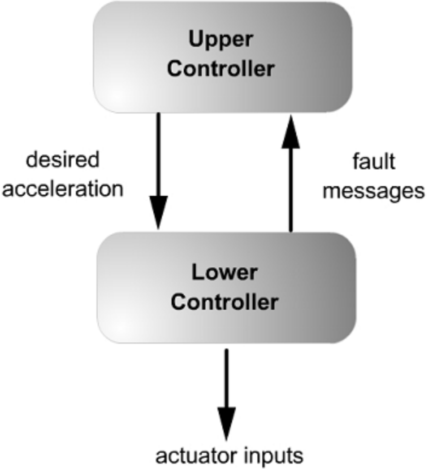

Longitudinal distance controller scheme, source: [raj]

Policies for platooning

- Safety: Vehicles must maintain a constant, non-zero spacing to each other in the steady-state
- Vehicle stability: Any disturbance of the steady-state must return the ideal spacing, at least asymptotically in t
- String stability: The disturbance must not amplify down the string; ideally, it will be dampened
- Available as input are: Own velocity, distance to the preceeding car, relative velocity to the preceeding car

Can we design a controller that works, given this specifications?

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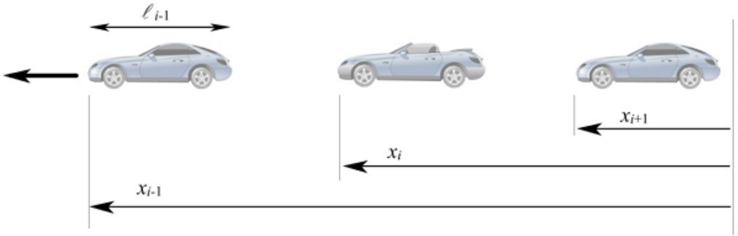
String Stability

- Define measured spacing: $d_i = l_{i-1} - (x_{i-1} - x_i)$
- Define spacing error: $\epsilon_i = L_{tot} - (x_{i-1} - x_i)$, with $L_{tot} = l_{i-1} + d_{des}$
- Vehicle stability: $\ddot{x}_{i-1} \to 0 \Rightarrow \epsilon_i \to 0$



Variables in a platoon, source: [raj]

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Assume a simple model, $\ddot{x} = \ddot{x}_{des}$ (immediate acceleration), and a linear control system, e.g. with a P(I)D-controller (Peppard 1974):

$$\ddot{x}_i = -k_p \epsilon_i - k_d \dot{\epsilon}_i$$

With the spacing definition, get the closed loop error dynamics:

$$\ddot{\epsilon}_i + k_d \dot{\epsilon}_i + k_p \epsilon_i = k_d \dot{\epsilon}_{i-1} + k_p \epsilon_{i-1}$$

String Stability

Is this system string stable? Consider transfer function and frequency response:

$$\ddot{\epsilon}_i + k_d\dot{\epsilon}_i + k_p\epsilon_i = k_d\dot{\epsilon}_{i-1} + k_p\epsilon_{i-1}$$

$\downarrow$ Laplace-transform $\downarrow$

$$G(i\omega) = \frac{\epsilon_i}{\epsilon_{i-1}} = \frac{k_d i\omega + k_p}{(i\omega)^2 + k_d i\omega + k_p}$$

Condition (Swaroop, 1997): $|G|^2 = \frac{k_p^2 + k_d^2\omega^2}{(k_p - \omega^2)^2 + k_d^2\omega^2} \leq 1 \; \forall \; \omega$

But: For $\omega^2 = k_p$, $k_p > 0$: $k_p^2 + k_d^2\omega^2 \not\leq k_d^2\omega^2$

Regardless the k_p, k_d, the system is never stable!

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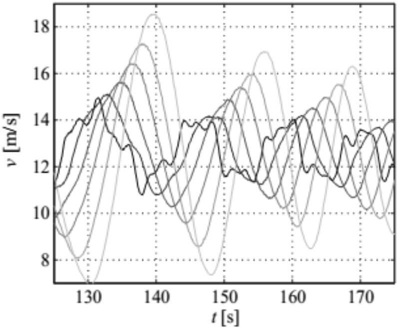

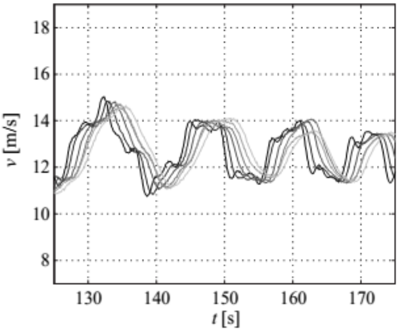

Experimentally measured velocities from a six-car-string, stable (right), instable (left), source: [exp]

String Stability

Solution: Constant *time* gap: $d = l_{i-1} + t_{gap}\,\dot{x}_i$.

Consider more realistic car model:

$$\ddot{x} = \frac{1}{\tau s + 1}\ddot{x}_{des}$$

There is no instant acceleration! Delay τ: ACC controller(s), engine controller, engine itself, ESC, ABS, ...

A similar analysis to before leads to $t_{gap} > 2\tau$. (Swaroop, 1997)

With a realistic delay of $> 750\,ms$, the result is a minimum time gap of $\simeq$1.5 s. Throughput: $n = 2200\,veh/h = n_{crit}$!

No improvement?!

A sad face. Source: [clipartpanda.com]

What is Cooperative ACC?

- Problem: insufficient information of the preeceding vehicle's actions
- Solution: Cooperative ACC, including additional input value forwarded from a preceeding vehicle, i.e. its acceleration

Technical realisation via ad-hoc wireless networks:

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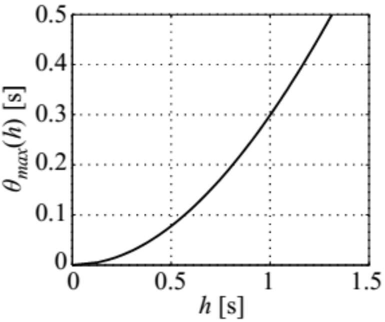
Technical realisation via ad-hoc wireless networks:

"CACC = ACC + Wifi"

Field test (Ploeg et. al, 2011)

Headway = time gap between two cars, including the length of the car in front: $0.7\,s$.



Relation between string-stable headway and latency, source: [exp]

Minimum headway is determined by latency of the wireless link!

Summary, so far:

- Traffic jams are the result of more cars on a lane than the $n_{crit} = 2200\, veh/h$
- To further increase capacity, headway must be reduced without losing string stability
- ACC offers minimum headways of $\gtrsim 1.5\, s$, which is no improvement
- CACC can offer minimum headways of $\approx 0.7\, s$, which theoretically doubles capacity

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Now let's see how ACC and CACC perform in realistic, large-scale simulations!

Macroscopic (Nikolos et. al., 2015)

Macroscopic models use global, macroscopic quantities such as the traffic density or the average speed. They don't consider the behaviour of individual vehicles.

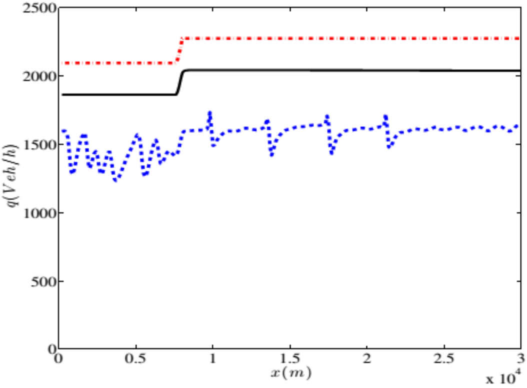
Nikolos et. al.: Flow described by a gas-kinetic model, examination of density evolution [veh/km]:

$$\partial_t \rho + \partial_x (\rho \bar{v}) = \Phi$$

Simulation parameters:

- 30 km of highway
- 150 minutes
- Pertubation in form of an on-ramp at $x = 0.8\,km$, $t = 0\,s$
- Compare manual cars, all with ACC, all with CACC

Macroscopic (Nikolos et. al., 2015)



Flow rates at $t = 150$ *min*, for manual cars (blue), ACC (black), CACC (red); on-ramp at $x = 8$ *km*, source: [mac]

Microscopic (Shladover et. al., 2011)

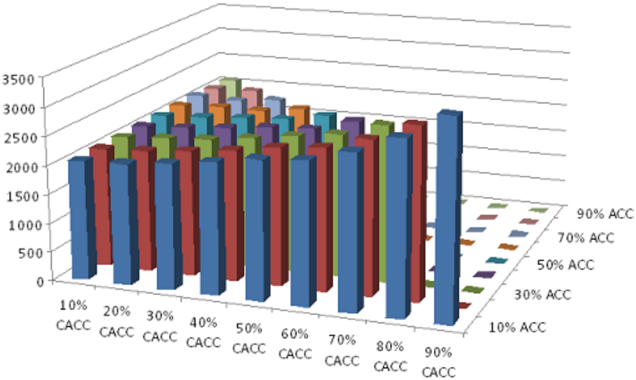
Microscopic models track the behaviour of every individual vehicle, using simulation tools such as MIXIC or Aimsun.

Shladover et. al.: Flow measured in the simulation, examination of the impact of ACC, CACC, and vehicle awareness devices (VAD).

Simulation parameters:

- 6.5 *km* of highway
- 60 minutes, flow measured every five minutes
- ACC, CACC and VAD percentage from 0% to 100%
- Headways as chosen by humans in a field test

Microscopic (Shladover et. al., 2011)



Maximum flow rates as a function of ACC and CACC distribution, source: [mic]

Summary

- Both ACC and CACC increase safety, assuming they are string stable
- Traffic flow in bottleneck situations is improved by ACC, and a lot improved by CACC
- Advantage ACC: It works starting from car one, whereas CACC needs a lot of cars equipped to have an impact - which makes it costly
- Advantage CACC: If distributed widely, it increases the capacity of the highway, whereas ACC offers no improvement

Summary

	Manual	ACC	CACC
Safety	–	✓	✓
Capacity	2200 veh/h	2200 veh/h	4000 veh/h
Traffic flow	Unstable	Partly stable	Stable
Functionality	Single car	Single car	Platoon only

Thanks for the attention!

Sources:

[sur]: Traffic Control and Intelligent Vehicle Highway Systems: A Survey, Baskar et.al., 2011

[bosch]: Bosch Professional Automotive Information: Brakes, Brake Control and Driver Assistance Systems, Springer 2014

[raj]: R. Rajamani: Vehicle Dynamics and Control 2nd Edition 2012, Springer

[rsc]: Autonomous driving in urban environments: approaches, lessons and challenges, Campbell et.al., 2010

[swa]: String Stablility of Interconnected Systems: An Application to Platooning in Automated Highway Systems, Swaroop 1997

[pep]: String Stability of Relative-Motion PID Vehicle Control Systems, Peppard, 1974

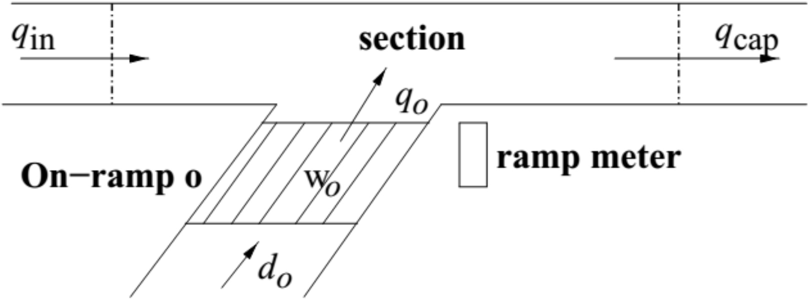
[exp]: Design and Experimental Evaluation of Cooperative Adaptive Cruise Control, Ploeg et.al., 2011

[mac]: Macroscopic Modelling and Simulation of ACC and CACC Traffic, Nikolos et.al., 2015

[mic]: Impacts of Cooperative Adaptive Cruise Control on Freeway Traffic Flow, Shladover et.al., 2011

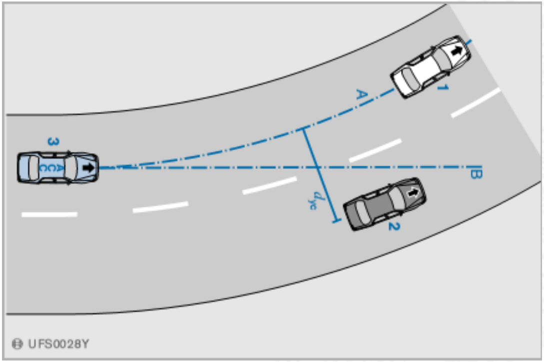
Appendix

Example for infrastructure controlled systems: Ramp metering



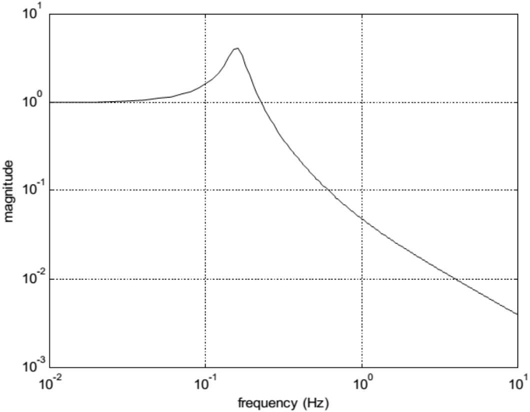
Simple example for infrastructure-controlled systems, source: [survey]

Example for problems arising in object identification: Curves



Curves an example of problems arising while identifying objects, source: [bosch]

Frequency Response function: Resonance peak



Log-log plot of $|G|(f)$, source: [raj]

Ploeg et. al.: Control law

Control law in a test fleet of six cars:

$$\dot{u}_i = -\frac{1}{h}u_i + \frac{1}{h}(k_p\epsilon_i + k_d\dot{\epsilon}_i) + \frac{1}{h}u_{i-1}$$

h is called "headway", and is the time the car needs to cross the distance to the preceeding car, measured e.g. front-to-front.

$h = 0.7\,s$

$k_p = 0.2$

$k_d = 0.7$

$$\Rightarrow \dot{a}_i = -\frac{1}{0.7}a_i + \frac{1}{0.7}(0.2\epsilon_i + 0.7\dot{\epsilon}_i) + \frac{1}{0.7}a_{i-1}$$

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$h = 0.7\,s$

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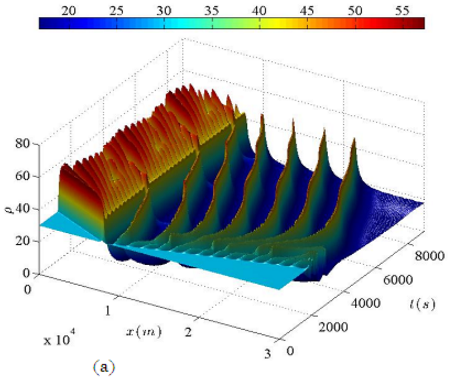
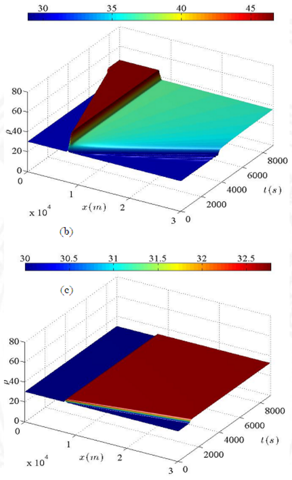
Headway without the feedforward term: $3.16\,s$!

Nikolos et. al.: Density evolution





Traffic density evolution near an on-ramp, manual cars (a), ACC (b), CACC (c), source: [mac]

Shladover et. al.: Headway distribution

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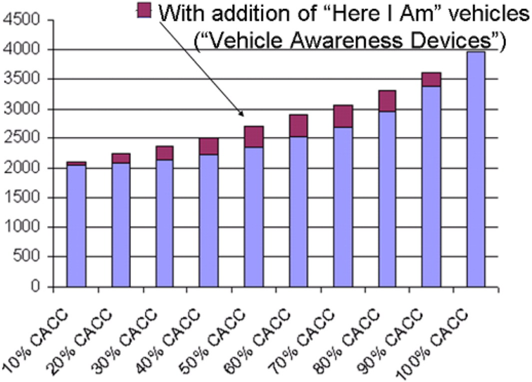
Shladover et. al.: Flow measured in the simulation, examination of the impact of ACC, CACC, and vehicle awareness devices (VAD).

Headway distribution, as chosen by human drivers in a field test:

- Manual cars: $1.64\,s$
- ACC: $31.1\% : 2.2\,s$, $18.5\% : 1.5\,s$, $50.4\% : 1.1\,s$
- CACC: $12\% : 1.1\,s$, $7\% : 0.9\,s$, $24\% : 0.7\,s$, $57\% : 0.6\,s$

Shladover et. al.: Impact of VAD



Maximum flow rates as a function of CACC/manual cars, CACC/VAD cars, source: [mic]