Networked Control and Autonomy

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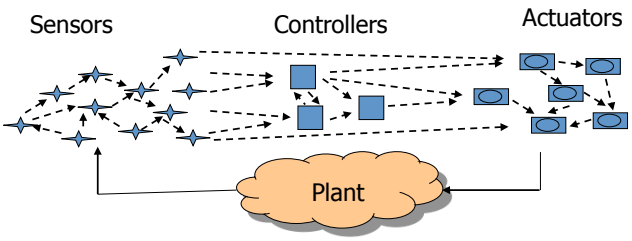
Slides available at http://www.ee.kth.se/~kallej

Networked control system



Outline

Lecture 1: Motivating applications and challenges

Lecture 2: Wireless control systems

Take-home message

Lecture 1: Motivating applications and challenges

- Networked control systems have societal importance
- Many new applications with challenging problems

Lecture 2: Wireless control systems

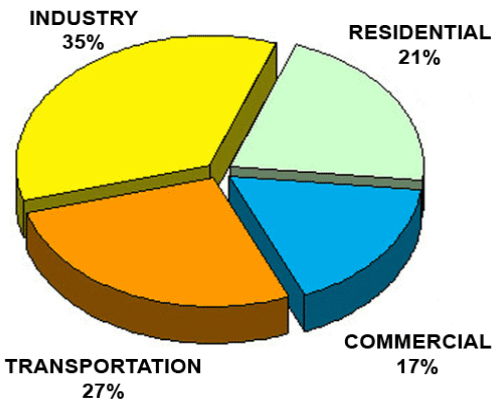
- Everything will be wireless, including control systems
- Interesting research challenges on the intersection between sensor networks, wireless communication, and control theory

Outline

Lecture 1: Motivating applications and challenges

Lecture 2: Wireless control systems

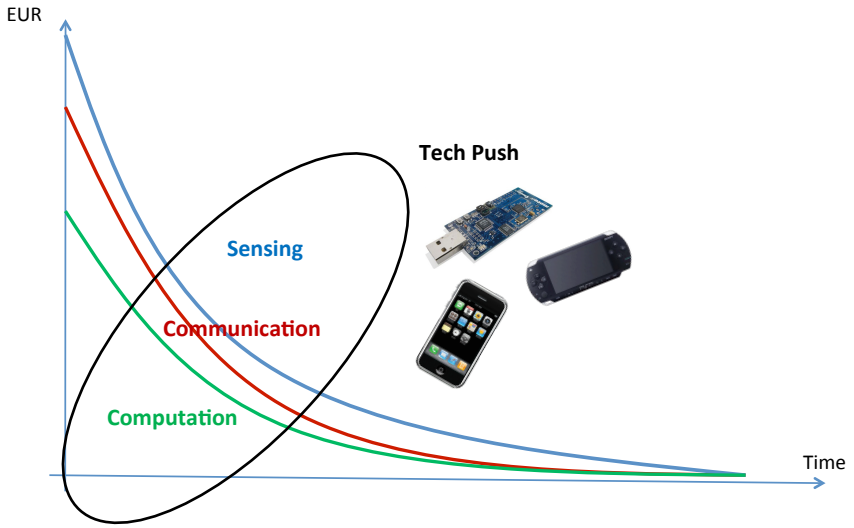
Energy consumption



More and better networked control reduces energy consumption

US Energy Information Administration

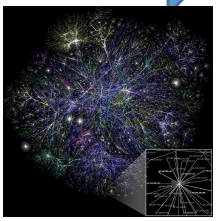
Why now?



Network evolution

- Internet
- WWW
- Ubiquitous computing

Info Web



The Internet

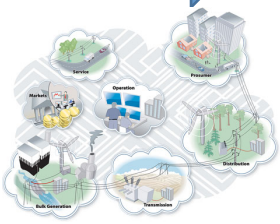
- Remote sensing
- Monitoring environments
- Wireless sensor networks

Sensor Web

Monitoring storm petrels at Great Duck Island

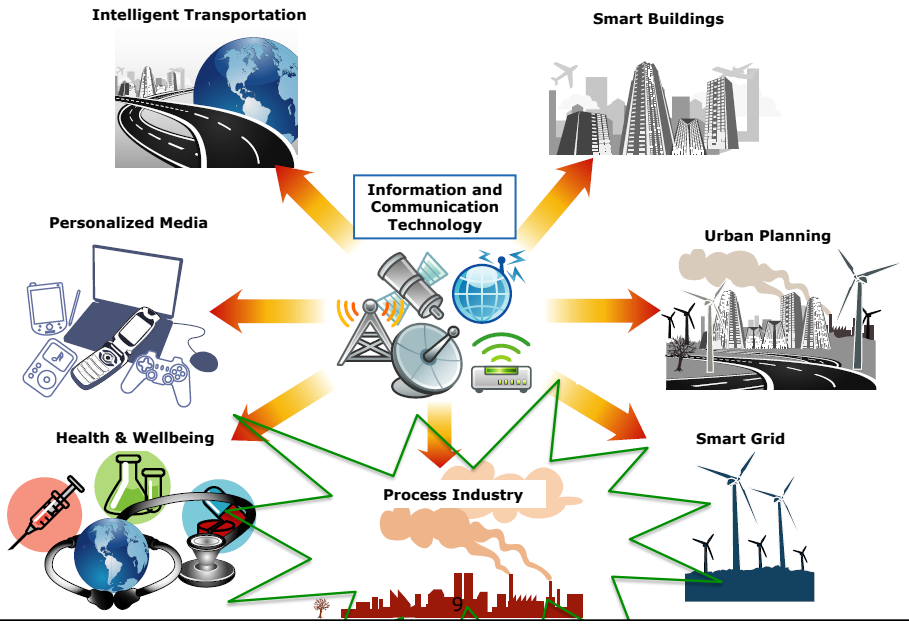
- Closing the loop
- Cyber-physical systems
- Humans in the loop

Control Web

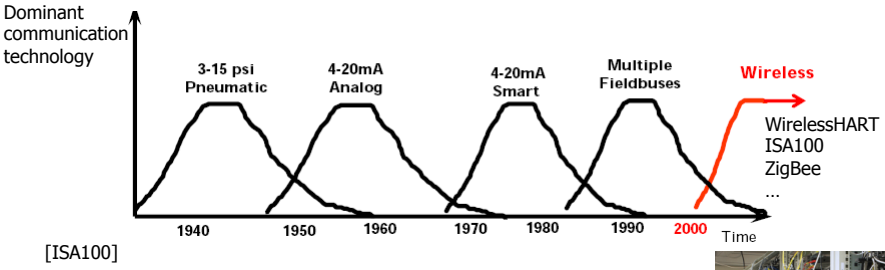


The smart energy grid

Networked Control Applications



Communication in process control



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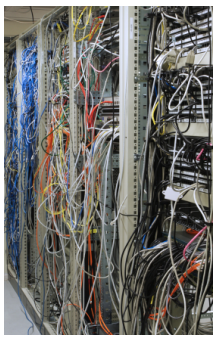


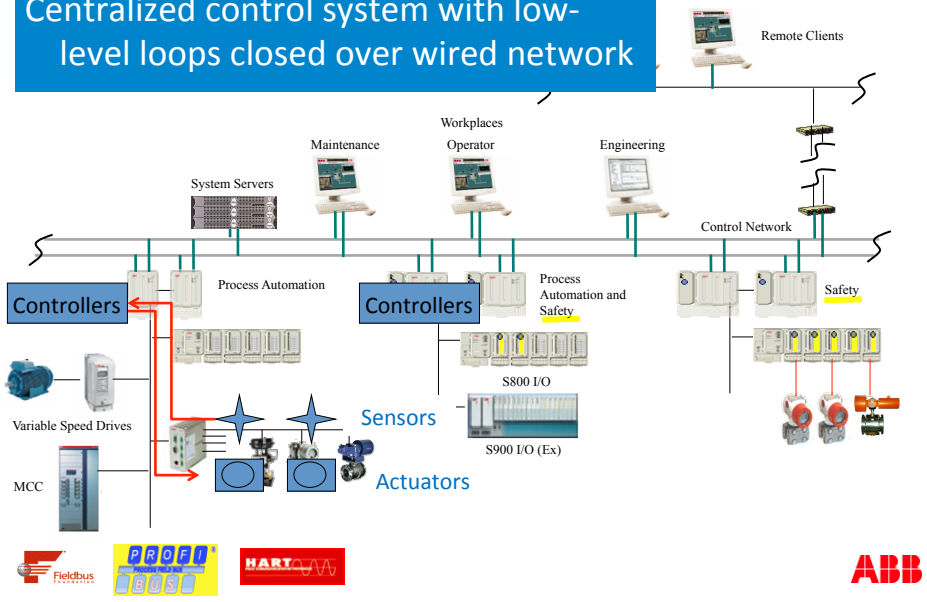
Wireless sensor systems benefit from

- Lower installation and maintenance costs
- Increased sensing capabilities and flexibility

Major consequences for control system architectures

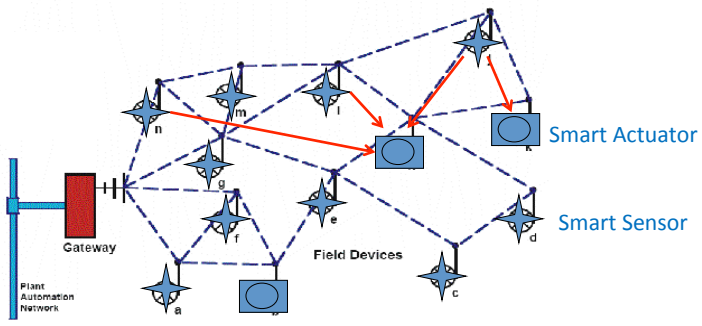
Today's industrial communication architecture

Centralized control system with low-level loops closed over wired network



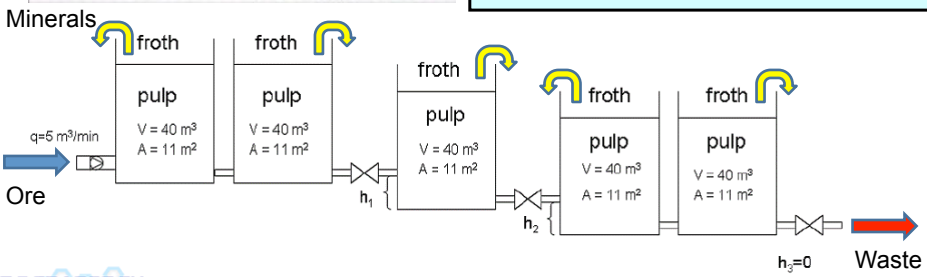
Towards wireless sensor and actuator network architecture

- Local control loops closed over **wireless multi-hop network**
- Potential for a dramatic change:
  - From fixed hierarchical centralized system to flexible distributed
  - Move intelligence from dedicated computers to sensors/actuators



Control of froth flotation process

- Froth flotation process concentrates the metal-bearing mineral in the ore



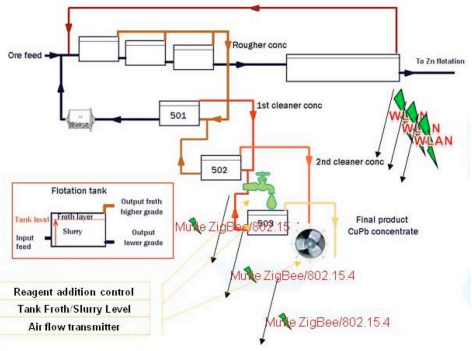
SOCRADES.EU

Wireless control of floatation process

The Boliden plant

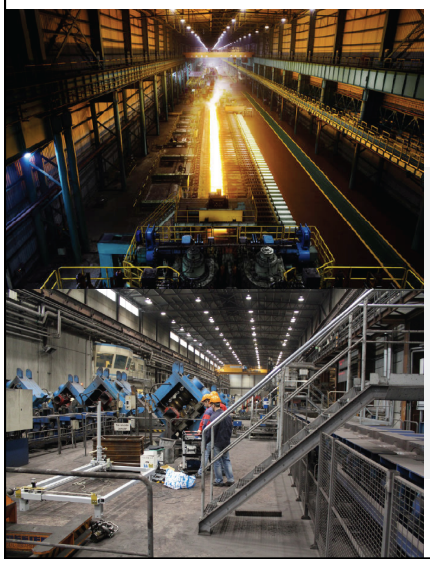
Existing wired communication system

Wireless communication for tank level control

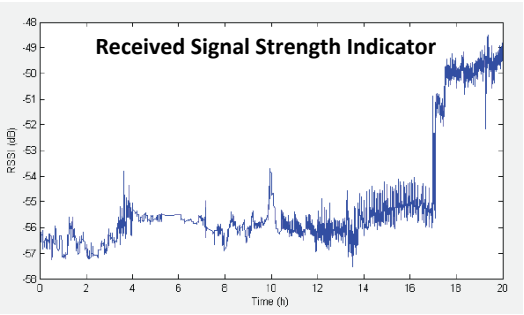


SOCRADES.EU BOLIDEN ABB

Radio Channel Measurements in Industrial Environment



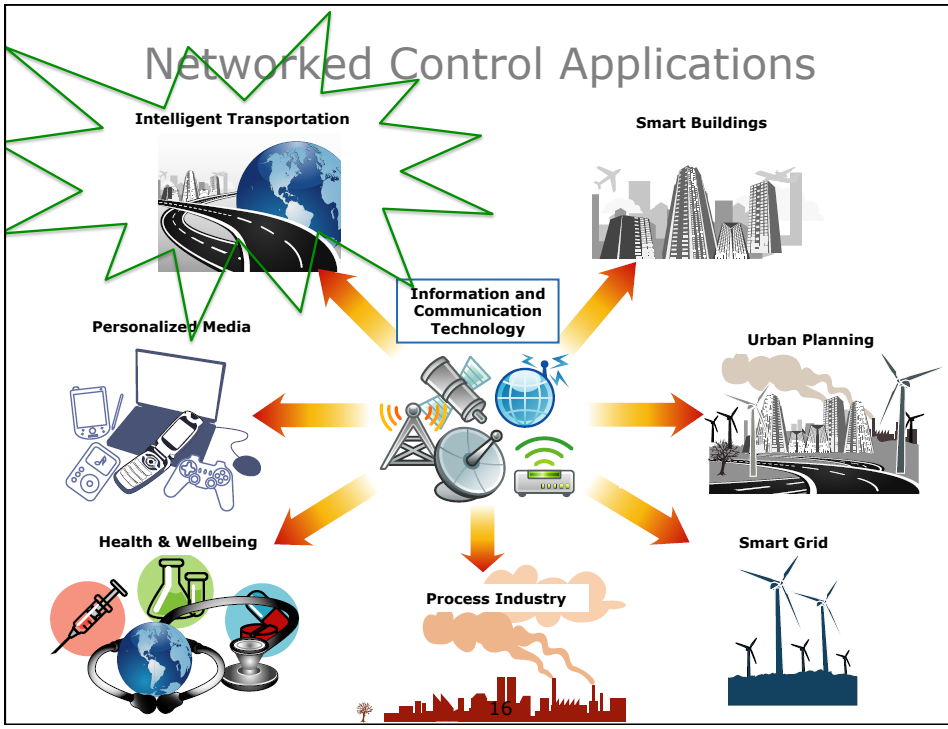
- Rolling mill at Sandvik in Sweden
- Study of 2.45 GHz radio channel properties
- Slow but substantial RSSI variations due to mobile machines

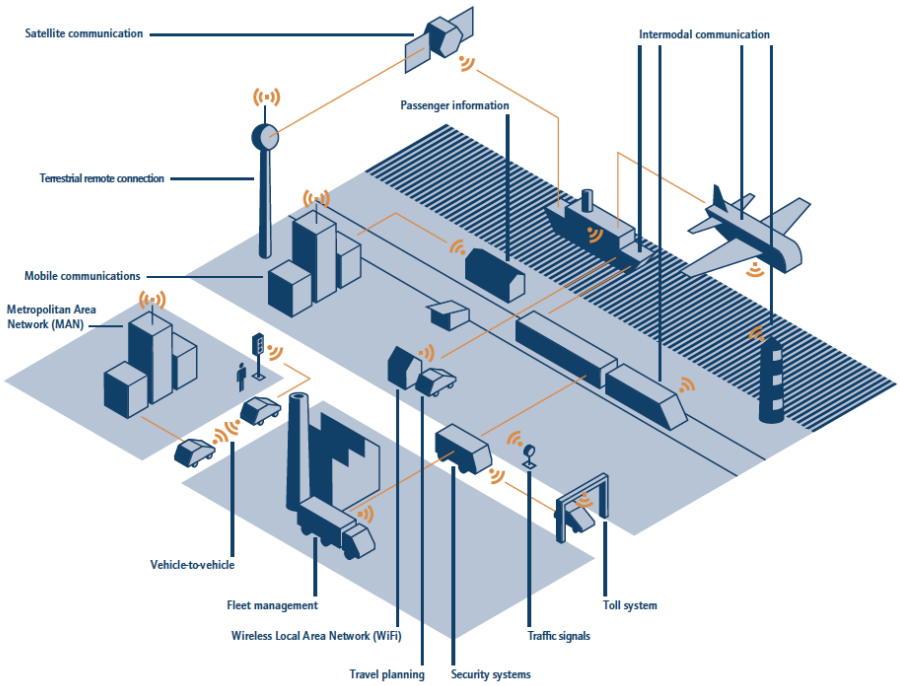


UPPSALA UNIVERSITET ABB KTH

Ahlen et al, 2012

Networked Control Applications





Cyber-Physical Systems Roadmap, German National Academy of Science and Engineering, 2011

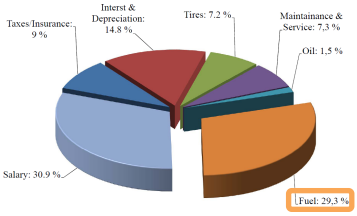
Demands from Goods Road Transportation

- Goods transportation accounts for
  - 30% of CO_2 emissions
  - 15% of greenhouse gas emissions

  of the global fossil fuel combustion
- Expected to increase by 50% for 2000-2020

International Transport Forum (2010), EC (2006)

Life cycle cost for European heavy-duty vehicles



Total fuel cost 80 k€/year/vehicle

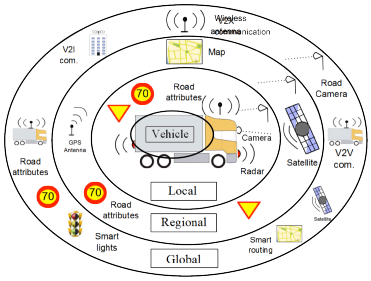
Schittler, 2003

24% of long haulage trucks run empty
57% average load capacity

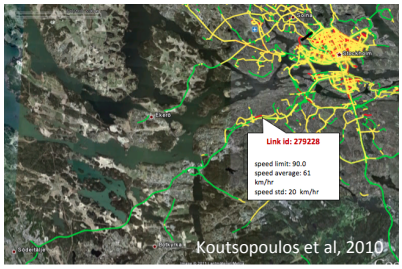
Dr. H. Ludanek, CTO, Scania

Technology Push

Sensor and commununication technology



Real-time traffic information

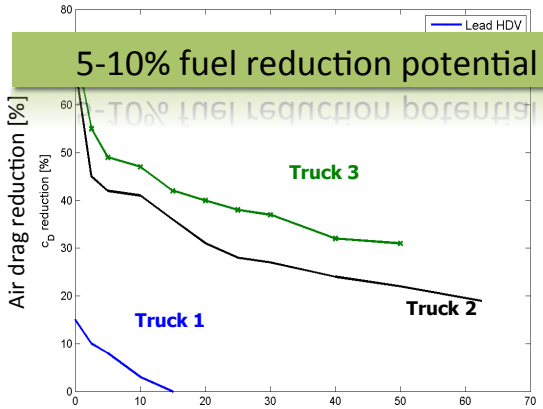


Vehicle platooning and semi-autonomous driving

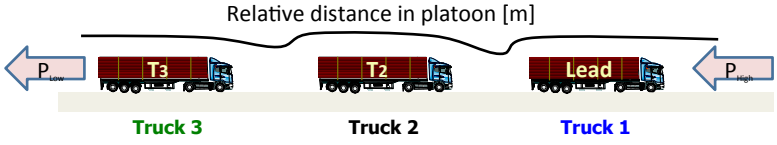
Air Drag Reduction in Platooning

KTH Electrical Engineering

5-10% fuel reduction potential



$$F_{\text{air}} = \frac{1}{2} c_D(d) A_a \rho_a v^2$$



Wolf-Heinrich & Ahmed (1998), Bonnet & Fritz (2000), Scania CV AB (2011)

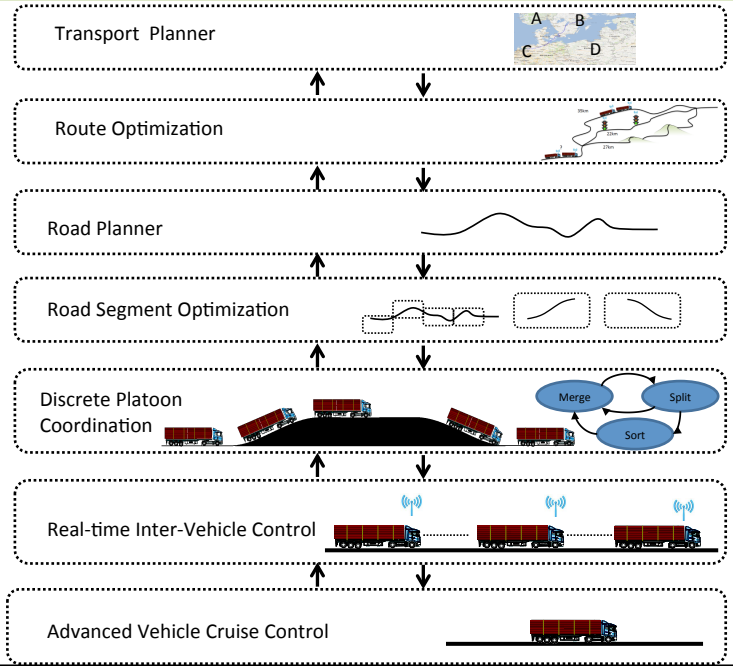
Fuel-Optimal Goods Transportation

- Goods transported between cities over European highway network
- 2 000 0000 long haulage trucks in EU (400 000 in Germany)
- Large distributed control systems with no real-time coordination today

Goal: Maximize total amount of platooning with limited intervention in vehicle speed and route

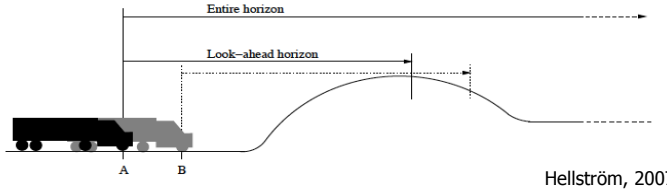
Larson et al., 2013

Architecture for Future Coordinated Goods Transportation



Alam et al., 2012

Look-ahead Cruise Control for Individual Vehicle



Hellström, 2007

Adjust driving force to **minimize fuel consumption based on road topology** info:

The total fuel consumption over time T is:

$$\int_0^T \delta(t) \left(\dots \frac{\mathrm{d}v(t)}{\mathrm{d}t} + \frac{1}{2} \rho_a A_a c_D v^2(t) \phi(d(t)) \right.$$
$$\left. + mgc_r \cos\alpha + mg \sin\alpha \right) \mathrm{d}t \qquad (3)$$

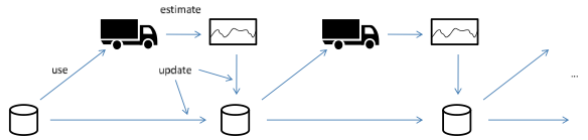
Require knowledge of road grade α, not available in today's navigators

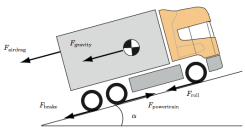
$$m_t \frac{\mathrm{d}v}{\mathrm{d}t} = F_{eng} - F_b - F_{ad}(v,d) - F_r(\alpha) - F_g(\alpha)$$
$$= F_{eng} - F_b - \frac{1}{2}\rho_a A_a c_D v^2 \phi(d)$$
$$- mgc_r \cos\alpha - mg \sin\alpha$$

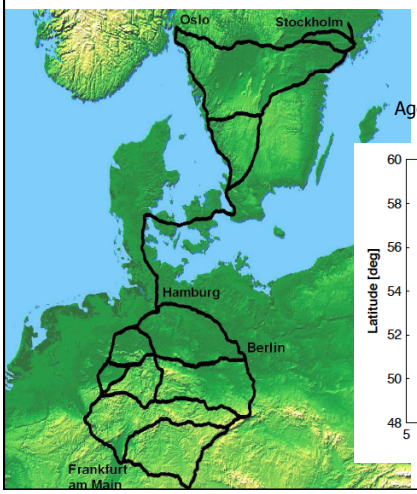
Implemented as reference change to existing cruise controller

Allam et al., 2011

Distributed Road Grade Estimation

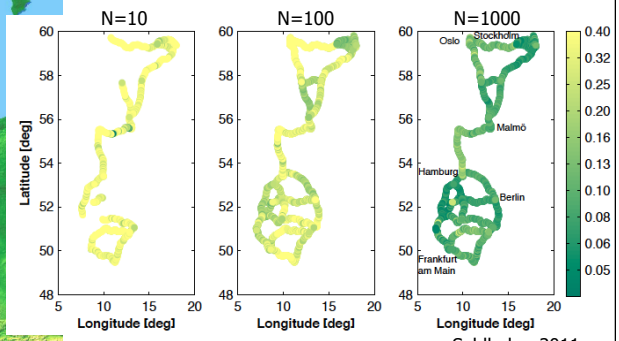






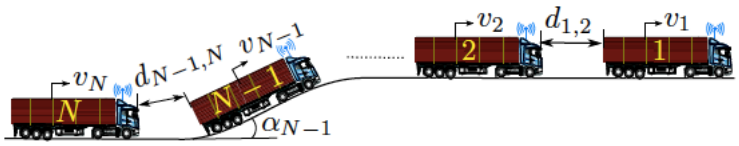
RMS Road Grade Error

Aggregated N=10, 100, 1000 profiles of lengths 50 to 500 km



Sahlholm, 2011

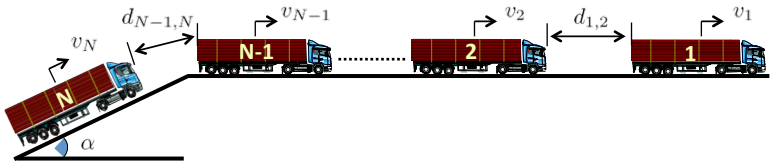
Look Ahead Cruise Control for Platoons



- How to jointly minimize fuel consumption for a platoon of vehicles?
  - Uphill and downhill segments
- How to order vehicles according to weight and other performance criteria?
  - Heavy and light vehicles

Alam et al., 2013

How to Control Vehicles in a Platoon?

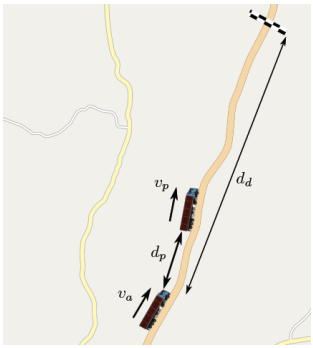


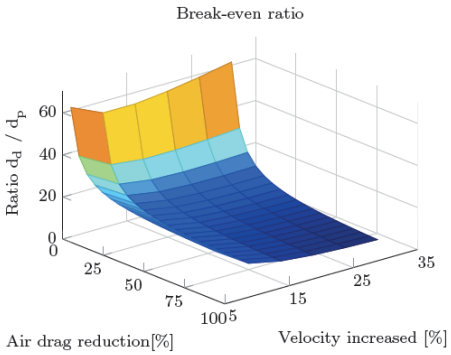
- Platooning control applications require **collaborative actions**
- Vehicles need **accurate estimates** of neighboring vehicles' states and actions
  - Vehicle-to-vehicle and vehicle-to-infrastructure communications
  - Wireless communication standards, e.g., IEEE 802.11p
- Control performance is tightly coupled to how well state information (position, velocity, braking etc) is communicated across the platoon

- How does the communication influence the system performance?
- What is an efficient communication strategy for specific control tasks?

Extensive theoretical and practical studies since Levine & Athans, 1966

When is it Fuel Efficient for a Heavy-Duty Vehicle to Catch Up with a Platoon?

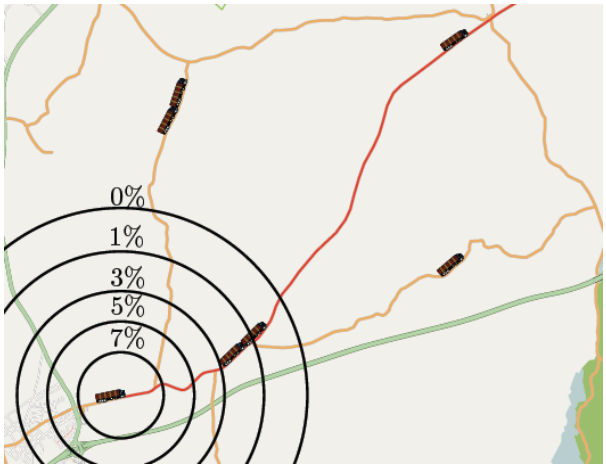




- Catch up costs fuel due to higher air drag at higher velocity
- Distance to platoon d_p needs to be small compared to total travel distance d_d
- Tradeoff velocity increase during catch-up and air drag reduction during platooning

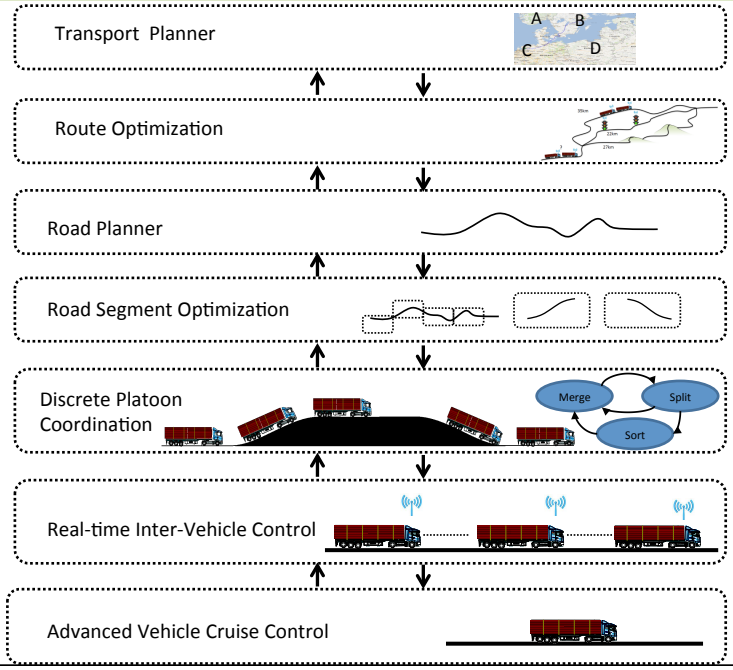
Liang et al., 2013

When is it Fuel Efficient for a Heavy-Duty Vehicle to Catch Up with a Platoon?



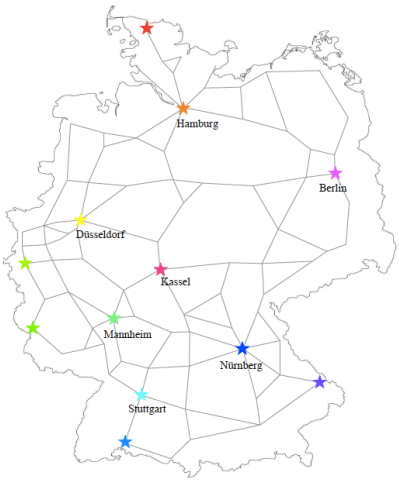
Liang et al., 2013

Architecture for Future Coordinated Goods Transportation



Alam et al., 2012

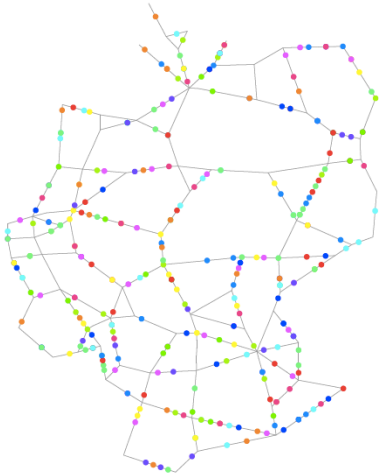
When create platoons?



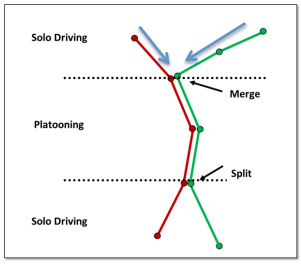
Larson et al., 2013

Platoon merge and split

Heavy-duty vehicle traffic without platooning



Merge and split platoons at highway intersections

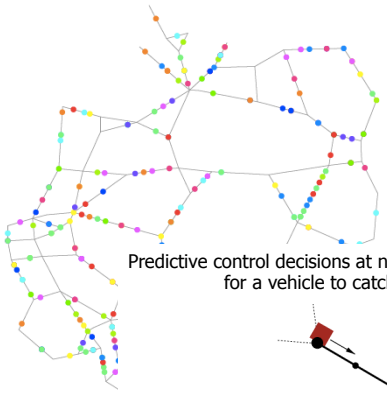


Only vehicles that are relatively close in space and time platoon

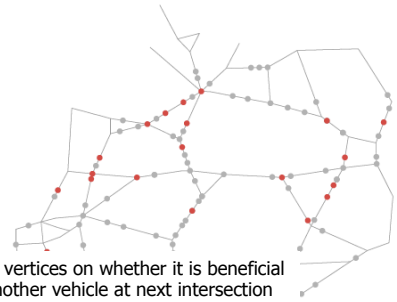
Larson et al., 2013

Distributed optimization of platooning

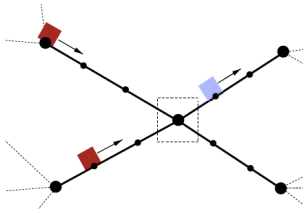
Heavy-duty vehicle traffic without platooning



With platooning

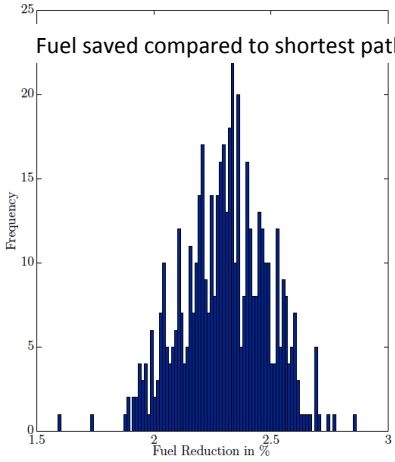


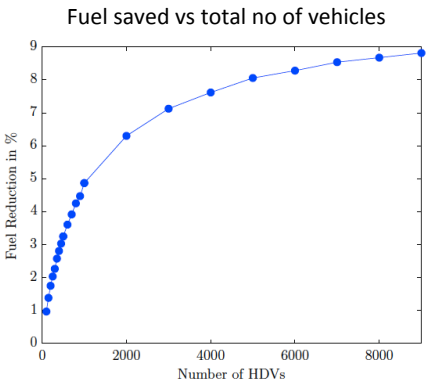
Predictive control decisions at network vertices on whether it is beneficial for a vehicle to catch up another vehicle at next intersection



Larson et al., 2013

Numerical evaluations





- German road network with 300 trucks
- Random starting points and destinations
- 500 Monte Carlo experiments

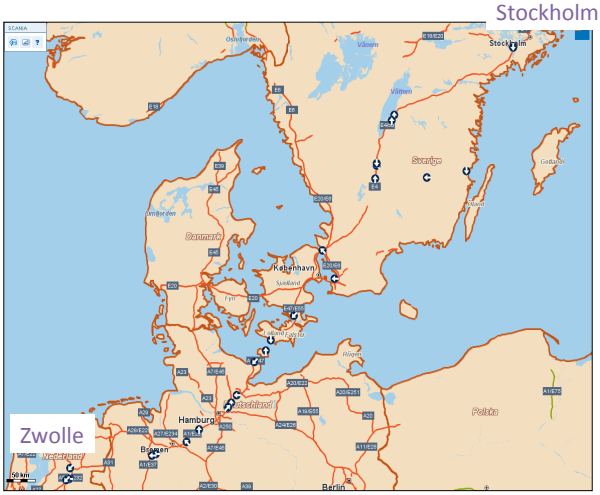
2-5% deployment enough for substantial benefit

Larsson et al., 2013

Stockholm-Zwolle Testsite

- Real-time fleet management
- Platooning in real traffic
- Fuel reductions and safety
- Driver acceptance
- Public acceptance

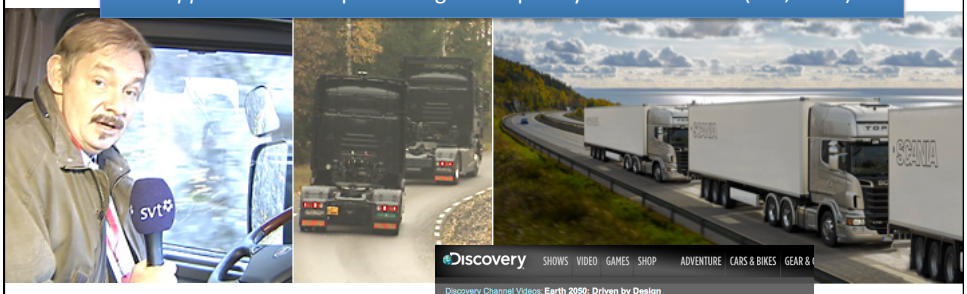
Scania Transport Lab
Internal haulage company
20 trucks, 360.000 km/year
75 trailers, 92% loaded
65 drivers, 40 h work/week



SCANIA vti

Platooning Demos in Media

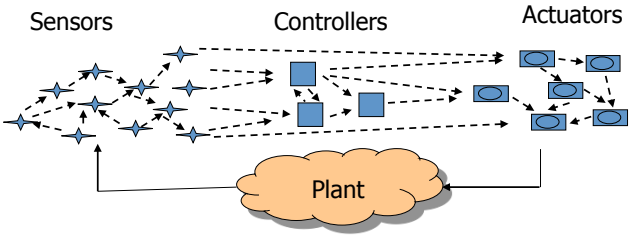
Rapport on vehicle platooning developed by KTH and Scania (Oct, 2011)



PhD student Assad Alam on *Discovery Channel* (Jan, 2012)

Wireless control system

How share common network resources while maintaining guaranteed closed-loop performance?



- How handle network imperfections: resource constraints, loss, conflicts, delays, outages?
- How move intelligence from a few central units to many distributed devices?