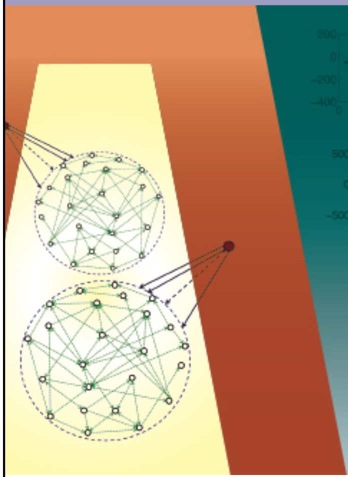
HKUST JOCKEY CLUB
Institute for Advanced Study
香港科技大學賽馬會 高等研究院

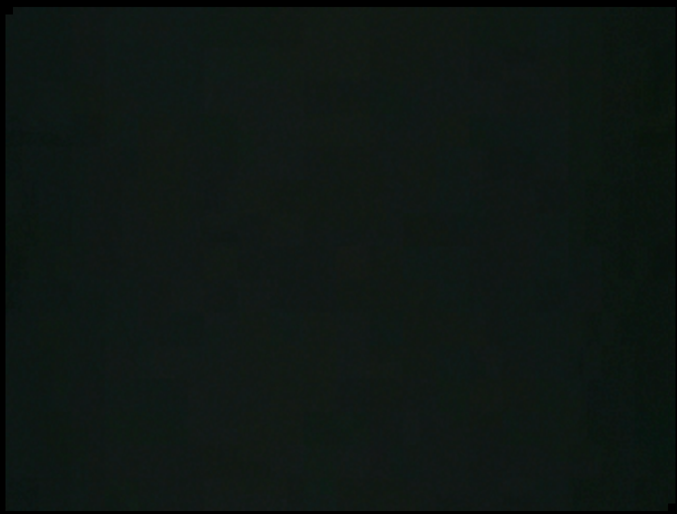
IAS DISTINGUISHED LECTURE



Cyber-physical Systems: Why Connecting the Physical World?

Karl Henrik Johansson
Professor at the School of Electrical Engineering, KTH Royal Institute of Technology;
Visiting Fellow of HKUST Jockey Club Institute for Advanced Study

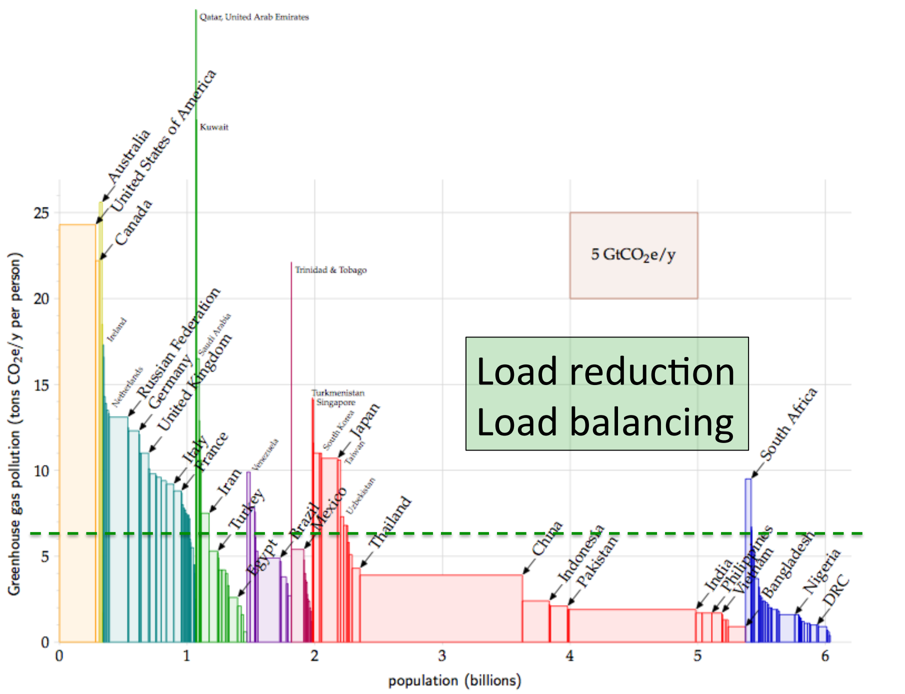
General Motors vision 76 years ago



Cyber = “Automatic radio control”
Physical = “Curved sides”

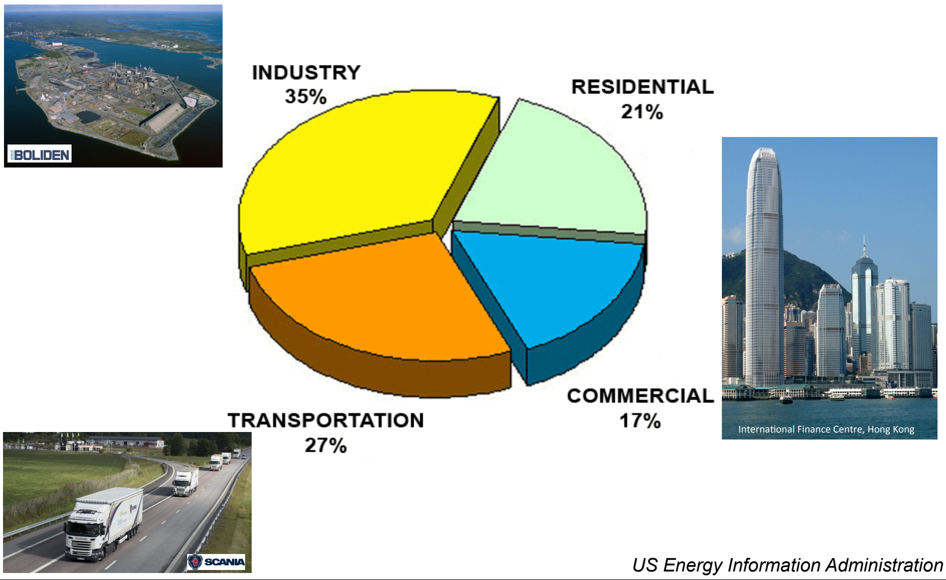
Outline

- Societal need and enabling technology
- Cyber-physical systems
- Scientific challenges
- Cyber-physical transportation systems
- Conclusions

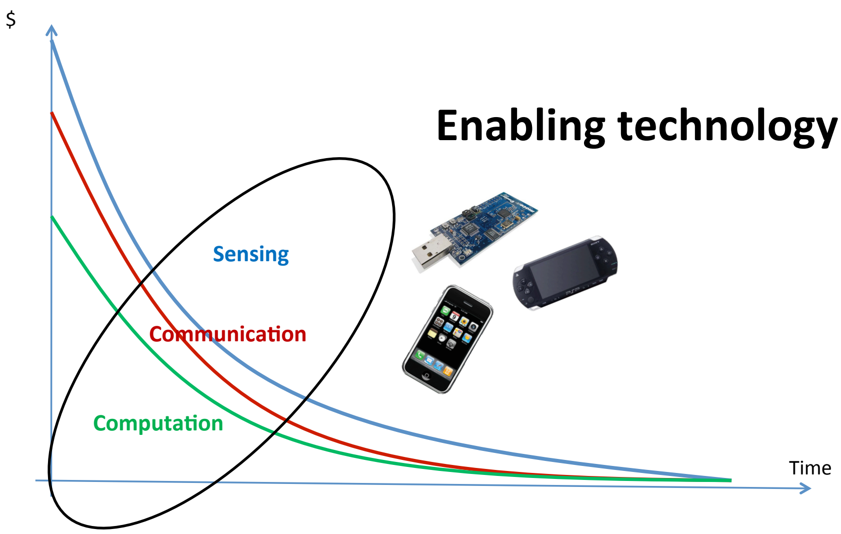


D. J.C. MacKay, Sustainable Energy–without the hot air, UIT Cambridge, 2008

Energy consumption



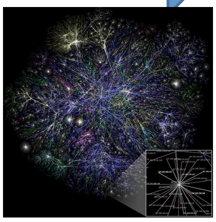
Why now?



From Information to Action Networks

- Internet
- WWW
- Ubiquitous computing

Info Web



The Internet

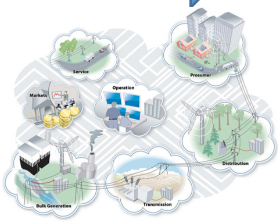
- Remote sensing
- Monitoring environments
- Wireless sensor networks

Sensor Web

Monitoring storm petrels at Great Duck Island

- Closing the loop
- Critical infrastructures
- Humans in the loop

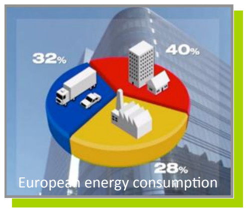
Action Web



Renewables integrated into energy grid

Potential Savings with Smarter Systems

Transportation systems, buildings, and industry pollute and waste energy

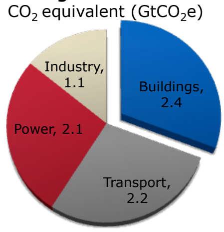


Need for more and better sensing, monitoring, processing, optimization, and control

Smarter use of **information and communication technology** has great potentials:

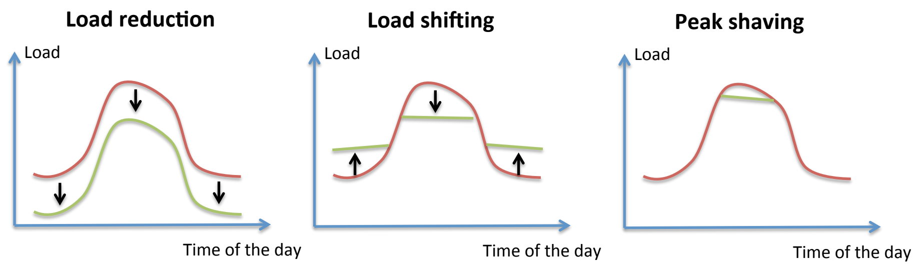
- Predicted savings of up to 15% by 2020 (1990 levels)
- Emission reductions 5x the ICT sector's own footprint
- Transportation can save 2.2 $GtCO_2e$

Savings in billion tonnes CO_2 equivalent ($GtCO_2e$)



SMART 2020: Enabling the low carbon economy in the information age, The Climate Group, Report, 2008

How to improve resource efficiency?



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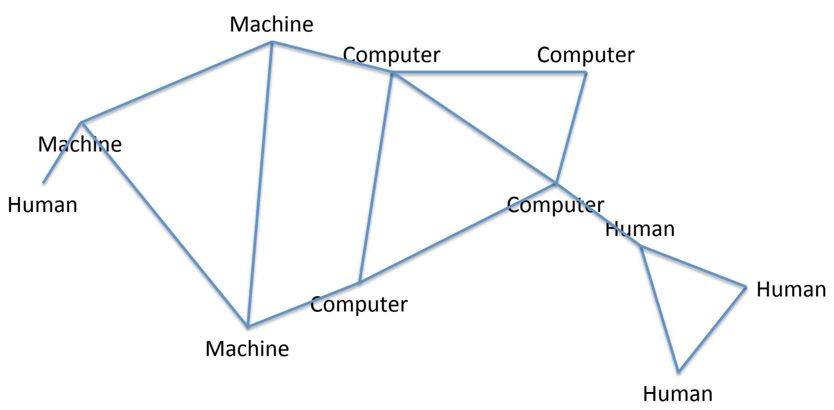
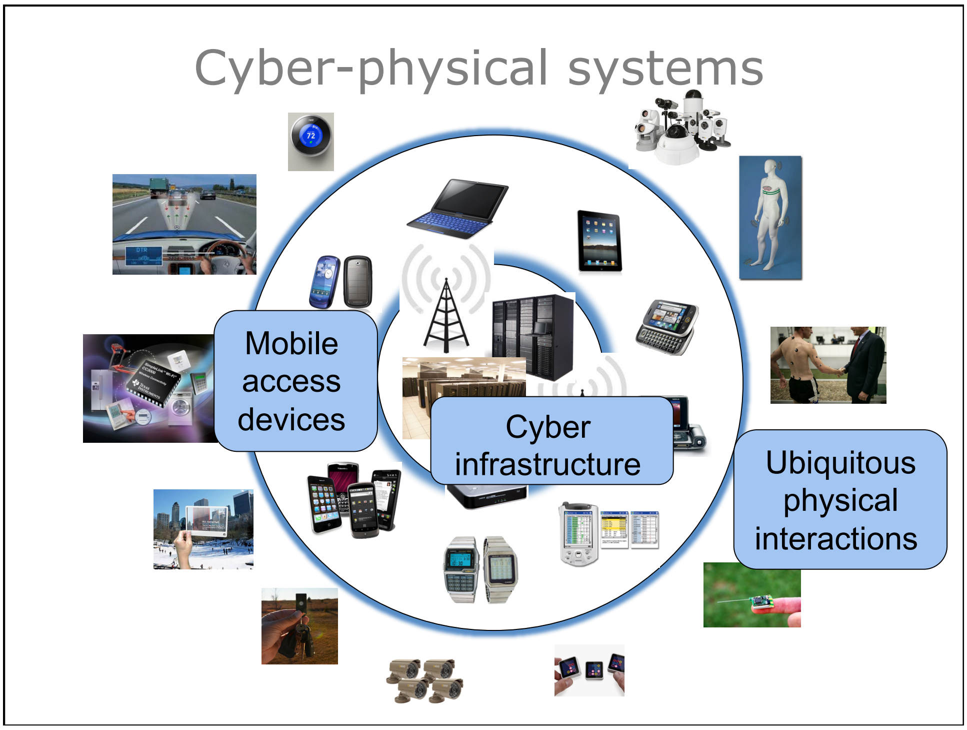
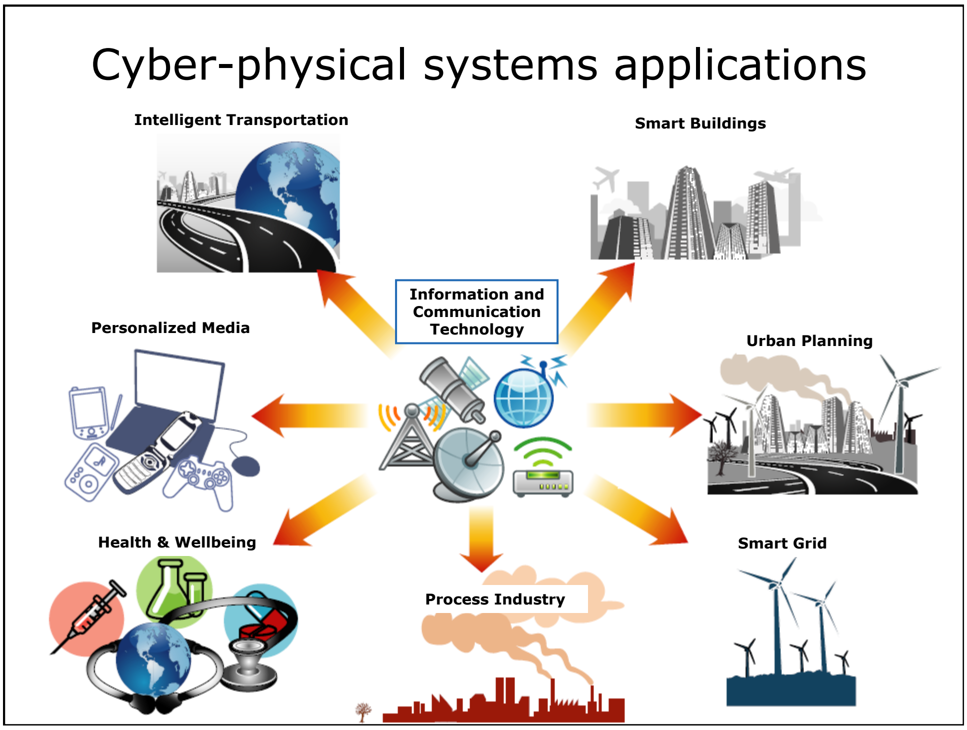
Cyber-physical system



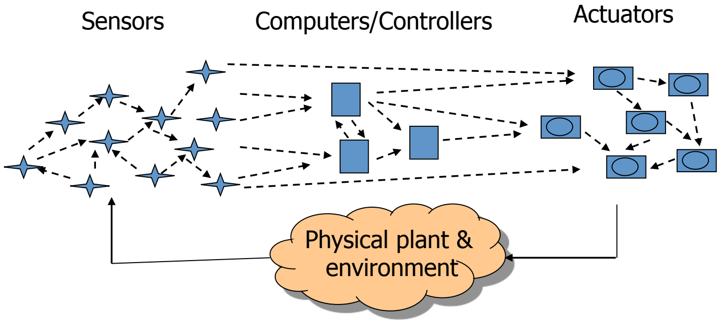
***Cyber-physical systems** are engineered systems whose operations are monitored and controlled by a computing and communication core embedded in objects and structures in the physical environment.*

US National Science Foundation


Cyber-physical systems
Mobile access devices
Cyber infrastructure
Ubiquitous physical interactions


Cyber-physical systems applications
Intelligent Transportation
Smart Buildings
Information and Communication Technology
Personalized Media
Urban Planning
Health & Wellbeing
Process Industry
Smart Grid

Cyber-physical systems *are engineered systems whose operations are monitored and controlled by a computing and communication core embedded in objects and structures in the physical environment.*



Cyber-physical systems challenges

Societal Scale

- Global and dense instrumentation of physical phenomena
- Interacting with a computational environment: closing the loop
- Security, privacy, usability

Distributed Services

- Self-configuring, self-optimization
- Reliable performance despite uncertain components, resilient aggregation

Programming the Ensemble

- Local rules with guaranteed global behavior
- Distributing control with limited information

Network Architectures

- Heterogeneous systems: local sensor/actuator networks and wide-area networks
- Self-organizing multi-hop, resilient, energy-efficient routing
- Limited storage, noisy channels

Real-Time Operating Systems

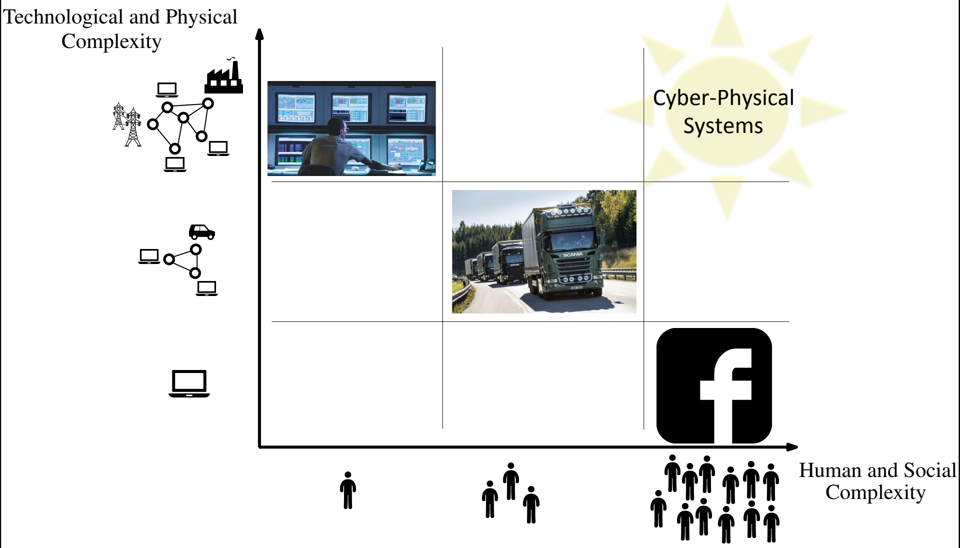
- Extensive resource-constrained concurrency
- Modularity and data-driven physics-based modeling

1000 Radios per Person

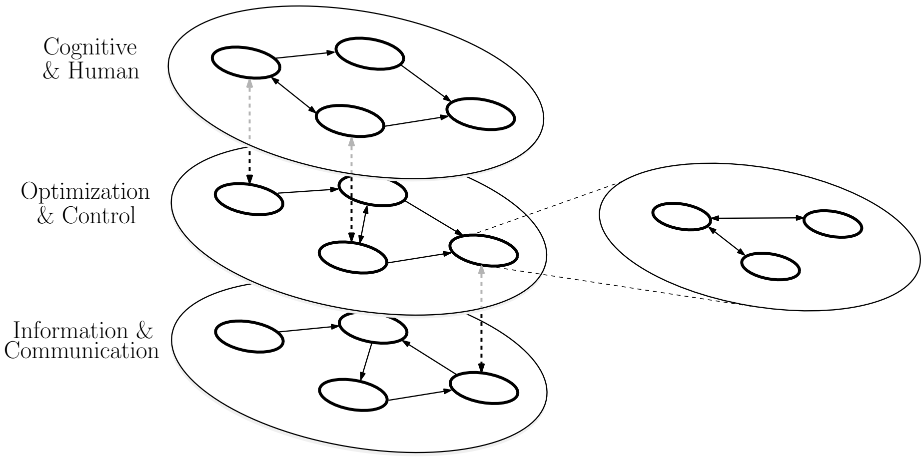
- Low-power processors, radio communication, encryption
- Coordinated resource management, spectrum efficiency

Sastry & J, 2010

How to tame the complexity?



Multi-Layer Dynamic Network Models



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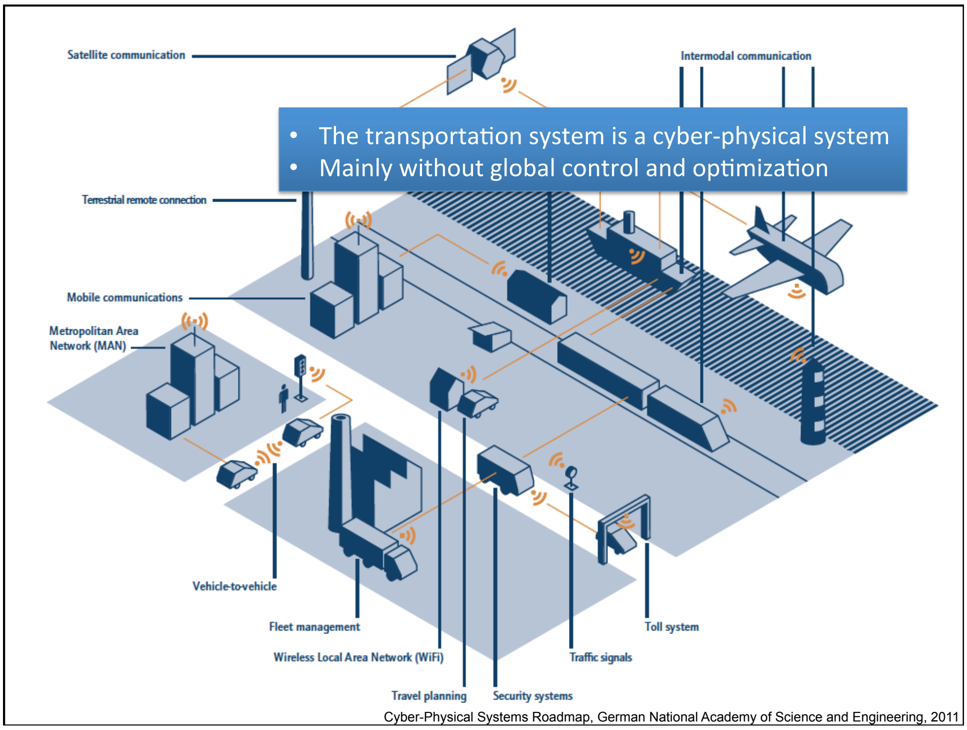
  - Architecture
  - Cooperative driving
  - Optimized transport planner

- Conclusions



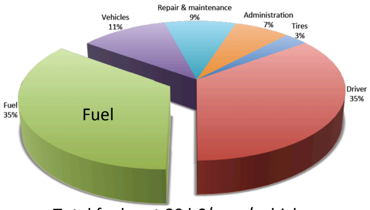
Cyber-Physical Systems Roadmap, German National Academy of Science and Engineering, 2011

Demands from Goods Road Transportation

- Road transport consumes 26% of total EU energy and accounts for 18% of greenhouse emissions
- 45% of all freight transport is on roads
- Emissions increased by 21% for 1990-2009

Eurostat (2011), EU Transport (2014)

Life cycle cost for European heavy-duty vehicle



Total fuel cost 80 k€/year/vehicle

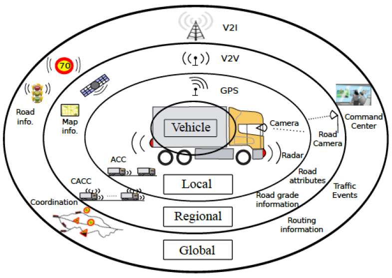
Schittler, 2003; Scania, 2012

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

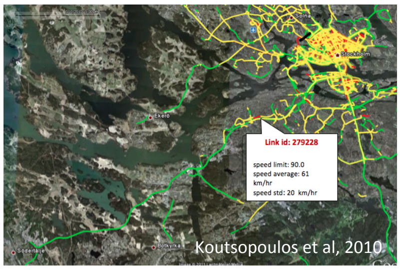
Dr. H. Ludanek, CTO, Scania

Technology Push

Sensor and commununication technology



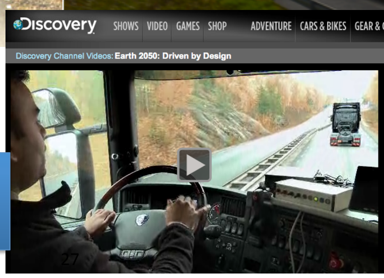
Real-time traffic information



Vehicle platooning and autonomous driving

Heavy-Duty Vehicle Platooning

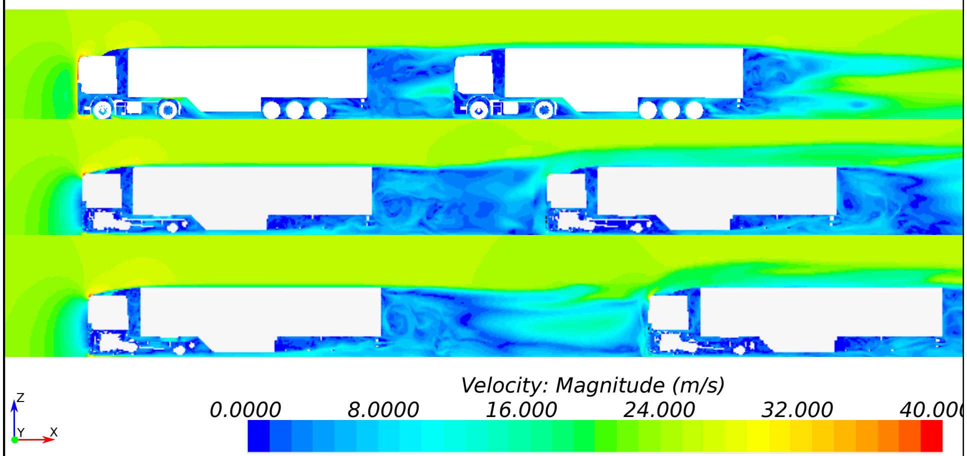
Rapport on vehicle platooning developed by KTH and Scania (Oct, 2011)



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

Zwolle, Netherlands, Feb 9, 2015

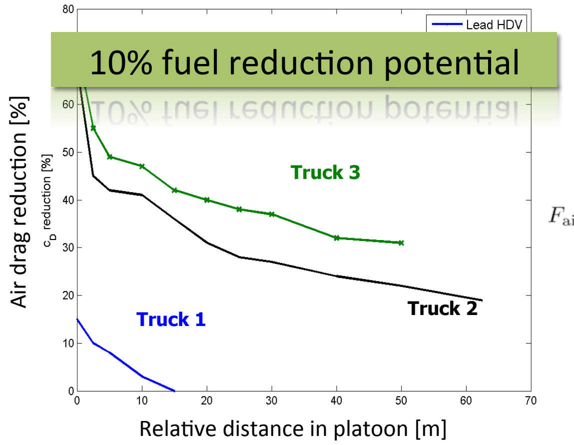
The Physics



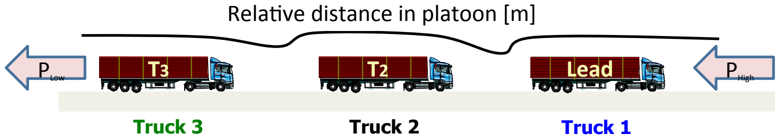
Liang (2014)

Air Drag Reduction in Truck Platooning

KTH Electrical Engineering



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

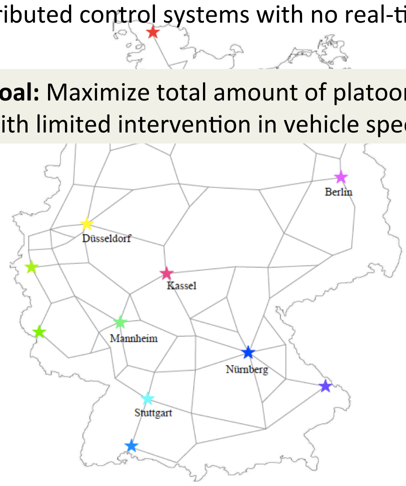


Wolf-Heinrich & Ahmed (1998), Bonnet & Fritz (2000), Scania CV AB (2011)

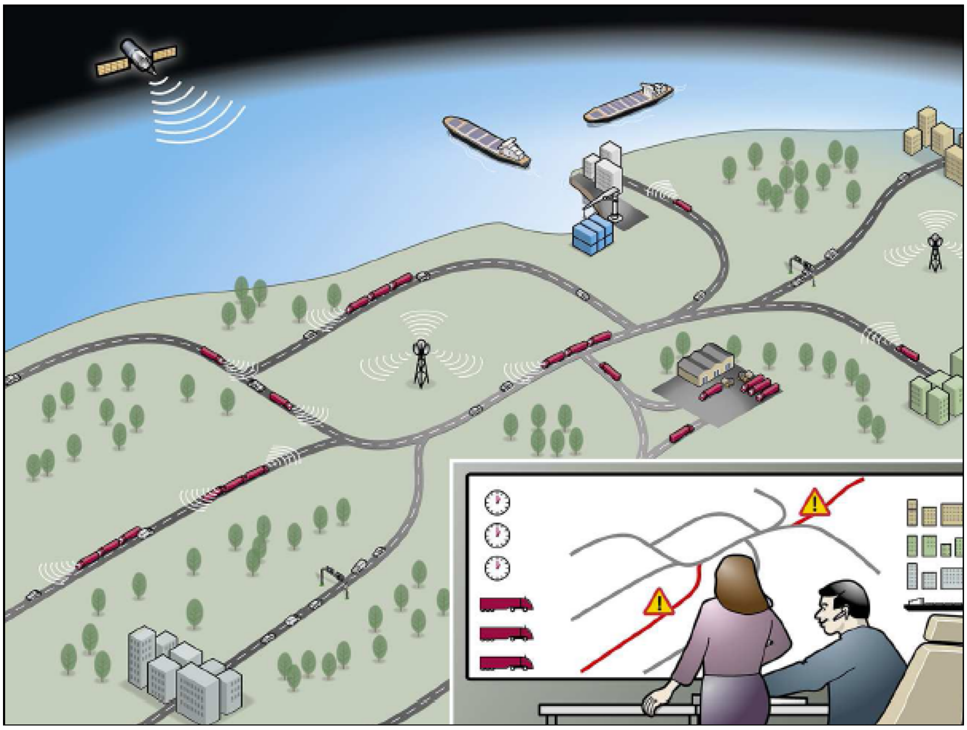
Fuel-Optimized Goods Transport

- Goods transported between cities over highway network
- 19 000 000 light+medium+heavy trucks in China
- 2 000 0000 heavy trucks in European Union (400 000 in Germany)
- Large distributed control systems with no real-time coordination today

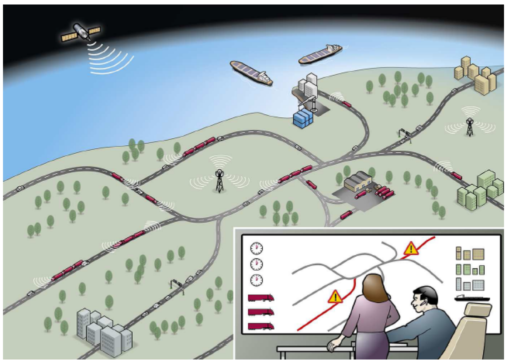
Goal: Maximize total amount of platooning with limited intervention in vehicle speed and route

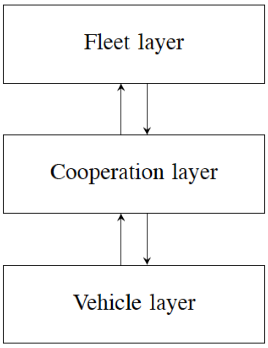


Larson et al., 2013

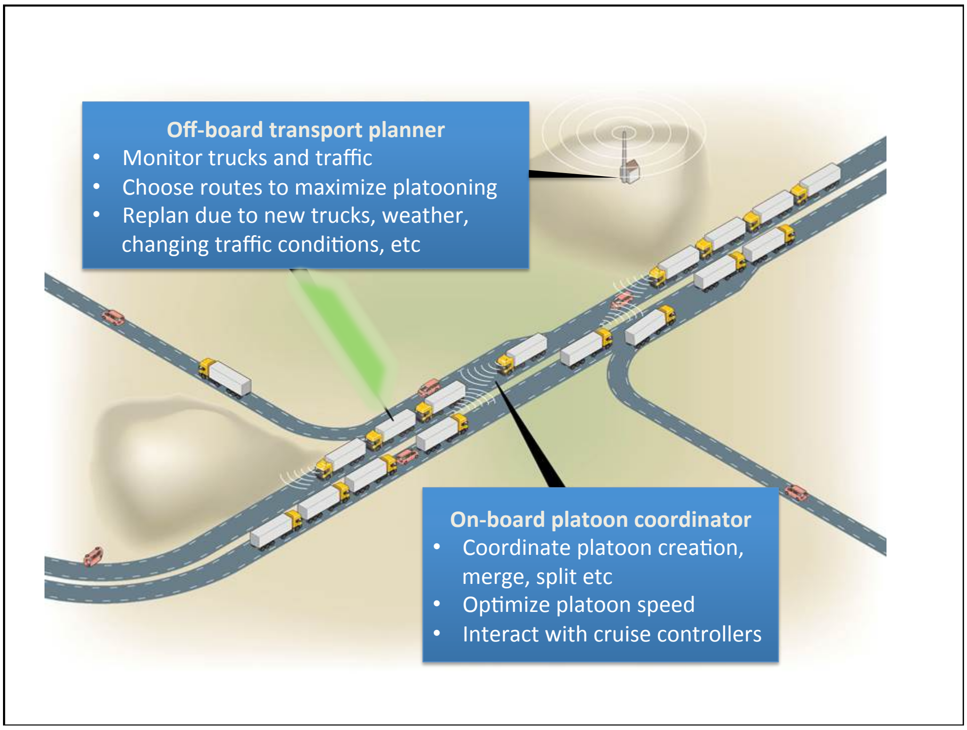


Functional Architecture for Goods Transport

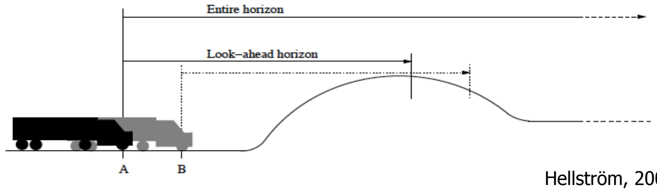




Alam et al., 2012


Off-board transport planner
• Monitor trucks and traffic
• Choose routes to maximize platooning
• Replan due to new trucks, weather, changing traffic conditions, etc
On-board platoon coordinator
• Coordinate platoon creation, merge, split etc
• Optimize platoon speed
• Interact with cruise controllers

Receding Horizon Cruise Control for Single Vehicle



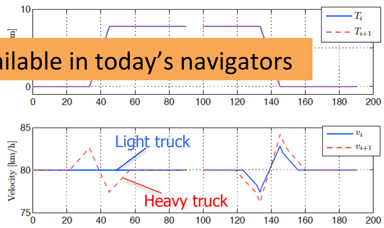
Hellström, 2007

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

The total fuel consumption over time T is:

$$+ mgc_r \cos\alpha + mg \sin\alpha \Big) \mathrm{d}t \qquad (3)$$

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

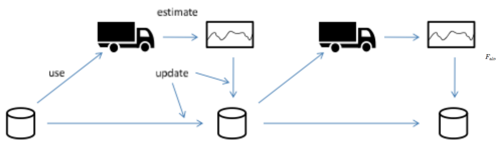


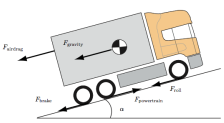
$$m_t \frac{\mathrm{d}v}{\mathrm{d}t} = F_{eng} - F_b - F_{ad}(v,d) - F_r(\alpha) - F_g(\alpha)$$
$$= F_{eng} - F_b - \frac{1}{2}\rho_a A_a c_D v^2 \phi(d) - mgc_r \cos\alpha - mg \sin\alpha$$

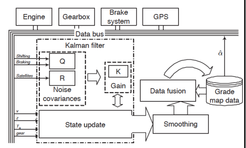
Implemented as velocity reference change in adaptive cruise controller

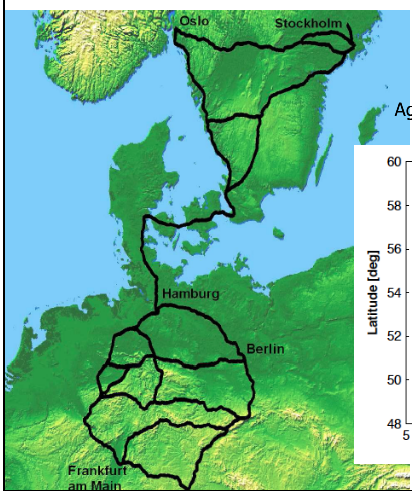
Alam et al., 2011

Distributed Road Grade Estimation



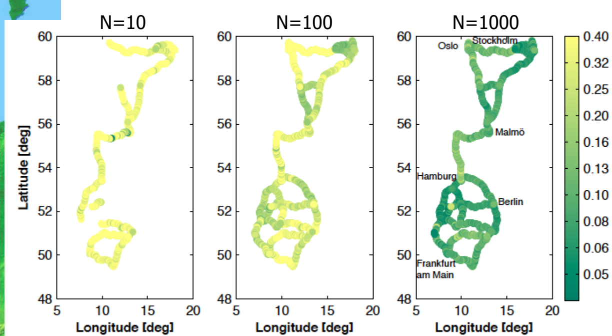






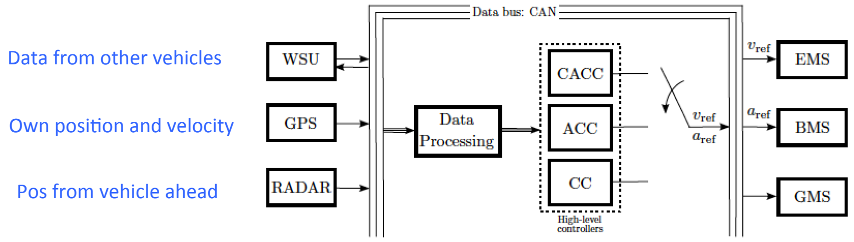
RMS Road Grade Error

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



Sahlholm, 2011

Vehicle System Architecture

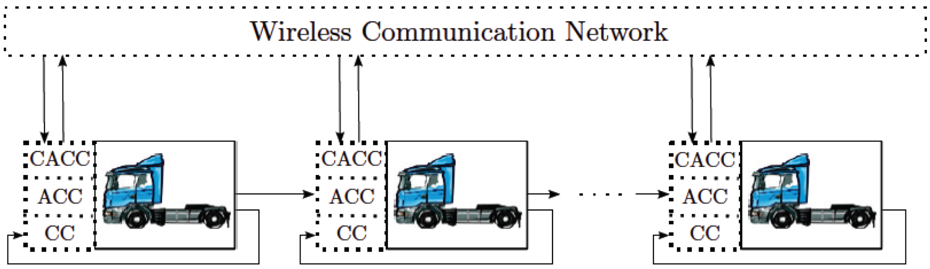


CACC – Collaborative adaptive cruise control
ACC – Adaptive cruise control
CC – Cruise control

EMS – Engine management system
BMS – Brake management system
GMS – Gear management system

Alam et al., 2014

Platoon System Architecture

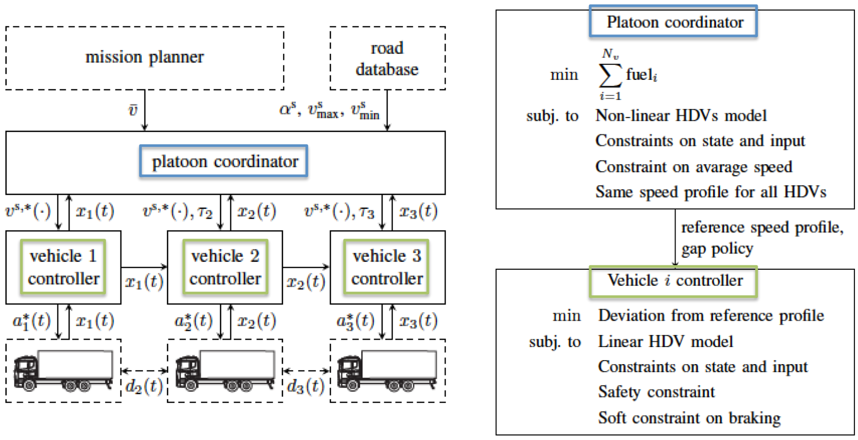


CACC – Collaborative adaptive cruise control
ACC – Adaptive cruise control
CC – Cruise control

Alam et al., 2014

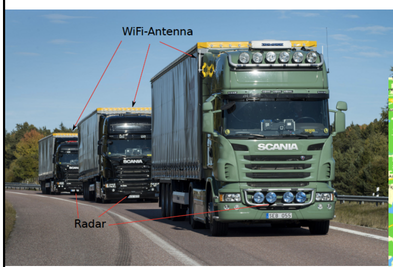
Fuel-efficient and Safe Vehicle Platooning

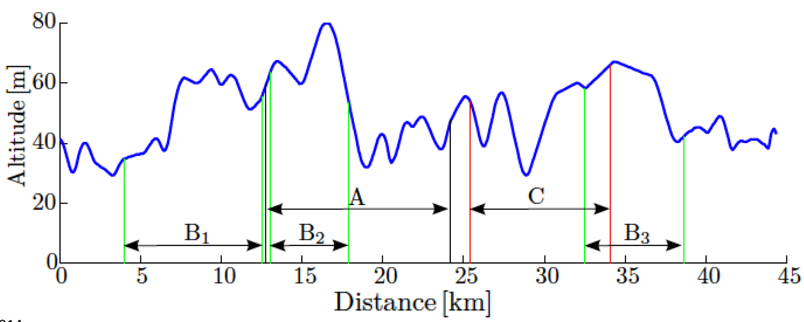
- Jointly minimize fuel consumption for a platoon of vehicles
- Keep small relative distances under strict safety constraints



Turri et al., 2015

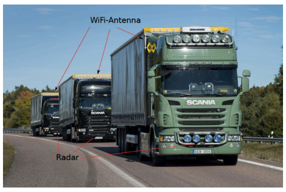
Experimental Evaluation

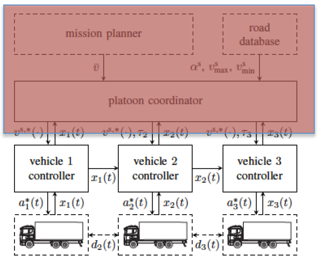


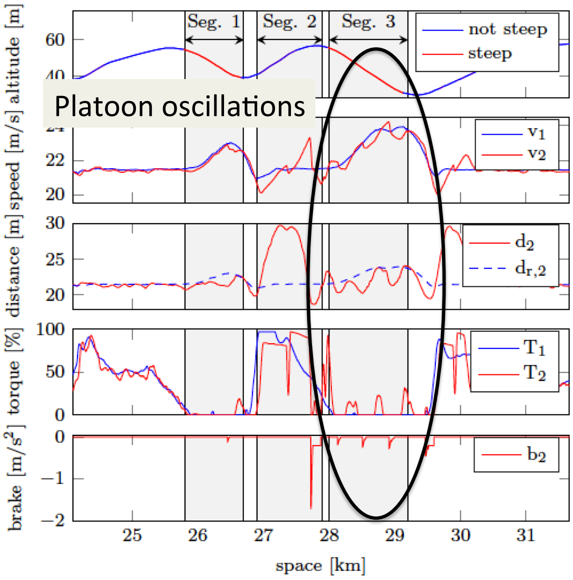


Alam, 2014

Experiments **without** Platoon Coordinator and Look-ahead Road Grade Information

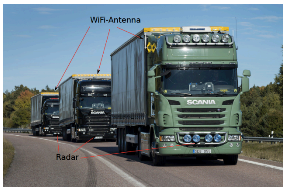


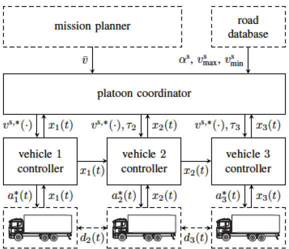


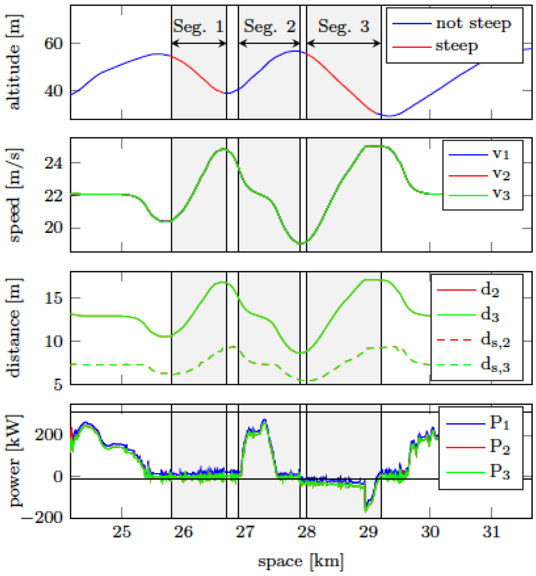


Alam, 2014; Turri et al., 2015

Simulations **with** Platoon Coordinator and Look-ahead Road Grade Information

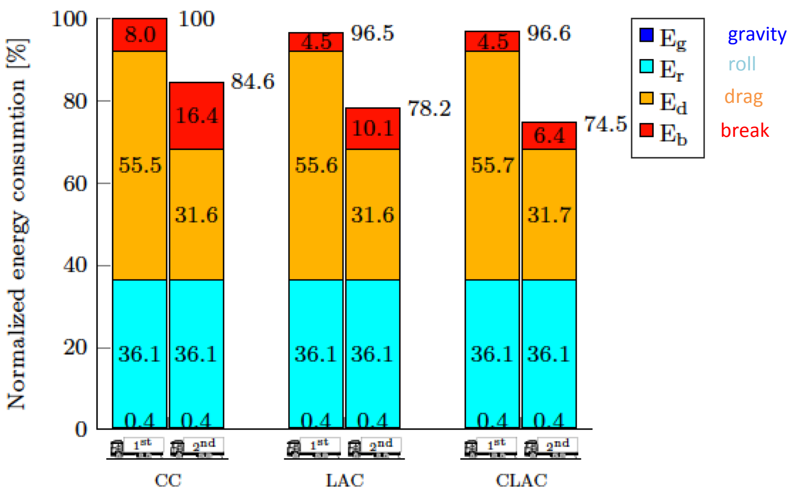






Turri et al., 2015

Evaluation of Energy Efficiency

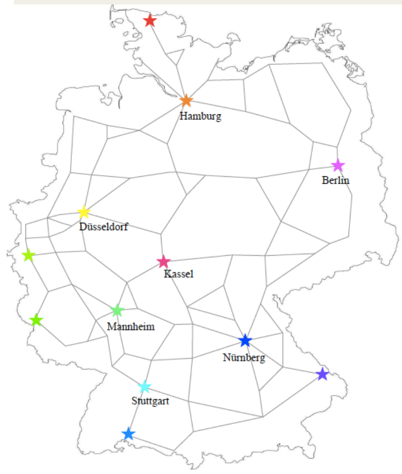


CC: First vehicle runs conventional cruise controller, second tries to keep fixed time gap
LAC: First vehicle runs instead look-ahead cruise controller, second still keeps fixed time gap
CLAC: Vehicles run cooperative look-ahead control with platoon coordinator

Turri et al., 2015

When and where to create platoons?

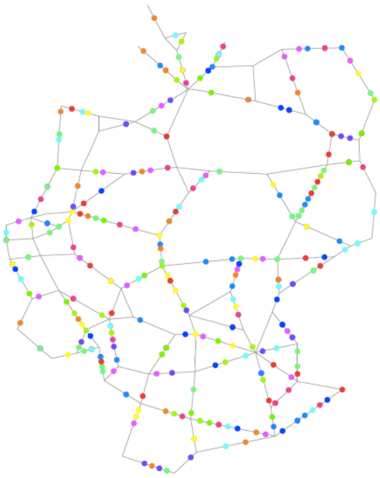
Goal: Maximize total amount of platooning
with limited intervention in vehicle speed and route



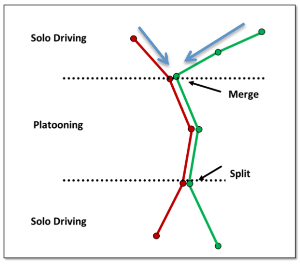
Larson et al., 2013

Platoon merge and split

Heavy-duty vehicle traffic without platooning



Merge and split platoons at highway intersections



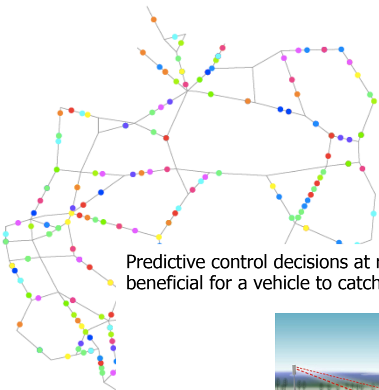
Only vehicles that are relatively close in space and time platoon

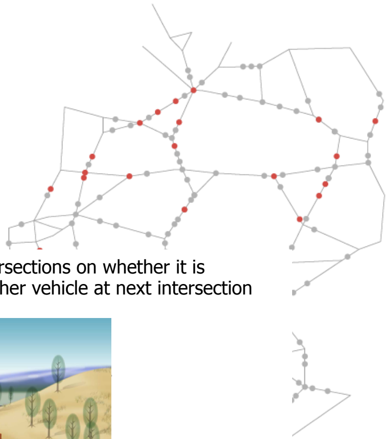
Larson et al., 2013

Distributed optimization of platooning

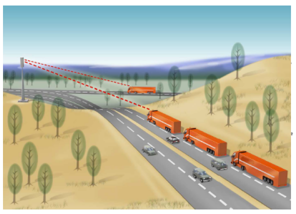
Heavy-duty vehicle traffic without platooning

With platooning



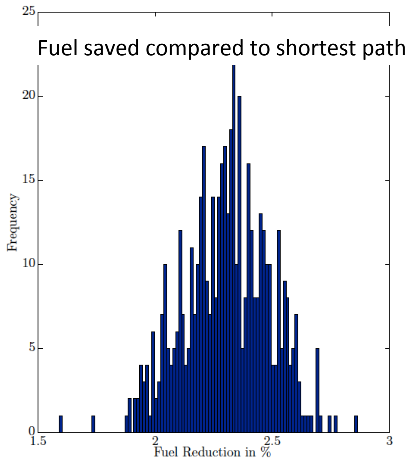


Predictive control decisions at road intersections on whether it is beneficial for a vehicle to catch up another vehicle at next intersection

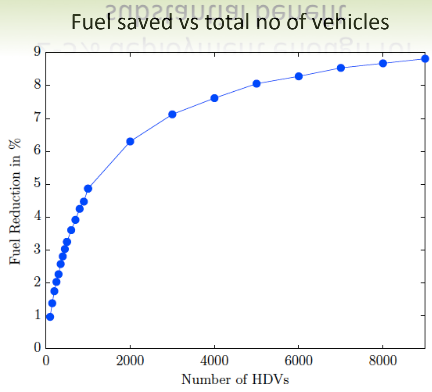


Larson et al., 2013

Numerical evaluations



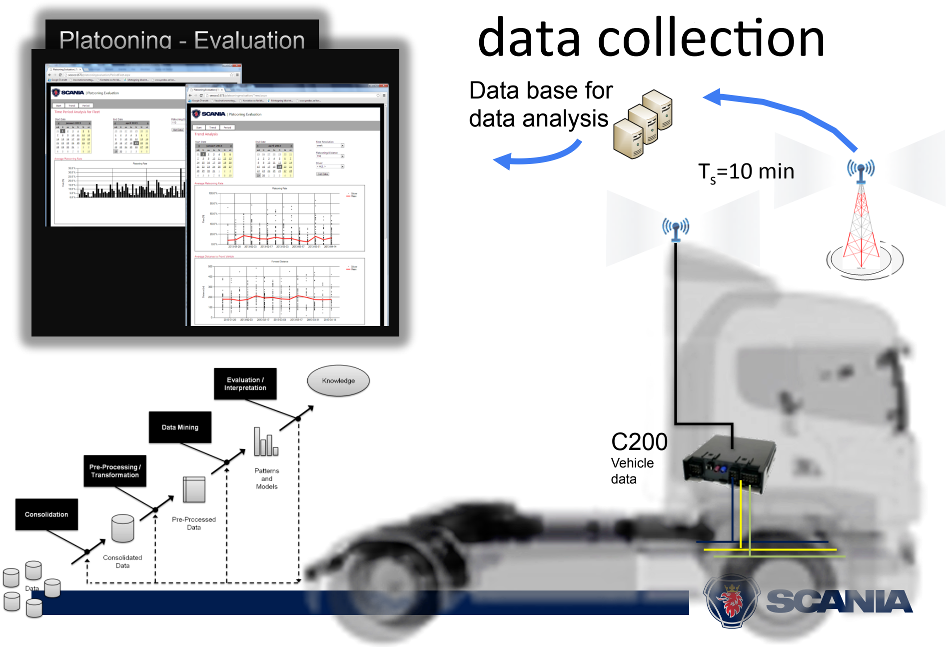
2-5% deployment enough for substantial benefit



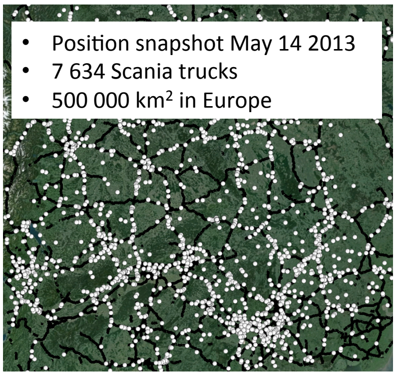
- German road network with 300 trucks
- Random starting points and destinations
- 500 experiments

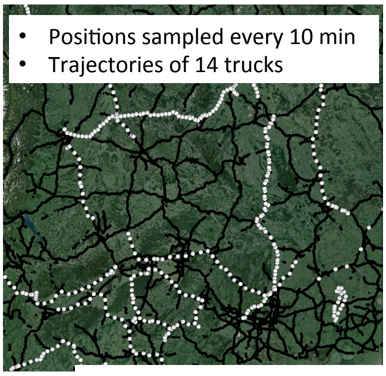
Larson et al., 2013

Infrastructure for data collection

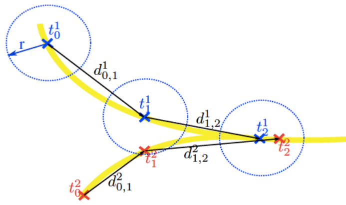


Feasibility Study Based on Real Truck Data



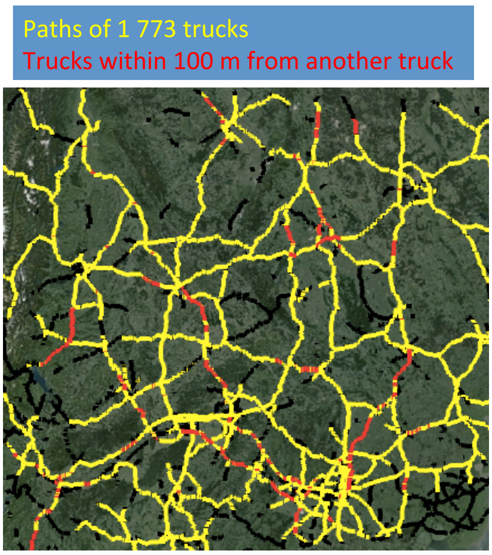


- 875 long-haulage trucks over European region
- Trucks close in time and space (<r m) could adjust speed to platoon and then save 10% fuel during platooning



Larson et al., 2013

Spontaneous vs Coordinated Platooning

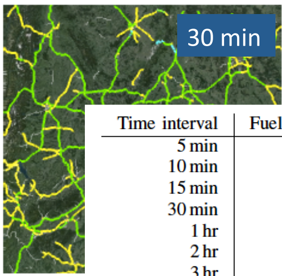


Liang et al., 2014

Spontaneous vs **Coordinated** Platooning

Adjust truck departure times

Individual trucks
Platoons of 2-5 trucks
Platoons of 6-10 trucks
Platoons of 11-25 trucks
Platoons of >25 trucks



Time interval	Fuel saved*	Platooning rate
5 min	0.68%	13.22%
10 min	1.19%	22.41%
15 min	1.64%	30.26%
30 min	2.74%	47.58%
1 hr	4.31%	68.07%
2 hr	5.94%	83.23%
3 hr	6.87%	89.93%
6 hr	8.06%	95.67%
12 hr	8.85%	98.38%
24 hr	9.37%	99.38%

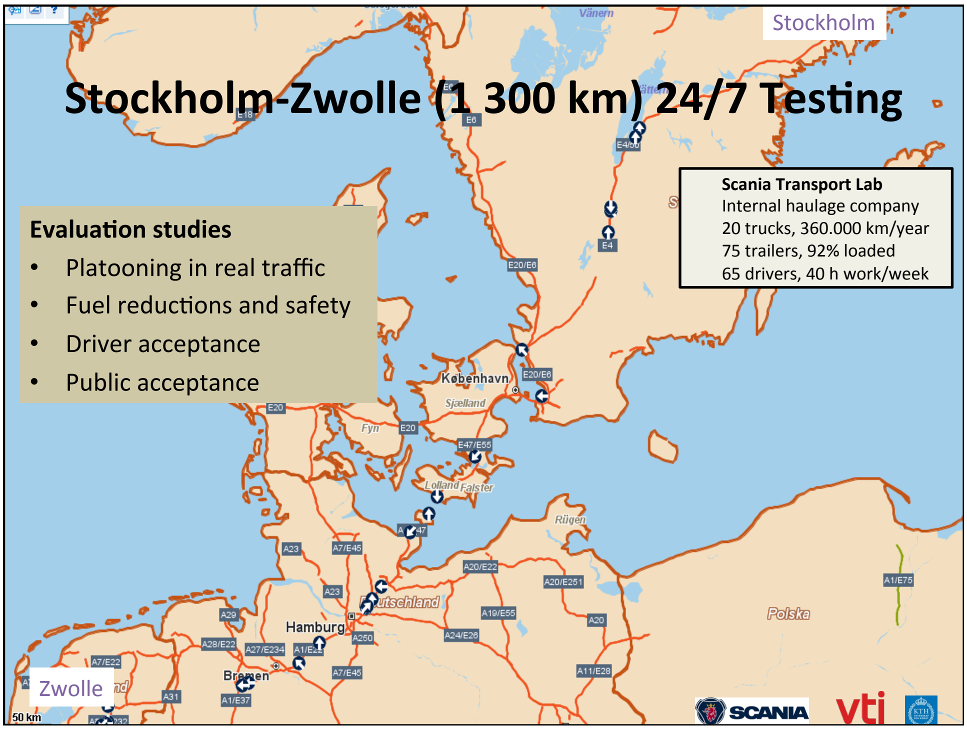
Coordinated departure times enable much more platooning

Liang et al., 2014

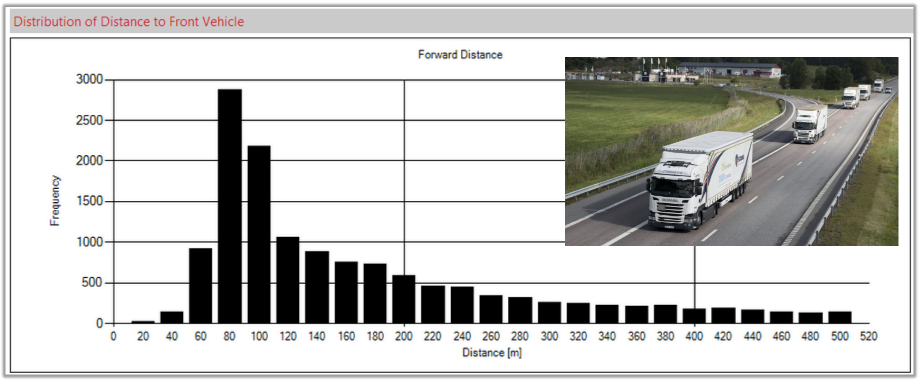
Stockholm-Zwolle (1 300 km) 24/7 Testing

Evaluation studies
- 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



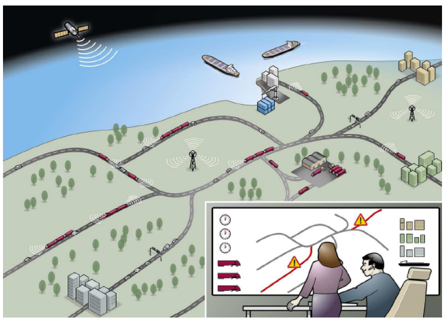
How willing are drivers to platoon?

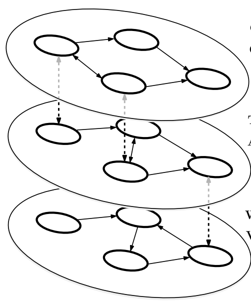


- Jan-Apr 2013 experimental evaluation
- Drivers in the loop with advanced ACC (radar etc)
- Encouraged but not enforced to platoon
- Notable fuel reductions

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

Cyber-physical-**human** system



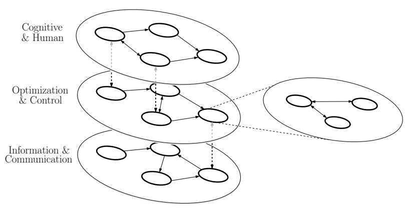


Outline

- Societal need and enabling technology
- Cyber-physical systems
- Scientific challenges
- Cyber-physical transportation systems
- Conclusions

Conclusions

- **Cyber-physical systems to tackle grand societal challenges**
  – Real-time control of infrastructure resources
- **Optimized cooperative driving for goods transportation**
  – High-level optimization and scheduling of transport
  – Low-level control and coordination of truck platoons
- **Open problems**
  – Global vs local objectives: Who owns the performance metric?
  – Local computing vs communication: When do it in the Cloud?
- **Large-scale testing and evaluations**



http://people.kth.se/~kallej

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Control of Vehicle Platoons

IEEE TRANSACTIONS ON AUTOMATIC CONTROL, VOL. AC-11, NO. 3, JULY, 1966

On the Optimal Error Regulation of a String of Moving Vehicles

W. S. LEVINE, STUDENT MEMBER, IEEE, AND M. ATHANS, MEMBER, IEEE

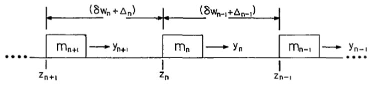
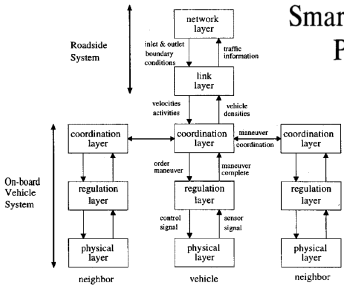


Fig. 1. Vehicles moving in a string.

PATH platoon demo San Diego 1997



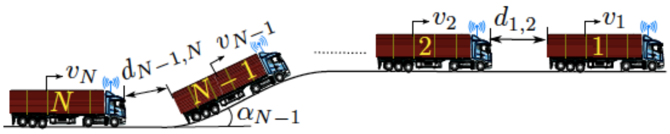
IEEE TRANSACTIONS ON AUTOMATIC CONTROL, VOL. 38, NO. 2, FEBRUARY 1993

Smart Cars on Smart Roads: Problems of Control

Pravin Varaiya, *Fellow, IEEE*

Demo for Dutch Minister of Infrastructure and the Environment Ms Schultz van Haegen

Collaborative Cruise Control

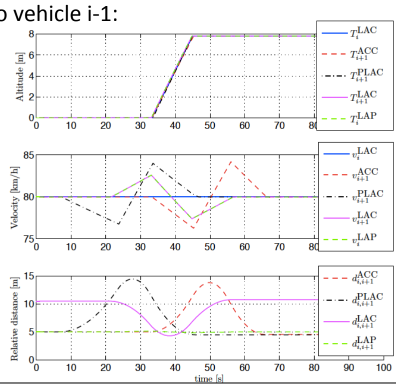


- How to jointly minimize fuel consumption for a platoon of vehicles?
  - Keep small relative distances *vs.* close to individual optimal trajectories?
  - Uphill and downhill segments; heavy and light vehicles

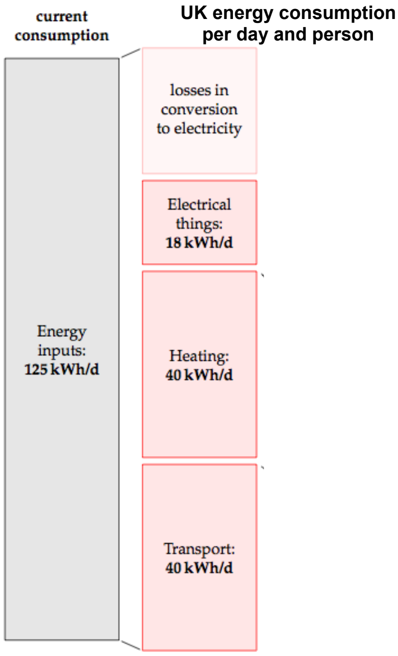
Dynamics of vehicle i depend on distance $d_{i-1,i}$ to vehicle i-1:

$$\frac{\mathrm{d}d_{i-1,i}}{\mathrm{d}t} = v_{i-1} - v_i$$

$$\begin{aligned} \mathrm{m}_{t_i}\frac{\mathrm{d}v_i}{\mathrm{d}t} &= F_{\text{engine}}(\delta_i, \omega_{e_i}) - F_{\text{brake}} - F_{\text{air drag}}(v_i, d_{i-1,i}) \\ &\quad - F_{\text{roll}}(\alpha_i) - F_{\text{gravity}}(\alpha_i) \\ &= \mathrm{k}_i^{\mathrm{e}} T_e(\delta_i, \omega_{e_i}) - F_{\text{brake}} - \mathrm{k}_i^{d} v_i^2 f_i(d_{i-1,i}) \\ &\quad - \mathrm{k}_i^{\mathrm{fr}} \cos\alpha_i - \mathrm{k}_i^{\mathrm{g}} \sin\alpha_i \end{aligned}$$



Alam et al., 2013



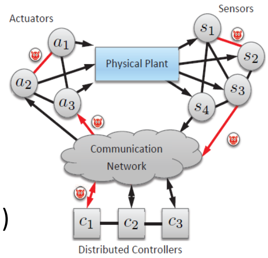
Higher efficiency thanks to improved control and coordination of energy use

D. J.C. MacKay, Sustainable Energy–without the hot air, UIT Cambridge, 2008

Cyber-Physical Security

Need **analysis and design tools** to understand and mitigate attacks

- Which threats should we care about?
- Which resources are more important to protect?
- What impact can we expect of an attack?
- How to create resilient systems?



Cross-disciplinary research agenda

- IT security (authentication, encryption, firewalls, etc.) is needed, but not sufficient
- Malicious actions can enter in the control loop, even if channels are secure

Grand societal challenges

- Impact on future infrastructure systems where everything is connected
- Systems need to be trusted by the general public