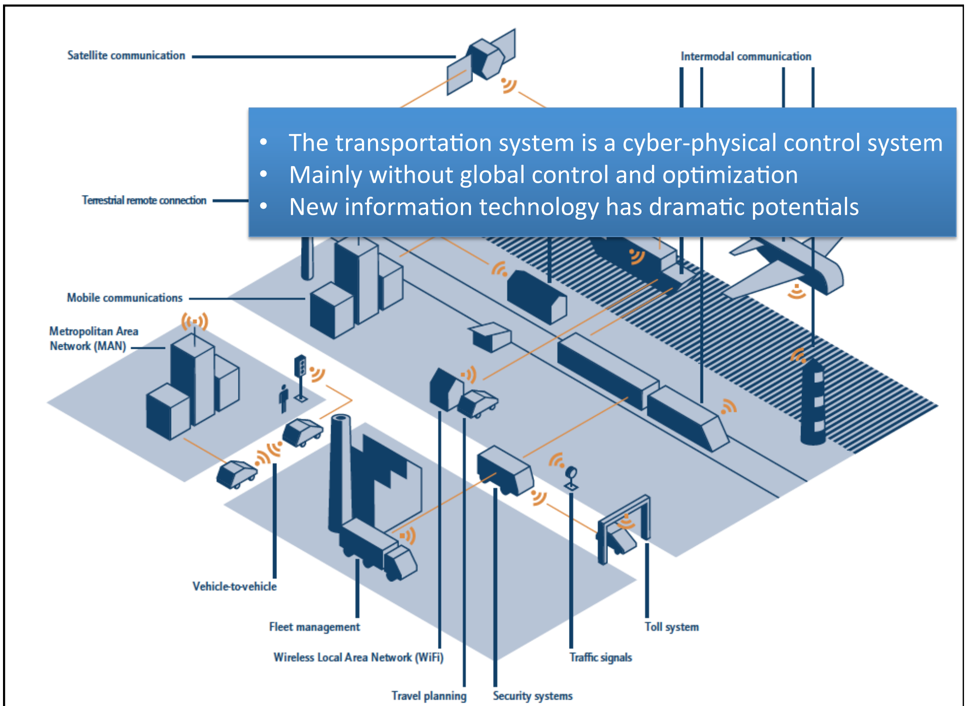
Plenary preparation at Mount Tai with CCC 2014 General Chairman

Acknowledgments

Assad Alam
Kuo-Yun Liang
Per Sahlholm

Jonas Mårtensson
Jeff Larson
Valerio Turri
Bart Besselink
Farhad Farokhi
Ather Gattami



- The transportation system is a cyber-physical control system
- Mainly without global control and optimization
- New information technology has dramatic potentials

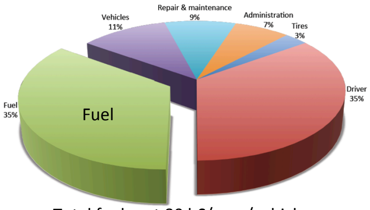
Cyber-Physical Systems Roadmap, German National Academy of Science and Engineering, 2011

Demands from Goods Road Transportation

- Transport sector consumes 1/3 of EU energy
- 45% of all freight transport is on roads
- Road transport accounts for 20% of CO_2 emissions
- Emissions increased by 21% for 1990-2009

Eurostat (2011), EU Transport (2013)

Life cycle cost for European heavy-duty vehicle



Total fuel cost 80 k€/year/vehicle

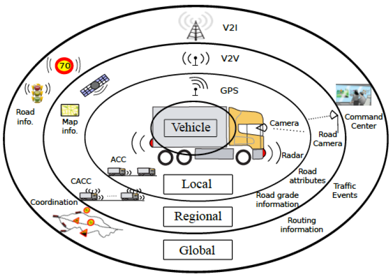
Schittler, 2003; Scania, 2012

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

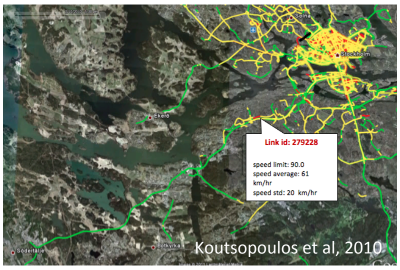
Dr. H. Ludanek, CTO, Scania

Technology Push

Sensor and commununication technology



Real-time traffic information



Vehicle platooning and semi-autonomous driving

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

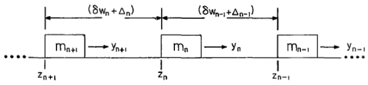


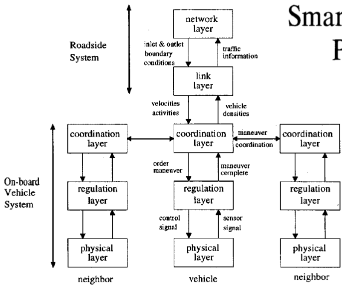
Fig. 1. Vehicles moving in a string.

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

Smart Cars on Smart Roads: Problems of Control

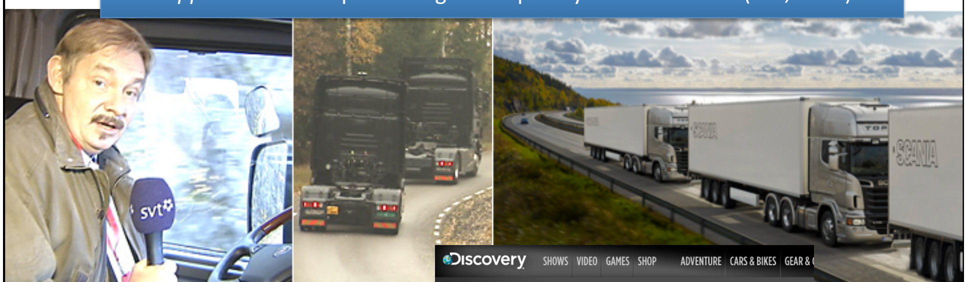
Pravin Varaiya, *Fellow, IEEE*

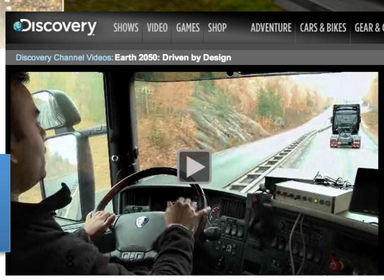
PATH platoon demo San Diego 1997



Heavy-Duty Vehicle Platooning

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

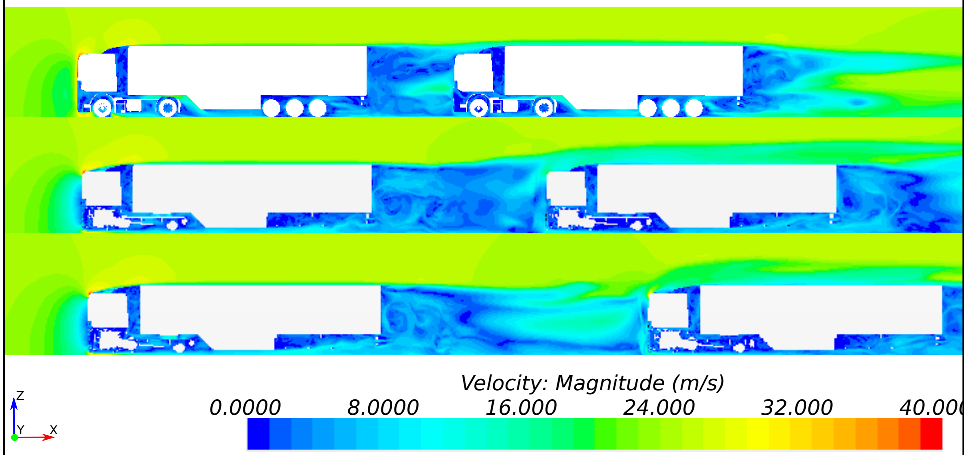




VIDEO

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

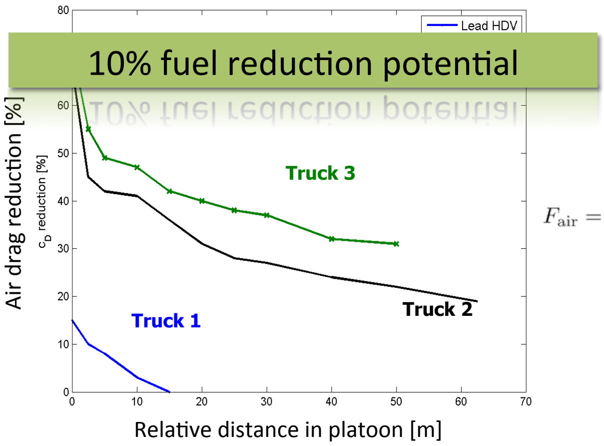
The Physics



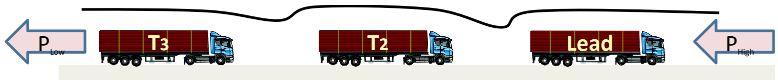
Liang (2014)

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)

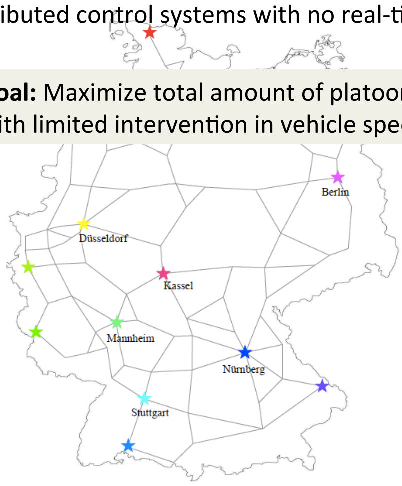
Outline

- Introduction
- Architecture for fuel-optimized goods transport
- Cruise control for vehicle platoons
- Optimized transport planner
- Humans in the loop
- Conclusions

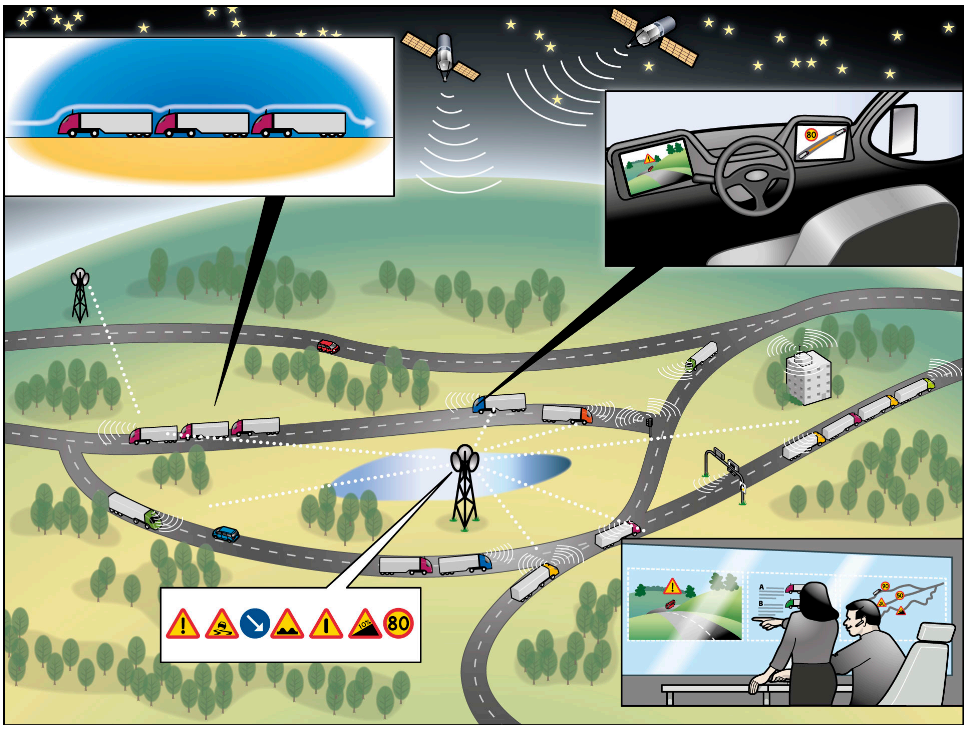
Fuel-Optimized Goods Transport

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

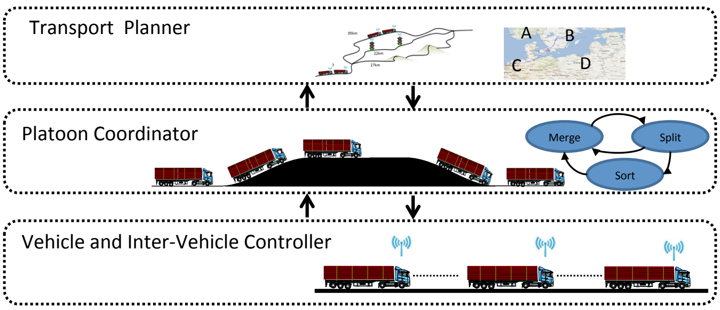
Goal: Maximize total amount of platooning
with limited intervention in vehicle speed and route



Larson et al., 2013



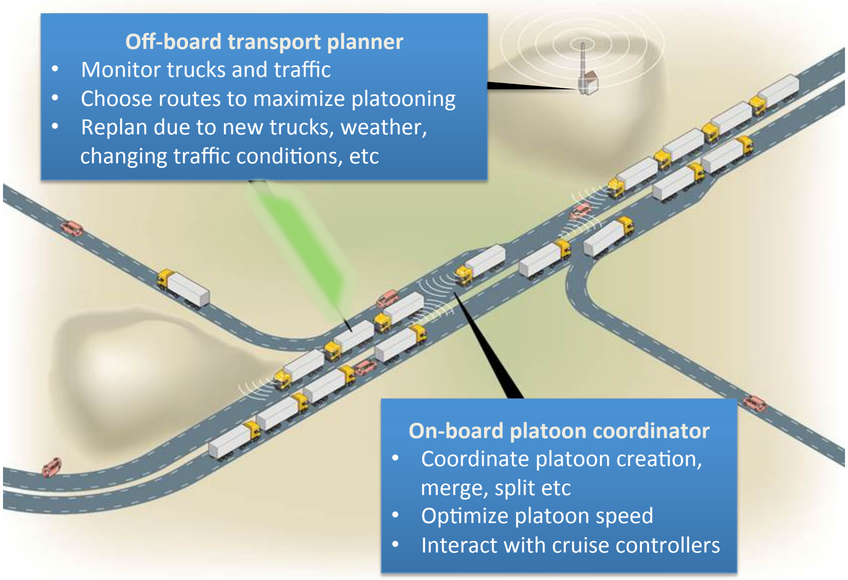
Functional Architecture for Goods Transport



VIDEO

Alam et al., 2012

Off- and On-board Computing



Outline

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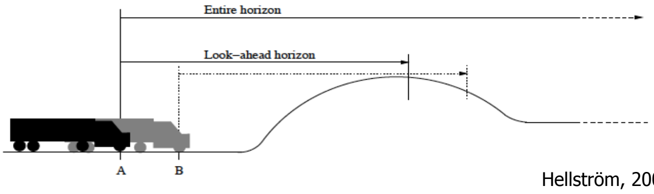
Receding Horizon Cruise Control for Single Vehicle



Hellström, 2007

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

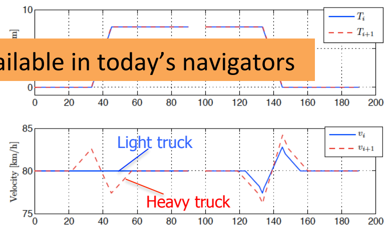
The total fuel consumption over time T is:

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

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

$$m_t \frac{\mathrm{d}v}{\mathrm{d}t} = F_{eng} - F_b - F_{ad}(v,d) - F_r(\alpha) - F_g(\alpha)$$

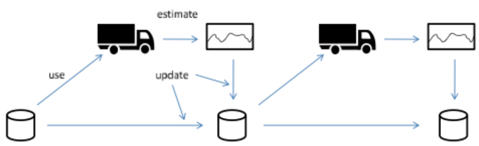
$$= F_{eng} - F_b - \frac{1}{2}\rho_a A_a c_D v^2 \phi(d) - mgc_r \cos\alpha - mg\sin\alpha$$

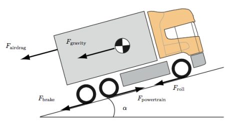


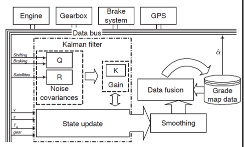
Implemented as velocity reference change in adaptive cruise controller

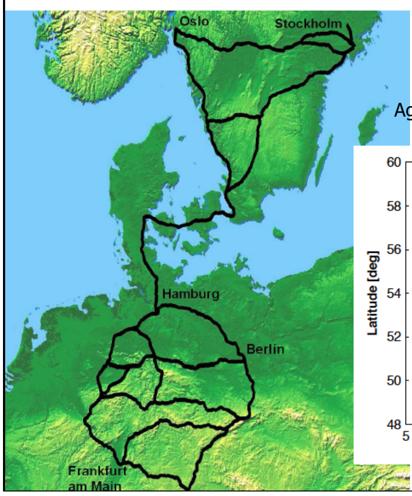
Alam et al., 2011

Distributed Road Grade Estimation



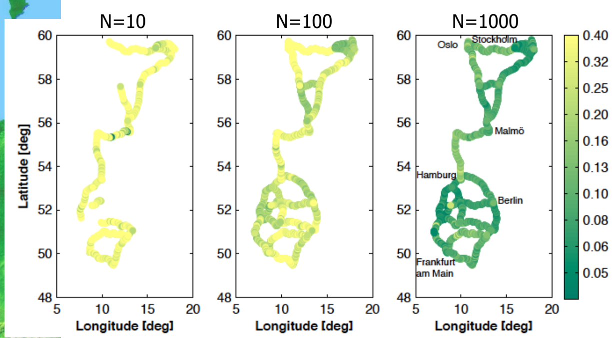






RMS Road Grade Error

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



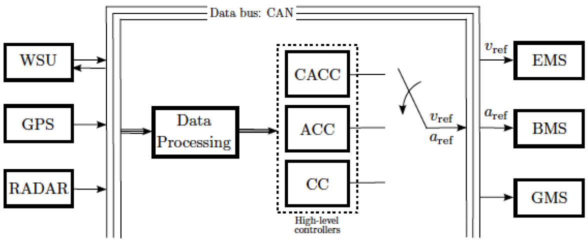
Sahlholm, 2011

Vehicle System Architecture

Data from other vehicles

Own position and velocity

Pos from vehicle ahead

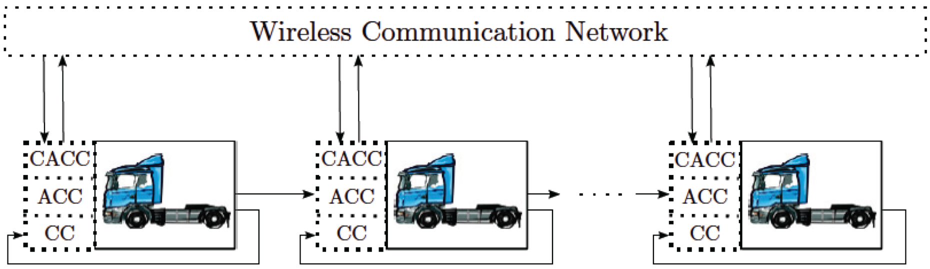


CACC – Collaborative adaptive cruise control
ACC – Adaptive cruise control
CC – Cruise control

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

Alam et al., 2014

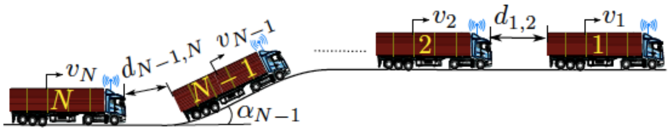
Platoon System Architecture



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

Alam et al., 2014

Collaborative Adaptive Cruise Control

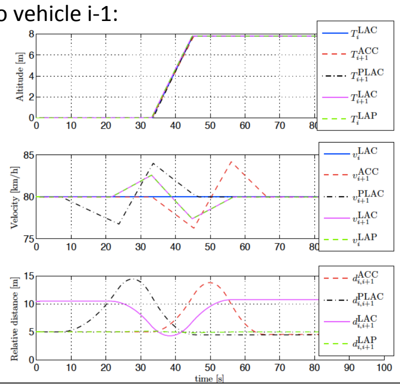


- How to jointly minimize fuel consumption for a platoon of vehicles?
  - Keep small relative distances or close to individual optimal trajectories?
  - Uphill and downhill segments; heavy and light vehicles

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

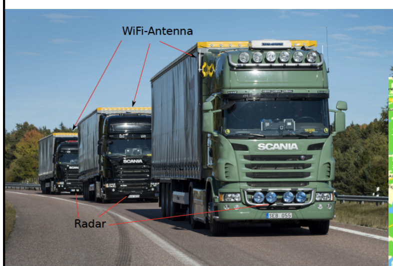
$$\frac{\mathrm{d}d_{i-1,i}}{\mathrm{d}t} = v_{i-1} - v_i$$

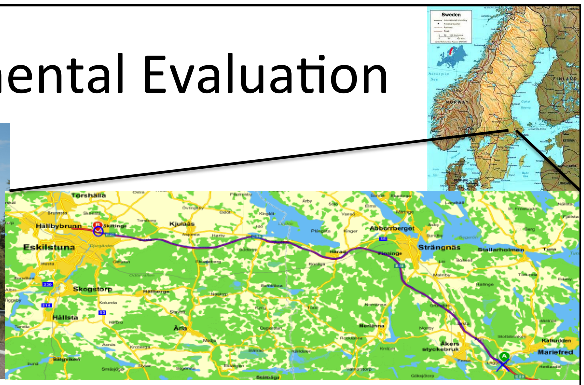
$$\begin{aligned} m_{t_i}\frac{\mathrm{d}v_i}{\mathrm{d}t} &= F_{\text{engine}}(\delta_i,\omega_{e_i}) - F_{\text{brake}} - F_{\text{air drag}}(v_i, d_{i-1,i}) \\ &\quad - F_{\text{roll}}(\alpha_i) - F_{\text{gravity}}(\alpha_i) \\ &= k_i^{e} T_e(\delta_i,\omega_{e_i}) - F_{\text{brake}} - k_i^{d} v_i^2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

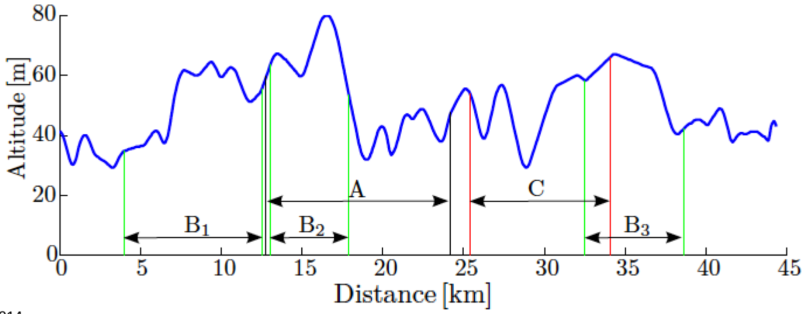


Alam et al., 2013

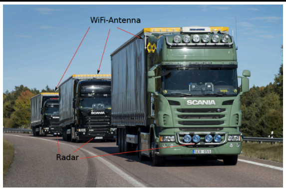
Experimental Evaluation







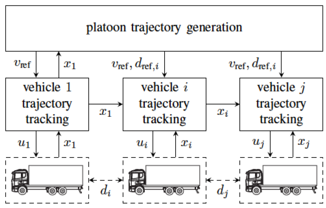
Alam, 2014

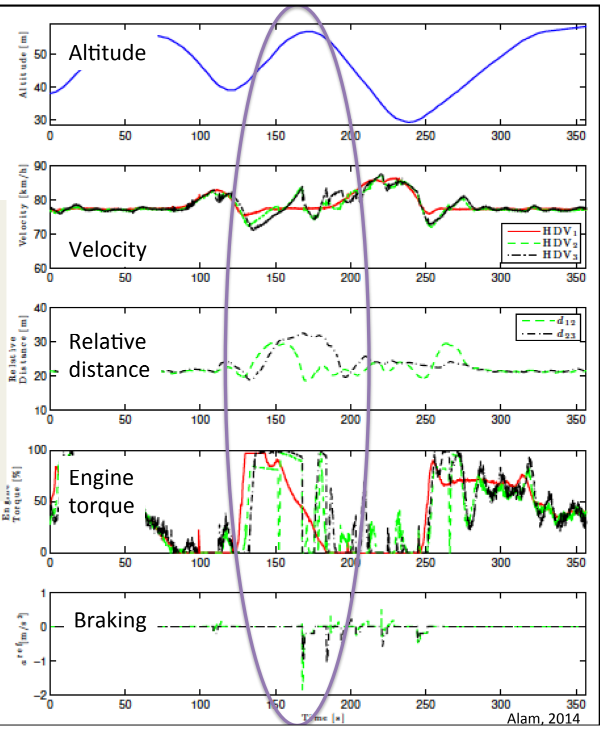


Hilly roads generate platoon **disturbances**

May impose fuel-inefficient braking commands

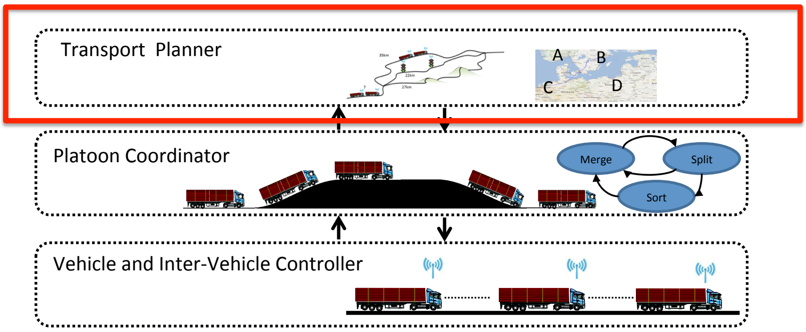
Compensated by **feedforward** communication of road topology and vehicle commands





Alam, 2014

Functional Architecture for Goods Transport



Alam et al., 2012

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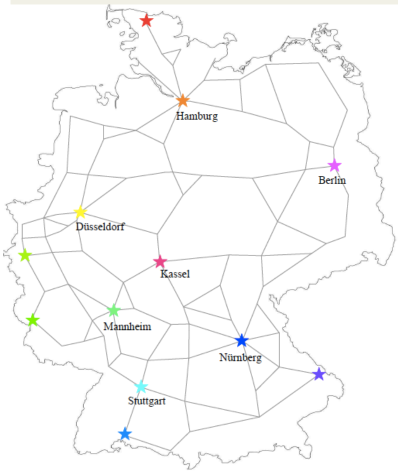
When and where to create platoons?

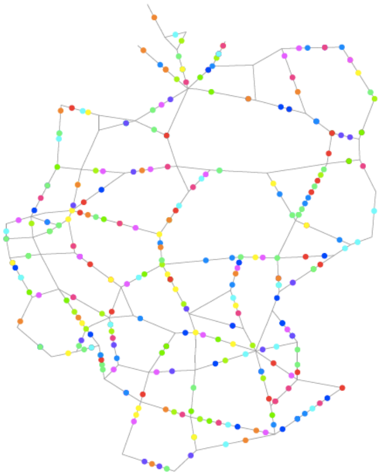
Goal: Maximize total amount of platooning
with limited intervention in vehicle speed and route



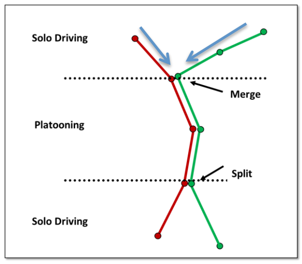
Larson et al., 2013

Platoon merge and split

Heavy-duty vehicle traffic without platooning



Merge and split platoons at highway intersections

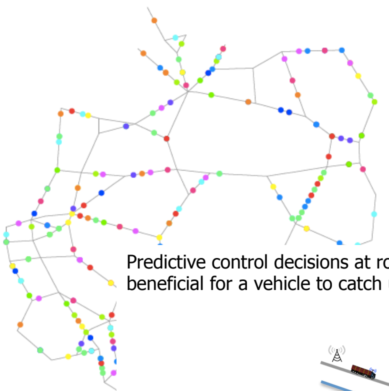


Only vehicles that are relatively close in space and time platoon

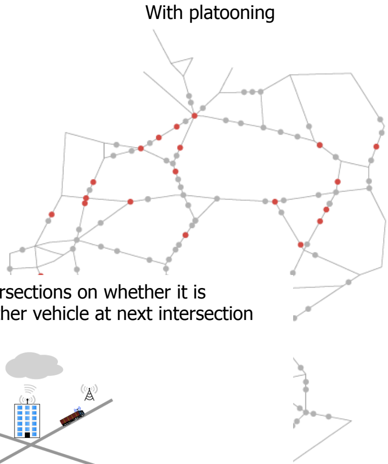
Larson et al., 2013

Distributed optimization of platooning

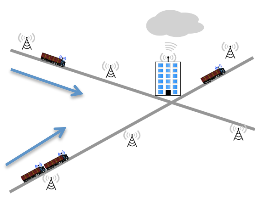
Heavy-duty vehicle traffic without platooning



With platooning

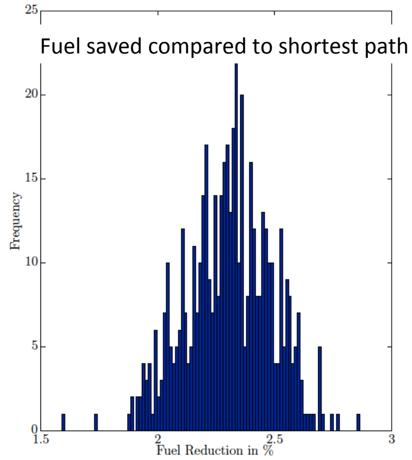


Predictive control decisions at road intersections on whether it is beneficial for a vehicle to catch up another vehicle at next intersection

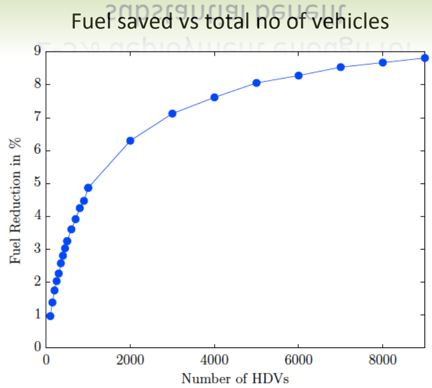


Larson et al., 2013

Numerical evaluations



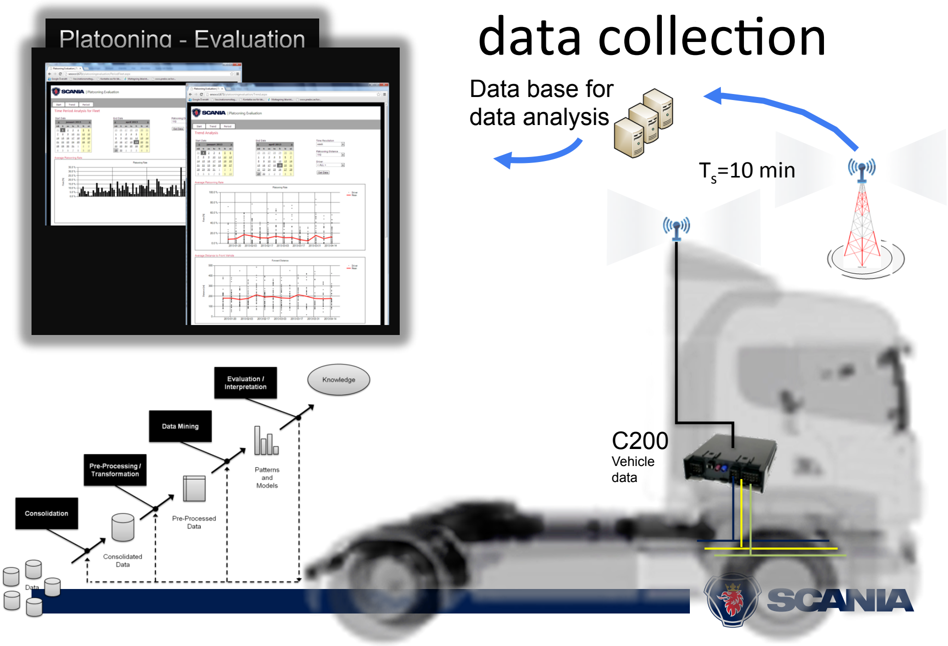
2-5% deployment enough for substantial benefit



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

Larson et al., 2013

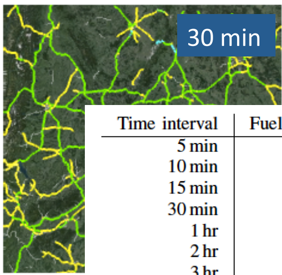
Infrastructure for data collection



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

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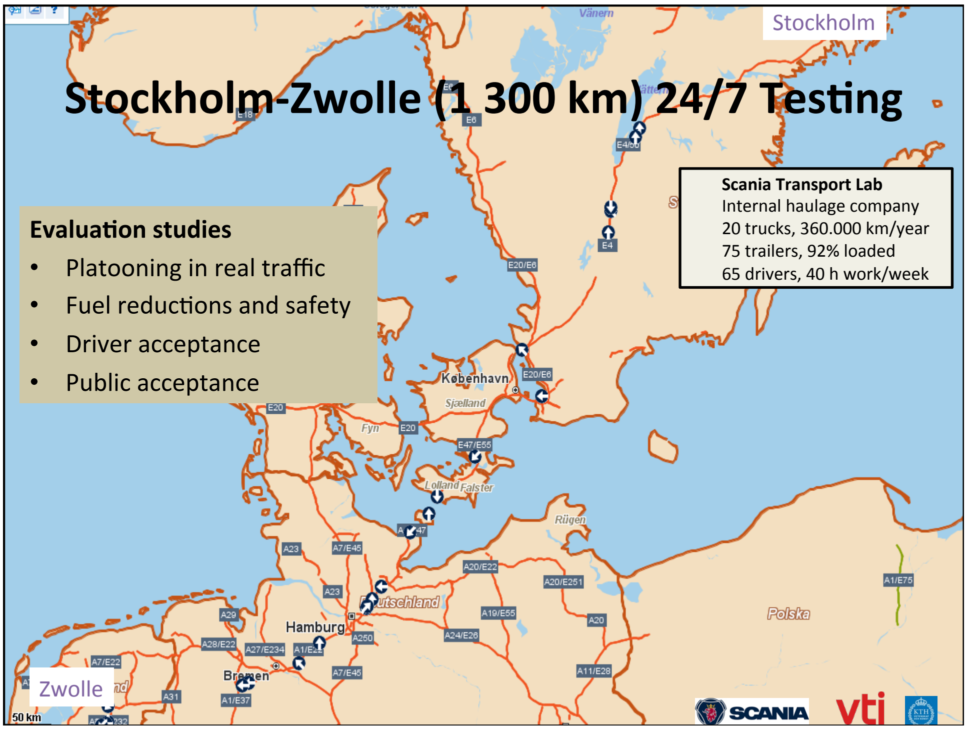
Stockholm-Zwolle (1 300 km) 24/7 Testing

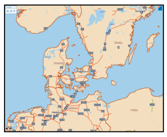


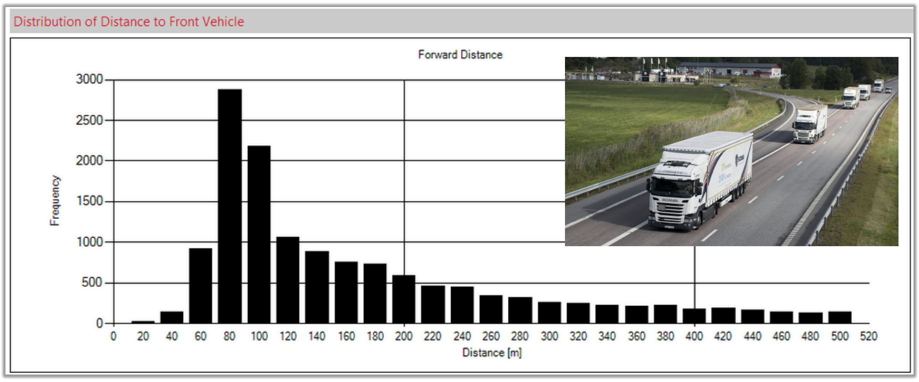
Evaluation studies

- 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?

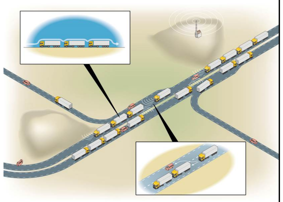




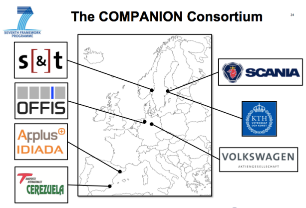
- Jan-Apr 2013 experimental evaluation
- Drivers in the loop with advanced ACC (radar etc)
- Encouraged but not enforced to platoon
- Notable fuel reductions

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

Conclusions



- **Architecture 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?
  - Safety-critical systems: How guarantee real-time?
- **Large-scale testing and evaluations**



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