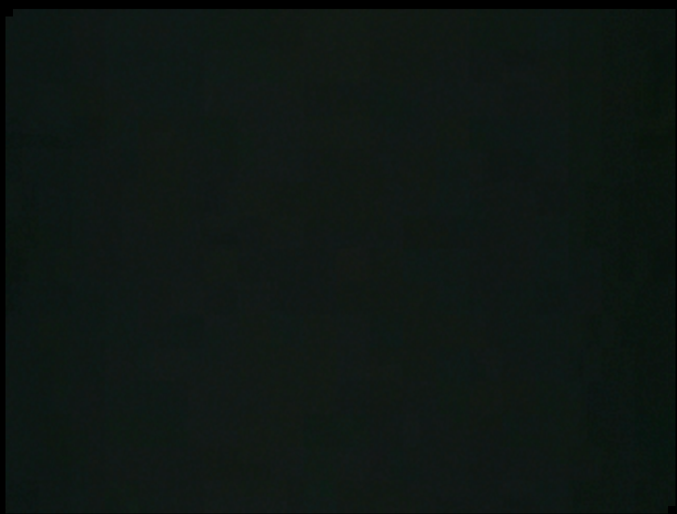

# Acknowledgments

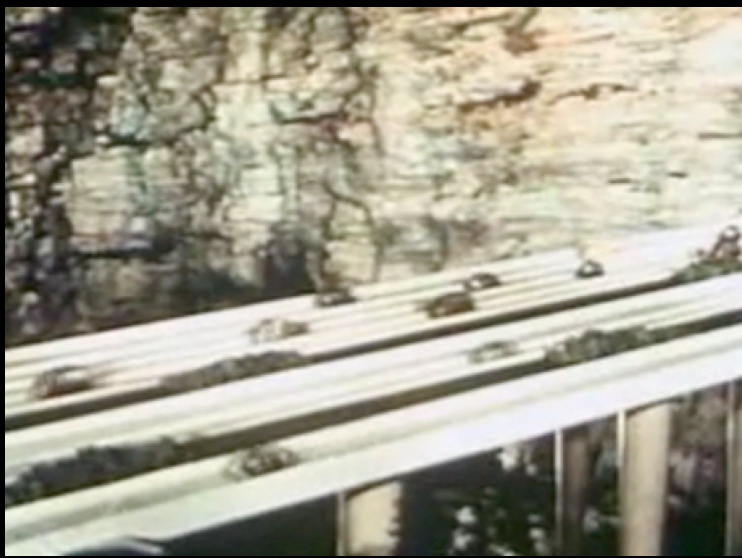
Assad Alam
Kuo-Yun Liang
Per Sahlholm

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

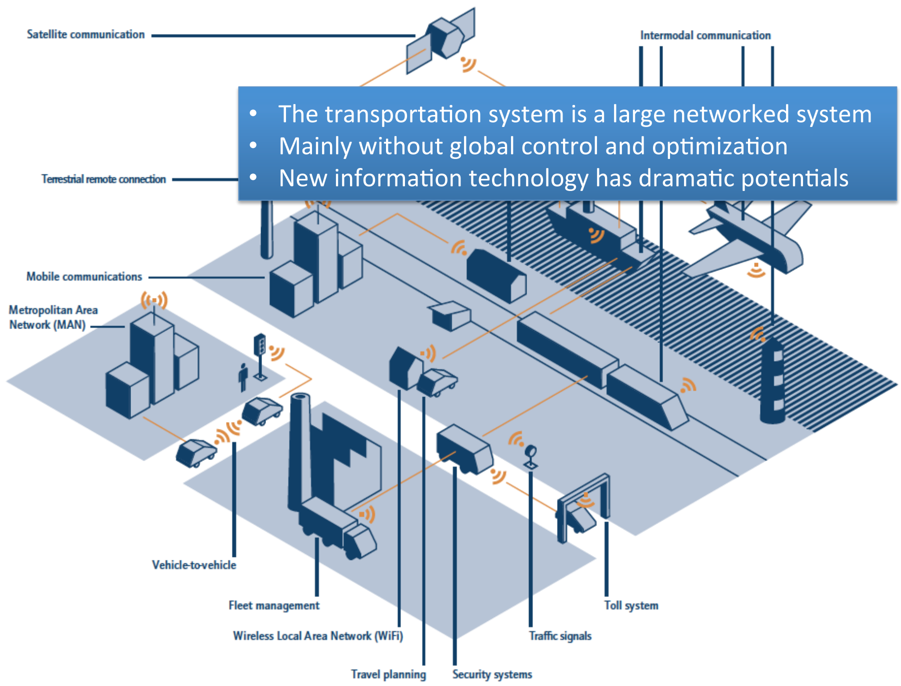
General Motors vision 75 years ago



# "Automatic radio control"



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



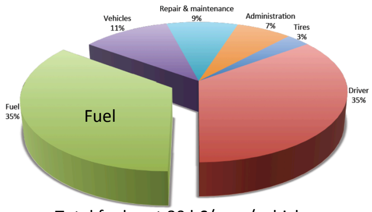

Cyber-Physical Systems Roadmap, German National Academy of Science and Engineering, 2011

# 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

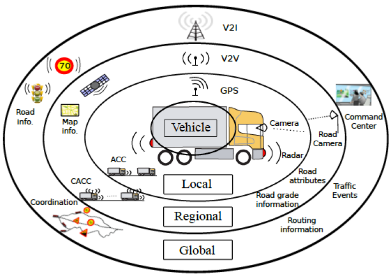
*Schittler, 2003; Scania, 2012*

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

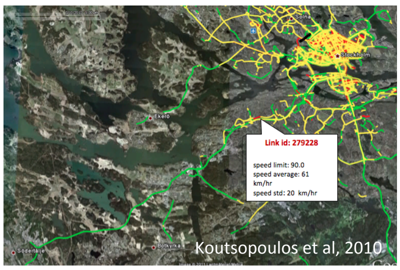
*Dr. H. Ludanek, CTO, Scania*

# Technology Push

**Sensor and communication 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

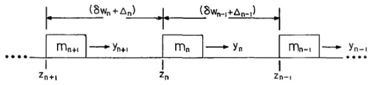


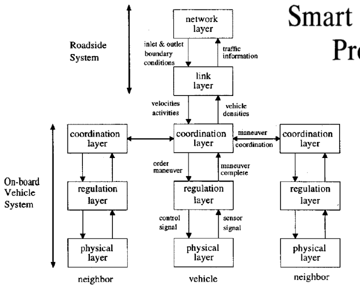
Fig. 1. Vehicles moving in a string.

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

Smart Cars on Smart Roads: Problems of Control

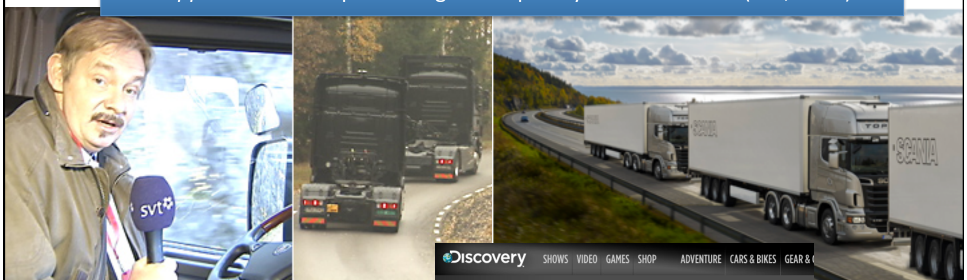
Pravin Varaiya, *Fellow, IEEE*

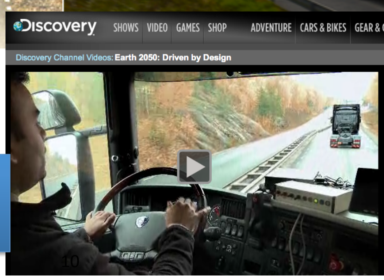
PATH platoon demo San Diego 1997




# Heavy-Duty Vehicle Platooning

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

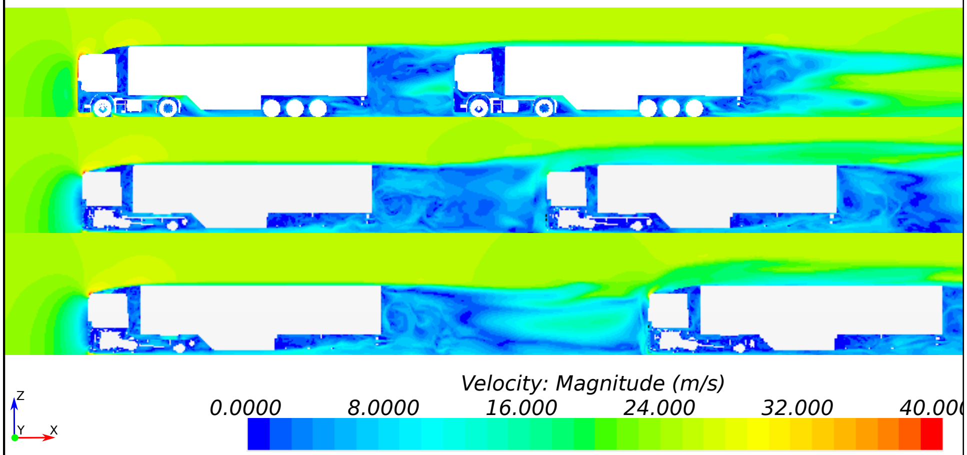





VIDEO

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

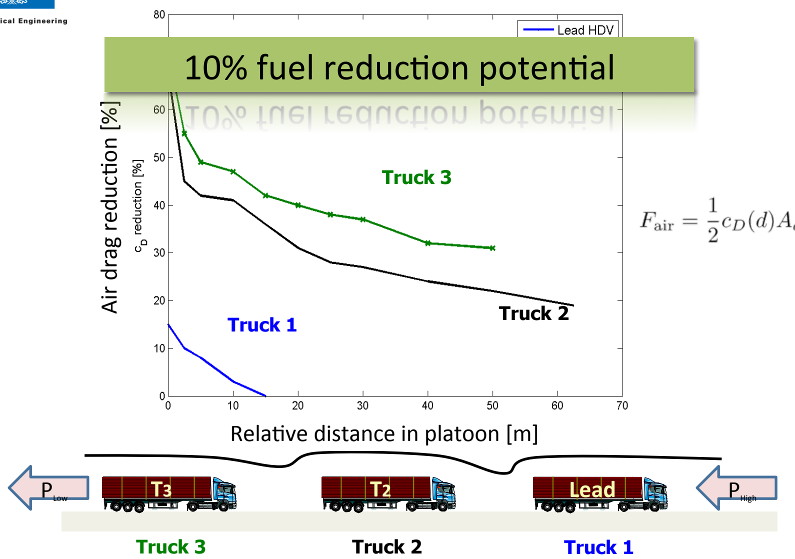
# The Physics




Liang (2014)

## Air Drag Reduction in Truck Platooning

KTH Electrical Engineering




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

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

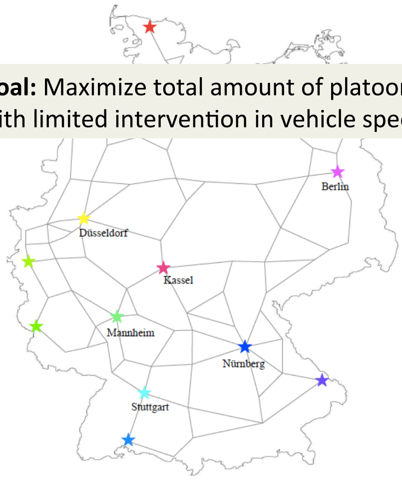
# Outline

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

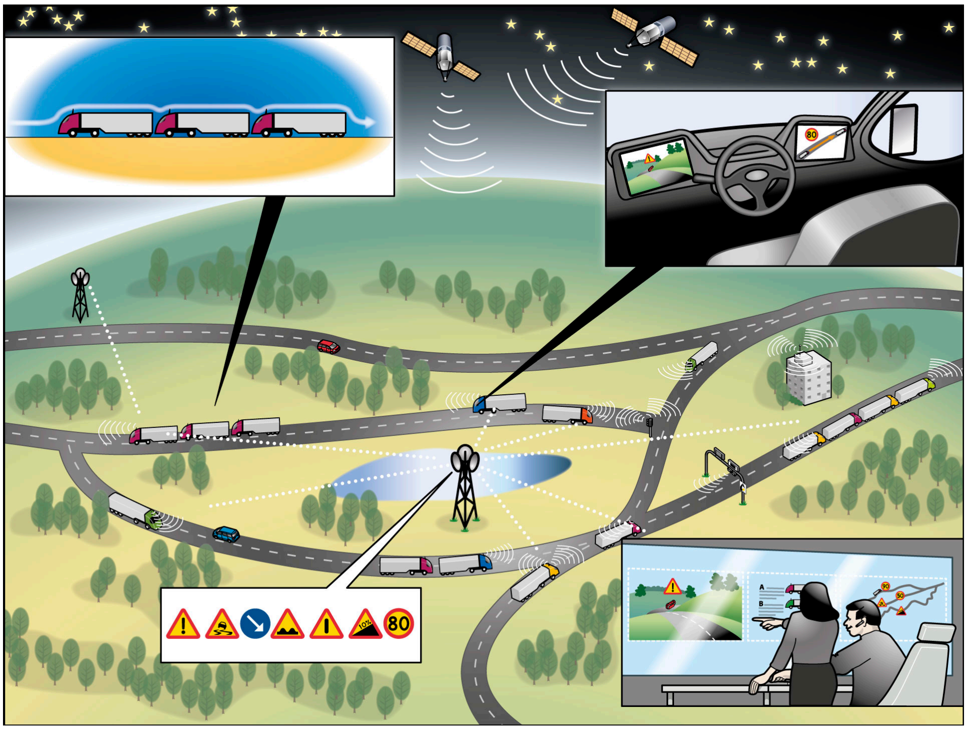
# Fuel-Optimized Goods Transport

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

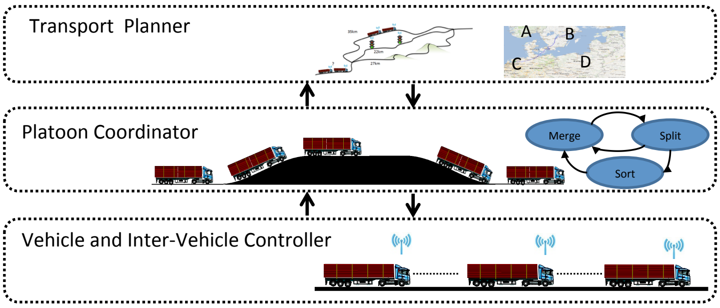
**Goal:** Maximize total amount of platooning
with limited intervention in vehicle speed and route




Larson et al., 2013



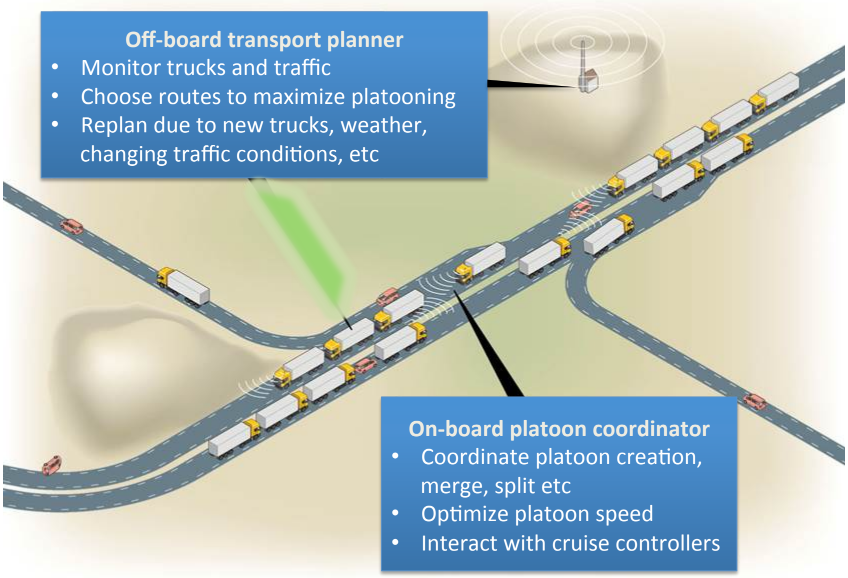

# Functional Architecture for Goods Transport




VIDEO

Alam et al., 2012

## Off- and On-board Computing

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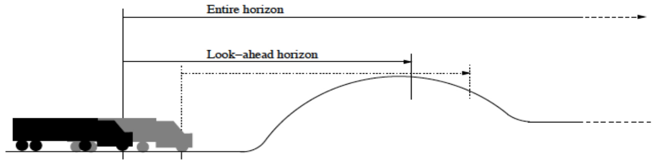
## Receding Horizon Cruise Control for Single Vehicle




Hellström, 2007

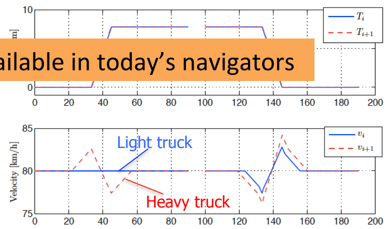
Adjust driving force to **minimize fuel consumption based on road topology** info:

The total fuel consumption over time $T$ is:

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

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

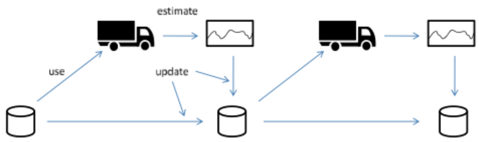
$$m_t \frac{\mathrm{d}v}{\mathrm{d}t} = F_{eng} - F_b - F_{ad}(v,d) - F_r(\alpha) - F_g(\alpha)$$
$$= F_{eng} - F_b - \frac{1}{2}\rho_a A_a c_D v^2 \phi(d)$$
$$- mgc_r \cos\alpha - mg\sin\alpha$$

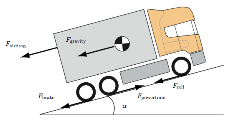


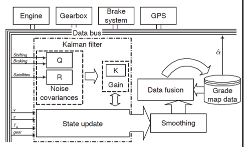

Implemented as velocity reference change in adaptive cruise controller

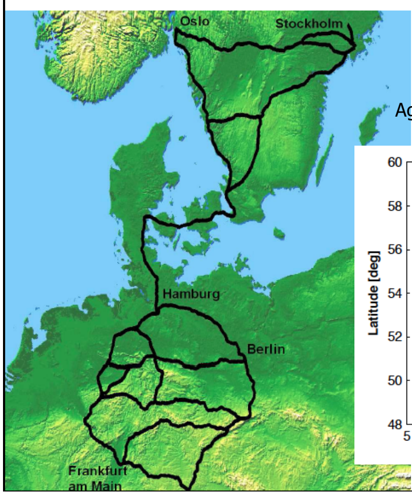
Alam et al., 2011

## Distributed Road Grade Estimation



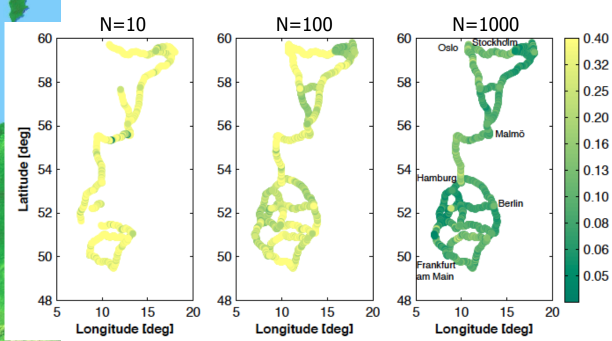





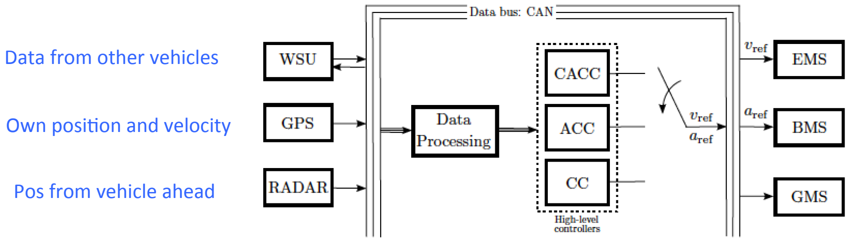

**RMS Road Grade Error**

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




Sahlholm, 2011

# Vehicle System Architecture

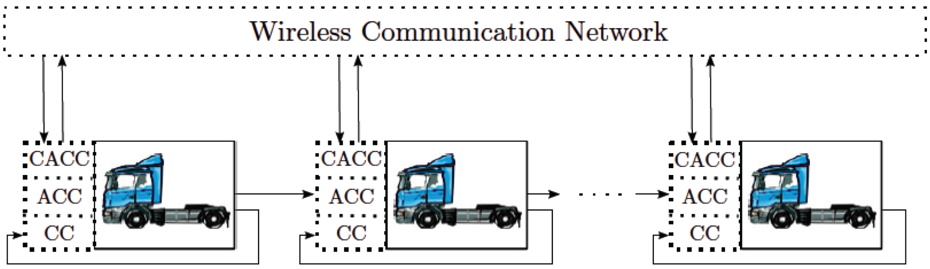



CACC – Collaborative adaptive cruise control
ACC – Adaptive cruise control
CC – Cruise control

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

Alam et al., 2014

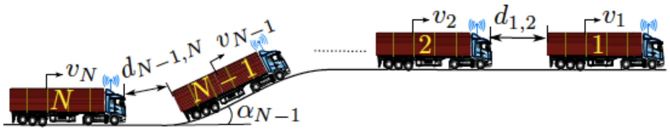
# Platoon System Architecture




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

Alam et al., 2014

# Collaborative Adaptive Cruise Control

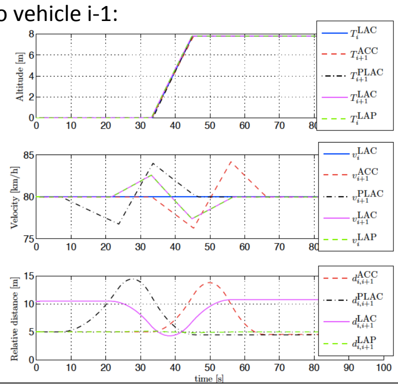


- How to jointly minimize fuel consumption for a platoon of vehicles?
  - Keep small relative distances *vs.* close to individual optimal trajectories?
  - Uphill and downhill segments; heavy and light vehicles

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

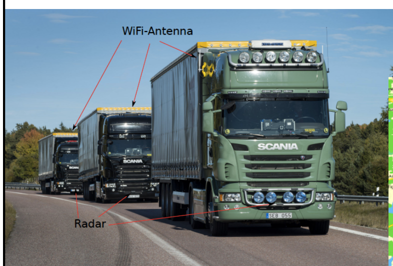
$$\frac{\mathrm{d}d_{i-1,i}}{\mathrm{d}t} = v_{i-1} - v_i$$

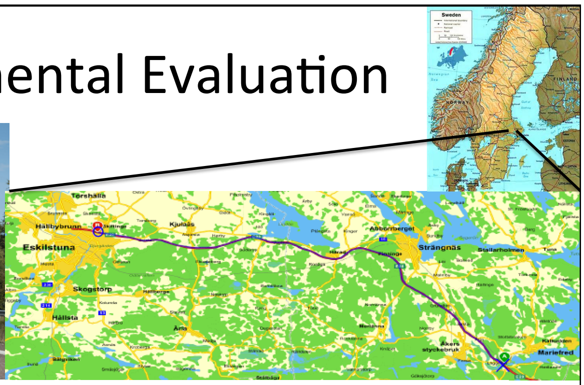
$$\begin{aligned} \mathrm{m}_{t_i}\frac{\mathrm{d}v_i}{\mathrm{d}t} &= F_{\text{engine}}(\delta_i,\omega_{e_i}) - F_{\text{brake}} - F_{\text{air drag}}(v_i,d_{i-1,i}) \\ &\quad - F_{\text{roll}}(\alpha_i) - F_{\text{gravity}}(\alpha_i) \\ &= \mathrm{k}_i^{\mathrm{e}} T_e(\delta_i,\omega_{e_i}) - F_{\text{brake}}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

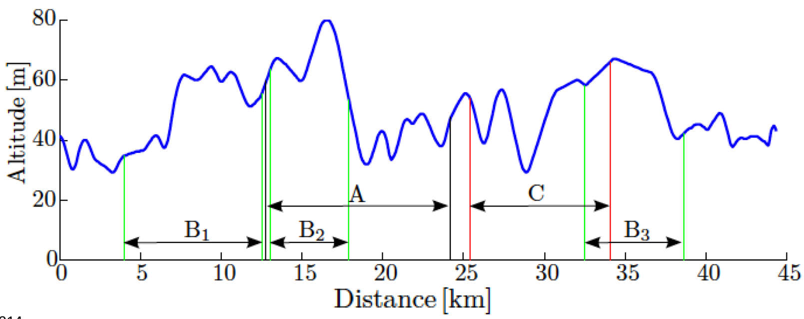



Alam et al., 2013

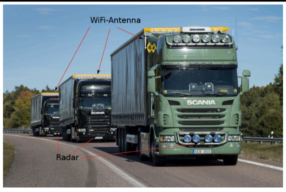
# Experimental Evaluation



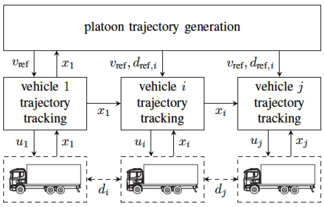

Alam, 2014

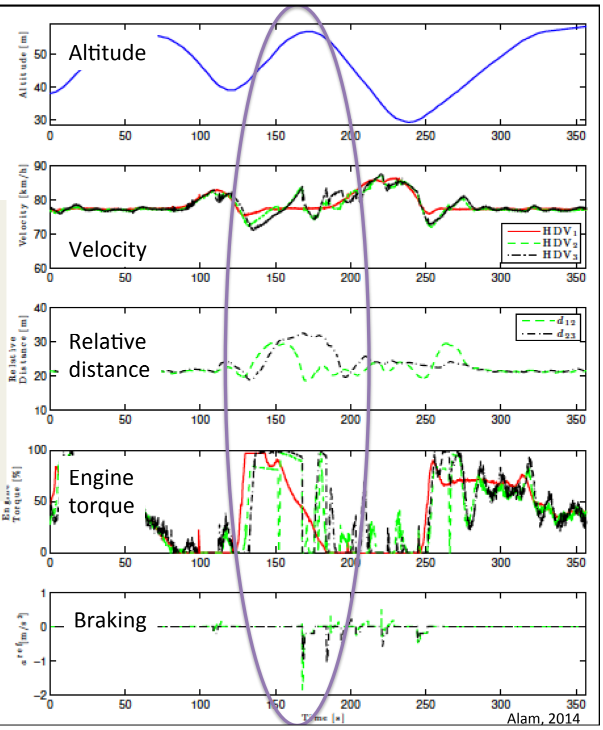



Hilly roads generate platoon **disturbances**

May impose fuel-inefficient braking commands

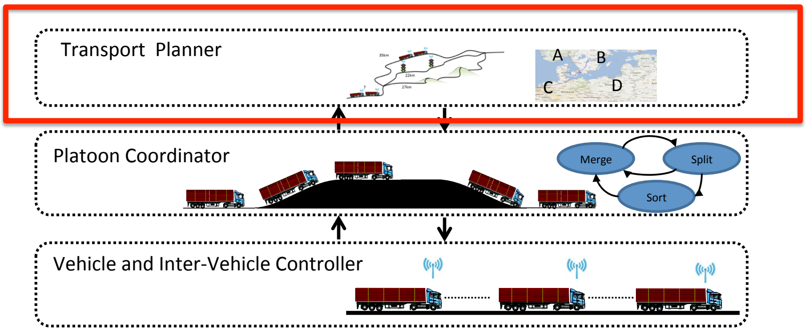
Compensated by **feedforward** communication of road topology and vehicle commands




Alam, 2014

# Functional Architecture for Goods Transport




Alam et al., 2012

# Outline

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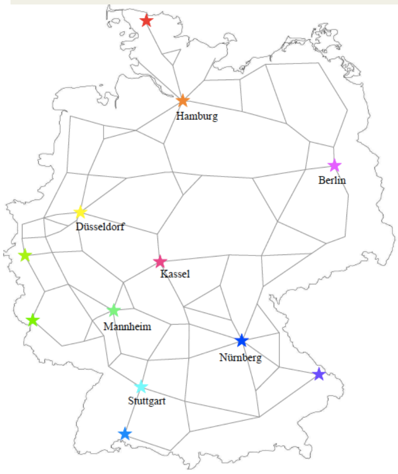
# When and where to create platoons?

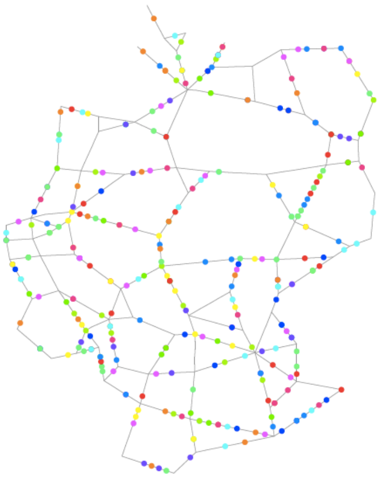
**Goal:** Maximize total amount of platooning
with limited intervention in vehicle speed and route



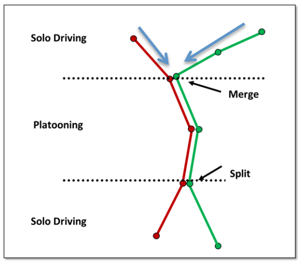

Larson et al., 2013

# Platoon merge and split

Heavy-duty vehicle traffic without platooning



Merge and split platoons at highway intersections

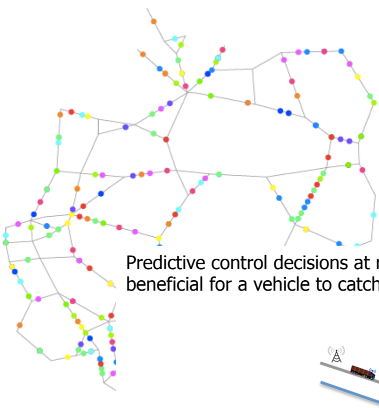



Only vehicles that are relatively close in space and time platoon

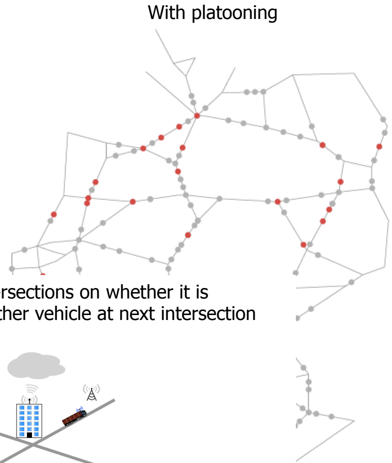
Larson et al., 2013

# Distributed optimization of platooning

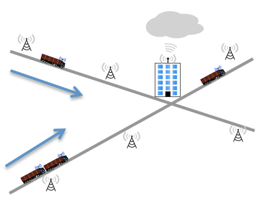
Heavy-duty vehicle traffic without platooning



With platooning

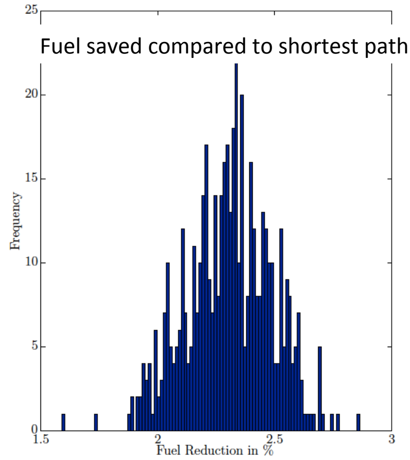


Predictive control decisions at road intersections on whether it is beneficial for a vehicle to catch up another vehicle at next intersection

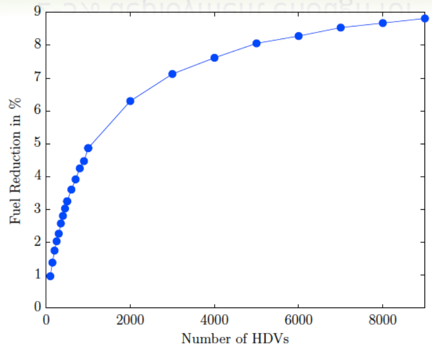


Larson et al., 2013

# Numerical evaluations



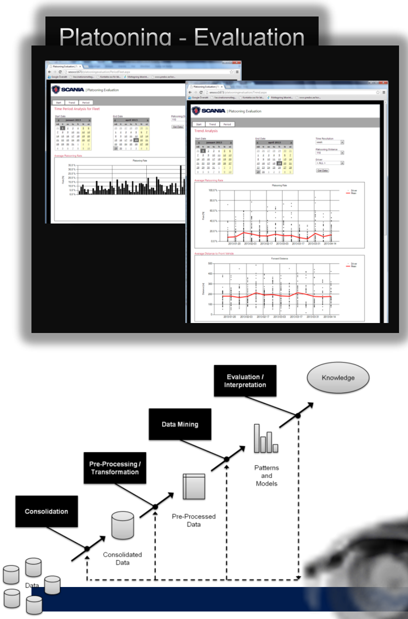

**2-5% deployment enough for substantial benefit**

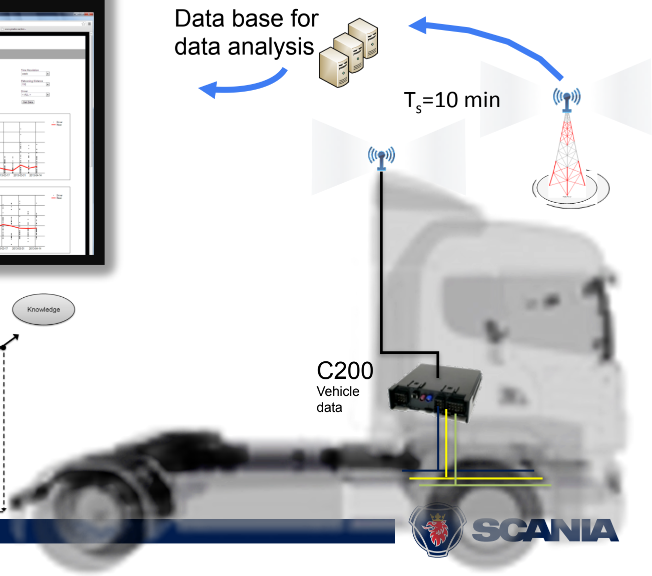



- German road network with 300 trucks
- Random starting points and destinations
- 500 experiments

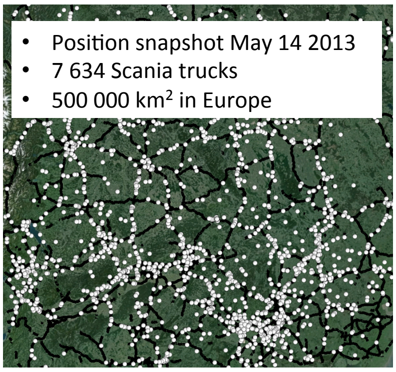
Larson et al., 2013

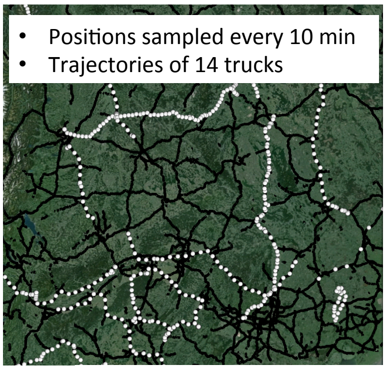
# Infrastructure for data collection



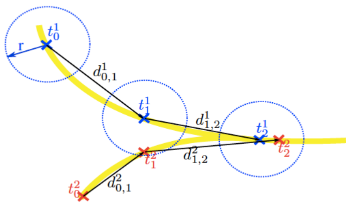



# Feasibility Study Based on Real Truck Data



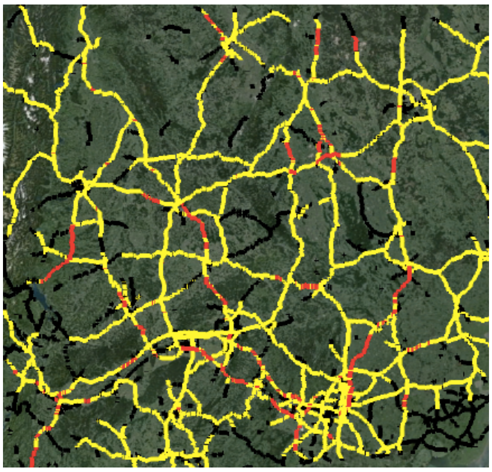

- 875 long-haulage trucks over European region
- Trucks close in time and space (<r m) could adjust speed to platoon and then save 10% fuel during platooning
- Benefits:
  - r = 0.2 km: 78 trucks platooned, 0.16% savings
  - r = 1 km: 241 trucks platooned, 0.38% savings
  - r = 5 km: 778 trucks platooned, 1.2% savings




Larson et al., 2013

# Spontaneous vs Coordinated Platooning

Paths of 1 773 trucks
Trucks within 100 m from another truck

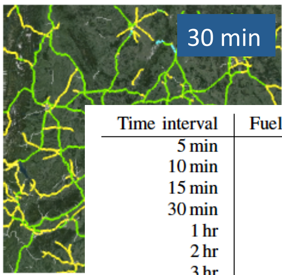


Liang et al., 2014

# 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

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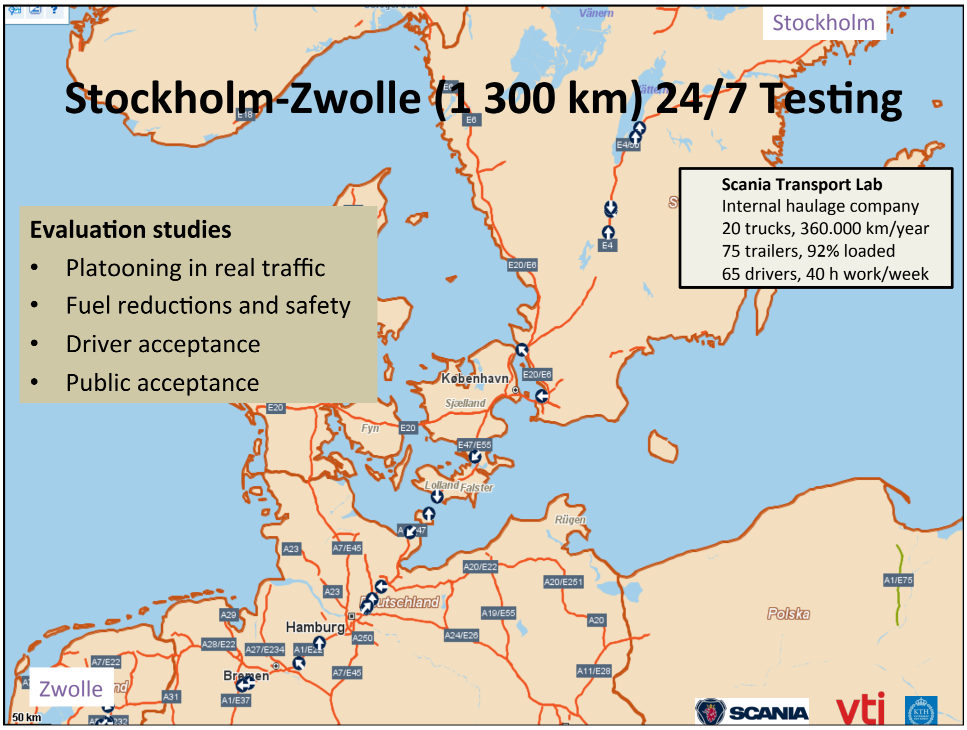


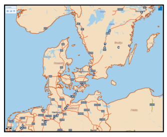

# Stockholm-Zwolle (1 300 km) 24/7 Testing

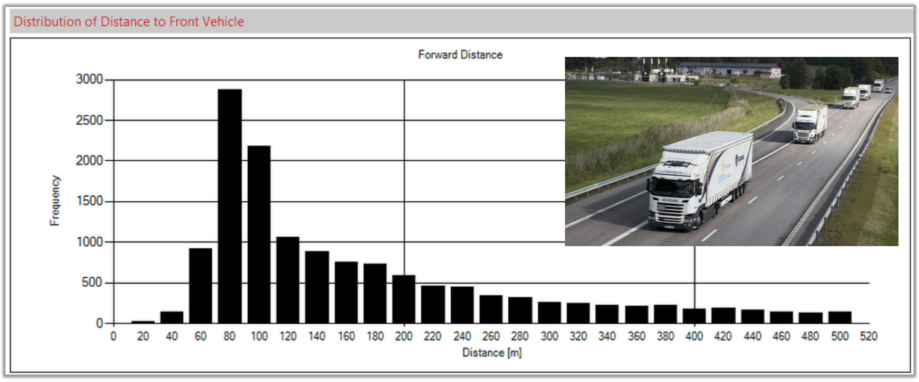
**Evaluation studies**

- 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?

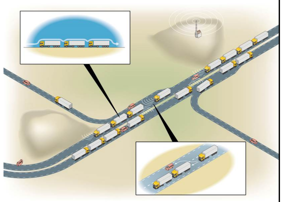




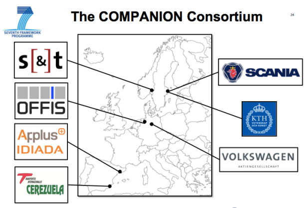

- Jan-Apr 2013 experimental evaluation
- Drivers in the loop with advanced ACC (radar etc)
- Encouraged but not enforced to platoon
- Notable fuel reductions

**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