# Optimizing Cooperative Driving for Road Goods Transportation

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# Acknowledgments

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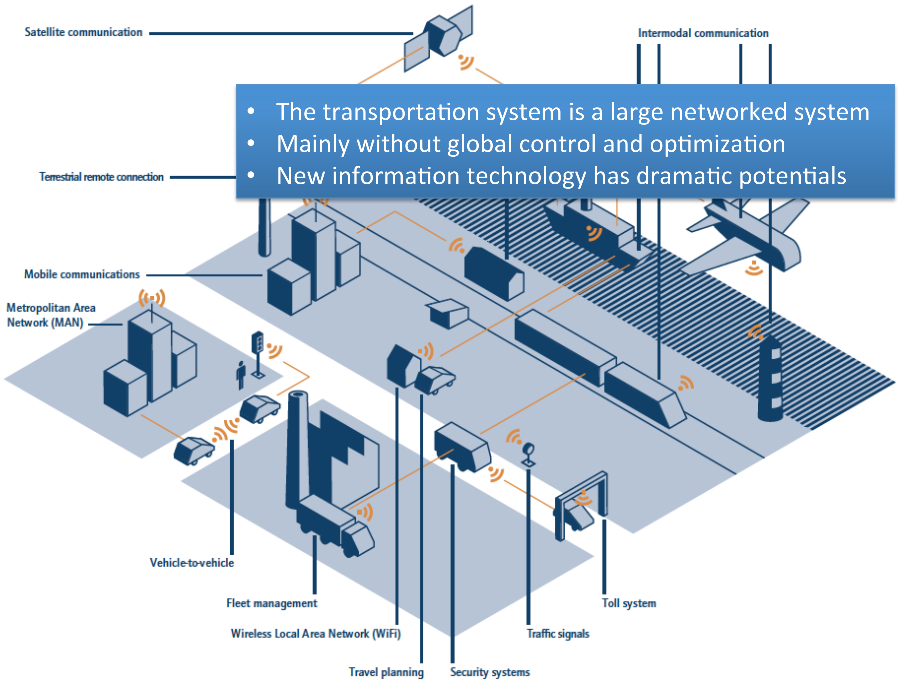
Farhad Farokhi
Jeff Larson
Håkan Terelius
Ather Gattami

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



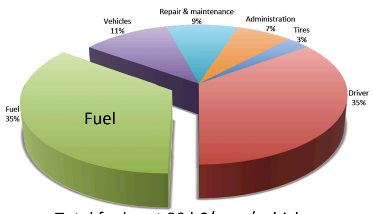

Cyber-Physical Systems Roadmap, German National Academy of Science and Engineering, 2011

# Demands from Goods Road Transportation

- 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

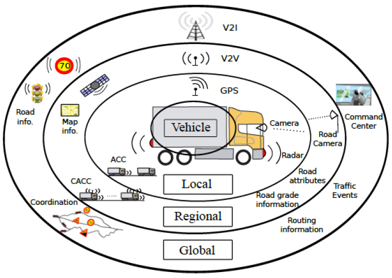
*Schittler, 2003; Scania, 2012*

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

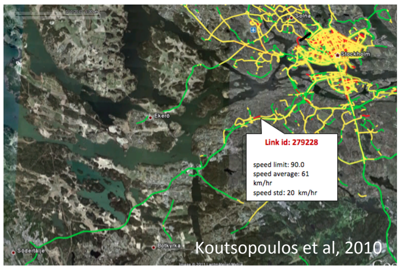
*Dr. H. Ludanek, CTO, Scania*

# Technology Push

**Sensor and commununication technology**




**Real-time traffic information**




**Vehicle platooning and 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

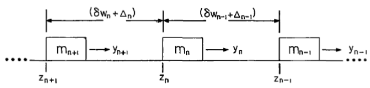
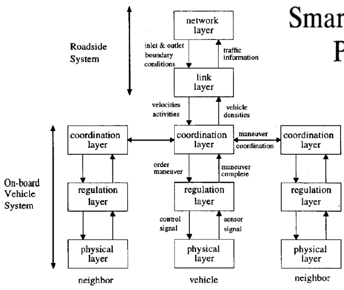



Fig. 1. Vehicles moving in a string.

PATH platoon demo San Diego 1997



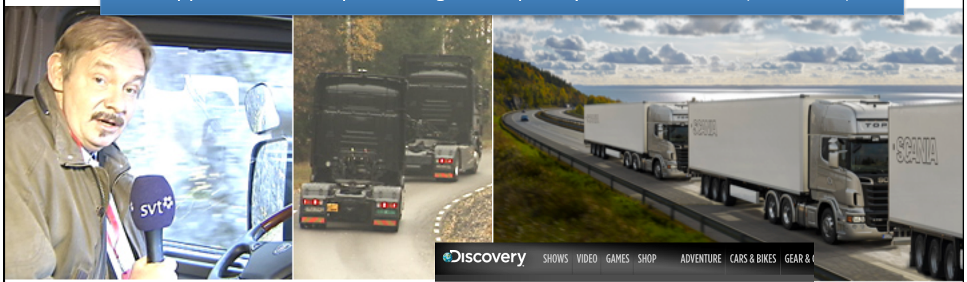

IEEE TRANSACTIONS ON AUTOMATIC CONTROL, VOL. 38, NO. 2, FEBRUARY 1993

Smart Cars on Smart Roads: Problems of Control

Pravin Varaiya, *Fellow, IEEE*

# Heavy-Duty Vehicle Platooning

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



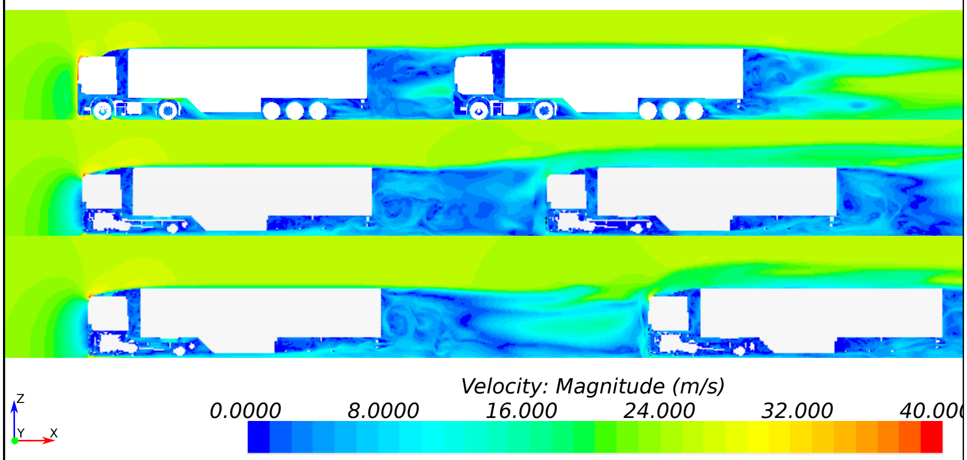


PhD student Assad Alam on *Discovery Channel* (Jan, 2012)

Zwolle, Netherlands, Feb 9, 2015

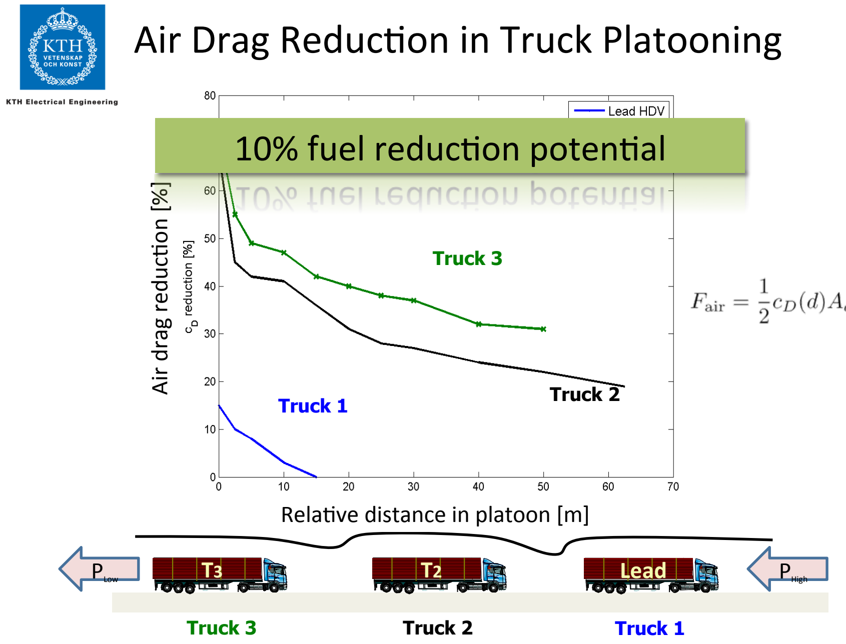
Demo for Dutch Minister of Infrastructure and the Environment Ms Schultz van Haegen

# The Physics




Liang (2014)

## Air Drag Reduction in Truck Platooning




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

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

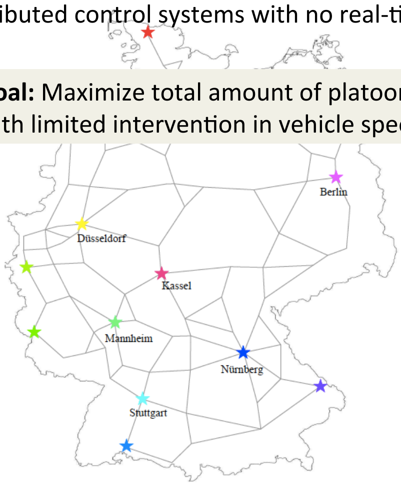
# Outline

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

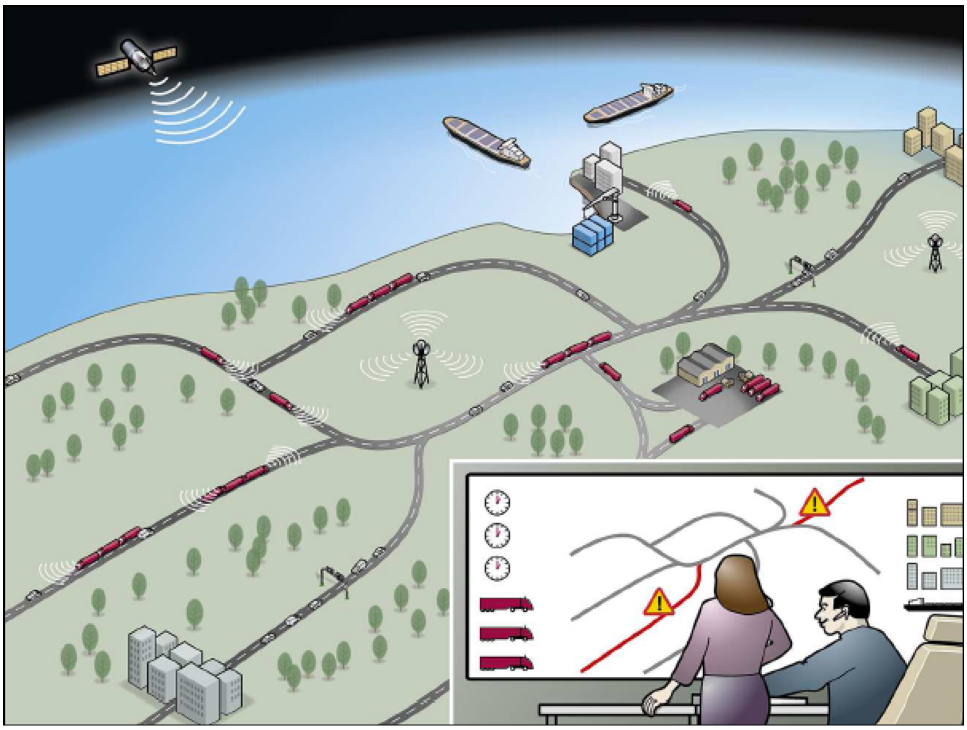
# Fuel-Optimized Goods Transport

- Goods transported between cities over highway network
- 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

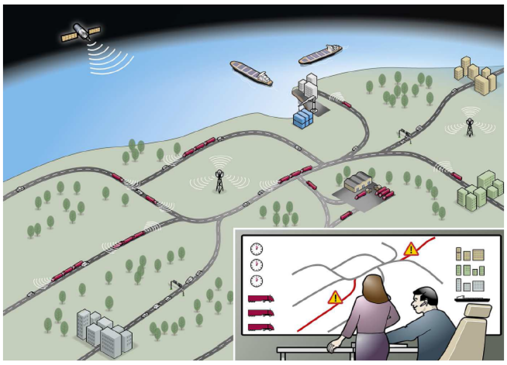
**Goal:** Maximize total amount of platooning
with limited intervention in vehicle speed and route

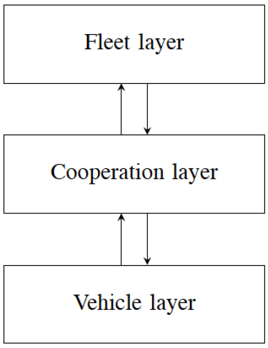



Larson et al., 2013



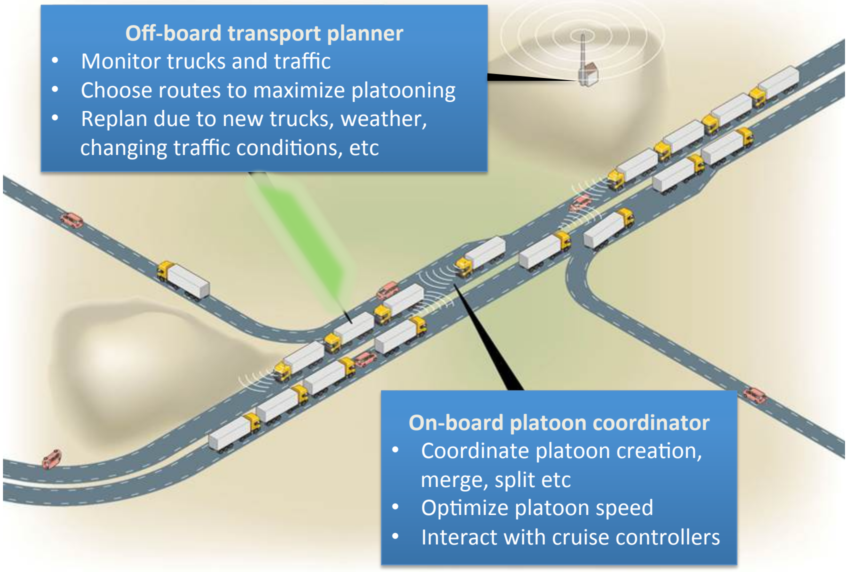
# Functional Architecture for Goods Transport






Alam et al., 2012

## Global and Local Control Systems

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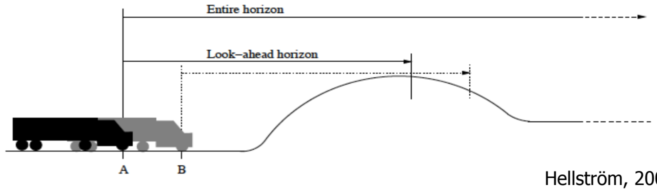
# Receding Horizon Cruise Control for Single Vehicle




Hellström, 2007

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

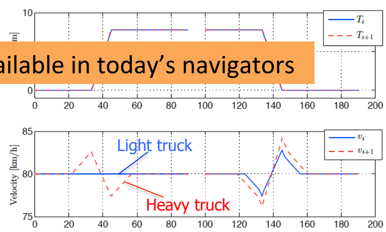
The total fuel consumption over time $T$ is:

$$f_t = \int^T \frac{\delta(t)}{} \ldots \Big( m \frac{dv(t)}{} + \frac{1}{} \ldots \Big)$$

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

$$+ mgc_r \cos\alpha + mg \sin\alpha \Big) \, dt \qquad (3)$$

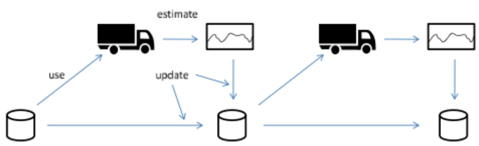
$$m_t \frac{dv}{dt} = F_{eng} - F_b - F_{ad}(v, d) - F_r(\alpha) - F_g(\alpha)$$
$$= F_{eng} - F_b - \frac{1}{2}\rho_a A_a c_D v^2 \phi(d)$$
$$- mgc_r \cos\alpha - mg \sin\alpha$$

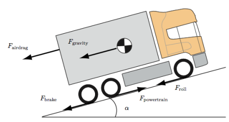


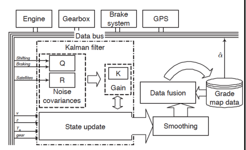

Implemented as velocity reference change in adaptive cruise controller

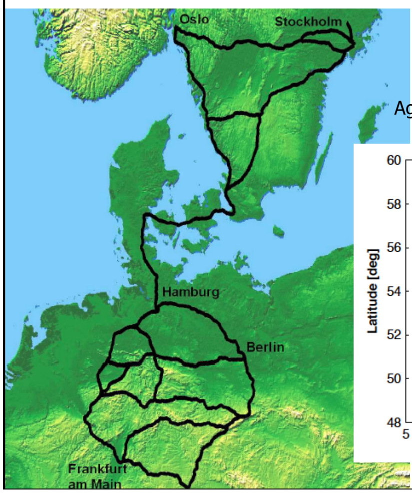
Alam et al., 2011

# Distributed Road Grade Estimation



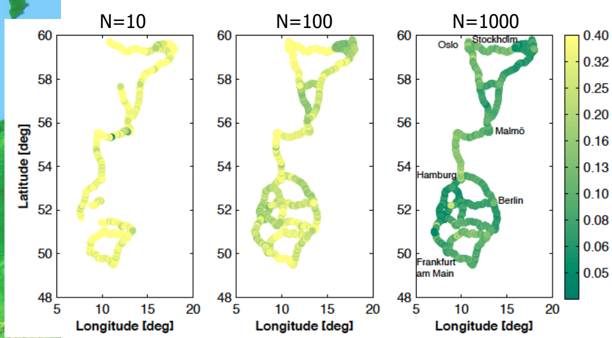






**RMS Road Grade Error**

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



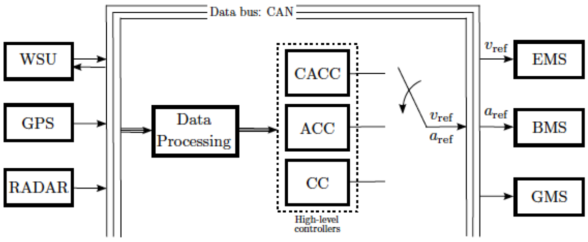

Sahlholm, 2011

# Vehicle System Architecture

Data from other vehicles

Own position and velocity

Pos from vehicle ahead

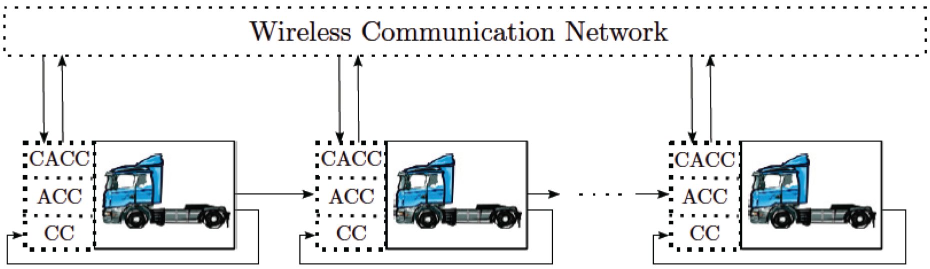



CACC – Collaborative adaptive cruise control
ACC – Adaptive cruise control
CC – Cruise control

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

Alam et al., 2014

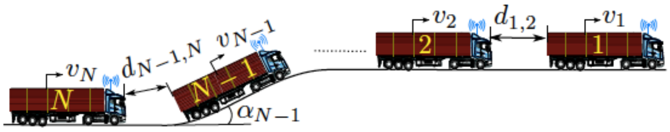
# Platoon System Architecture




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

Alam et al., 2014

## Collaborative Adaptive Cruise Control

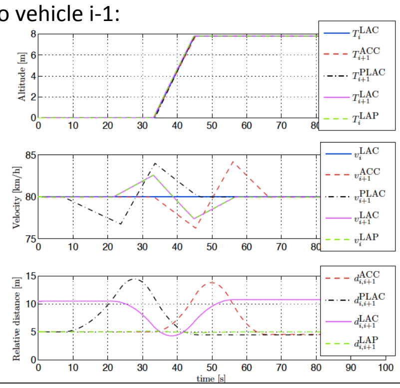



- How to jointly minimize fuel consumption for a platoon of vehicles?
  - Keep small relative distances *vs.* close to individual optimal trajectories?
  - Uphill and downhill segments; heavy and light vehicles

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

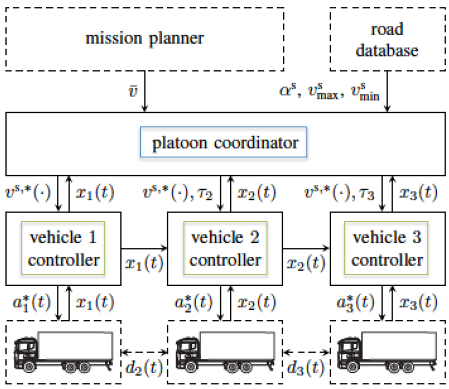
$$\frac{\mathrm{d}d_{i-1,i}}{\mathrm{d}t} = v_{i-1} - v_i$$

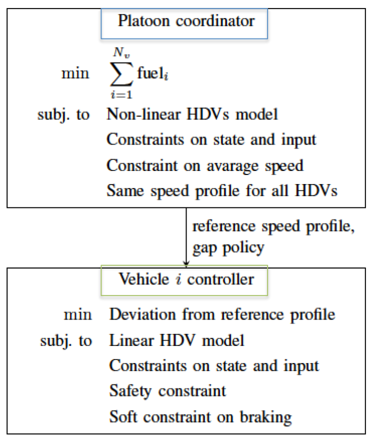
$$\begin{aligned} m_{t_i}\frac{\mathrm{d}v_i}{\mathrm{d}t} &= F_{\text{engine}}(\delta_i,\omega_{e_i}) - F_{\text{brake}} - F_{\text{air drag}}(v_i, d_{i-1,i}) \\ &\quad - F_{\text{roll}}(\alpha_i) - F_{\text{gravity}}(\alpha_i) \\ &= k_i^{e} T_e(\delta_i,\omega_{e_i}) - F_{\text{brake}} - k_i^{d} v_i^2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



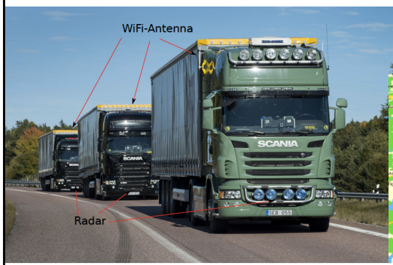

Alam et al., 2013

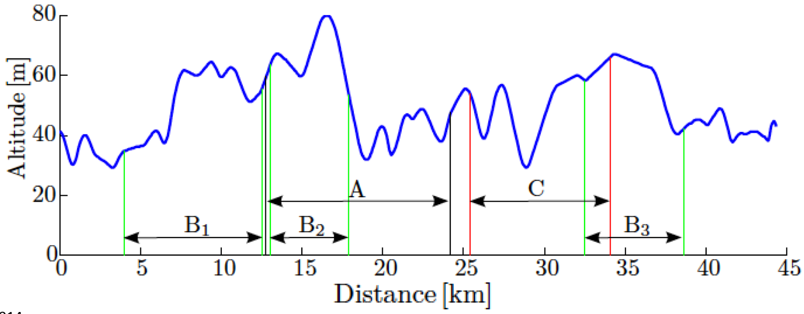
## Look-ahead Control for Fuel-efficient and Safe Vehicle Platooning



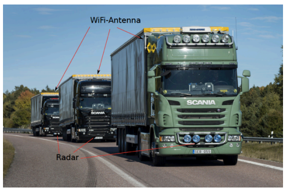
# Experimental Evaluation

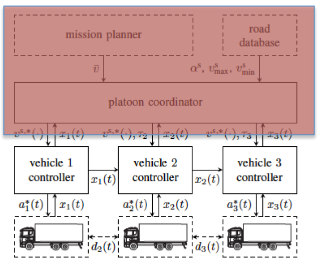


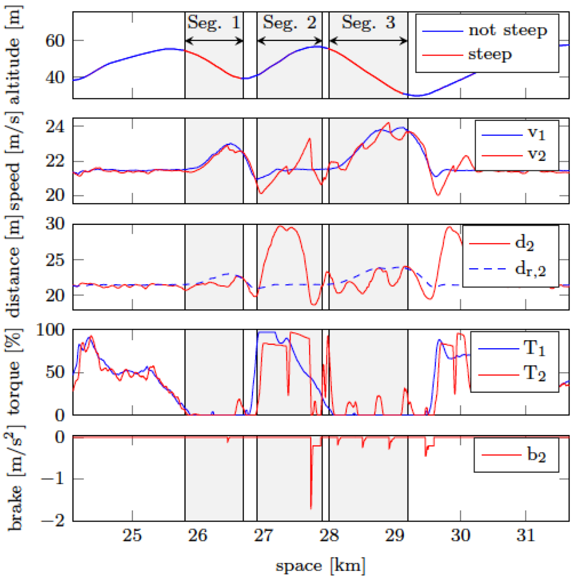




Alam, 2014

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

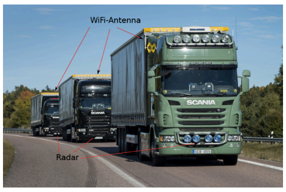


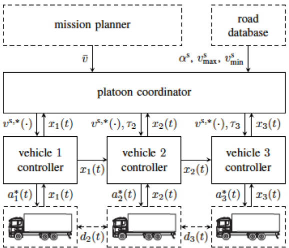



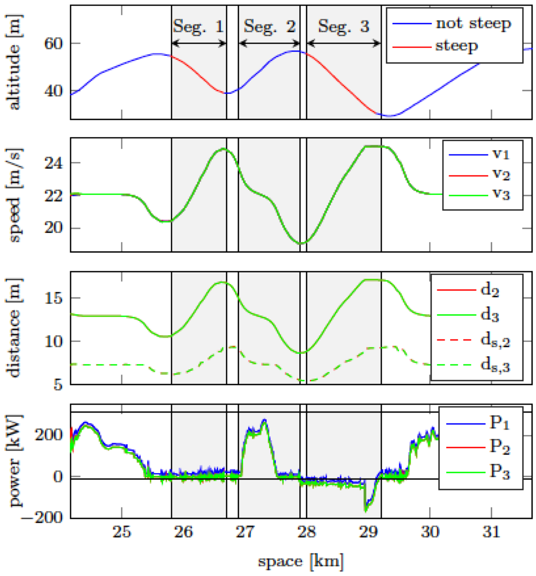




Turri et al., 2015

# Simulation **with** Platoon Coordinator and Look-ahead Road Grade Information

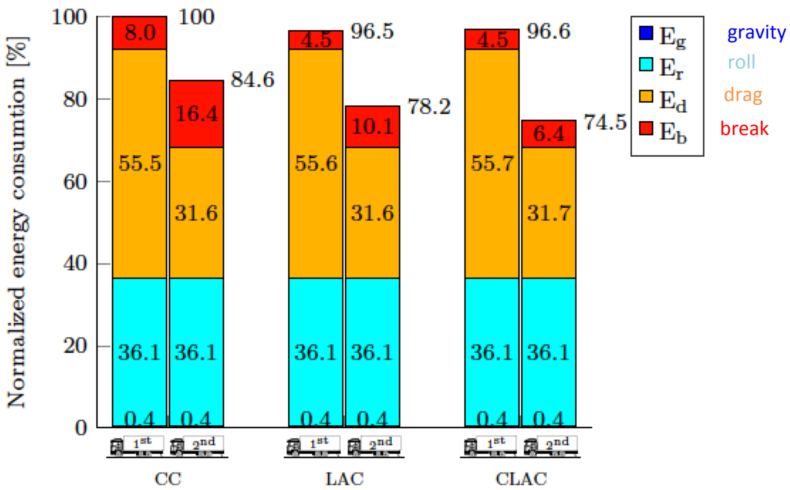



Turri et al., 2015

# 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

# Outline

- Introduction
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- Optimized transport planner
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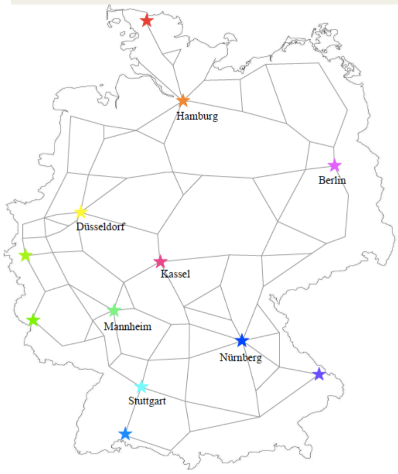
- Conclusions

# When and where to create platoons?

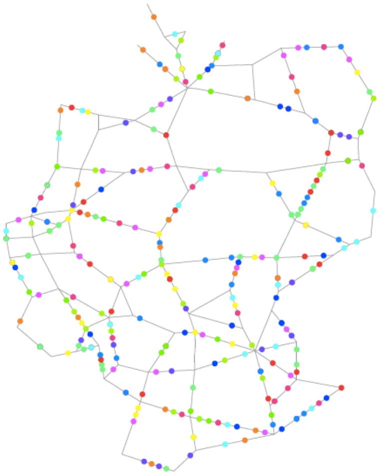
**Goal:** Maximize total amount of platooning
with limited intervention in vehicle speed and route



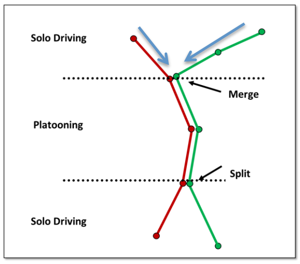

Larson et al., 2013

# Platoon merge and split

Heavy-duty vehicle traffic without platooning



Merge and split platoons at highway intersections



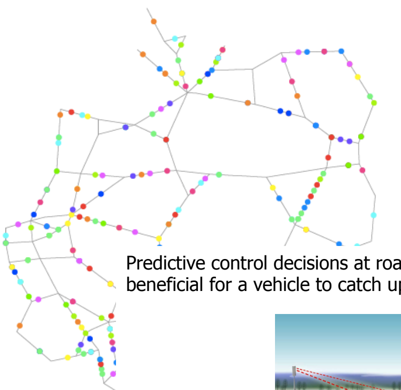

Only vehicles that are relatively close in space and time platoon

Larson et al., 2013

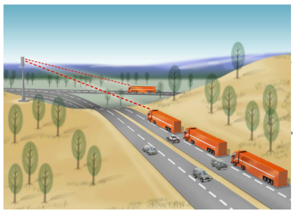
# Distributed optimization of platooning

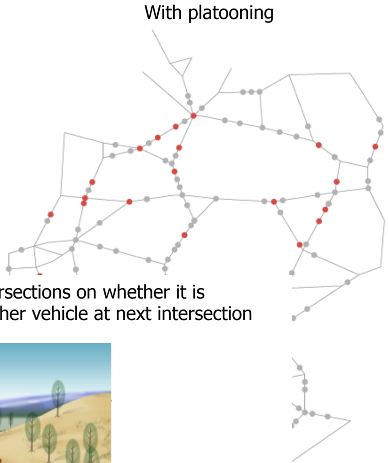
Heavy-duty vehicle traffic without platooning

With platooning



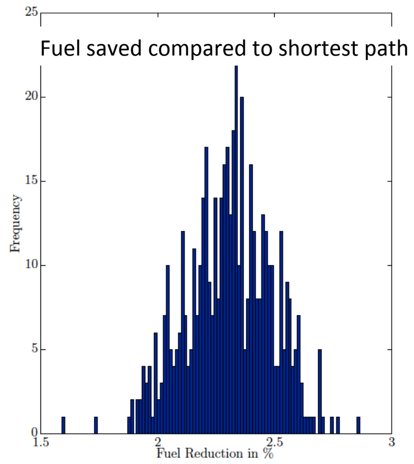
Predictive control decisions at road intersections on whether it is beneficial for a vehicle to catch up another vehicle at next intersection



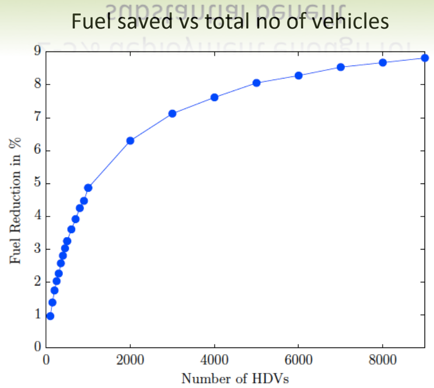


Larson et al., 2013

# Numerical evaluations



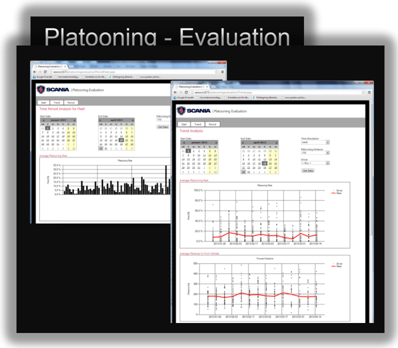

**2-5% deployment enough for substantial benefit**

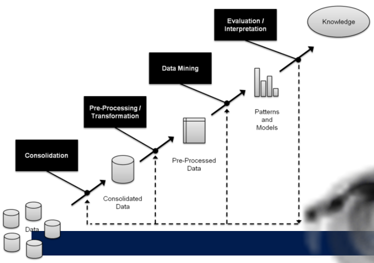


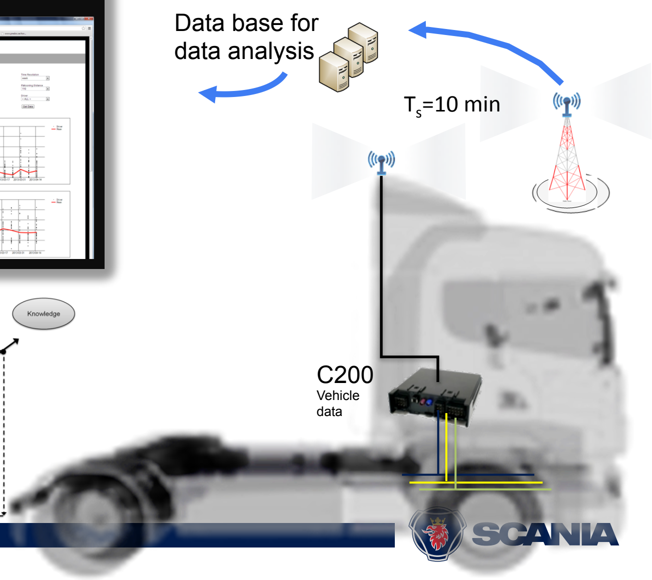

- German road network with 300 trucks
- Random starting points and destinations
- 500 experiments

Larson et al., 2013

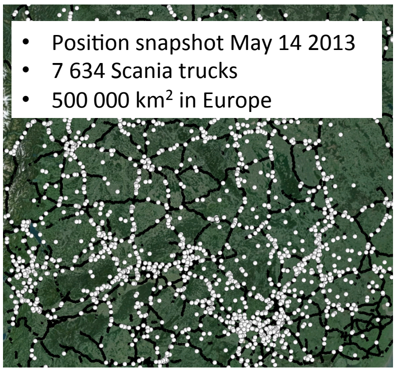
# Infrastructure for data collection

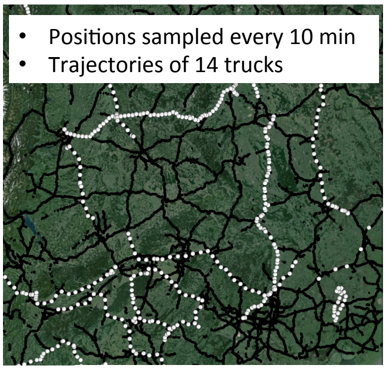


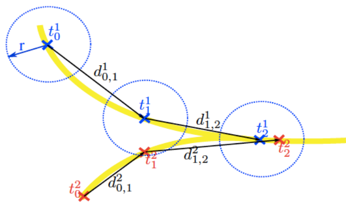



# Feasibility Study Based on Real Truck Data



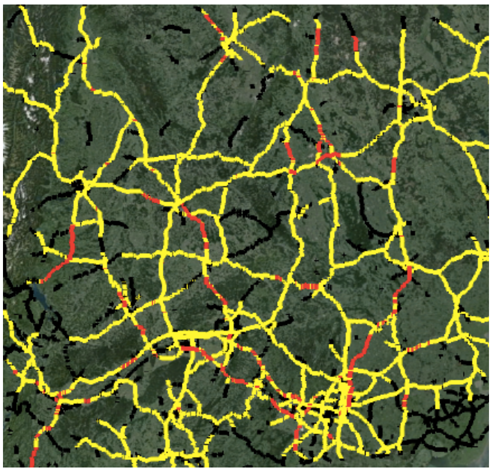

- 875 long-haulage trucks over European region
- Trucks close in time and space (<r m) could adjust speed to platoon and then save 10% fuel during platooning
- Benefits:
  - r = 0.2 km: 78 trucks platooned, 0.16% savings
  - r = 1 km: 241 trucks platooned, 0.38% savings
  - r = 5 km: 778 trucks platooned,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



Larson et al., 2013

# Spontaneous vs Coordinated Platooning

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

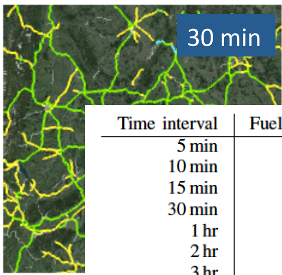


Liang et al., 2014

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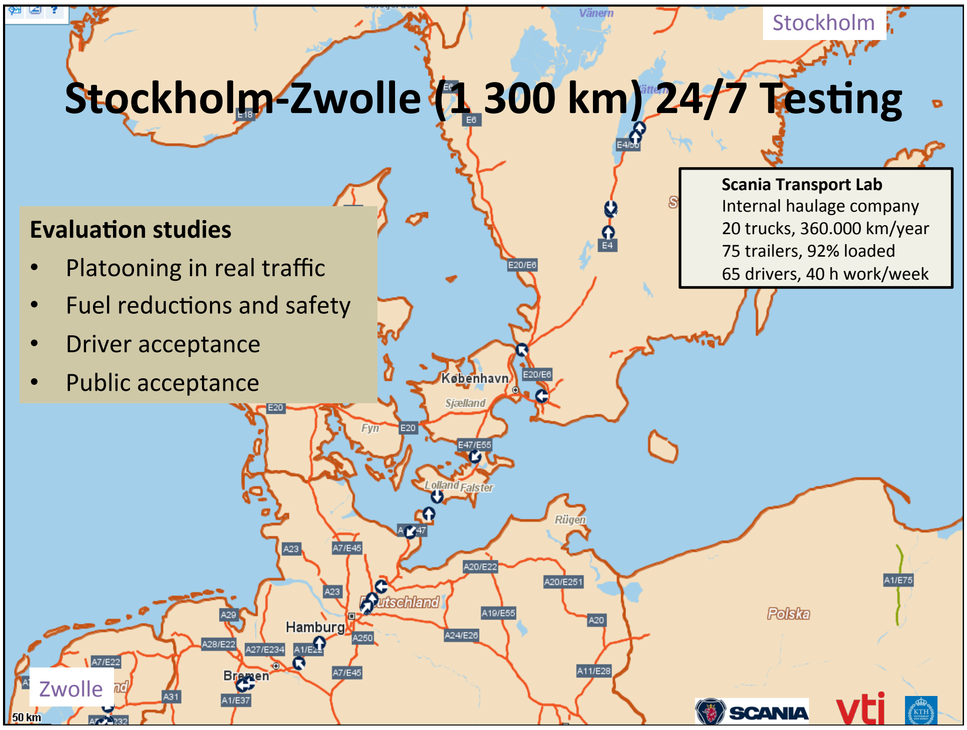
# Stockholm-Zwolle (1 300 km) 24/7 Testing

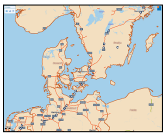


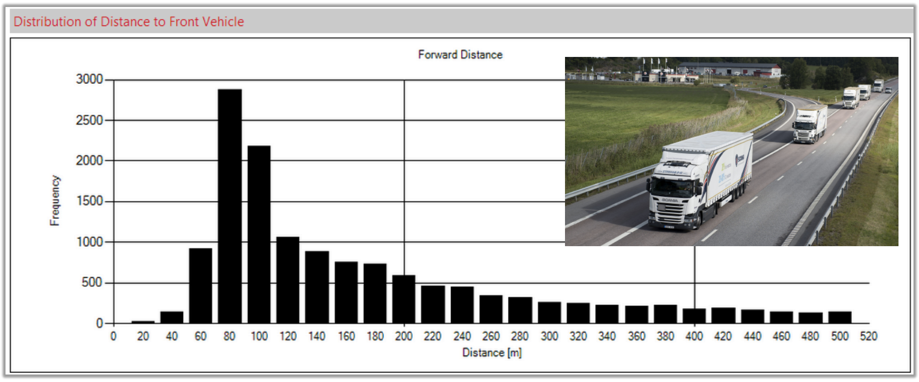

**Evaluation studies**

- 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

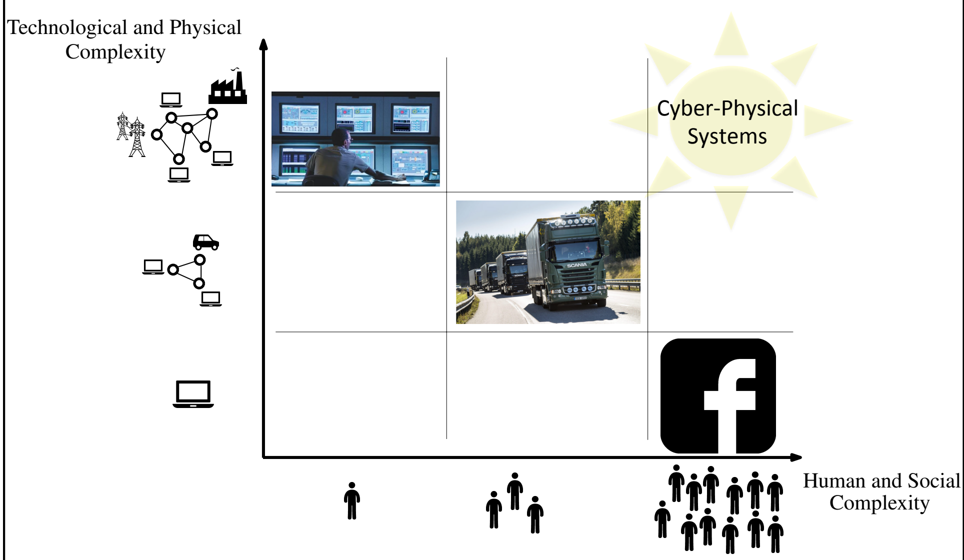
# How willing are drivers to platoon?



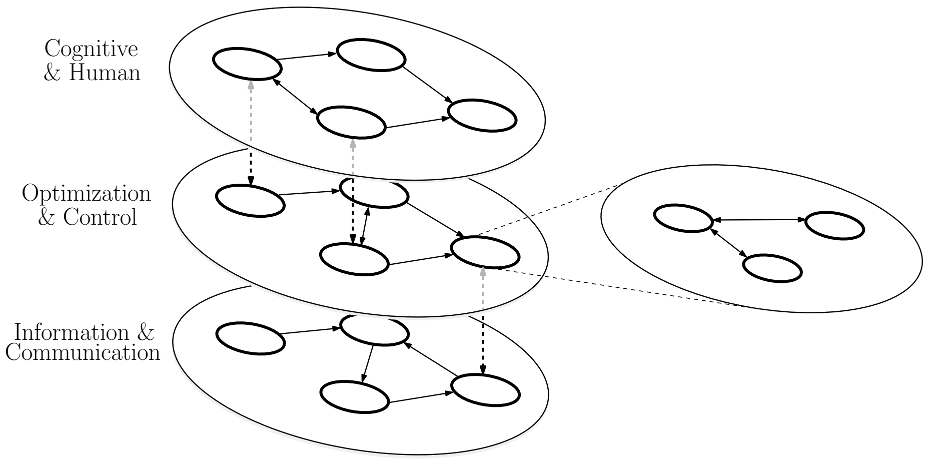


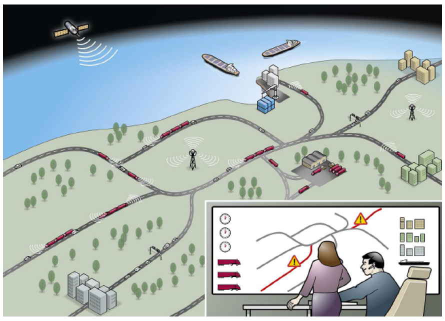

- Jan-Apr 2013 experimental evaluation
- Drivers in the loop with advanced ACC (radar etc)
- Encouraged but not enforced to platoon
- Notable fuel reductions

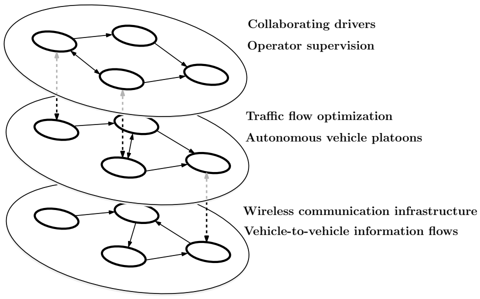
**Scania Transport Lab**
Internal haulage company
20 trucks, 360.000 km/year
75 trailers, 92% loaded
65 drivers, 40 h work/week



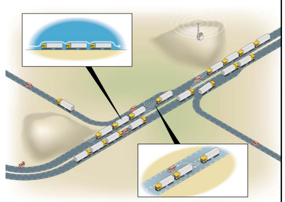

# Multi-Layer Dynamic Network Models



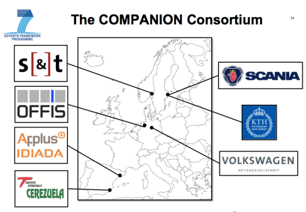





# Conclusions



- **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**

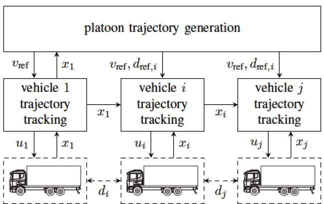


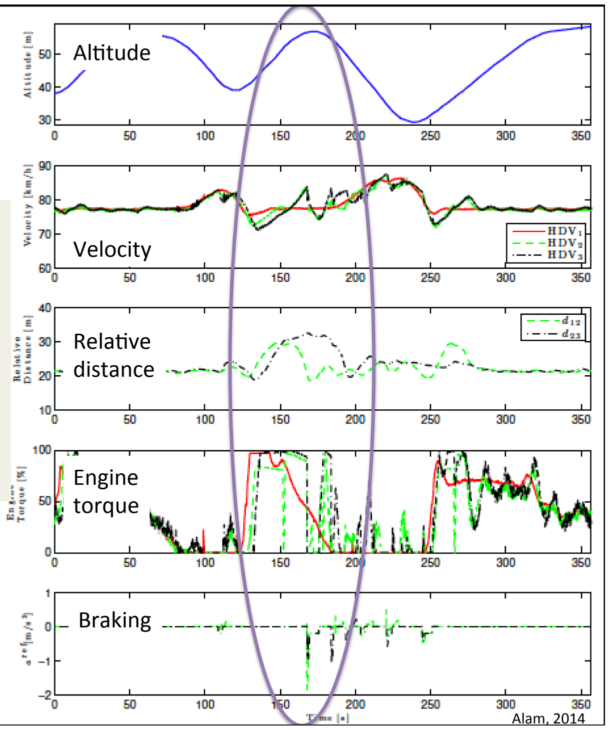

http://people.kth.se/~kallej


Hilly roads generate platoon **disturbances**

May impose fuel-inefficient braking commands

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

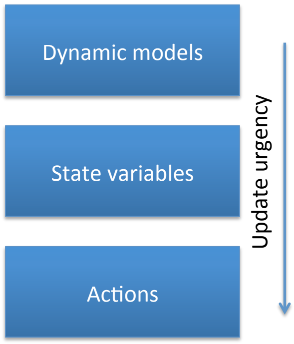


# Information Propagation in Platoons

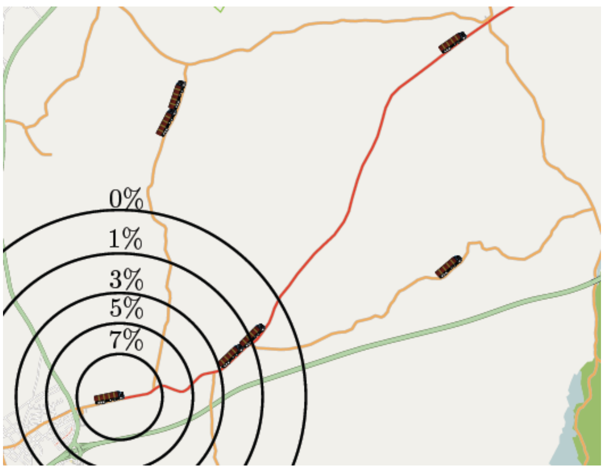
- Platooning vehicles need common information on
  - **Dynamics:** vehicle mass, platoon references etc
  - **States:** velocity, acceleration etc
  - **Actions:** breaking, disturbances etc
- Varying urgency and time constants
- Existing vehicle-to-vehicle communication is based on broadcasting protocols for traffic warnings etc

- How synchronize information in a network with guaranteed performance despite changing topology?





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




Liang et al., 2013

# The role of plant model information


Inter-vehicle distances $d_{12}$ and $d_{23}$ are locally controlled through vehicle torques $u_i$

$$\begin{bmatrix} \dot{v}_1(t) \\ \dot{d}_{12}(t) \\ \dot{v}_2(t) \\ \dot{d}_{23}(t) \\ \dot{v}_3(t) \end{bmatrix} = \begin{bmatrix} -\varrho_1/m_1 & 0 & 0 & 0 & 0 \\ 1 & 0 & -1 & 0 & 0 \\ 0 & 0 & -\varrho_2/m_2 & 0 & 0 \\ 0 & 0 & 1 & 0 & -1 \\ 0 & 0 & 0 & 0 & -\varrho_3/m_3 \end{bmatrix} \begin{bmatrix} v_1(t) \\ d_{12}(t) \\ v_2(t) \\ d_{23}(t) \\ v_3(t) \end{bmatrix} + \begin{bmatrix} b_1/m_1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & b_2/m_2 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & b_3/m_3 \end{bmatrix} \begin{bmatrix} u_1(t) \\ u_2(t) \\ u_3(t) \end{bmatrix} + \begin{bmatrix} w_1(t) \\ w_2(t) \\ w_3(t) \\ w_4(t) \\ w_5(t) \end{bmatrix}$$

How does knowledge of the vehicle mass $m_i$ influence performance?

# Motivating Example Revisited


- Regulating inter-vehicle distances $d_{12}$ and $d_{23}$

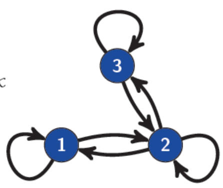
$$\begin{bmatrix} \dot{v}_1(t) \\ \dot{d}_{12}(t) \\ \dot{v}_2(t) \\ \dot{d}_{23}(t) \\ \dot{v}_3(t) \end{bmatrix} = \begin{bmatrix} -\varrho_1/m_1 & 0 & 0 & 0 & 0 \\ 1 & 0 & -1 & 0 & 0 \\ 0 & 0 & -\varrho_2/m_2 & 0 & 0 \\ 0 & 0 & 1 & 0 & -1 \\ 0 & 0 & 0 & 0 & -\varrho_3/m_3 \end{bmatrix} \begin{bmatrix} v_1(t) \\ d_{12}(t) \\ v_2(t) \\ d_{23}(t) \\ v_3(t) \end{bmatrix} + \begin{bmatrix} b_1/m_1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & b_2/m_2 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & b_3/m_3 \end{bmatrix} \begin{bmatrix} u_1(t) \\ u_2(t) \\ u_3(t) \end{bmatrix} + \begin{bmatrix} w_1(t) \\ w_2(t) \\ w_3(t) \\ w_4(t) \\ w_5(t) \end{bmatrix}$$

$$z(t) = \begin{bmatrix} d_{12}(t) & d_{23}(t) & u_1(t) & u_2(t) & u_3(t) \end{bmatrix}^\top$$

- Find a saddle point of $J(\Gamma, \alpha) = \|T_{zw}(s; \Gamma, \alpha)\|_\infty$ when $\alpha = [m_1\, m_2\, m_3]^\top \in [0.5, 1.0]^3$ and $\Gamma$ belongs to the set of polynomials of $\alpha_i$, $i = 1, 2, 3$, up to the second order.

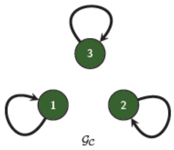
$$\inf_{\Gamma \in \mathcal{C}} \sup_{\alpha \in \mathcal{A}} J(\Gamma, \alpha) = \inf_{\Gamma \in \mathcal{C}} \sup_{\alpha \in \mathcal{A}} \|T_{zw}(s; \Gamma, \alpha)\|_\infty$$

$\mathcal{G}_\mathcal{K}$




Farokhi & J, 2013

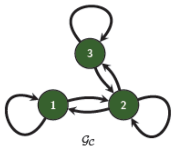
# Motivating Example Revisited




Control Design with Local Model Information

$$\max_{\alpha\in\mathcal{A}} \left\|T_{zw}\left(s;\Gamma^{\text{local}},\alpha\right)\right\|_\infty = 4.7905$$

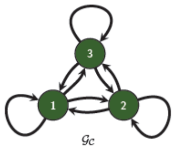
25.8%




Control Design with Limited Model Information

$$\max_{\alpha\in\mathcal{A}} \left\|T_{zw}\left(s;\Gamma^{\text{limited}},\alpha\right)\right\|_\infty = 3.5533$$

5.4%



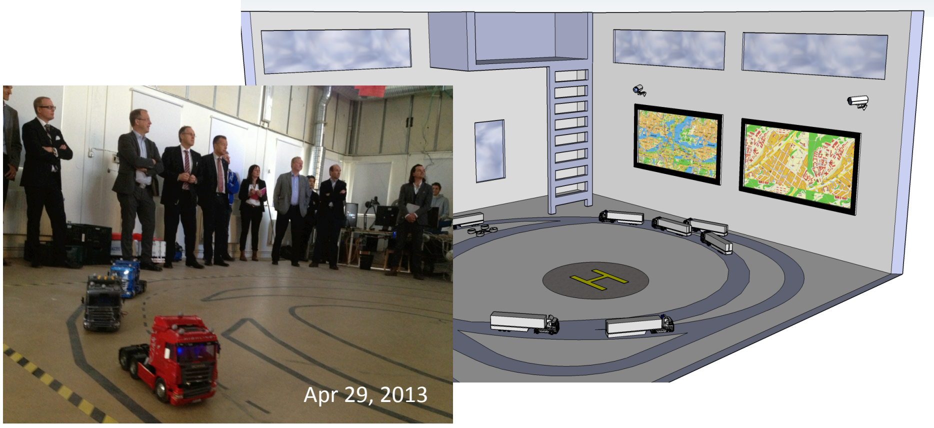

Control Design with Full Model Information

$$\max_{\alpha\in\mathcal{A}} \left\|T_{zw}\left(s;\Gamma^{\text{full}},\alpha\right)\right\|_\infty = 3.3596$$

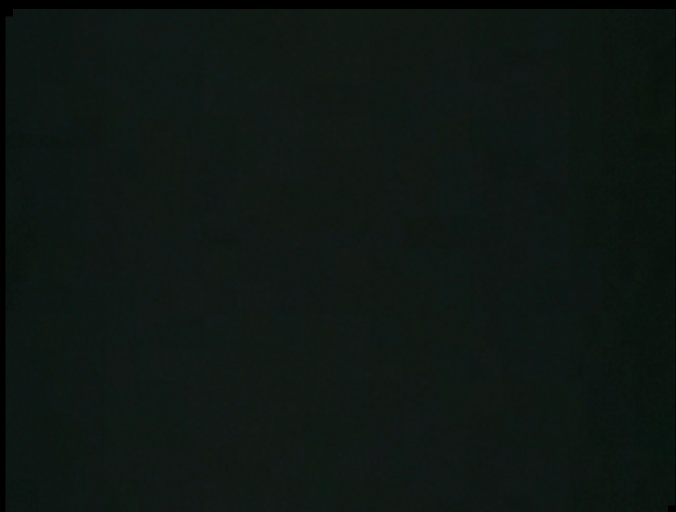
Farokhi & J, 2013

# Visualization and demonstration of future transportation in Smart Mobility Lab

- Autonomous toy trucks equipped with V2V and V2I communication
- Indoor GPS, real-time traffic information and dynamic road network
- Reach-out activities to industrial and political leadership, high school students etc



General Motors vision 76 years ago



“Automatic radio control”