Networked Control Challenges in Collaborative Road Freight Transport

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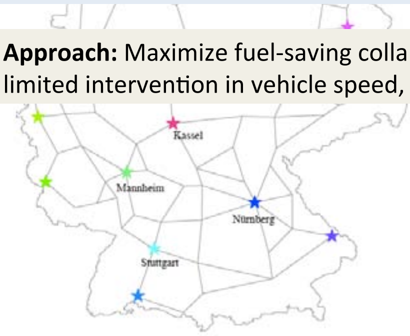
The Problem

How to efficiently transport goods between cities over a highway network?

Characteristics
- Large distributed control system with no real-time coordination today
- 2 000 0000 heavy trucks in EU (400 000 in Germany) over fixed road network
- A few large and many small fleet owners with heterogeneous truck fleets
- Tight delivery deadlines and high expectations on reliability

Approach: Maximize fuel-saving collaborations with limited intervention in vehicle speed, route, and timing



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)

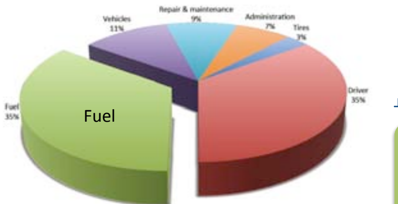
- 24% of long haulage trucks run empty
- 57% average load capacity

H. Ludanek, CTO, Scania (2014)

- Digital transformation of transport represent 2.9 tUSD value at stake 2017-2026
- Trucks correspond to 1.0 tUSD, relatively large due to high use and inefficiency

A. Mai, Dir. Connected Vehicle, Cisco (2016)

Life cycle cost for European heavy-duty vehicle



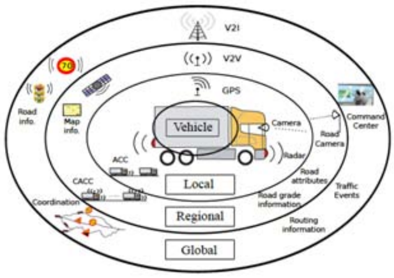
Total fuel cost 80 k€/year/vehicle

Schittler, 2003; Scania, 2012

Technology Push

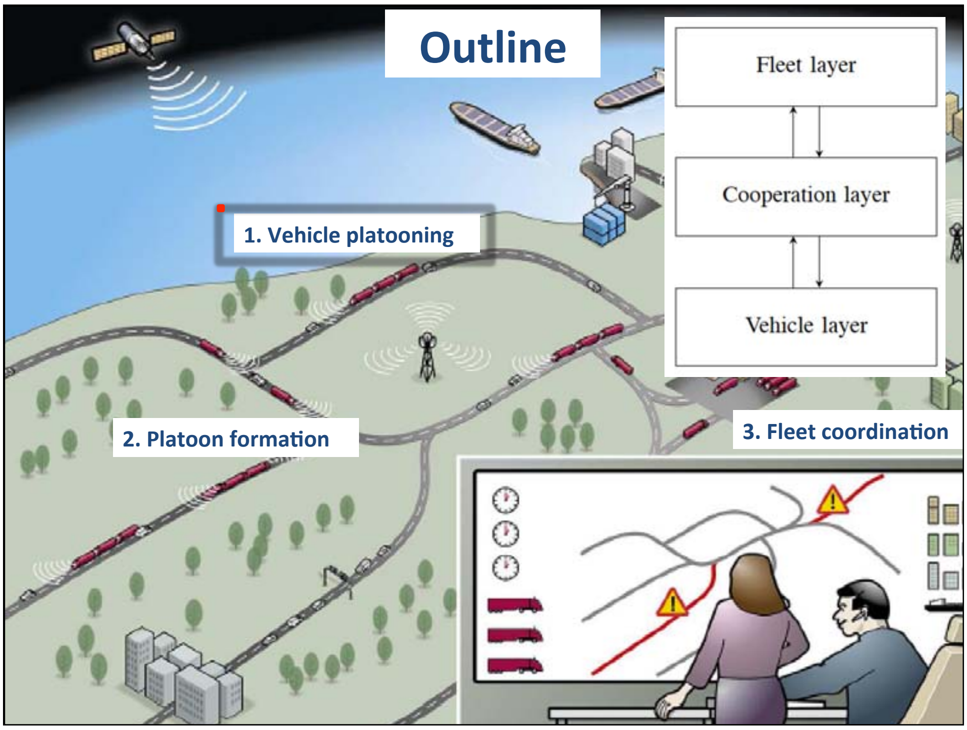
Real-time traffic information

Sensor and commununication technology



Electric highways

Vehicle platooning and 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

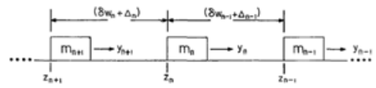


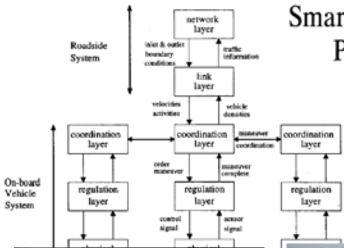
Fig. 1. Vehicles moving in a string.

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

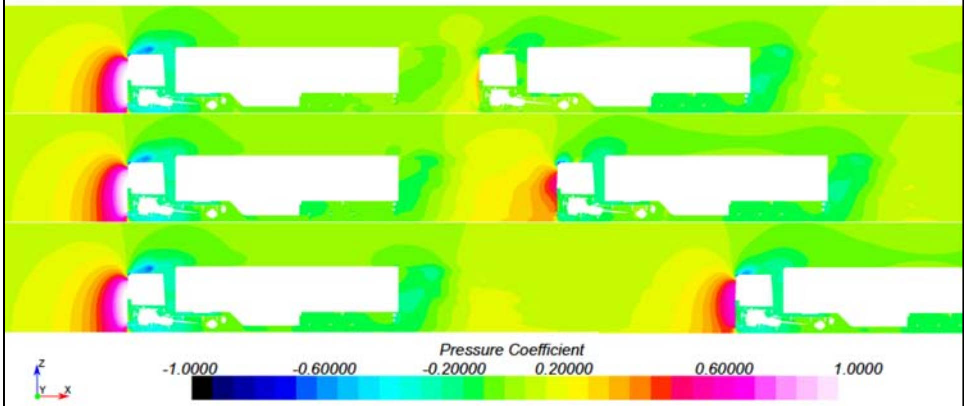


Scania

Swedish success stories

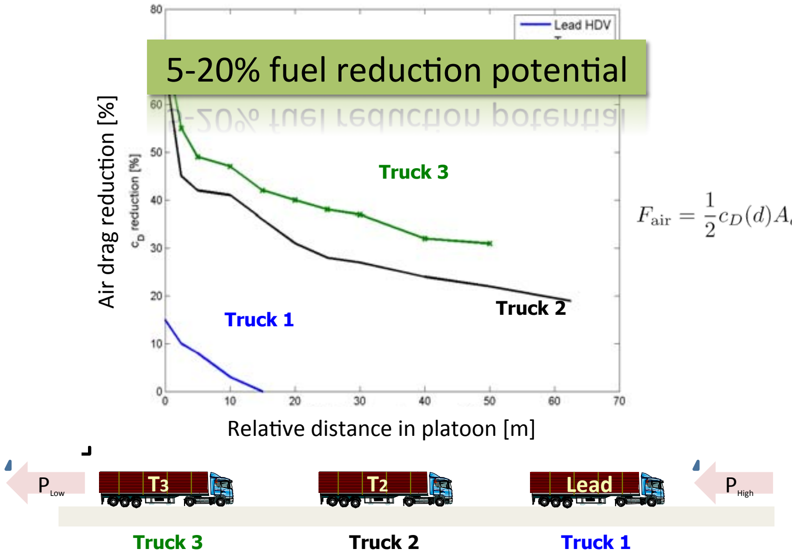
Volvo

The Physics



Norrby (2014), Liang (2016)

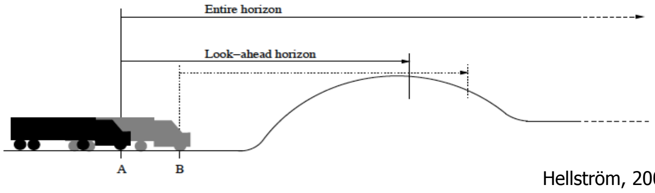
Air Drag Reduction in Truck Platooning



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

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

Receding Horizon Cruise Control for Single Vehicle



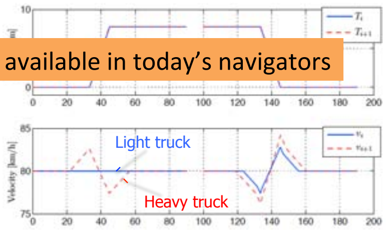
Hellström, 2007

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 freely available in today's navigators

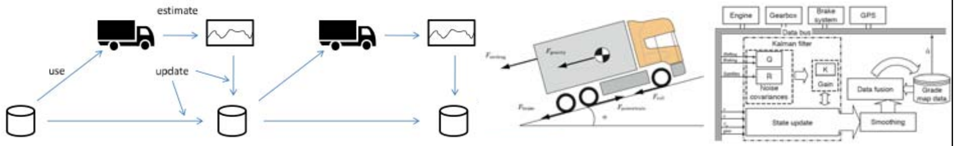
$$m_t \frac{\mathrm{d}v}{\mathrm{d}t} = F_{eng} - F_b - F_{ad}(v,d) - F_r(\alpha) - F_g(\alpha)$$
$$= F_{eng} - F_b - \frac{1}{2}\rho_a A_a c_D v^2 \phi(d)$$
$$- mgc_r \cos\alpha - mg\sin\alpha$$

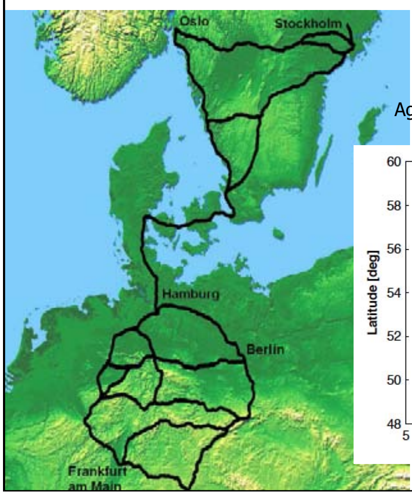


Implemented as velocity reference change in adaptive cruise controller

Alam et al., 2011

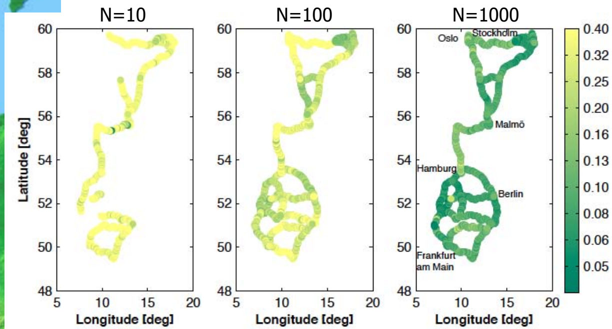
Distributed Road Grade Estimation





RMS Road Grade Error

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



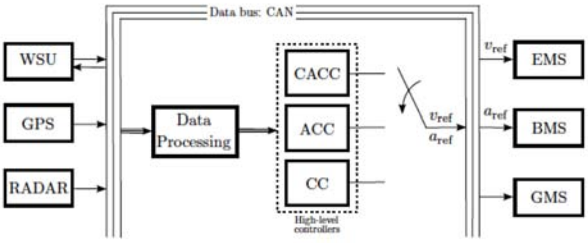
Sahlholm, 2011

Vehicle System Architecture

Data from other vehicles

Own position and velocity

Pos from vehicle ahead

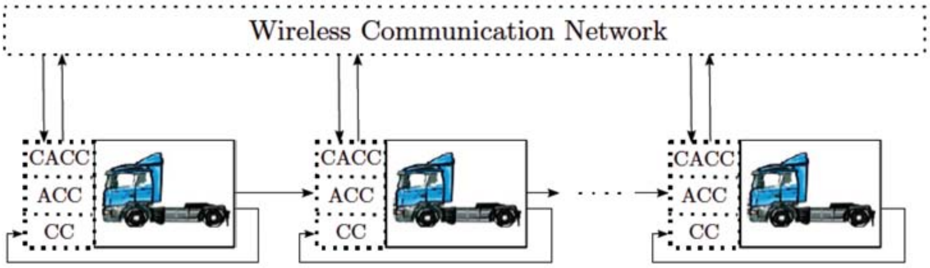


CACC – Collaborative adaptive cruise control
ACC – Adaptive cruise control
CC – Cruise control

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

Alam et al., 2014

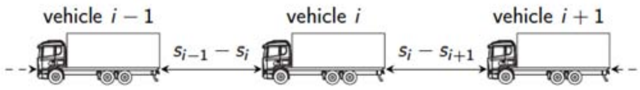
Platoon System Architecture



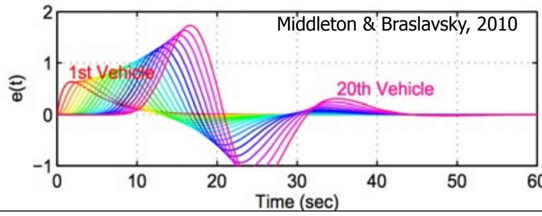
CACC – Collaborative adaptive cruise control
ACC – Adaptive cruise control
CC – Cruise control

Alam et al., 2014

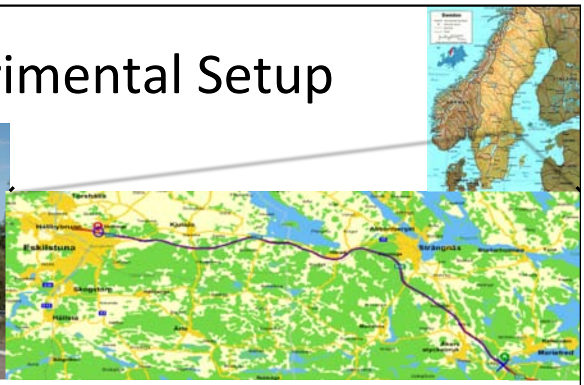
How to Control Inter-vehicular Spacings?

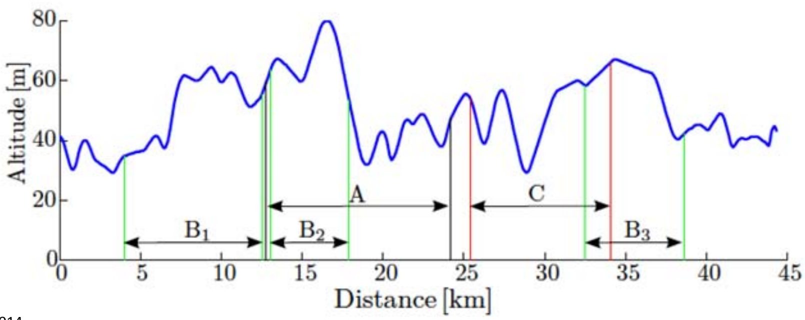


- Limited sensing and inter-vehicle communication suggests **distributed** control strategy
- Important to attenuate disturbances: **string stability**
- Extensively studied problem in ideal environments
  - E.g., Levine & Athans (1966), Peppard (1974), Ioannou & Chien (1993), Swaroop et al. (1994), Stankovic et al. (2000), Seiler et al. (2004), Naus et al. (2010)



Experimental Setup



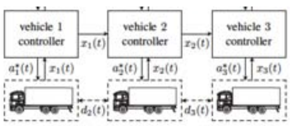


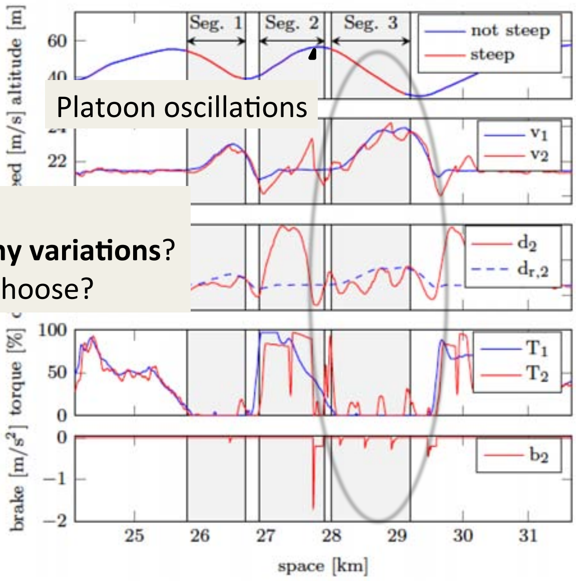
Alam, 2014

Experimental Results

Platoon oscillations

Challenge
How to handle **topography variations**?
Which **spacing policy** to choose?





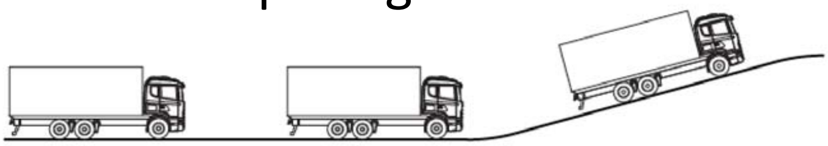
Alam, 2014

Spacing Policies

Constant spacing: $s_{\text{ref},i}(t) = s_{i-1}(t) - d$

Besselink & J, 2015

Spacing Policies



Constant spacing: $s_{\mathrm{ref},i}(t) = s_{i-1}(t) - d$

Besselink & J, 2015

Spacing Policies

Constant headway: $s_{\mathrm{ref},i}(t) = s_{i-1}(t) - d - hv_i(t)$

Besselink & J, 2015

Spacing Policies

Constant headway: $s_{\text{ref},i}(t) = s_{i-1}(t) - d - hv_i(t)$

Constant time gap: $s_{\text{ref},i}(t) = s_{i-1}(t - \Delta t)$

Besselink & J, 2015

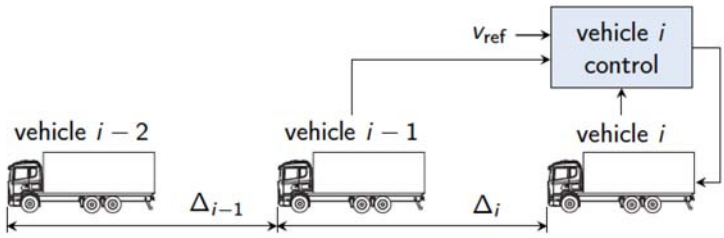
Constant Time Gap Spacing Policy

For the constant time gap policy it holds that

$$s_i(t) = s_{i-1}(t - \Delta t) \iff v_i(s) = v_{i-1}(s)$$

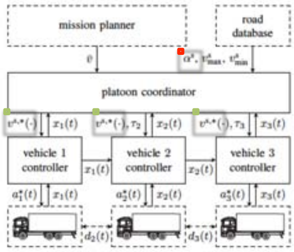
Control objectives: $v_i(t) \to v_{\text{ref}}(s_i(t))$,

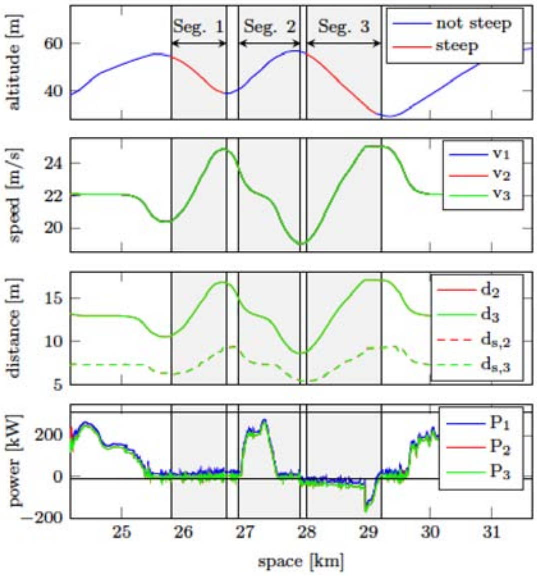
$$s_i(t) \to s_{i-1}(t - \Delta t)$$



Besselink & J, 2015

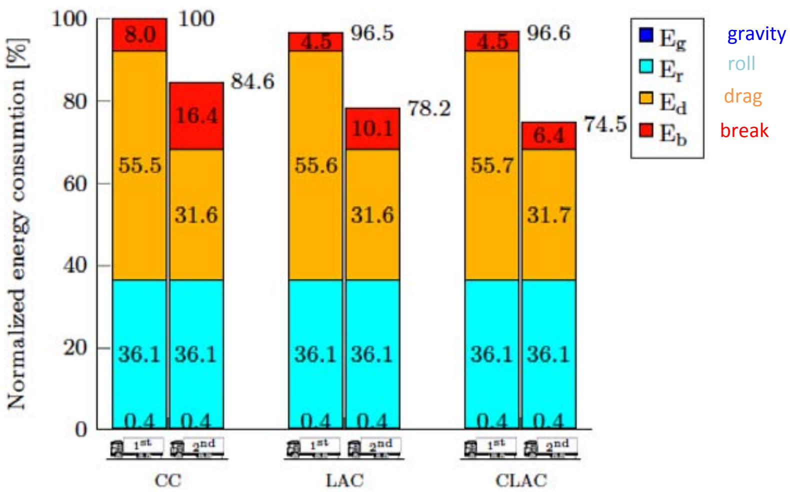
Simulations **with** Platoon Coordinator and Look-ahead Road Grade Information





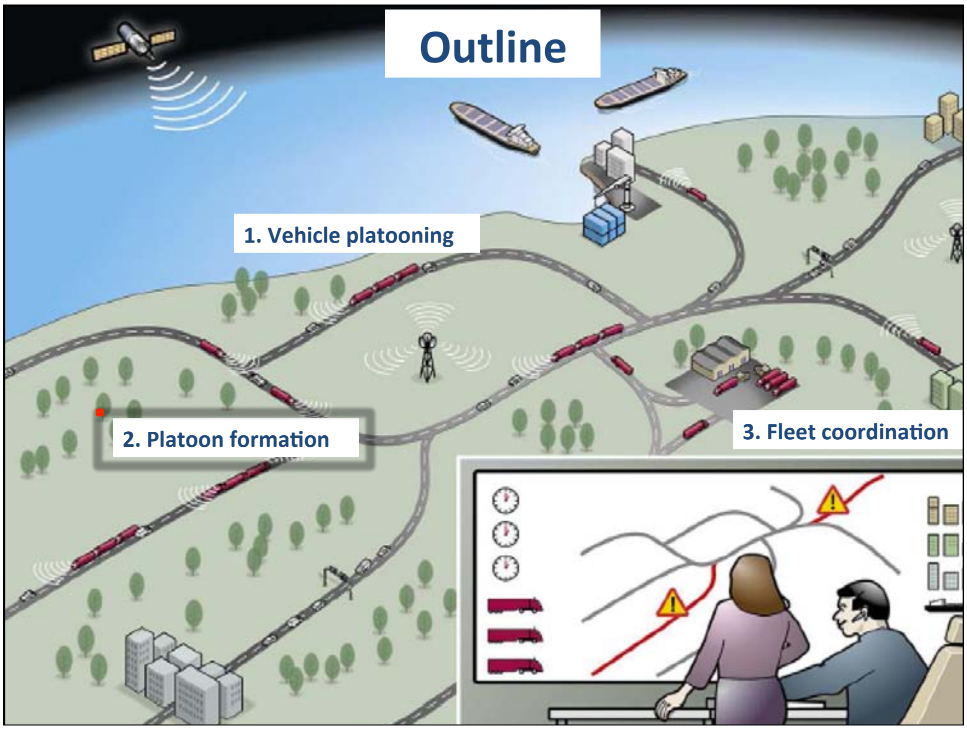
Turri et al., 2015

Evaluation of Energy Efficiency



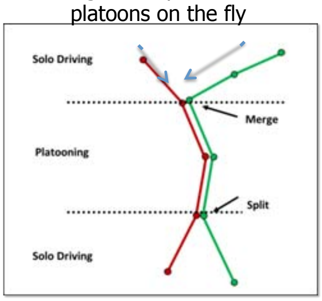
CC: First vehicle runs conventional cruise controller, second keeps fixed time gap
LAC: First vehicle runs look-ahead cruise controller, second keeps fixed time gap
CLAC: Vehicles run new cooperative look-ahead control with platoon coordinator

Turri et al., 2015



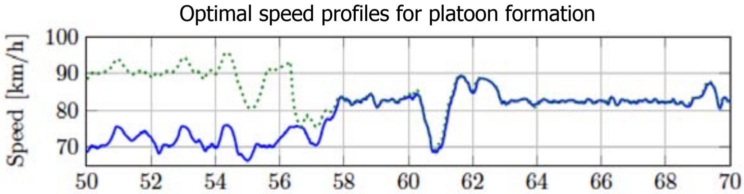
Platoon Formation

Merge and split vehicle platoons on the fly



Predictions on whether it is beneficial for a vehicle to catch up another vehicle

Optimal speed profiles for platoon formation



Liang et al., 2016

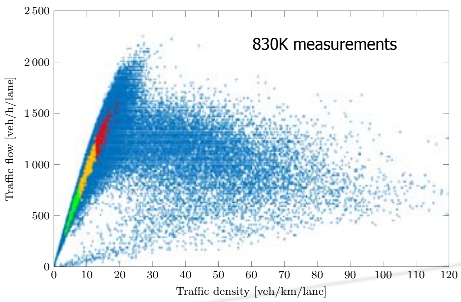
Traffic Influence on Platoon Formation

- Platoon formation of two trucks under various traffic conditions
- 600 test runs on E4 in Nov 2015
- Traffic measurements from road units together with onboard sensors

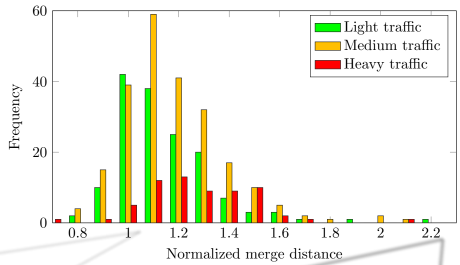
Liang , 2016

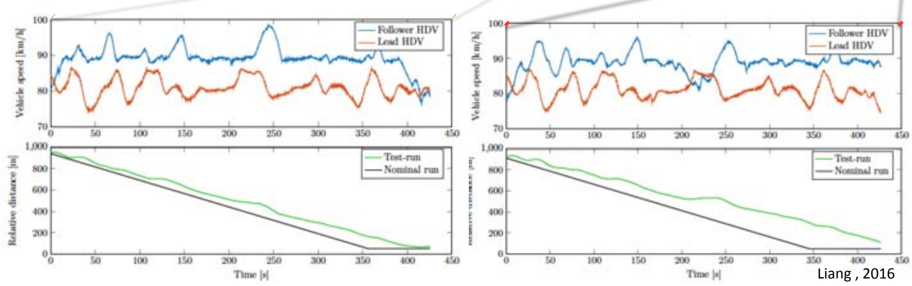
Traffic Influence on Platoon Formation

Fundamental diagram



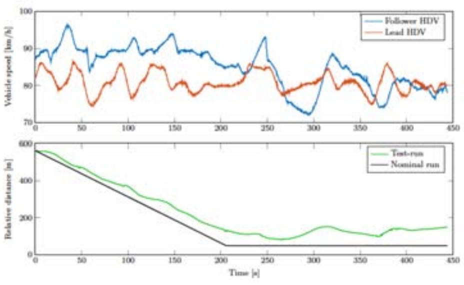
Distribution of merge distances

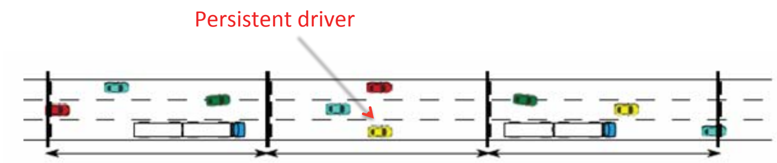




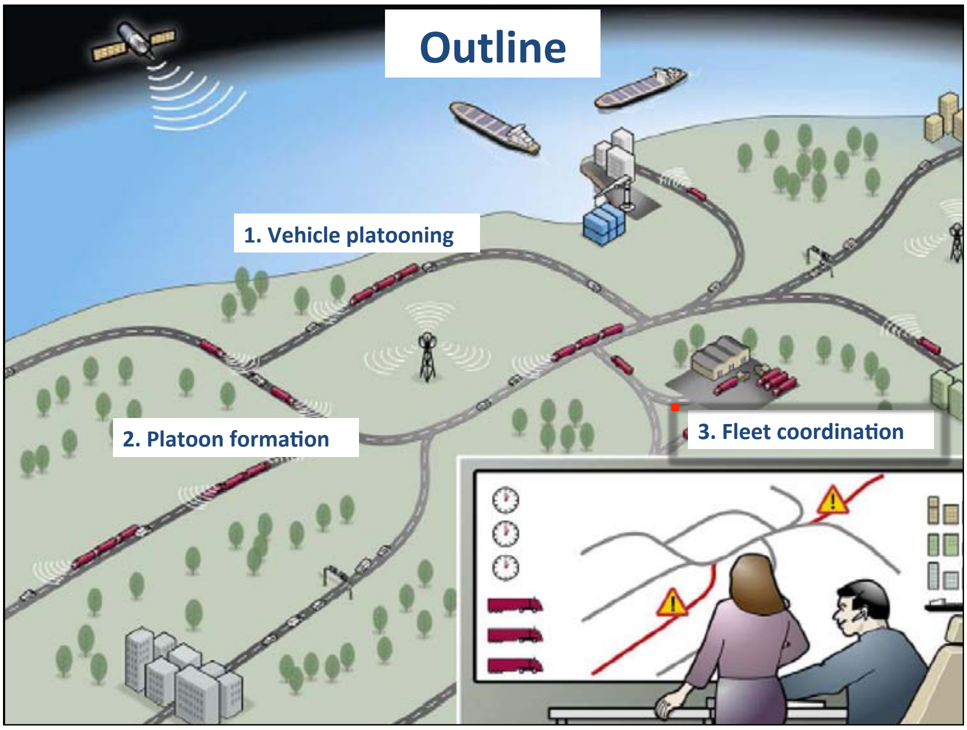
Liang , 2016

Persistent Driver Phenomena

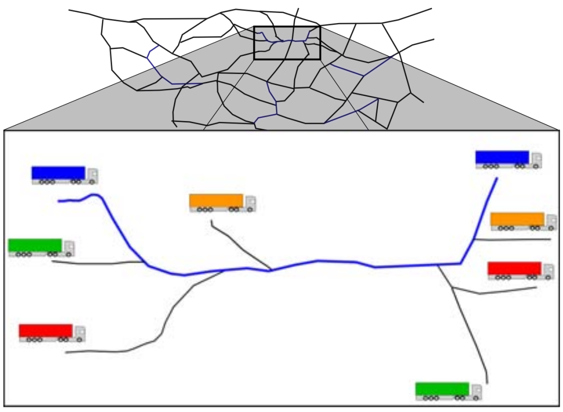




Liang , 2016



How to coordinate platoon formation?

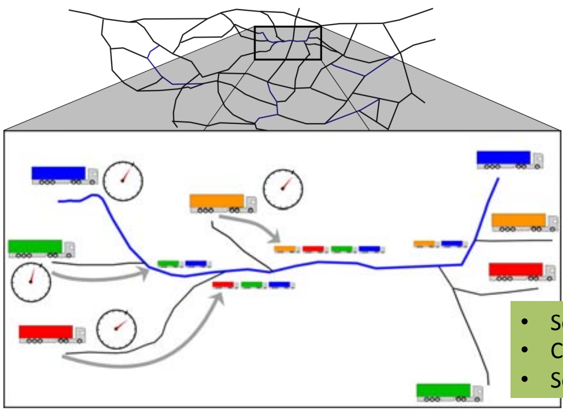


Platoon coordination
Shortest path to destination given for each truck

1. Select some **trucks** as leaders, with fixed schedules

van de Hoef et al., 2015

How to coordinate platoon formation?



Platoon coordination
Shortest path to destination given for each truck

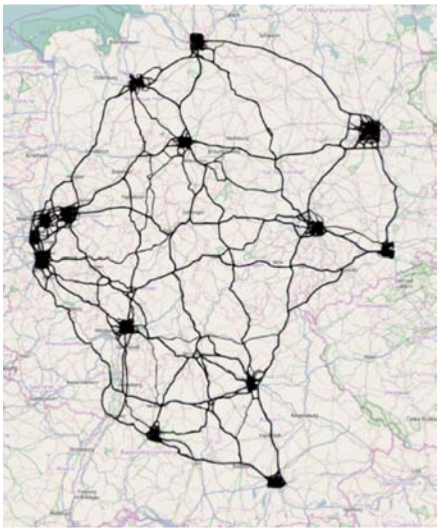
1. Select some **trucks** as leaders, with fixed schedules
2. For the other trucks, pairwise compute timing adjustments
3. Joint optimization of velocities

- Scales to large fleets and networks
- Cloud implementation
- Sep 2016 Stockholm-Barcelona demo

van de Hoef et al., 2015

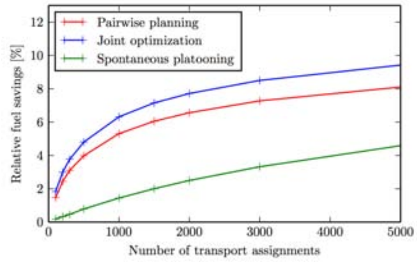
How does platoon benefits scale?

Randomly generated transport assignments

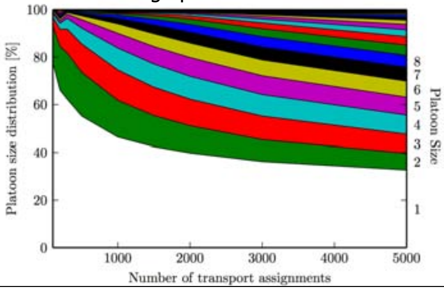


Liang et al., 2016

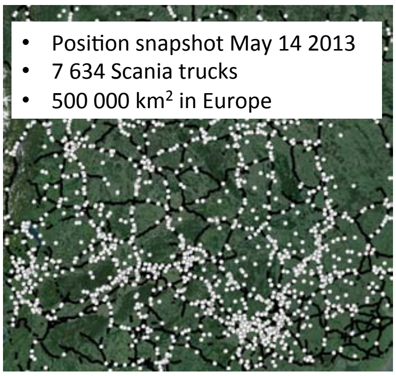
How many vehicles are needed for significant fuel savings?



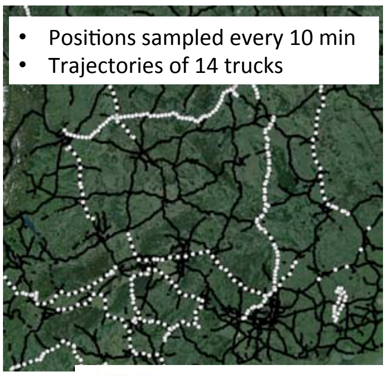
How large platoons will evolve?



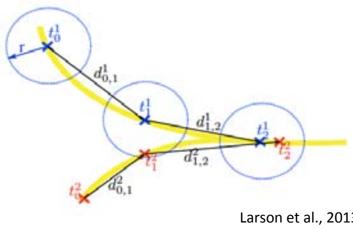
Feasibility Study Based on Real Truck Data



700 km



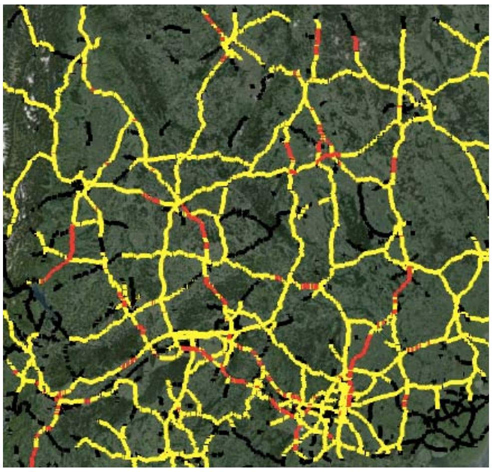
- 875 long-haulage trucks over European region
- Trucks close in time and space (<r m) could adjust speed to platoon and then save 10% fuel during platooning



Larson et al., 2013

Spontaneous vs Coordinated Platooning

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

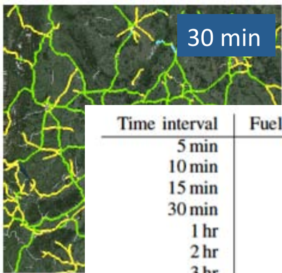


Liang et al., 2014

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



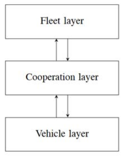
Time interval	Fuel saved*	Platooning rate
5 min	0.68%	13.22%
10 min	1.19%	22.41%
15 min	1.64%	30.26%
30 min	2.74%	47.58%
1 hr	4.31%	68.07%
2 hr	5.94%	83.23%
3 hr	6.87%	89.93%
6 hr	8.06%	95.67%
12 hr	8.85%	98.38%
24 hr	9.37%	99.38%

Coordinated departure times enable much more platooning

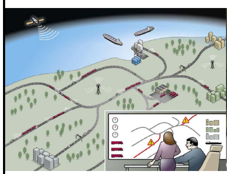
Liang et al., 2014

Conclusions

- **Large potential for networked control in road transport systems**
  - Real-time control over mobile wireless networks
- **Integrated 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? Pricing?
  - Real-time cloud computing: Vehicle control from infrastructure?
- **Large-scale testing and evaluations**



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