Large-scale and Networked Control of Automated Freight Transport

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SCANIA

The Problem

How to efficiently transport goods over a highway network?

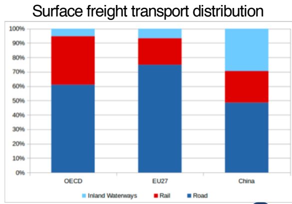
Characteristics
- 2 000 000 heavy long-haulage trucks in EU
  - 400 000 in Germany
- Large distributed control system with no real-time coordination today
- A few large and many small fleet owners with heterogeneous truck fleets
  - 97% operate 20 or fewer trucks in US
- Tight delivery deadlines and high expectations on reliability

Goal: Maximize automation and fuel-saving cooperations with limited intervention in vehicle speed, route, and timing

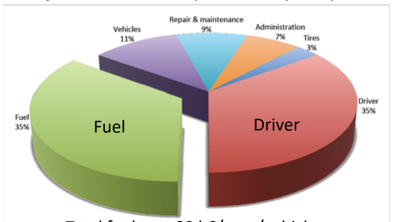
Demands from Goods Road Transportation

- Road transport consumes 26% of total EU energy and accounts for 18% of greenhouse emissions
- 75% of all surface freight transport is on roads in EU
- 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

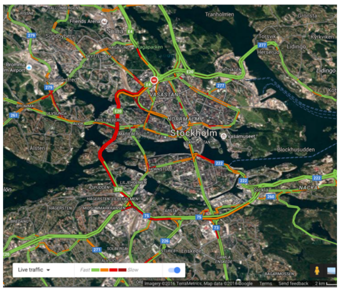
H. Ludanek, CTO, Scania (2014)

- 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

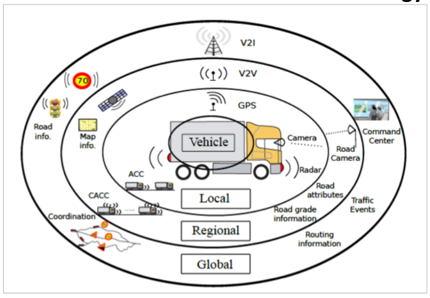
A. Mai, Dir. Connected Vehicle, Cisco (2016)

Technology Push

Real-time traffic information

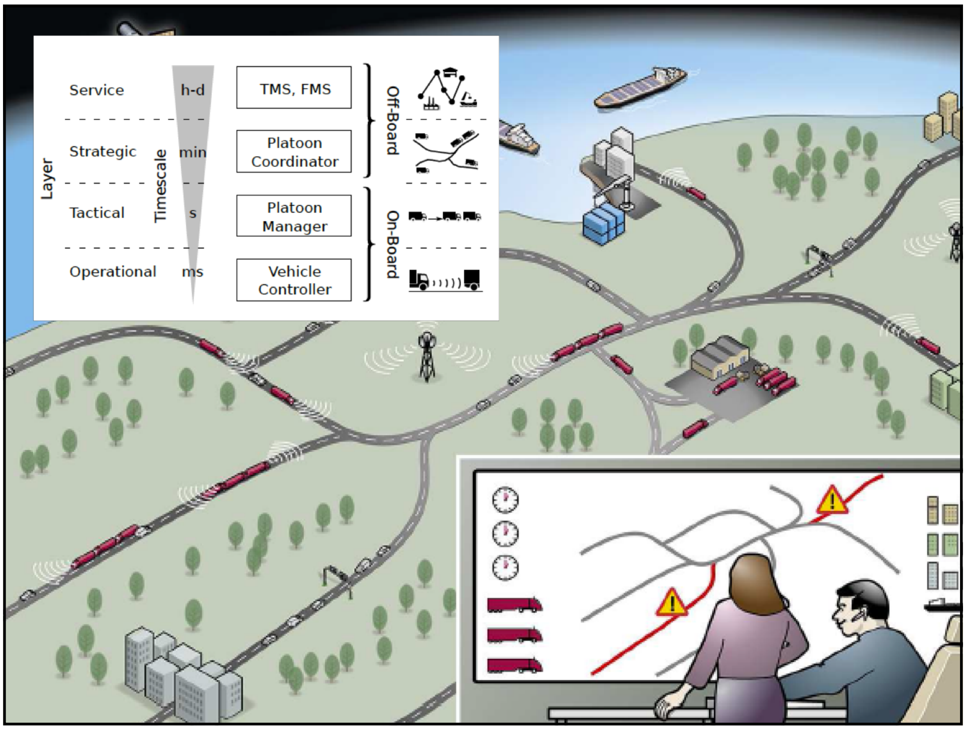


Sensor and commununication technology

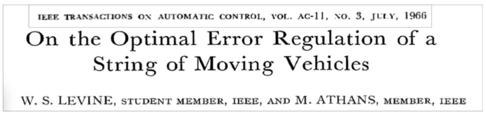


Electric highways

Vehicle platooning and automated 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

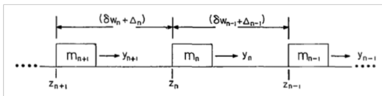


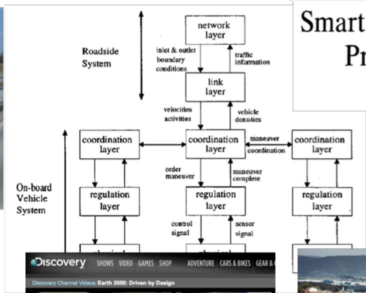
Fig. 1. Vehicles moving in a string.


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

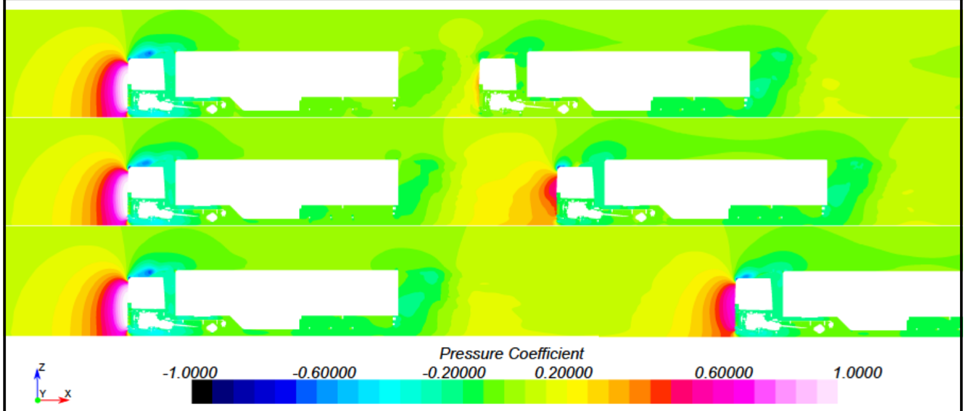



Scania

Swedish success stories

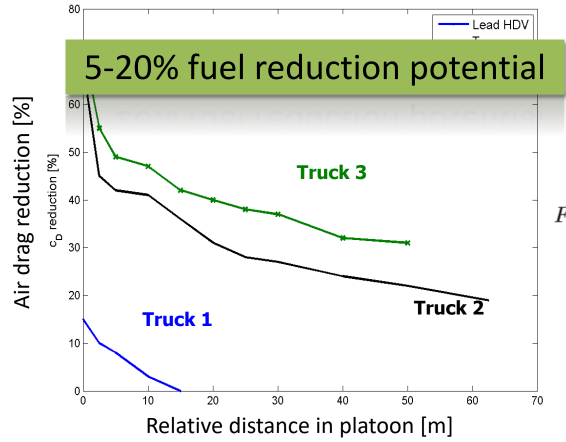

Volvo

The Physics

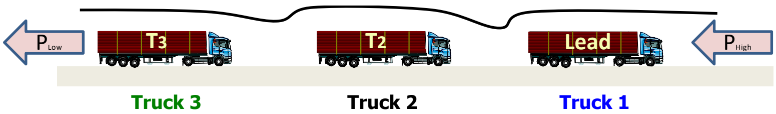


Norrby (2014), Liang (2016)

Air Drag Reduction in Truck Platooning



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



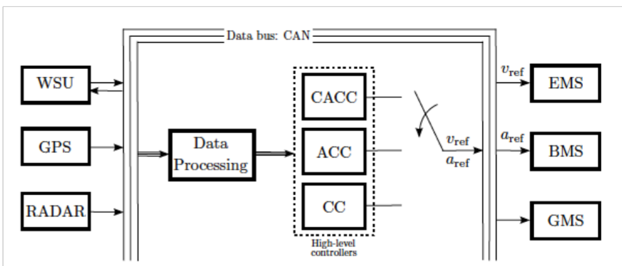
Wolf-Heinrich & Ahmed (1998), Bonnet & Fritz (2000), Scania CV AB (2011)

Vehicle System Architecture

Data from other vehicles

Own position and velocity

Pos from vehicle ahead

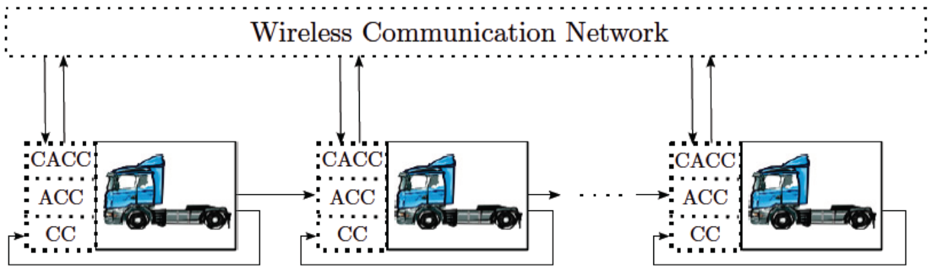


CACC – Collaborative adaptive cruise control
ACC – Adaptive cruise control
CC – Cruise control

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

Alam et al., 2014

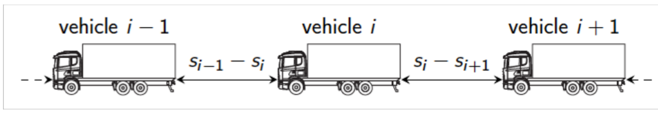
Platoon System Architecture



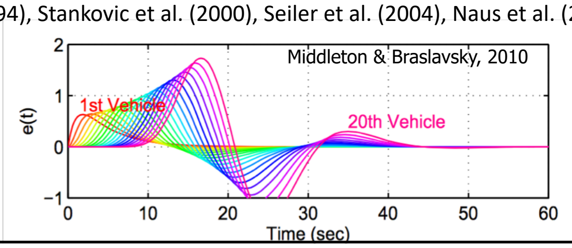
CACC – Collaborative adaptive cruise control
ACC – Adaptive cruise control
CC – Cruise control

Alam et al., 2014

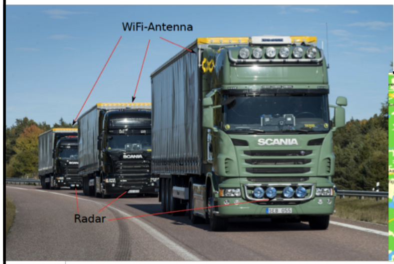
How to Control Inter-vehicular Spacings?

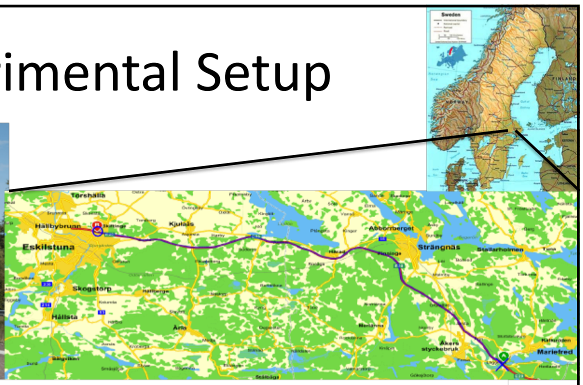


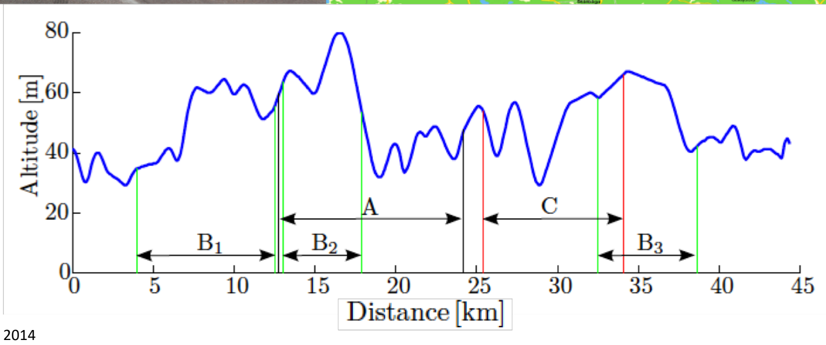
- Limited sensing and inter-vehicle communication suggests **distributed** control strategy
- Important to attenuate disturbances: **string stability**
- Extensively studied problem in ideal environments
  - E.g., Levine & Athans (1966), Peppard (1974), Ioannou & Chien (1993), Swaroop et al.(1994), Stankovic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



Experimental Setup

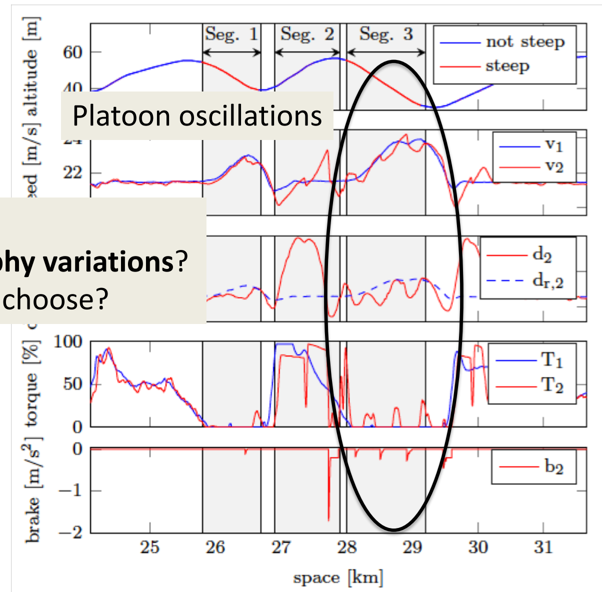






Alam, 2014

Experimental Results

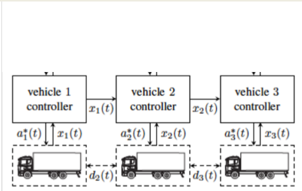


Platoon oscillations

Challenge

How to handle **topography variations**?

Which **spacing policy** to choose?



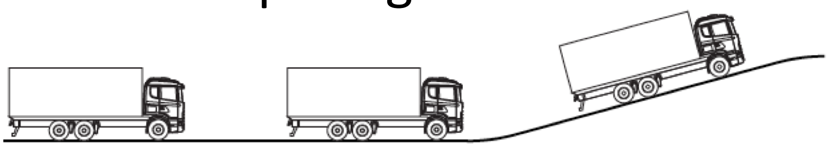
Alam, 2014

Spacing Policies

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

Besselink & J, 2017

Spacing Policies



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

Besselink & J, 2017

Spacing Policies

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

Besselink & J, 2017

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, 2017

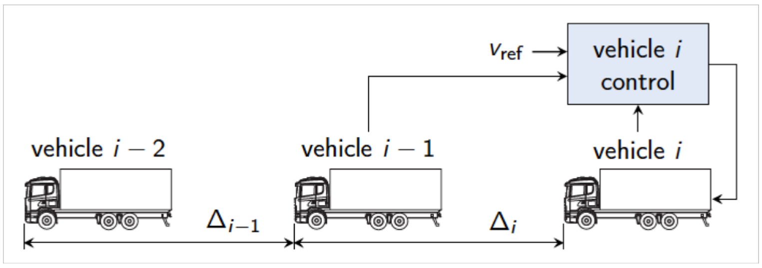
Constant Time Gap Spacing Policy

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

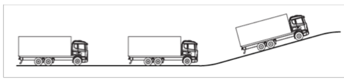
$s_i(t) \to s_{i-1}(t - \Delta t)$



Besselink & J, 2017

Disturbance String Stability

Platoon dynamics



$$\dot{x}_0 = f(x_0, 0, w_0),$$
$$\dot{x}_i = f(x_i, x_{i-1}, w_i), \quad i \in \mathcal{I}_N \setminus \{0\}$$

Definition. The platoon dynamics is disturbance string stable if there exist functions $\bar{\beta} \in \mathcal{KL}$ and $\bar{\sigma} \in \mathcal{K}_\infty$ such that, for all $N \in \mathbb{N}$,

$$\sup_{i \in \mathcal{I}_N} |x_i(t)| \le \bar{\beta}\left(\sup_{i \in \mathcal{I}_N} |x_i(t_0)|, t - t_0\right) + \bar{\sigma}\left(\sup_{i \in \mathcal{I}_N} \|w_i\|_\infty^{[t_0,t]}\right)$$

Theorem. Let each vehicle satisfy, for some $\beta \in \mathcal{KL}$, $\gamma, \sigma \in \mathcal{K}_\infty$,

$$|x_i(t)| \le \beta(|x_i(t_0)|, t - t_0) + \gamma(\|x_{i-1}\|_\infty^{[t_0,t]}) + \sigma(\|w_i\|_\infty^{[t_0,t]}).$$

If $\gamma(r) \le \bar{\gamma} r$, $\bar{\gamma} < 1$, then the platoon is disturbance string stable

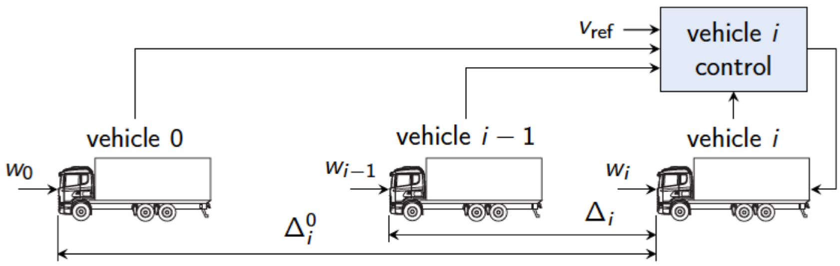
Besselink & J, 2017

Control objectives

1. Track reference $v_{\text{ref}}(\cdot)$ and constant time-gap spacing policy
2. Achieve disturbance string stability with respect to $v_{\text{ref}}(\cdot)$

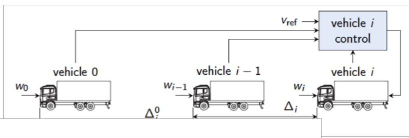
Timing error with $0 \leq \kappa_0 < 1$, $\kappa > 0$ and velocity error e_i

$$\delta_i(s) = (1 - \kappa_0)\Delta_i(s) + \kappa_0 \Delta_i^0(s) + \kappa e_i(s)$$



Besselink & J, 2017

Control Design



Timing error with $0 \leq \kappa_0 < 1$, $\kappa > 0$

$$\delta_i(s) = (1 - \kappa_0)\Delta_i(s) + \kappa_0 \Delta_i^0(s) + \kappa e_i(s)$$

Theorem. For any vehicle controller that achieves, for some functions $\beta_\delta \in \mathcal{KL}$, $\sigma_\delta \in \mathcal{K}_\infty$,

$$|\delta_i(s)| \leq \beta_\delta(|\delta(s_0)|, s - s_0) + \sigma_\delta(\|\bar{w}_i\|_\infty^{[s_0,s]}),$$

the platoon is disturbance string stable if $\kappa_0 > 0$

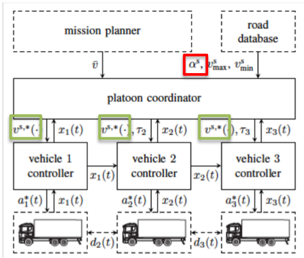
Properties

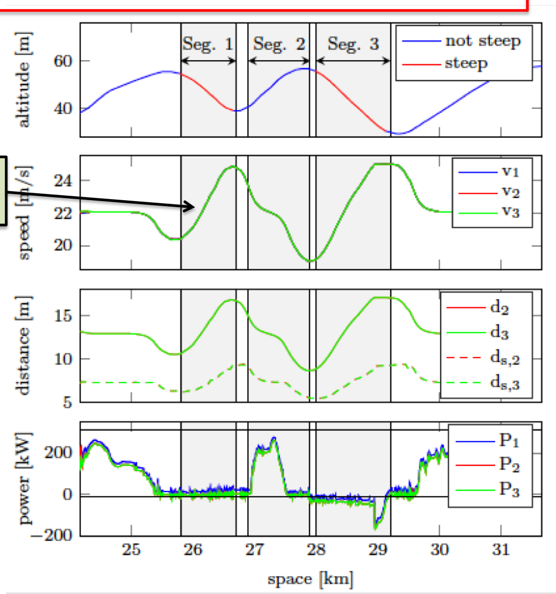
- Class of decentralized controllers
- Definition of the timing error is crucial
- Inclusion of leader information necessary for string stability

Besselink & J, 2017

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

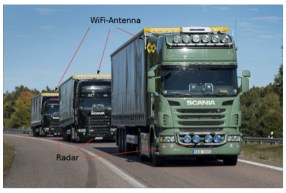
Successful tracking of common platoon velocity reference



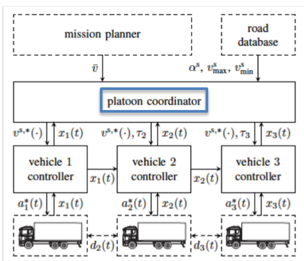


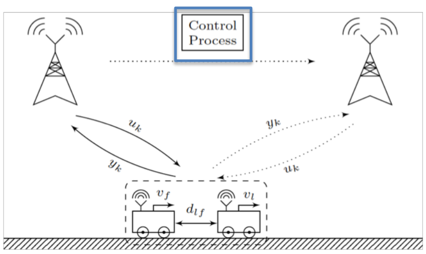
Turri et al., 2015

Cloud-based Implementation of Platoon Coordinator



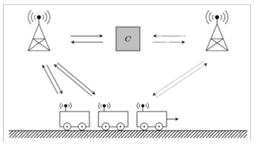
- Platoon coordinator generates common velocity reference: $v_i(t) \to v_{\text{ref}}(s_i(t))$,
- Can be computed in the cellular system
- Requires new handover scheme for control computations between base stations

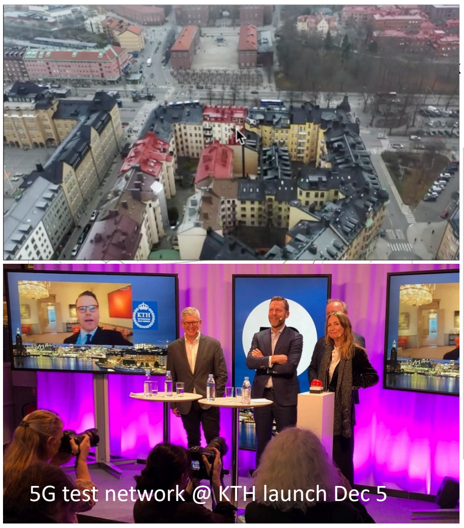




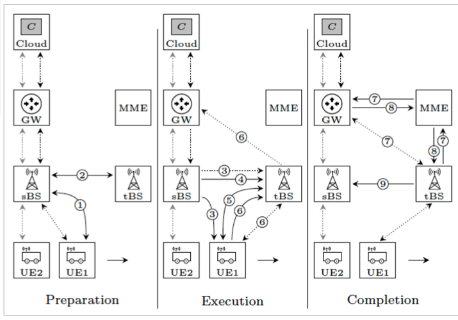
van Dooren et al., 2017

Controller Code Handover Supporting Vehicle Platooning





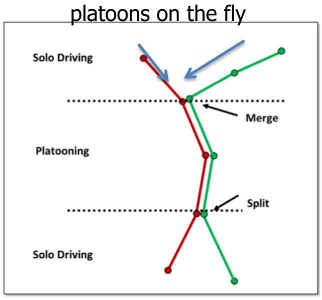
- Proposed new handover schemes for 5G
- Support real-time control from edge cloud



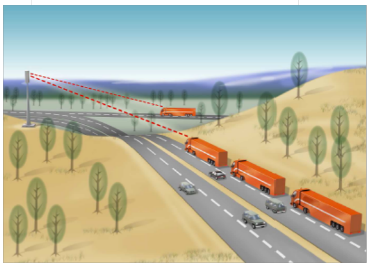
van Dooren et al., 2017, 2018

Platoon Formation

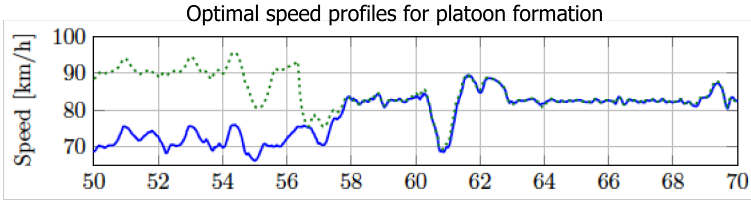
Merge and split vehicle platoons on the fly



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



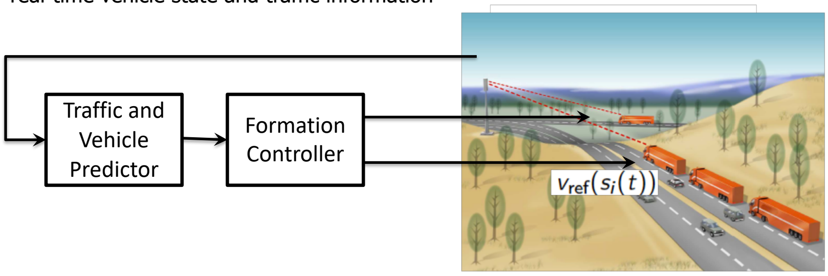
Optimal speed profiles for platoon formation



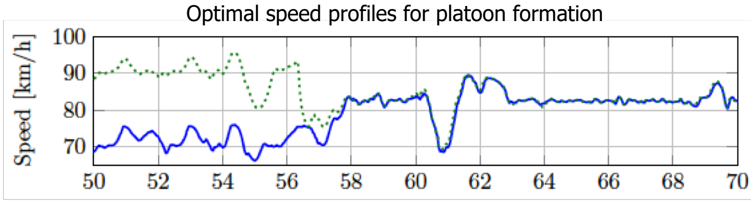
Liang et al., 2016

Platoon Formation

Feedback control of merging point based on real-time vehicle state and traffic information



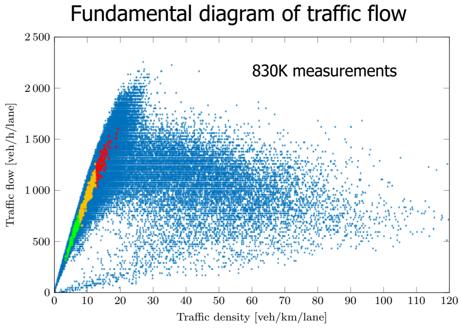
Optimal speed profiles for platoon formation



Liang et al., 2016; Cicic et al., 2017

Platoon Formation Experiments

Fundamental diagram of traffic flow



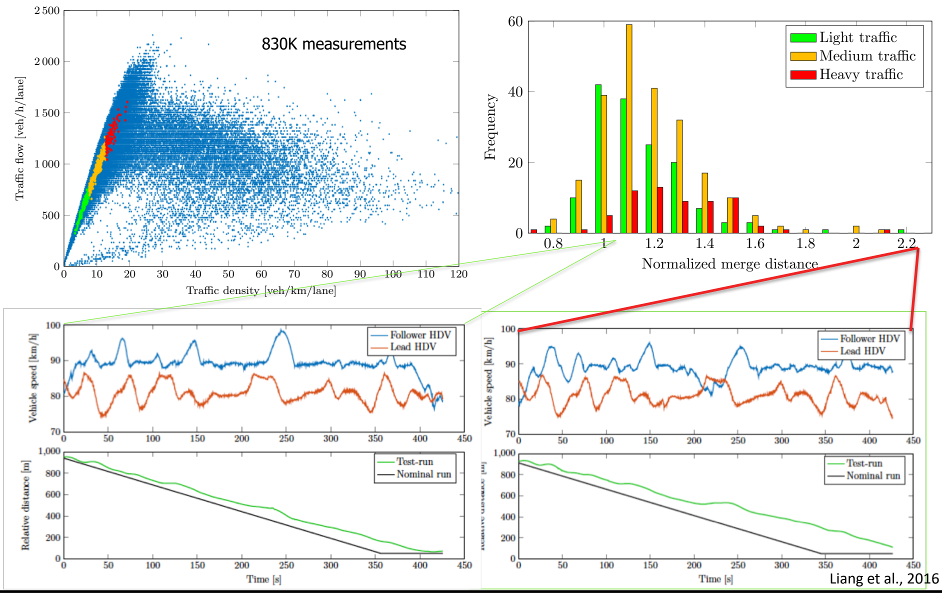
- 600 test runs on E4 in Nov 2015
- Traffic measurements from road units together with onboard sensors

Liang et al., 2016

Traffic Influence on Platoon Formation

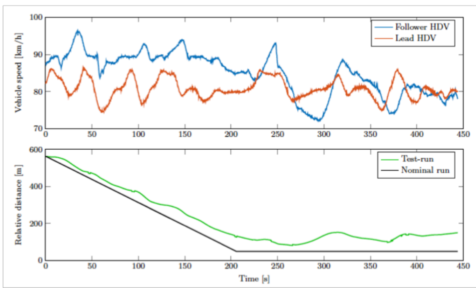
Fundamental diagram of traffic flow

Distribution of merge distances

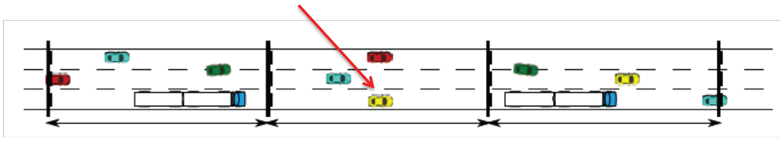


Liang et al., 2016

Persistent Driver Phenomena



Persistent driver blocking platoon formation



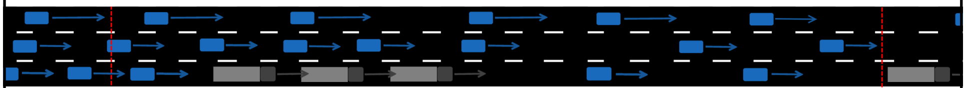
How to predict driver decisions for the control of truck platoons? [Stefansson et al., 2019]

Liang et al., 2016

How will massive truck platooning influence highway traffic?

- Model truck platoons as bottlenecks moving in car traffic
- Extend cell transmission model to capture evolution of traffic density and flow

  Cf., Daganzo and Lavel, 2005



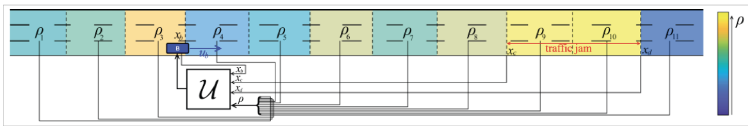
Discretization of the Lighthill-Whitham-Richards PDE model [Lebacque, 1996]

$$\rho_i(t+1) = \rho_i(t) + \frac{T}{L}\left(q_{i-1}(t) - q_i(t)\right)$$
$$q_i(t) = \min\left(V\rho_i(t), V\sigma, W(P - \rho_{i+1}(t))\right)$$

- $\rho_i(t)$ – traffic density in cell i
- $q_i(t)$ – traffic flow from cell i to cell $i+1$

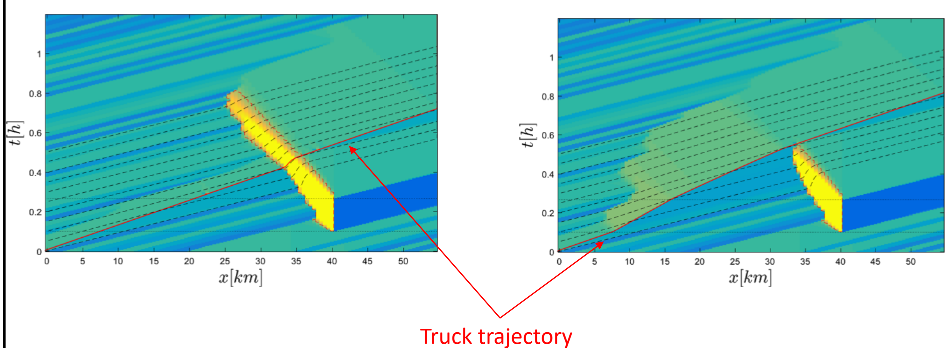
Lin et al., 2018; Cicic and J, 2018

Control truck velocity to dissipate congestion based on traffic densities



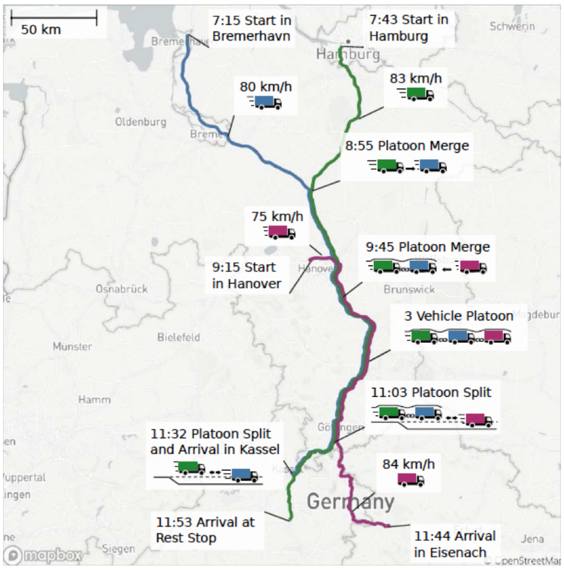
Traffic density **without** truck control

Traffic density **with** truck control

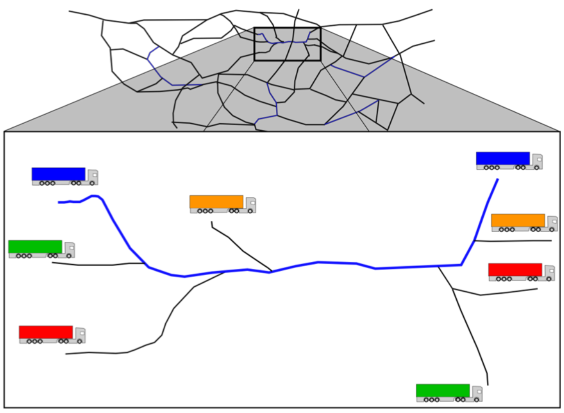


Cicic and J, 2018

The platoon matching problem



How to coordinate platoon formation?

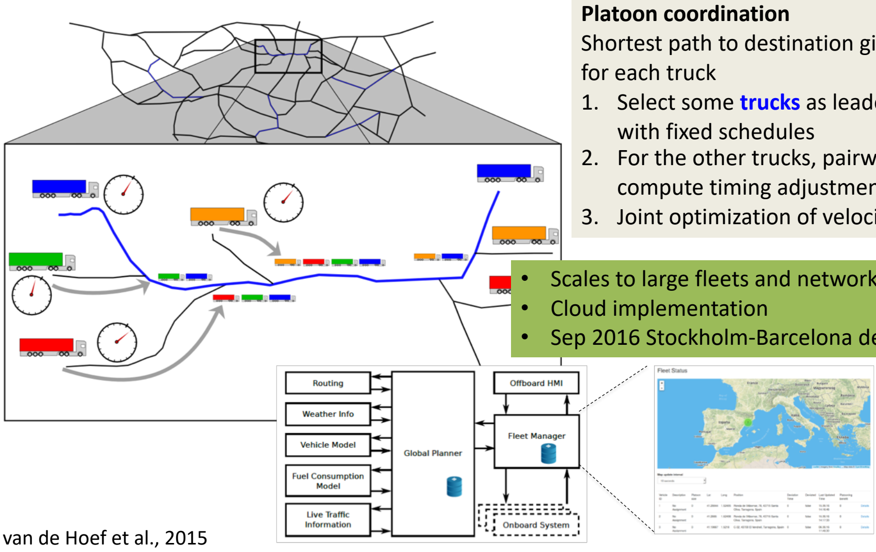


Platoon coordination
Shortest path to destination given for each truck

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

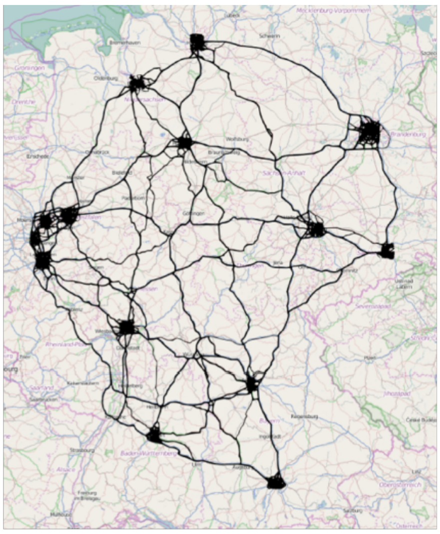
1. Select some **trucks** as leaders, with fixed schedules
2. For the other trucks, pairwise compute timing adjustments
3. Joint optimization of velocities

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

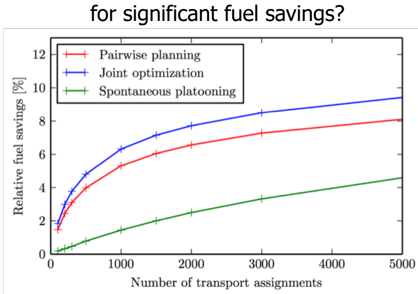
van de Hoef et al., 2015

How does platooning benefit from scale?

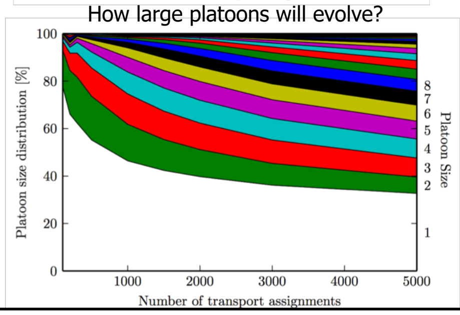
Randomly generated transport assignments



How many vehicles are needed for significant fuel savings?



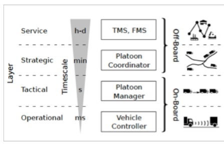
How large platoons will evolve?



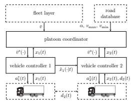
Liang et al., 2016

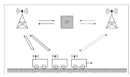
Conclusions

- **Architecture** for automated road freight transport
  - Automated vehicle match-making and platoon formation
  - Platoon control over V2V and V2I cellular communication
  - Integrated platoon coordinator and cruise-controller



- **Platoon control** to attenuate topography variations
- **Vehicle automation** enabled by **cellular infrastructure**





- **Ongoing studies**
  - Global vs local objectives: Pricing? Social optimum?
  - Fair sharing of data under conflicting objectives?
  - Predicting human decisions in multi-vehicle scenarios?

ENSEMBLE multi-brand platooning H2020 project 2018-2021
European Truck Platooning Challenge 2016

people.kth.se/~kallej

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