Resilient Control of Automated Transport Vehicles and Their Influence on Traffic

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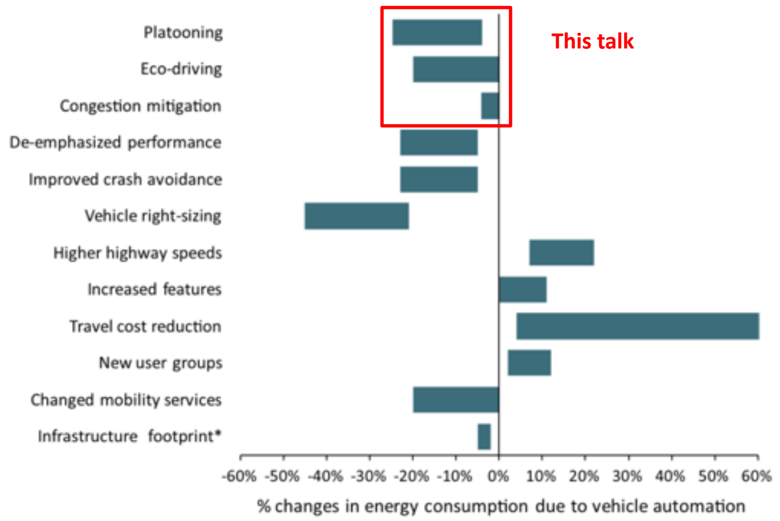
Operational Energy Impact of Vehicle Automation



Wadud et al., 2016

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Yulong Gao
Frank Jiang
Alexander Johansson
Elis Stefansson

Valerio Turri
Jonas Mårtensson

And other collaborators

The Problem

How to efficiently transport goods over a highway network?

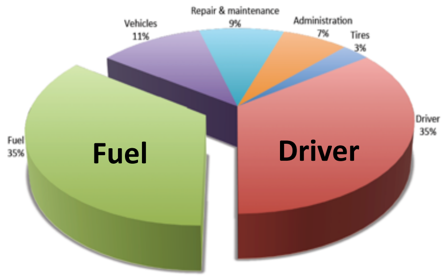
Characteristics

- 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

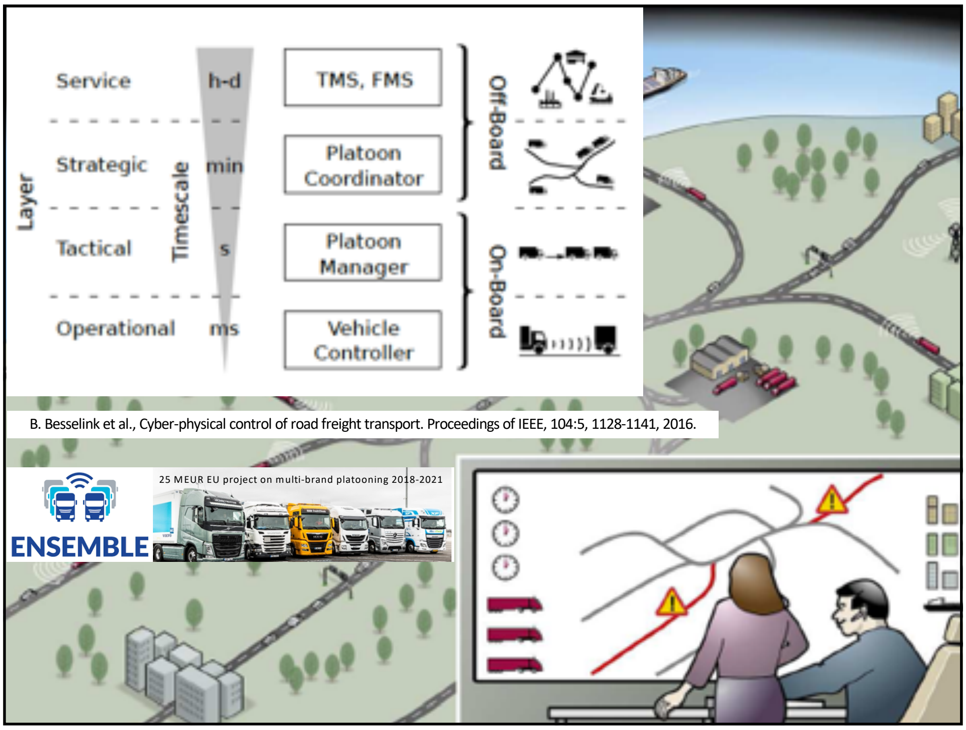
Why focus on fuel and automation?

Life cycle cost for European heavy-duty vehicle



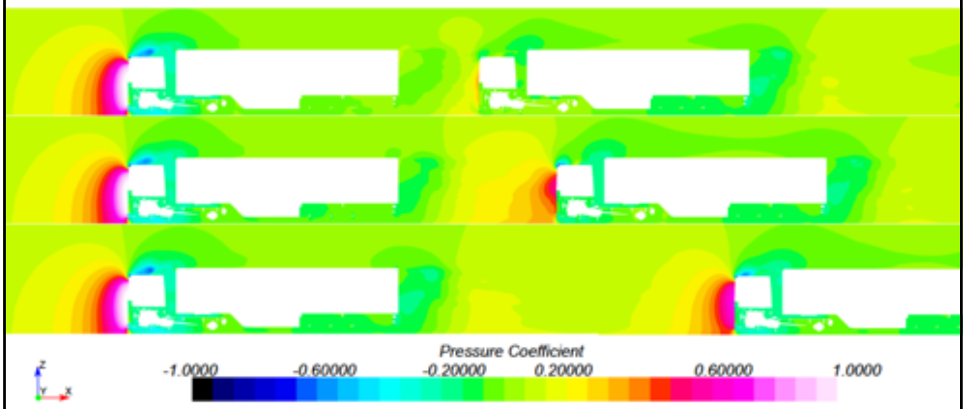
Total fuel cost 80 k€/year/vehicle

Schittler, 2003; Scania, 2012



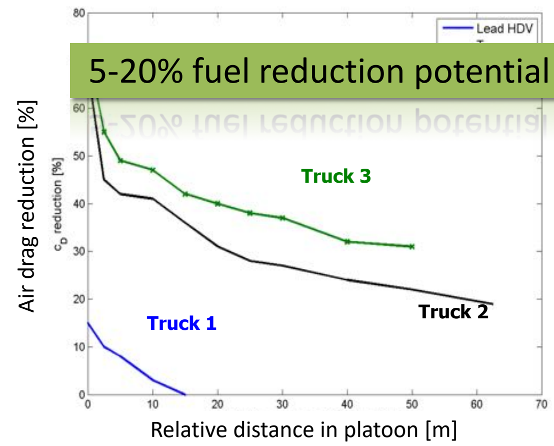
B. Besselink et al., Cyber-physical control of road freight transport. Proceedings of IEEE, 104:5, 1128-1141, 2016.

The Physics

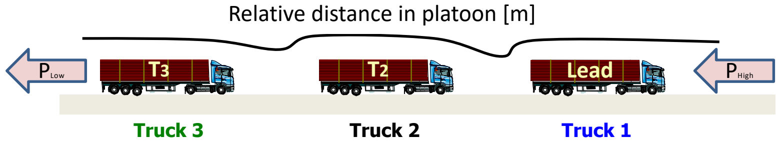


Norrby (2014), Liang (2016)

Air Drag Reduction in Truck Platooning



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



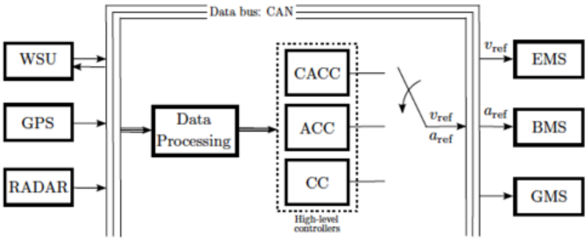
Wolf-Heinrich & Ahmed (1998), Bonnet & Fritz (2000), Scania CV AB (2011)

Vehicle System Architecture

Data from other vehicles

Own position and velocity

Pos from vehicle ahead

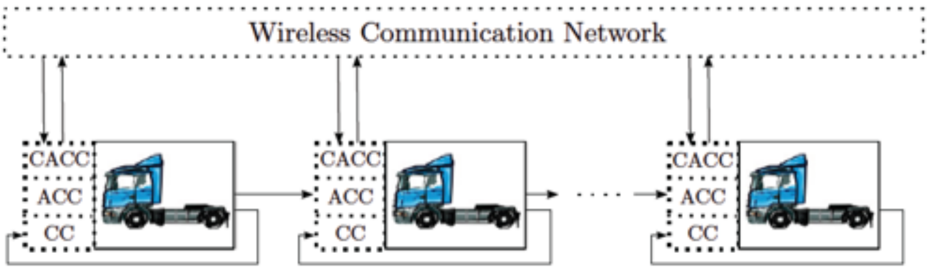


CACC – Collaborative adaptive cruise control
ACC – Adaptive cruise control
CC – Cruise control

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

Alam et al., 2014

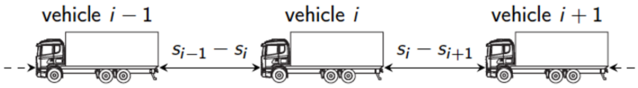
Platoon System Architecture



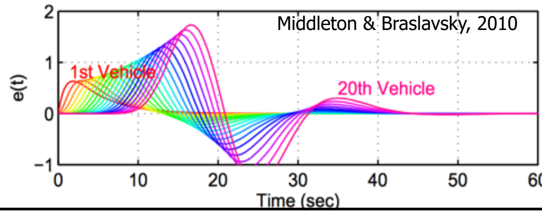
CACC – Collaborative adaptive cruise control
ACC – Adaptive cruise control
CC – Cruise control

Alam et al., 2014

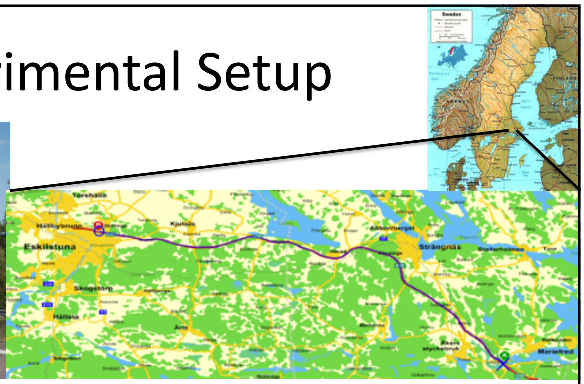
How to Control Inter-vehicular Spacings?

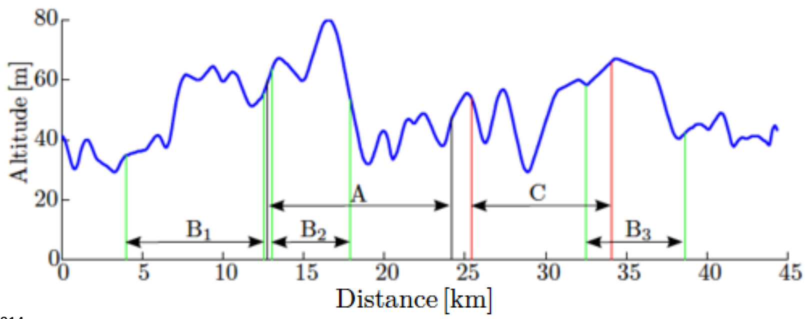


- Limited sensing and inter-vehicle communication suggests **distributed** control strategy
- Important to attenuate disturbances: **string stability**
- Extensively studied problem in ideal environments
  - E.g., Levine & Athans (1966), Peppard (1974), Ioannou & Chien (1993), Swaroop et al. (1994),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



Experimental Setup



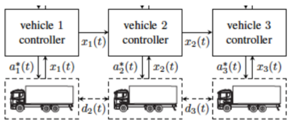


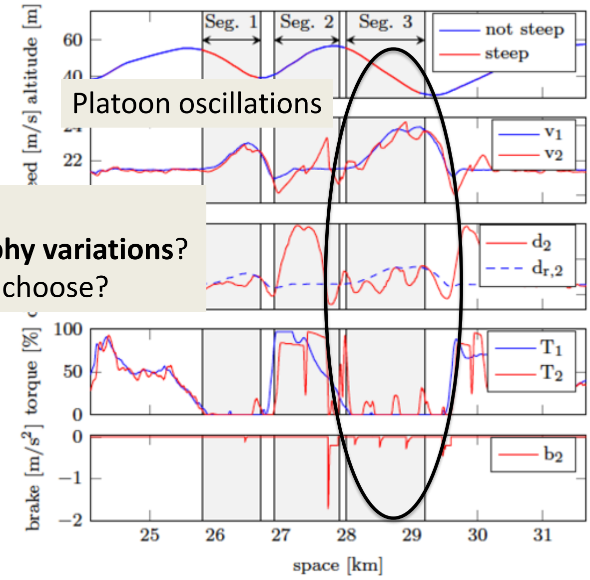
Alam, 2014

Experimental Results

Challenge

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

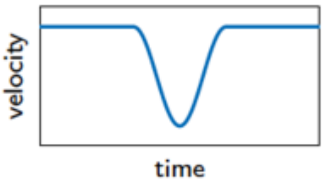


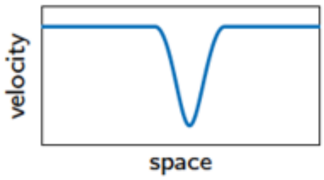


Alam, 2014

Spacing Policies

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





Besselink & J, 2017

Spacing Policies

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

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

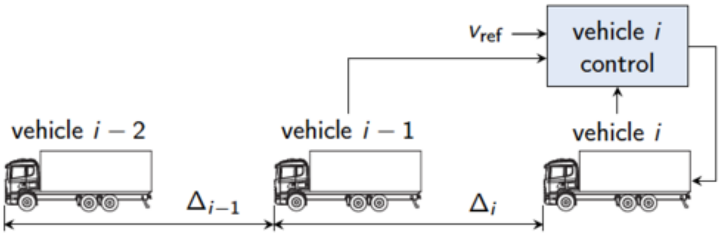
Constant Time Gap Spacing Policy

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 $N \in \mathbb{N}$,

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

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

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

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

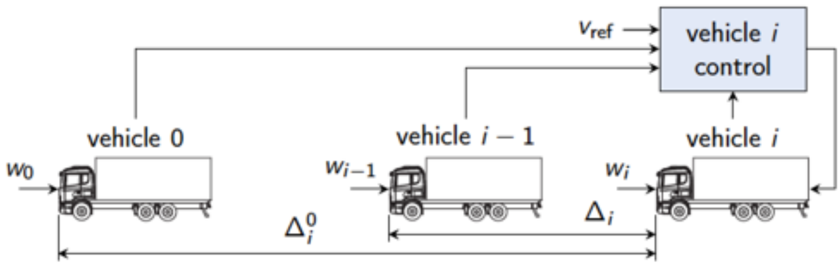
Besselink & J, 2017

Control objectives

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

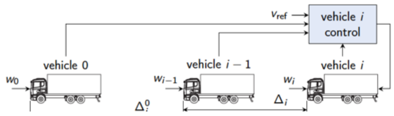
Timing error with $0 \leq \kappa_0 < 1$, $\kappa > 0$ and velocity error e_i

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



Besselink & J, 2017

Control Design



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

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

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

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

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

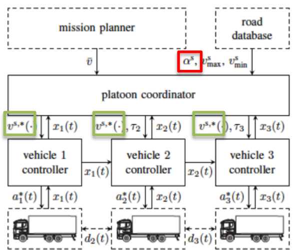
Properties

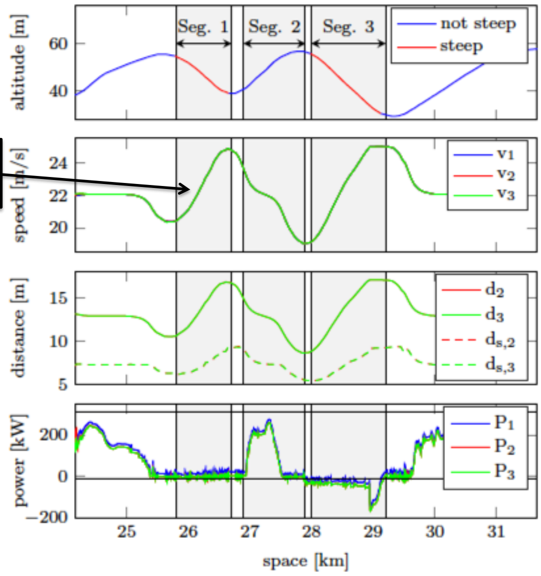
- Class of decentralized controllers
- Definition of the timing error is crucial
- Inclusion of leader information necessary for string stability

Besselink & J, 2017

Simulations with Platoon Coordinator and Look-ahead Road Grade Information

Successful tracking of common platoon velocity reference

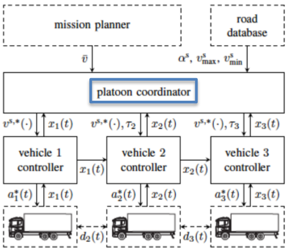


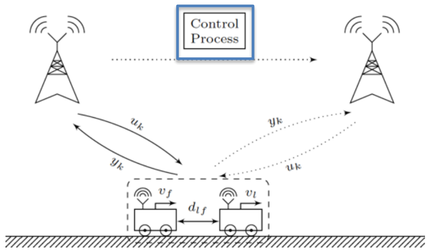


Turri et al., 2015

Cellular Implementation of Platoon Coordinator

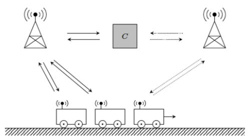
- Platoon coordinator generates common velocity reference: $v_i(t) \to v_{\text{ref}}(s_i(t))$.
- Can be computed in the cellular system
- New handover scheme for moving control computations between base stations

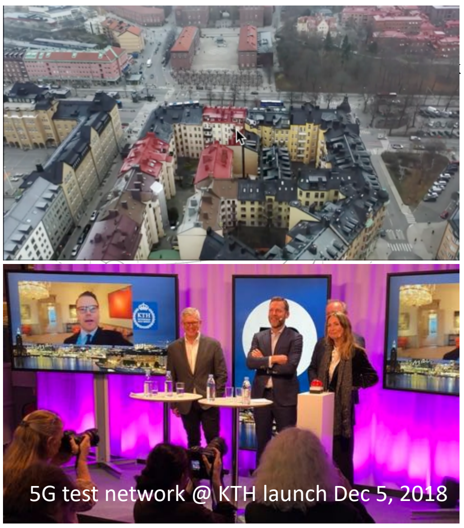




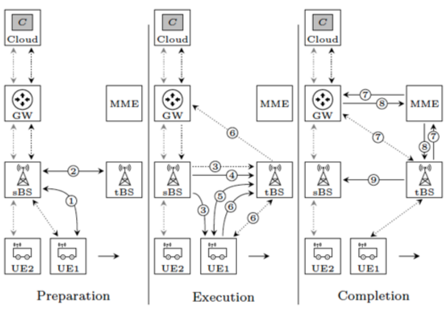
van Dooren et al., 2017

Controller Code Handover Supporting Vehicle Platooning





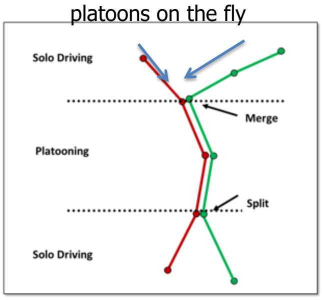
- Proposed new handover schemes for 5G
- Support real-time control from edge cloud



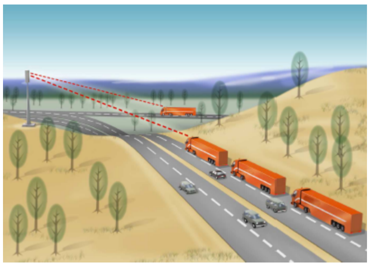
van Dooren et al., 2017, 2018

Platoon Formation

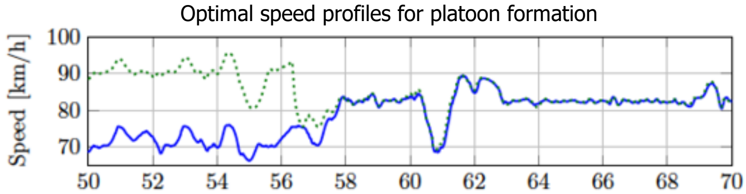
Merge and split vehicle platoons on the fly



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



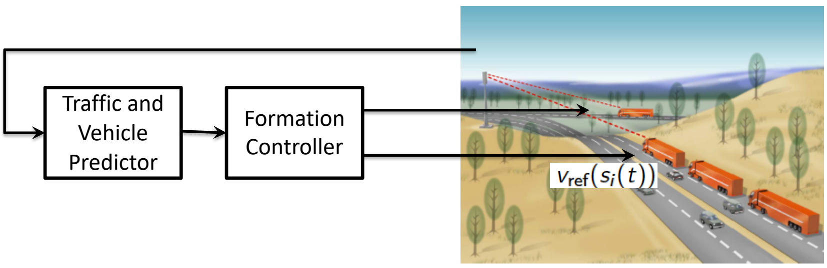
Optimal speed profiles for platoon formation



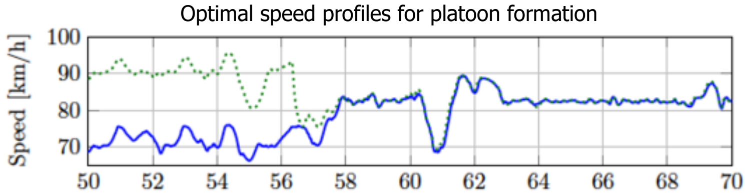
Liang et al., 2016

Platoon Formation

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

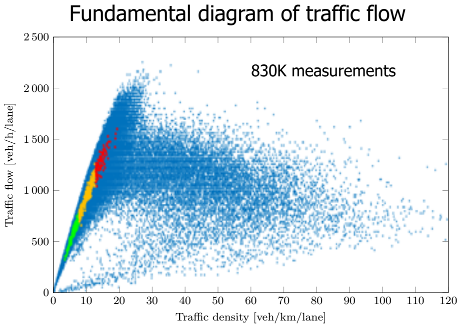


Optimal speed profiles for platoon formation



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

Platoon Formation Experiments



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

Liang et al., 2016

Platoon Formation Optimization

minimize $v_1, v_2, v_p \in [v_{\min}, v_{\max}]$	Total fuel consumption
subject to	controlled vehicles dynamics and constraints
	traffic dynamics with moving bottlenecks

Traffic dynamics represented by extending the Daganzo (1994) cell transmission model (CTM) to handle moving bottlenecks

Cicic and J, 2019

Platoon Formation Optimization

v_2 v_1 v_p

Catch-up phase — Merge point $\chi_1(\tau_m) = \chi_2(\tau_m)$ — **Platooning phase** — Final split point $\chi_1(\tau_f) = \chi_2(\tau_f) = \chi_f$

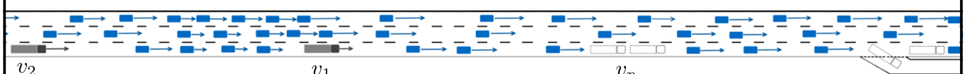
$$\underset{v_1, v_2, v_p}{\text{minimize}} \quad \int_0^{\tau_m} \left(v_1(\tau)^3 + v_2(\tau)^3\right) \mathrm{d}\tau + \phi \int_{\tau_m}^{\tau_f} v_p(\tau)^3 \mathrm{d}\tau$$

subject to
- $\chi_1(\tau_m) = \chi_2(\tau_m)$ — Merge point
- $\chi_1(\tau_f) = \chi_2(\tau_f) = \chi_f$ — Final split point
- $v_1, v_2, v_p \in [v_{\min}, v_{\max}]$
- Constraints on v_1, v_2 and v_p due to traffic

- Higher fuel consumption during the **catch-up phase**
- Lower fuel consumption during the **platooning phase**
- Merge point depends on velocities during the **catch-up phase**
- Final split point is fixed to give desired average velocity

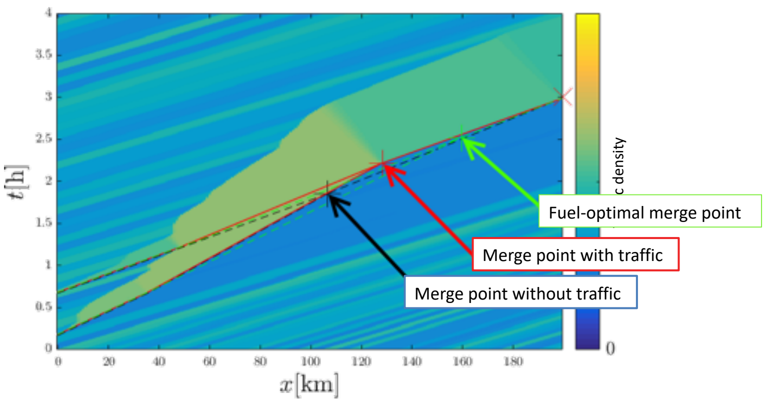
Cicic and J, 2019

Numerical Example



v_2 v_1 v_p

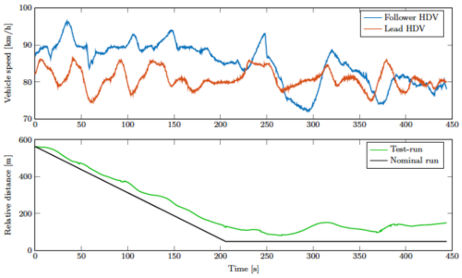
Catch-up phase — **Platooning phase** — Split



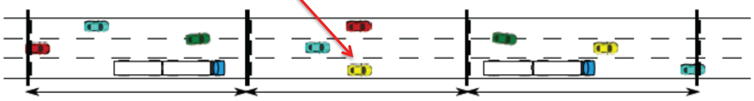
- Slowing down lead vehicle causes heavier traffic for follower vehicle
- Fuel consumption reduced for proposed controller despite later merging

Cicic and J, 2019

Persistent Driver Phenomena



Persistent driver blocking platoon formation



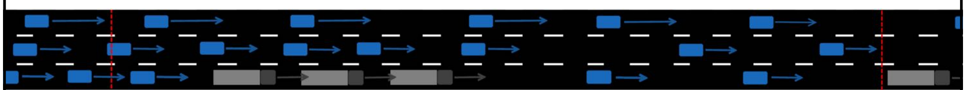
How to incorporate human driver behavior into the design of the automated truck platoon?

Stefansson et al., 2019

Liang et al., 2016

Can truck platooning be used to improve traffic conditions?

- Model truck platoons as bottlenecks moving in car traffic, cf., Lebacque et al. 1998; Delle Monache & Goatin 2014
- Extend Daganzo's cell transmission model to capture evolution of traffic



Discretize the Lighthill-Whitham-Richards PDE model and include truck platoon:

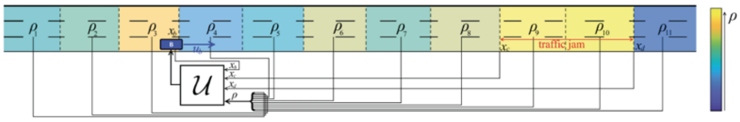
$$\rho_i(t+1) = \rho_i(t) + \frac{T}{L}\left(q_{i-1}(t) - q_i(t)\right)$$

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

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

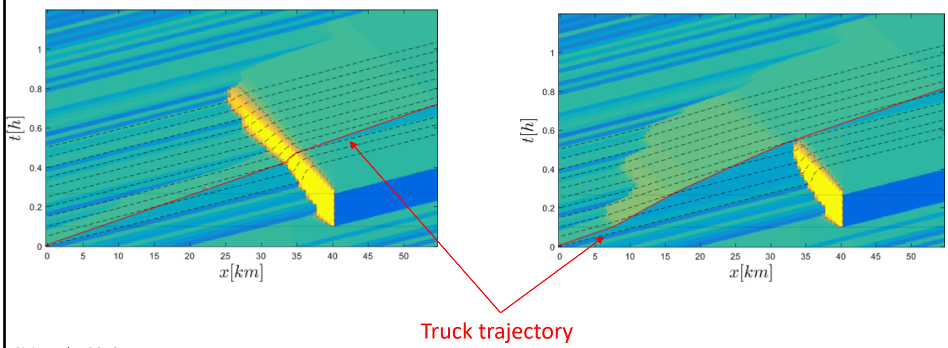
Lin et al., 2018; Cicic and J, 2018

Control truck velocity to dissipate congestion based on traffic densities



Traffic density **without** truck control

Traffic density **with** truck control

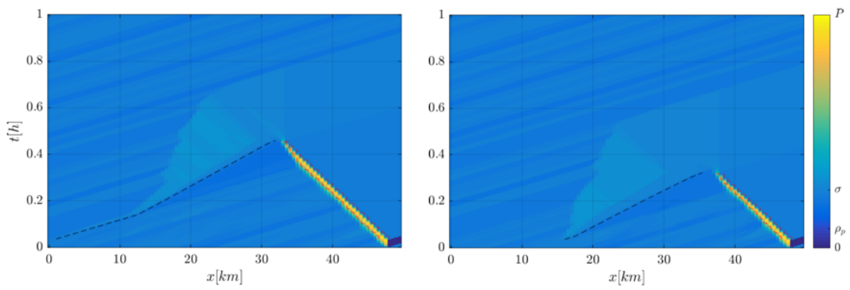


Cicic and J, 2018

Aggregated actuation from many controlled vehicles

5% controlled vehicles

10% controlled vehicles



What ratio of controlled vehicles are needed for significant influence on the traffic conditions?

Cicic and J, 2019

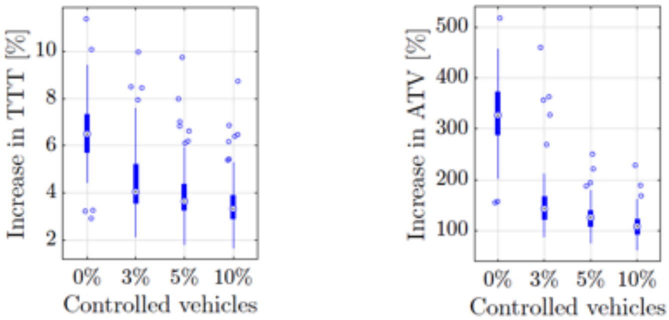
Improvements in travel time and density variations

Total travel time

$$\mathrm{TTT} = \sum_{t=0}^{t_{\mathrm{end}}} \sum_{i=1}^{N} \rho_i(t) T L$$

Average total variation

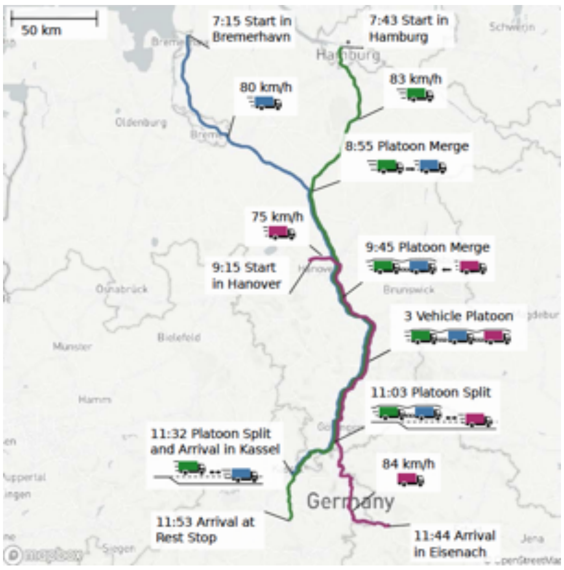
$$\mathrm{ATV} = \sum_{t=0}^{t_{\mathrm{end}}} \sum_{i=2}^{N} \frac{|\rho_i(t) - \rho_{i+1}(t)|}{t_{\mathrm{end}}}$$



Reduced travel times and density variations already with 3% of controlled vehicles

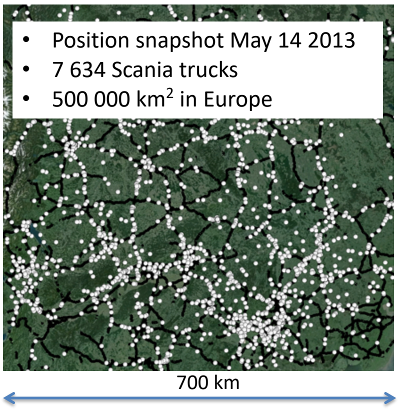
Cicic and J, 2019

The platoon matching problem

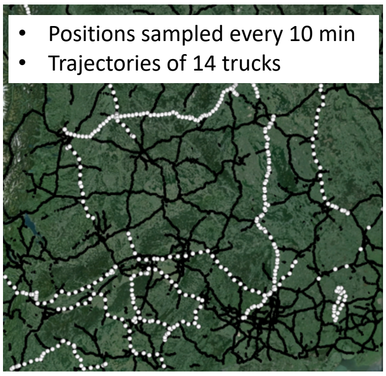


Feasibility Study Based on Real Truck Data

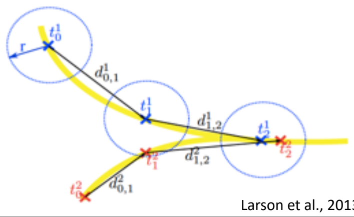
- Position snapshot May 14 2013
- 7 634 Scania trucks
- 500 000 km^2 in Europe



- Positions sampled every 10 min
- Trajectories of 14 trucks



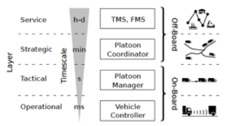
- 875 long-haulage trucks over European region
- Trucks close in time and space (<r m) could adjust speed to platoon and then save 10% fuel during platooning

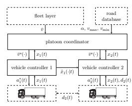


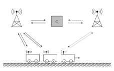
Larson et al., 2013

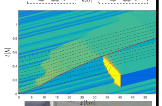
Conclusions

- **Automated road freight transport**
  - Integrated platoon coordinator and cruise-controller
  - Platoon control over V2V and V2I cellular communication
  - Automated vehicle match-making and platoon formation
- **Platoon controller** to attenuate disturbances
- **Optimization** enabled by **cellular infrastructure**
- Control automated platoons to **reduce congestion**
- **Ongoing work**
  - Global vs local objectives: pricing, social optimum, data privacy
  - Integrating human behavior in automated platoon control









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