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VINNOVA COMPANION HORIZON 2020 ENSEMBLE

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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

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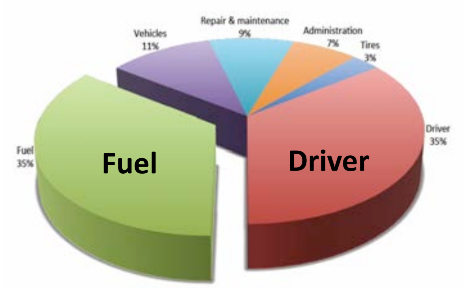
Why focus on fuel and automation?

Life cycle cost for European heavy-duty vehicle



Total fuel cost 80 k€/year/vehicle

Schittler, 2003; Scania, 2012

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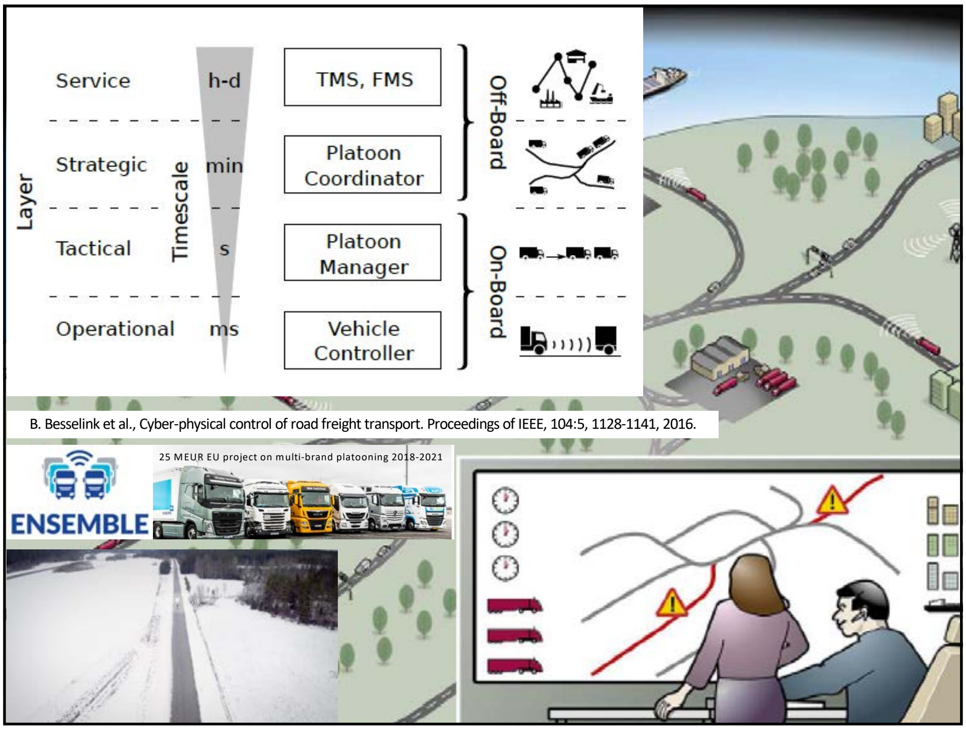
Layer
Service
Strategic
Tactical
Operational
Timescale
h-d
min
s
ms
TMS, FMS
Platoon Coordinator
Platoon Manager
Vehicle Controller
Off-Board
On-Board
B. Besselink et al., Cyber-physical control of road freight transport. Proceedings of IEEE, 104:5, 1128-1141, 2016.
ENSEMBLE
25 MEUR EU project on multi-brand platooning 2018-2021

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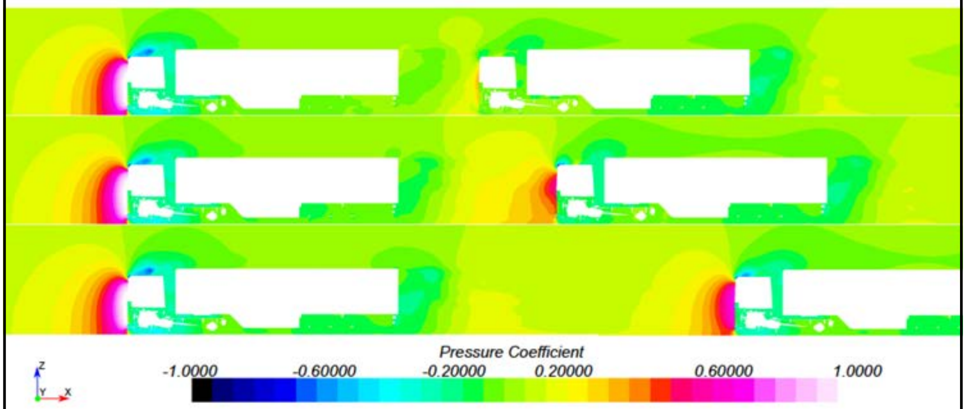
The Physics



Norrby (2014), Liang (2016)

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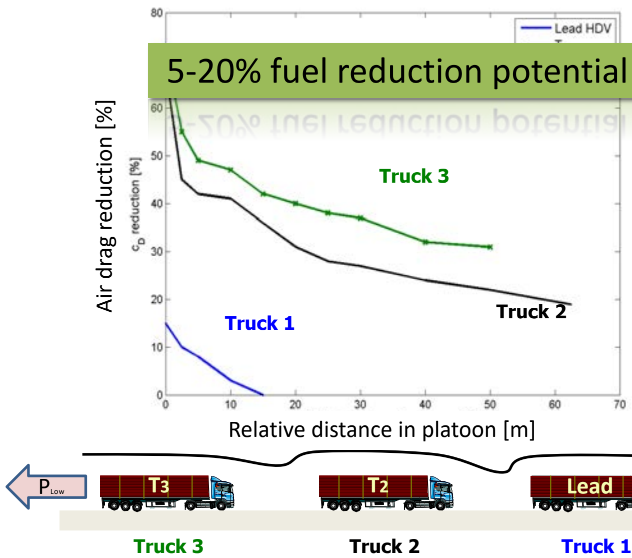
Air Drag Reduction in Truck Platooning



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

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

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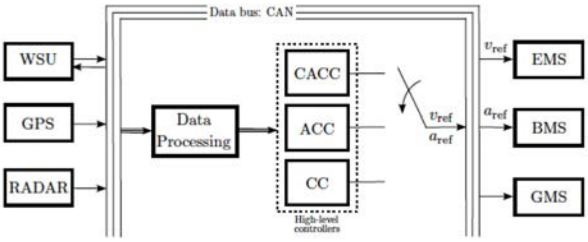
Vehicle System Architecture

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

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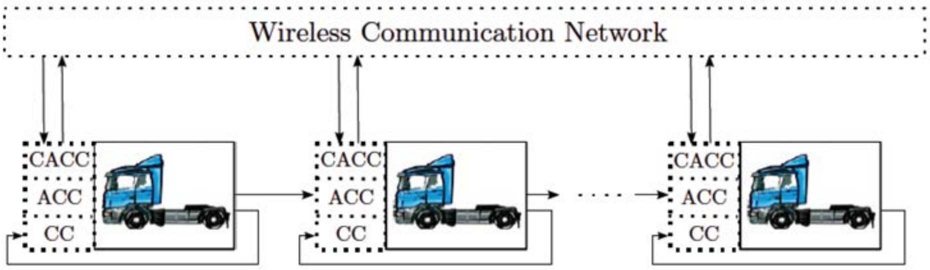
Platoon System Architecture



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

Alam et al., 2014

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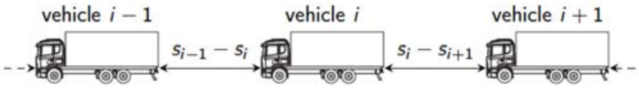
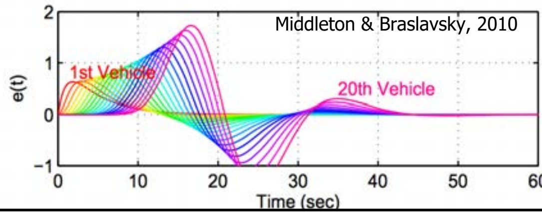
How to Control Inter-vehicular Spacings?



- 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)



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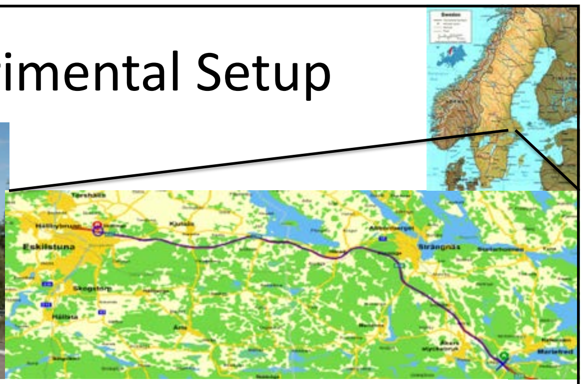
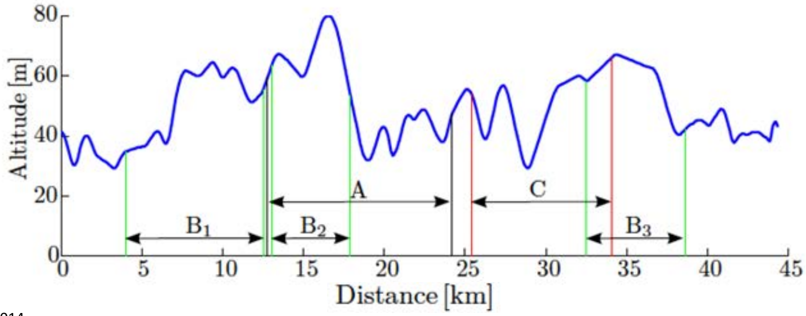
Experimental Setup





Alam, 2014

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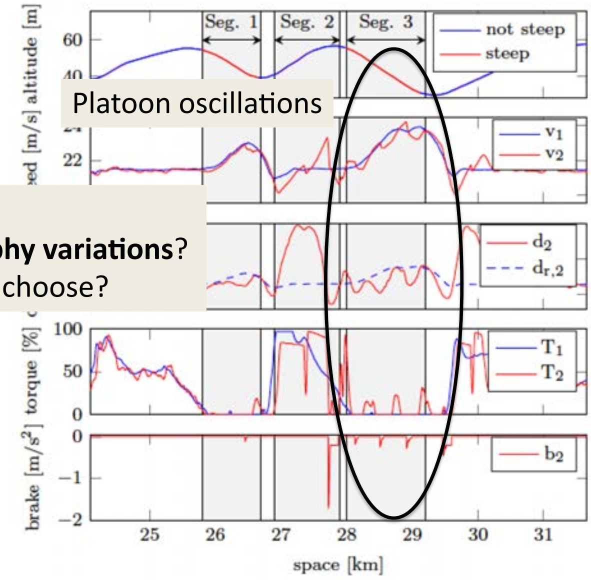
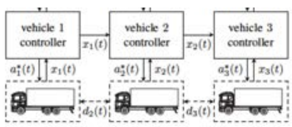
Experimental Results



Platoon oscillations

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



Alam, 2014

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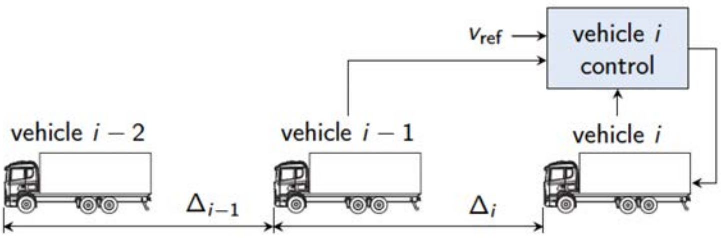
Constant Time Gap Spacing Policy

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

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



Besselink & J, 2017

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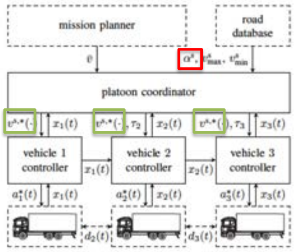
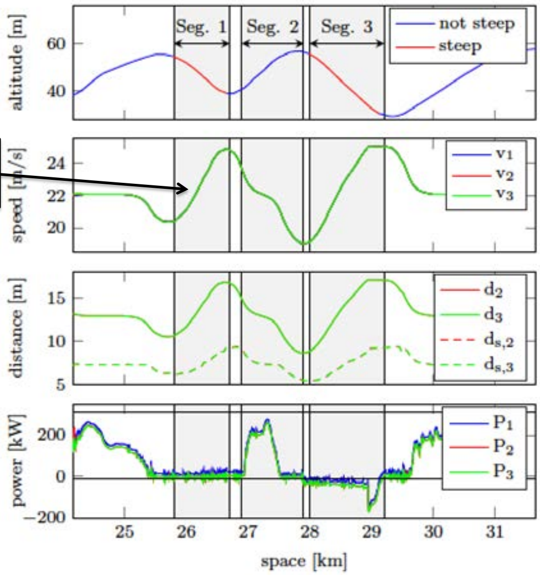
Simulations with Platoon Coordinator and Look-ahead Road Grade Information

Successful tracking of common platoon velocity reference





Turri et al., 2015

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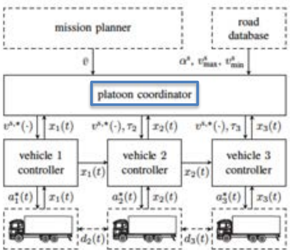
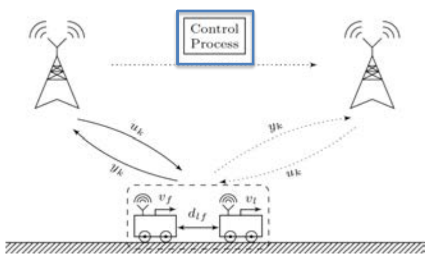
5G Cellular Implementation of Platoon Coordinator

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





van Dooren et al., 2017

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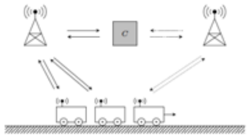
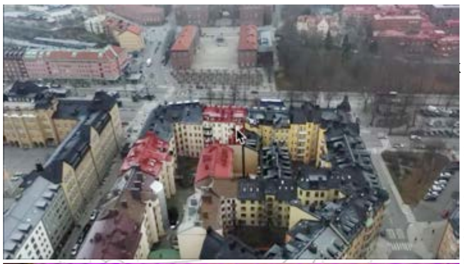
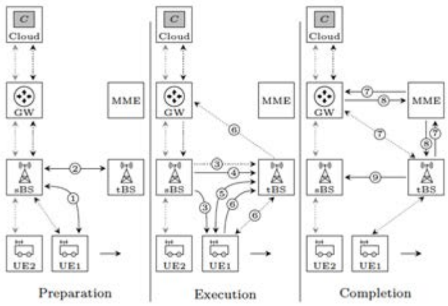
Controller Code Handover Supporting Vehicle Platooning






5G test network @ KTH launch Dec 5, 2018

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



van Dooren et al., 2017, 2018

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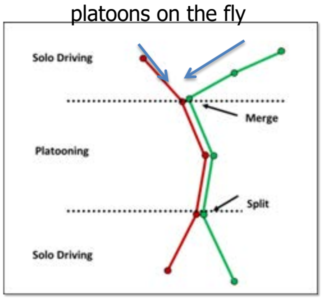
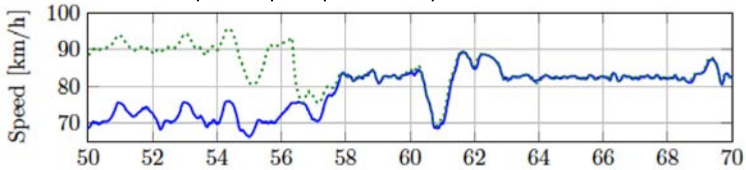
Platoon Formation

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

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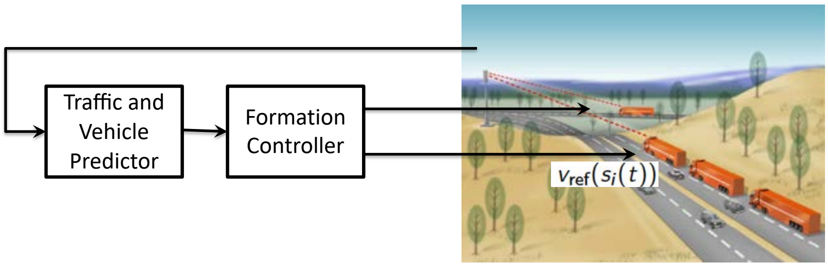
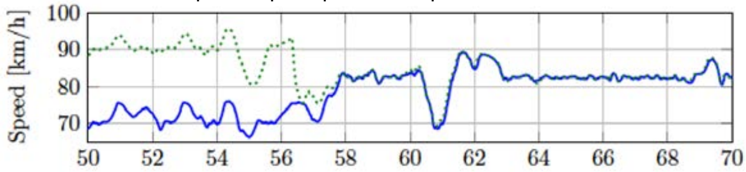
Platoon Formation

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

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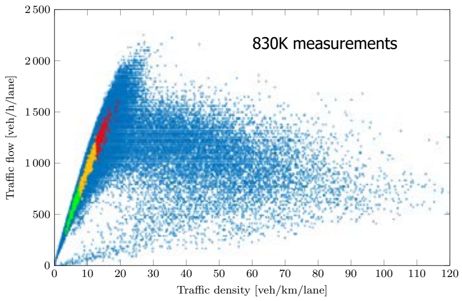
Platoon Formation Experiments

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

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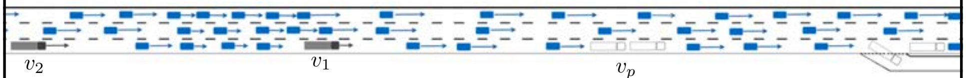
Platoon Formation Optimization



v_2 v_1 v_p

Catch-up phase Platooning phase Split

$$\underset{v_1, v_2, v_p \in [v_{\min}, v_{\max}]}{\text{minimize}} \quad \text{Total fuel consumption}$$
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

Discretize Lighthill-Whitham-Richards PDE $\partial_\tau \rho(x,\tau) + \partial_x Q(\rho(x,\tau)) = 0$ with 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 $i+1$

Cicic and J, 2019

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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

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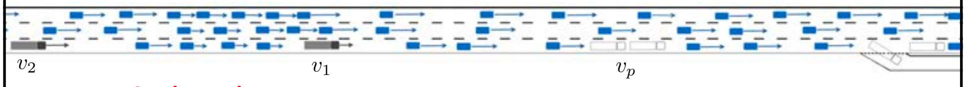
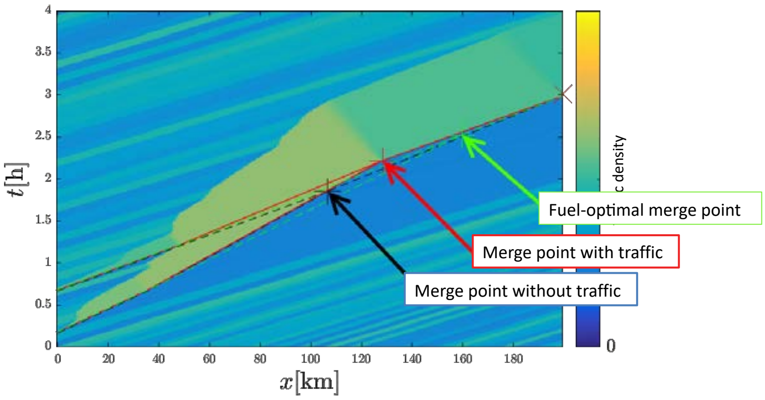
Numerical Example





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

Cicic and J, 2019

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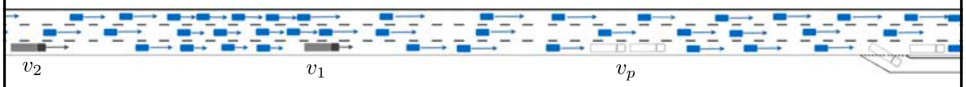
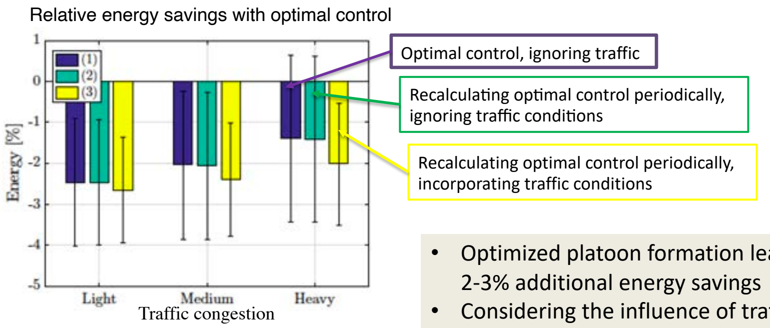
Energy Savings





- Optimized platoon formation leads to 2-3% additional energy savings
- Considering the influence of traffic improves energy savings

Cicic and J, 2019

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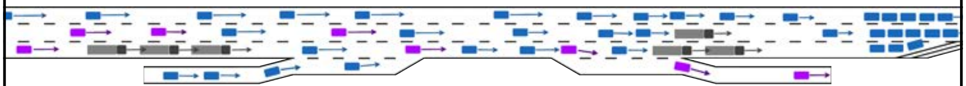
Can truck platooning be used to improve traffic conditions?

- Model truck platoons as bottlenecks moving in car traffic, cf., Lebacque et al. 1998; Delle Monache & Goatin 2014
- Restrict the traffic flow into the congested areas using controlled truck platoons



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

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

- $\rho_i(t)$ – 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

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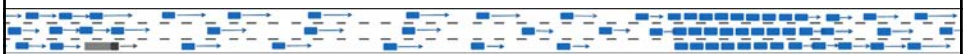
Stop-and-go wave dissipation



Upstream-propagating wave of slowed or stationary vehicles without an apparent bottleneck

Euler approach
- Control of vehicle flows, e.g., variable speed limits

[Hegyi et al., 2008]

Lagrange approach
- Control of individual vehicles or platoons, e.g., connected automated vehicles

[Stern et al., 2018, Kreidieh et al., 2018, Čičić & J, 2018]

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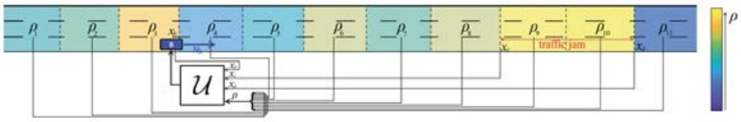
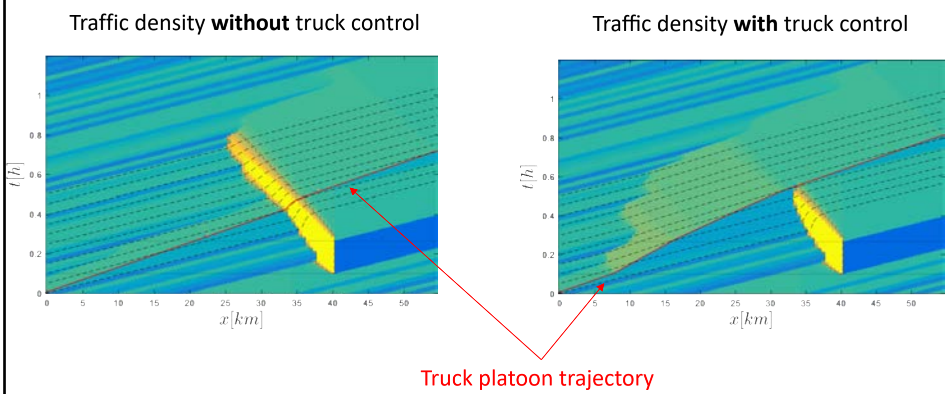
Control truck platoon velocity to dissipate congestion based on traffic densities





Cicic and J, 2018

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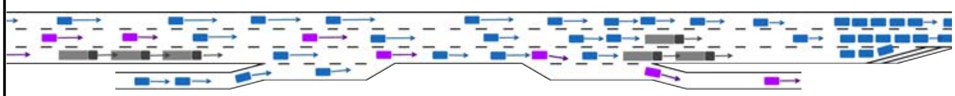
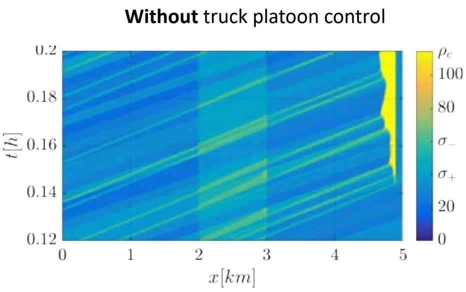
Truck platoon control reduces traffic congestion





38% total travel time increase
due to traffic congestion

Cicic, Jin and J, 2019

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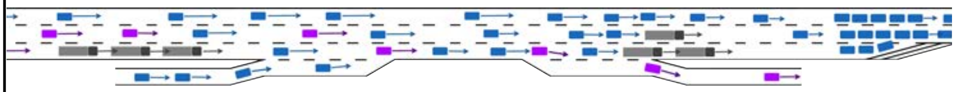
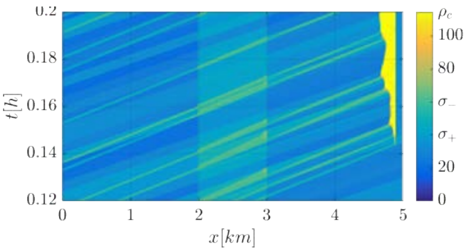
Truck platoon control reduces traffic congestion

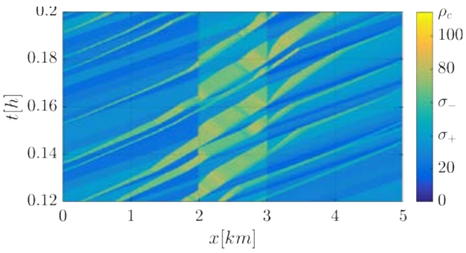


Without truck platoon control



38% total travel time increase
due to traffic congestion

With truck platoon control



8% total travel time increase
due to traffic congestion

Cicic, Jin and J, 2019

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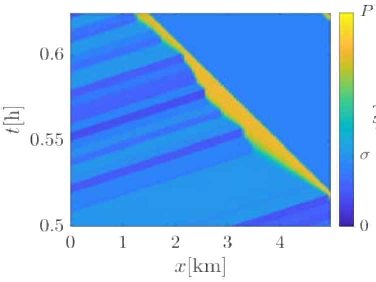
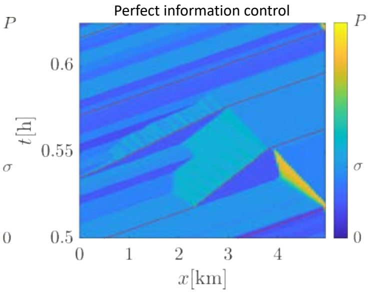
Stop-and-go wave dissipation based on state reconstruction

No control



Perfect information control



- What if perfect traffic state information is not available?
- Use reconstructed traffic state based on adaptively selected vehicle measurements

[Čičić et al., 2020]

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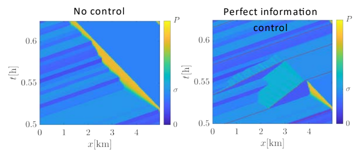
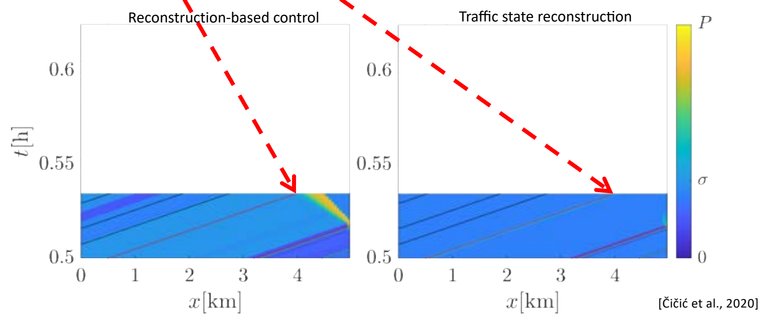
Stop-and-go wave dissipation based on state reconstruction

1. Probe vehicles detect congestion





[Čičić et al., 2020]

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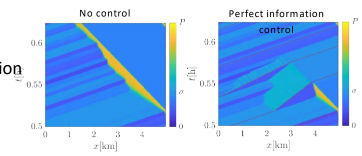
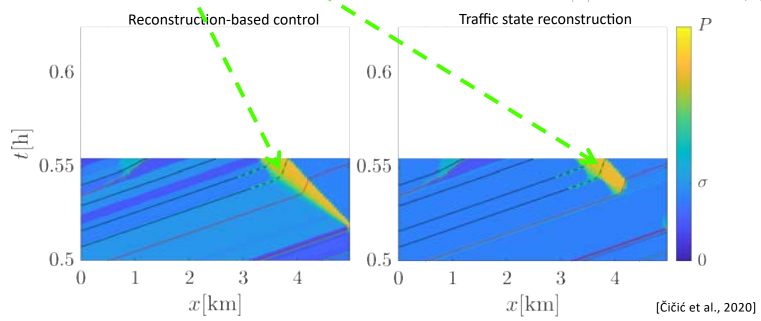
Stop-and-go wave dissipation based on state reconstruction

1. Probe vehicles detect congestion
2. More probe vehicles are activated to better reconstruct the congestion





[Čičić et al., 2020]

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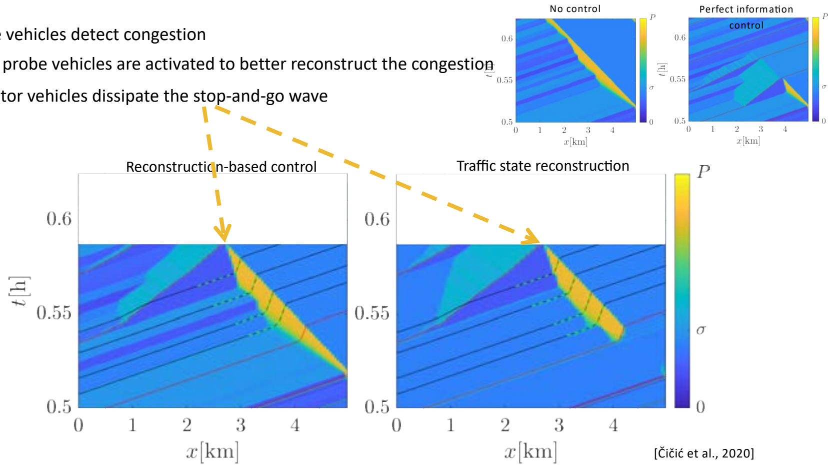
Stop-and-go wave dissipation based on state reconstruction

1. Probe vehicles detect congestion
2. More probe vehicles are activated to better reconstruct the congestion
3. Actuator vehicles dissipate the stop-and-go wave



[Čičić et al., 2020]

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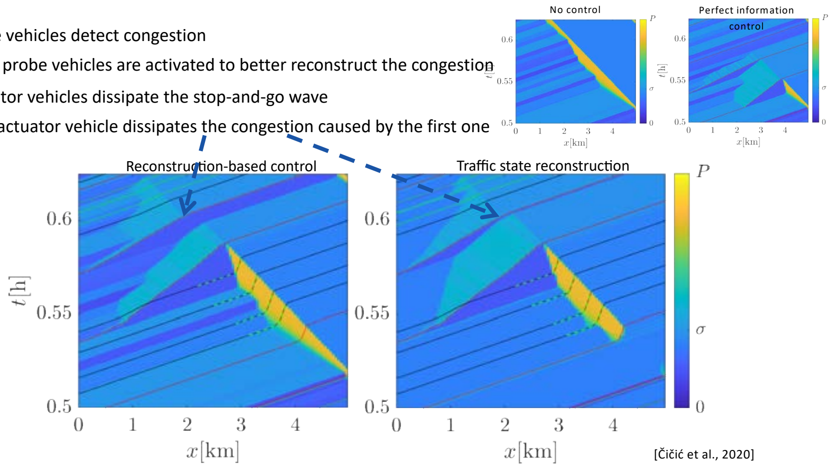
Stop-and-go wave dissipation based on state reconstruction

1. Probe vehicles detect congestion
2. More probe vehicles are activated to better reconstruct the congestion
3. Actuator vehicles dissipate the stop-and-go wave
4. Next actuator vehicle dissipates the congestion caused by the first one



[Čičić et al., 2020]

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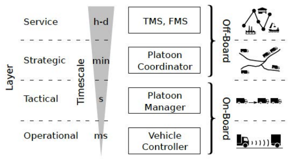
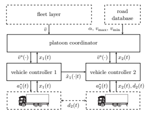
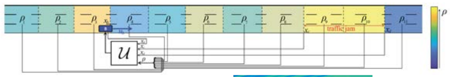
Conclusions



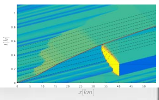
- **Automated road freight transport**
  - Integrated platoon coordinator and cruise-controller
  - Platoon control over V2V and V2I cellular communication
  - Automated vehicle match-making and platoon formation

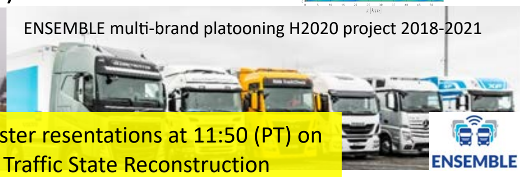


- Leads to significantly **lower fuel and operation costs**
- Control automated platoons to **reduce traffic congestion**



- Platoons acting as probe vehicles (sensors) and moving bottlenecks (actuators)





ENSEMBLE multi-brand platooning H2020 project 2018-2021

Matthieu Barreau poster resentations at 11:50 (PT) on Learning-based Traffic State Reconstruction

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