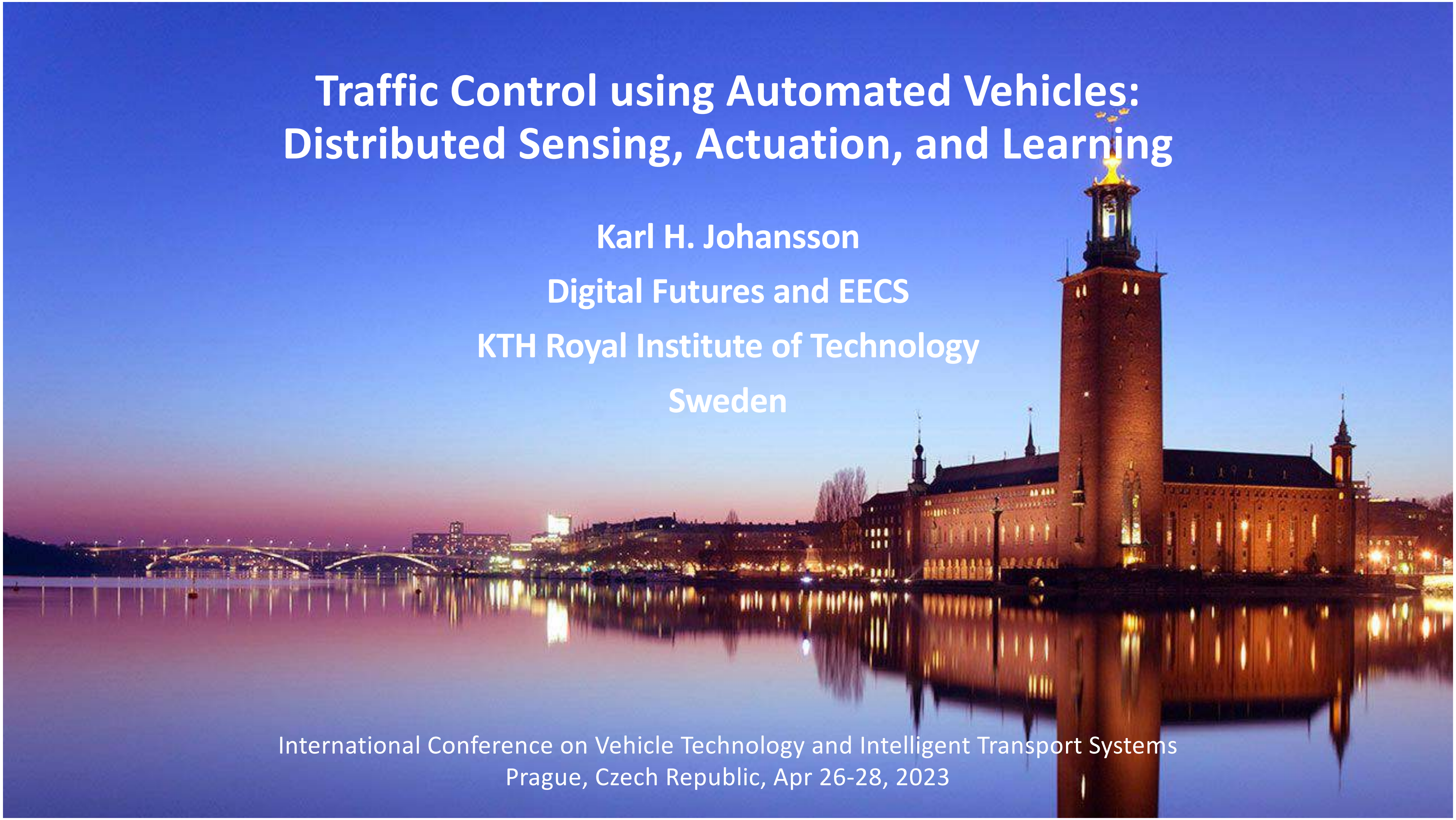

Traffic Control using Automated Vehicles: Distributed Sensing, Actuation, and Learning

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Digital Futures and EECS

KTH Royal Institute of Technology

Sweden

International Conference on Vehicle Technology and Intelligent Transport Systems
Prague, Czech Republic, Apr 26-28, 2023

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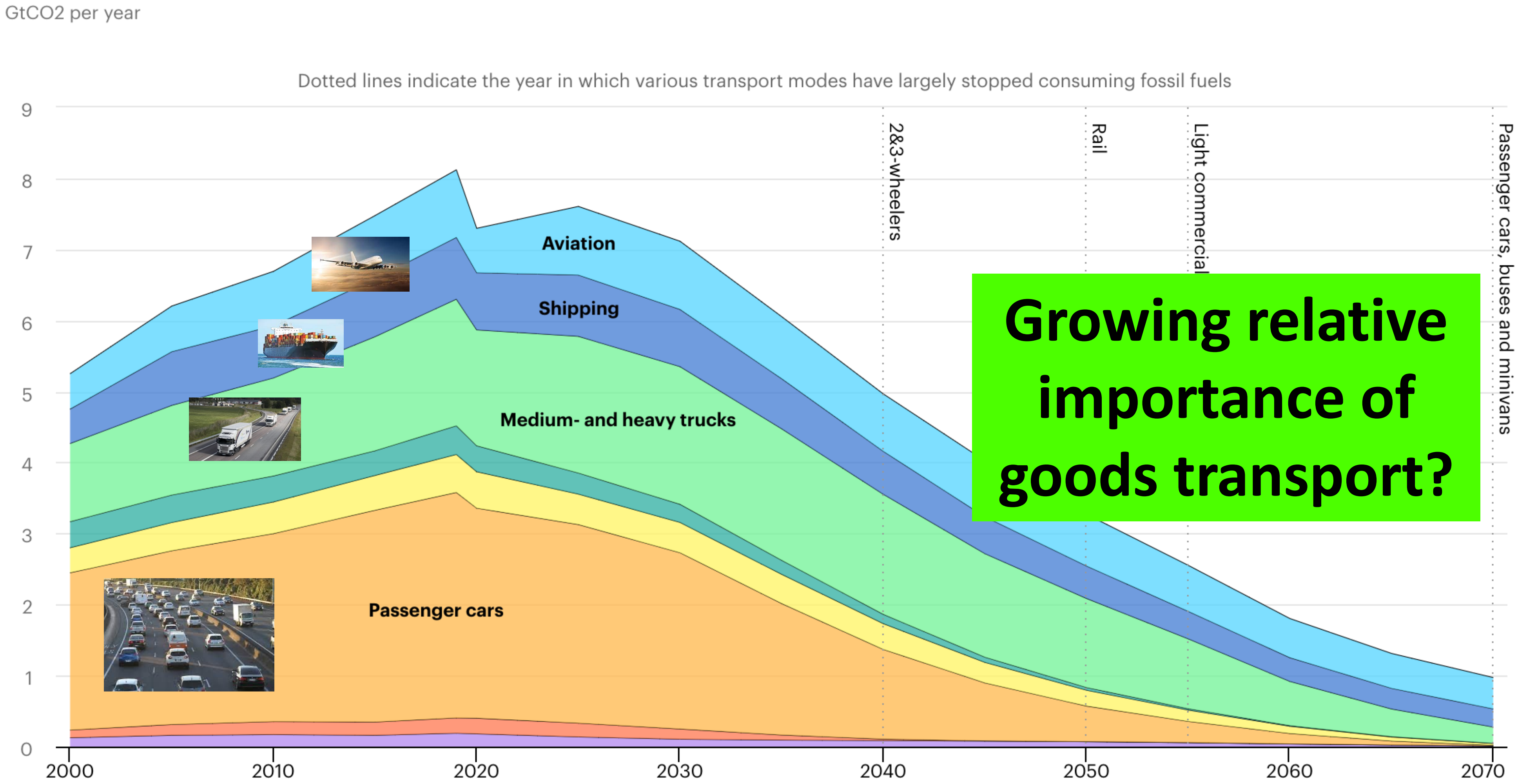
VINNOVA
SEVENTH FRAMEWORK PROGRAMME
COMPANION
THE FRAMEWORK PROGRAMME FOR RESEARCH AND INNOVATION HORIZON 2020
ENSEMBLE

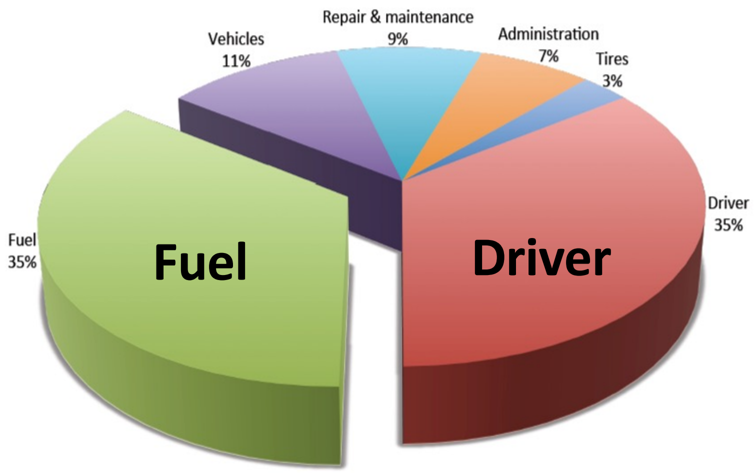
Transport CO2 Emissions in the Sustainable Development Scenario



International Energy Agency, http://www.iea.org

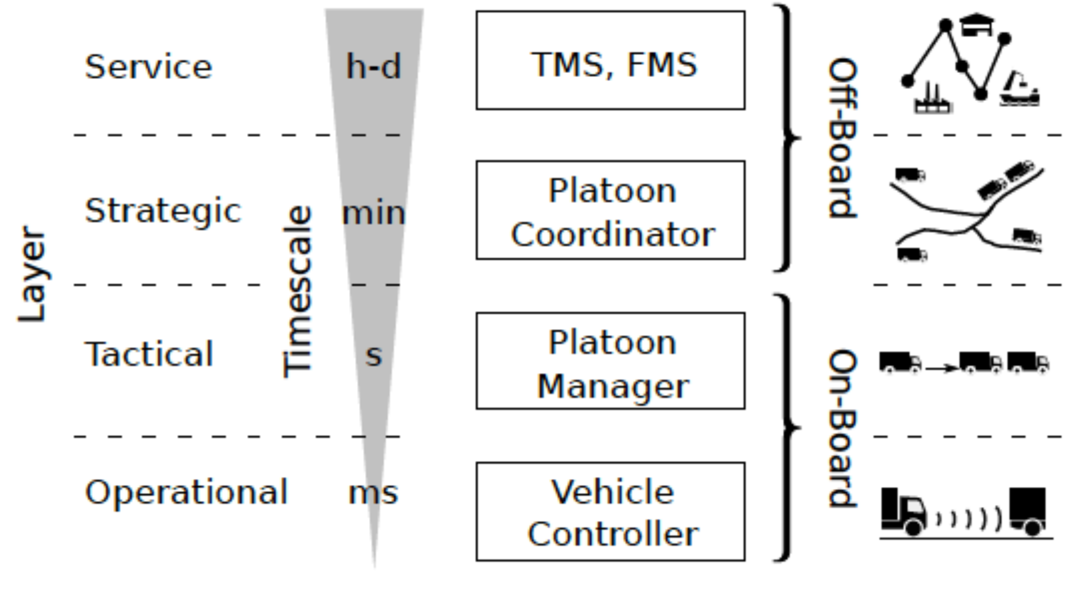
Why focus on fuel and automation for trucks?

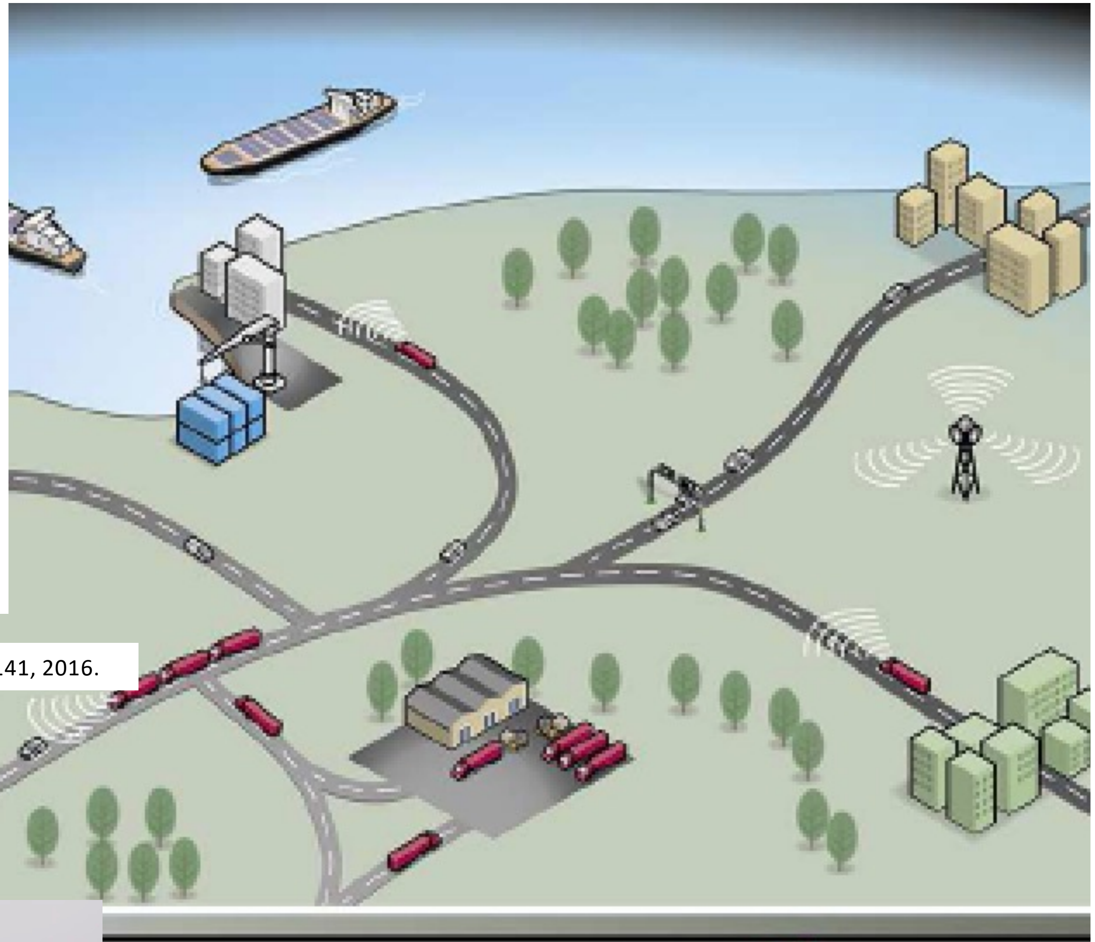
Life cycle cost for European heavy-duty vehicle



Total fuel cost 80 k€/year/vehicle

Schittler, 2003; Scania, 2012

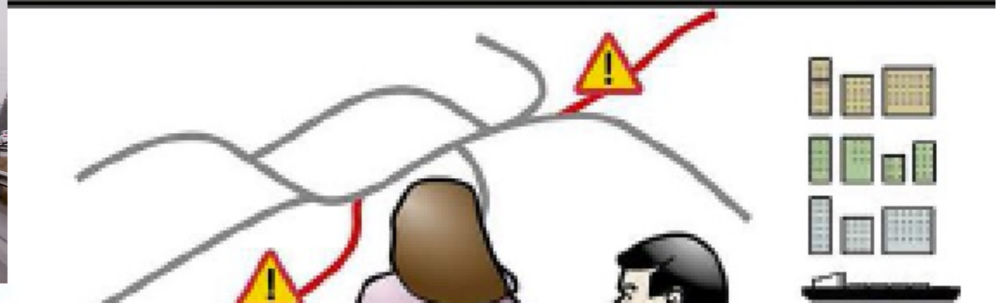




B. Besselink et al., Cyber-physical control of road freight transport. Proceedings of IEEE, 104:5, 1128-1141, 2016.

ENSEMBLE

25 MEUR EU project on multi-brand platooning 2018-2022



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

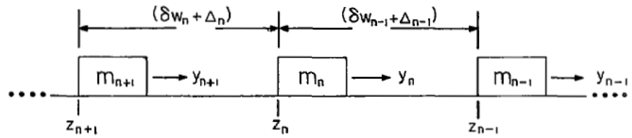
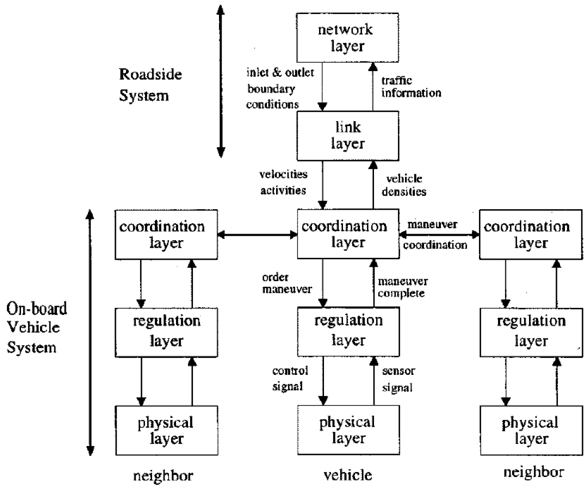


Fig. 1. Vehicles moving in a string.


PATH platoon demo San Diego 1997

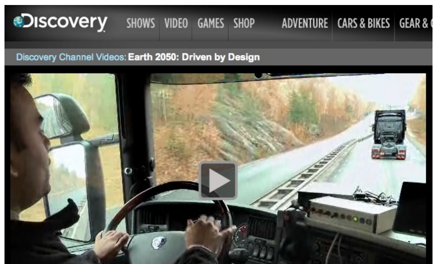


IEEE TRANSACTIONS ON AUTOMATIC CONTROL, VOL. 38, NO. 2, FEBRUARY 1993

Smart Cars on Smart Roads: Problems of Control

Pravin Varaiya, *Fellow, IEEE*

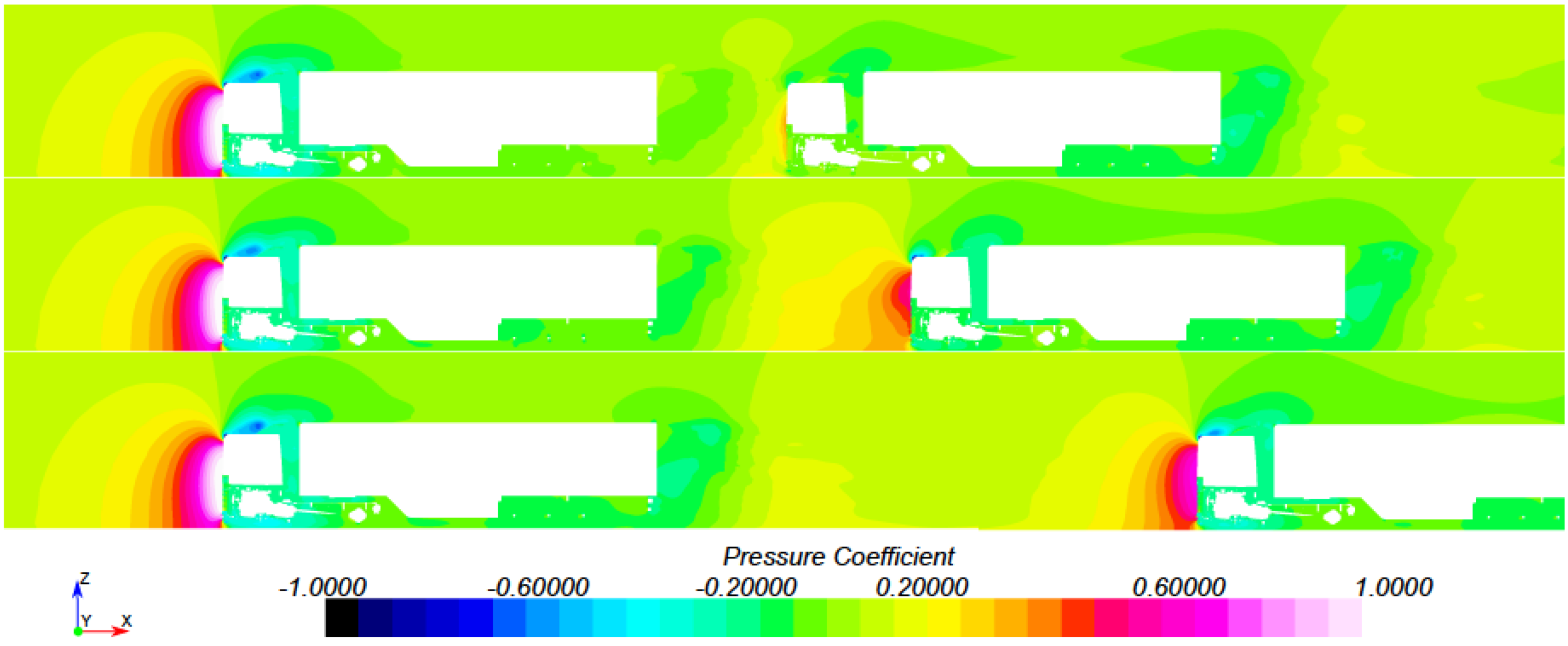

Scania



Swedish success stories

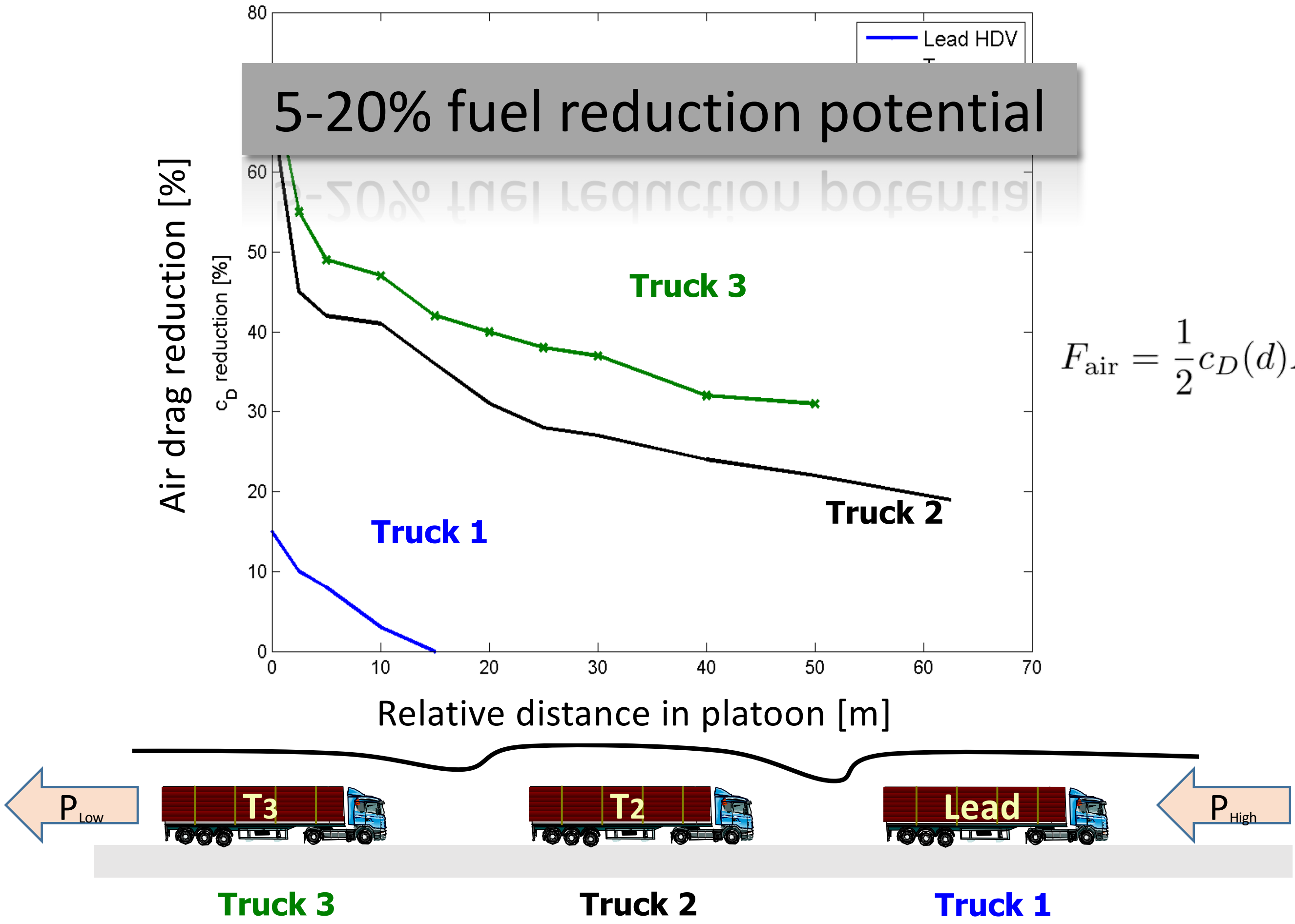

Volvo

The Physics



Norrby (2014), Liang (2016)

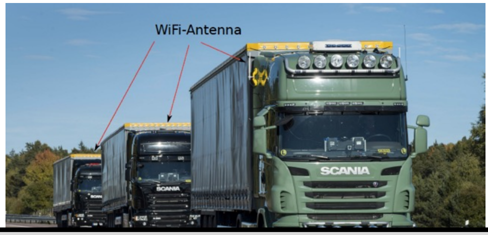
Air Drag Reduction in Truck Platooning



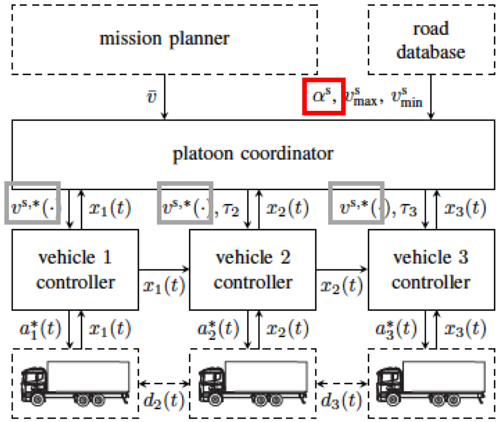
$$F_{\mathrm{air}} = \frac{1}{2} c_D(d) A_a \rho_a v^2$$

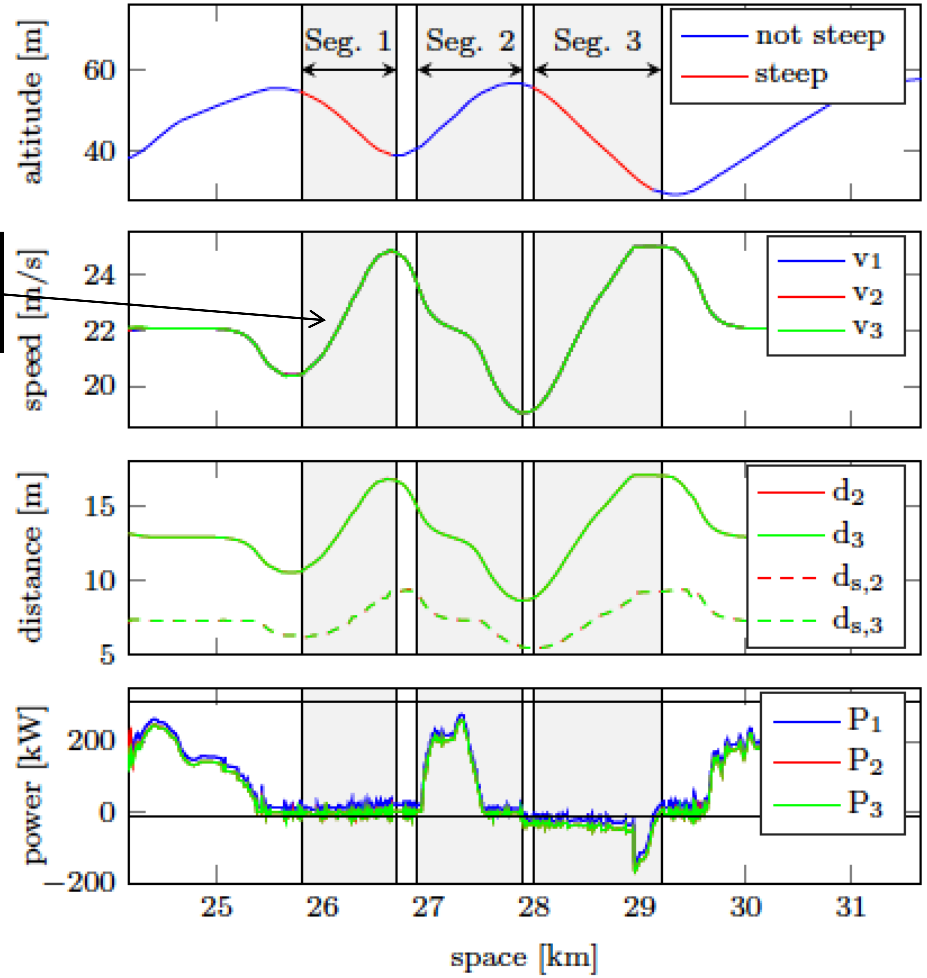
Wolf-Heinrich & Ahmed (1998), Bonnet & Fritz (2000), Scania CV AB (2011)

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



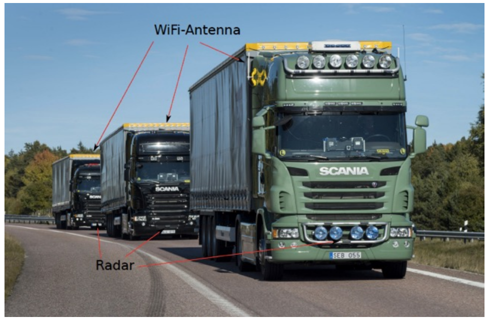
Successful tracking of common platoon velocity reference



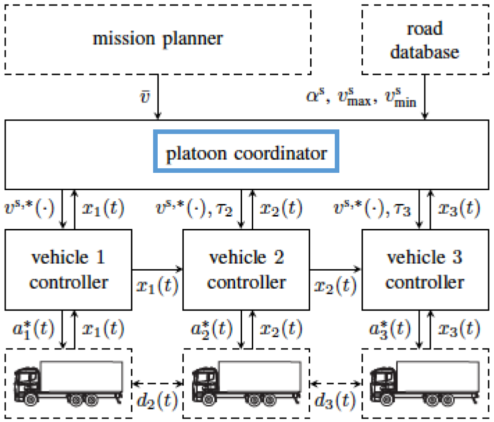


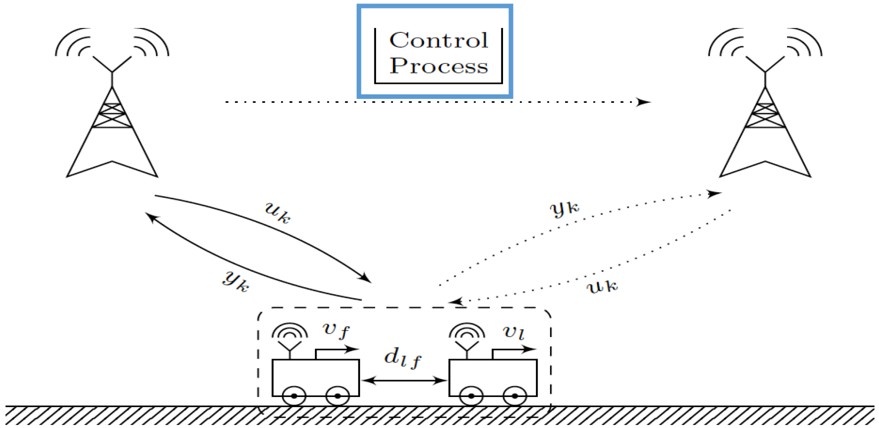
Turri et al., 2015

5G Cellular Implementation of Platoon Coordinator



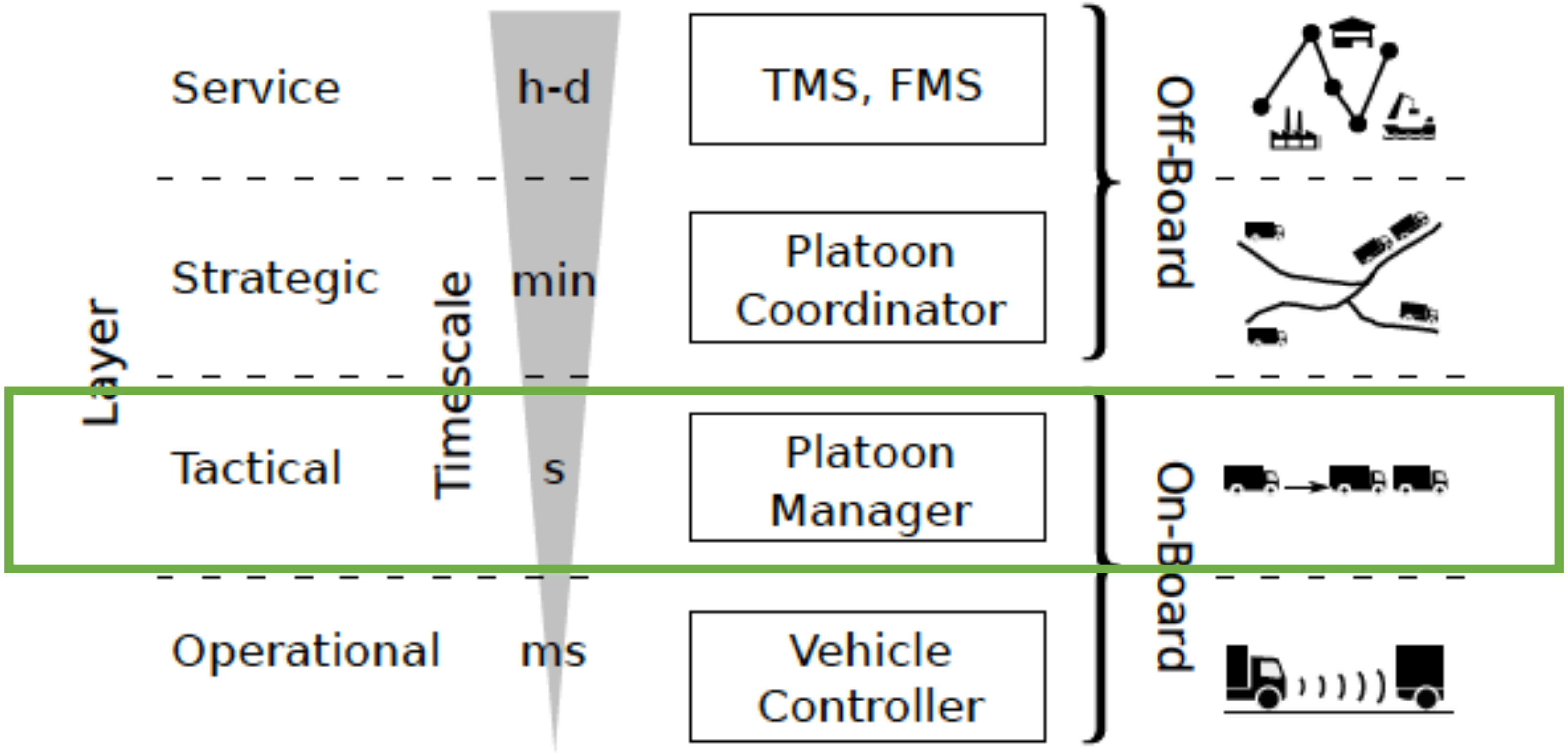
- Platoon coordinator generates common velocity reference: $v_i(t) \to v_{\text{ref}}(s_i(t))$,
- Can be computed in the cellular system (4G, 5G, 6G)
- New handover scheme for moving control computations between base stations





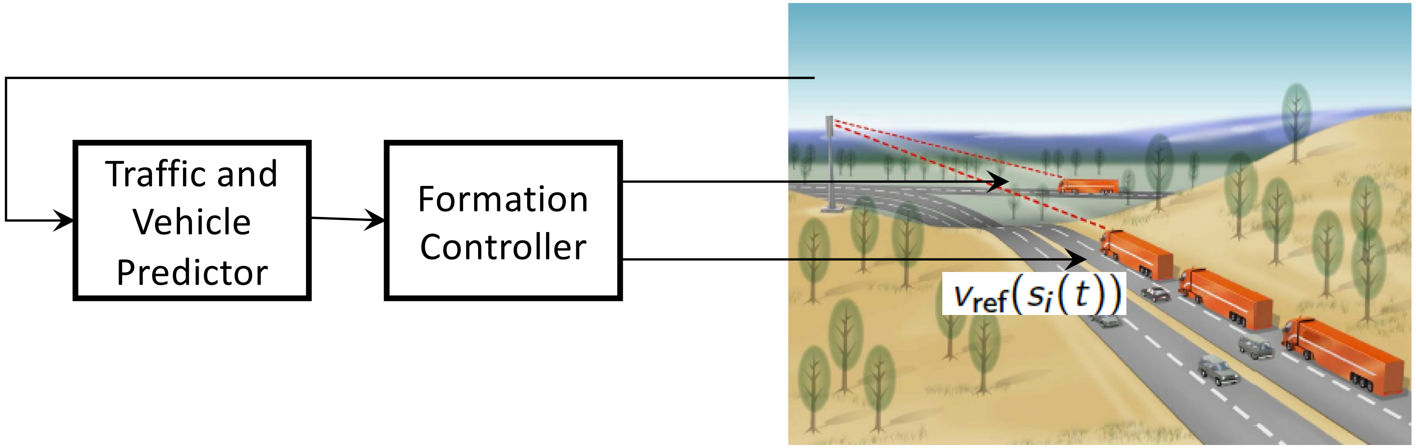
van Dooren et al., 2017

How to form platoons?

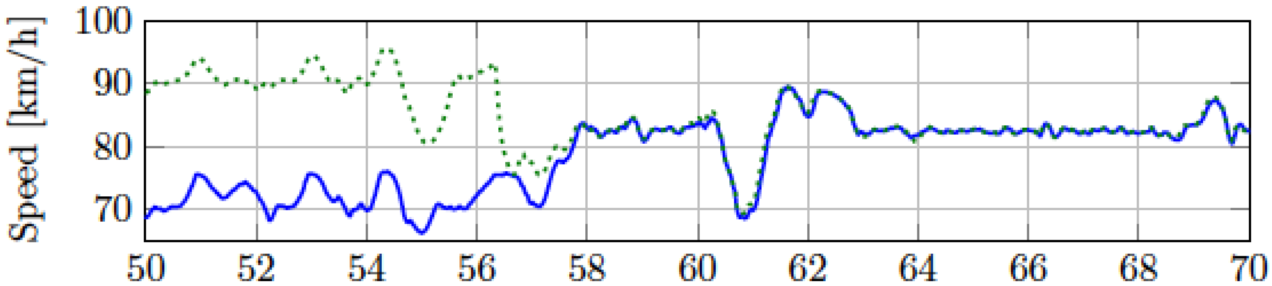


Platoon Formation

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



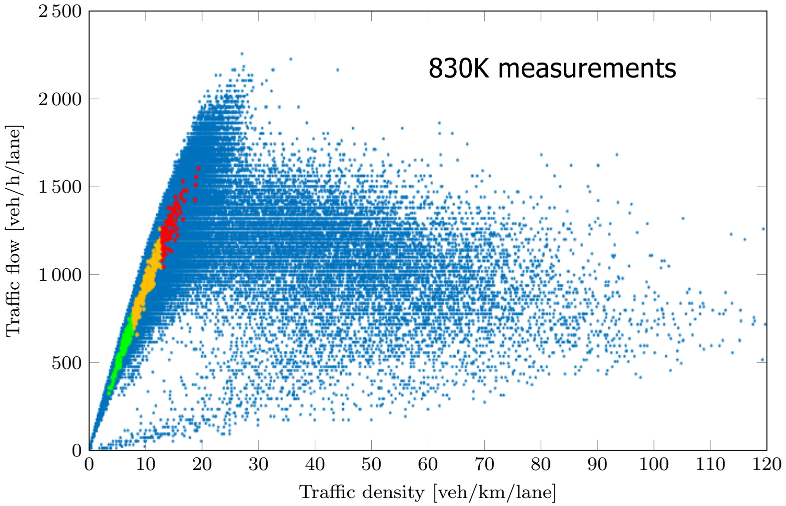
Optimal speed profiles for platoon formation



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

Platoon Formation Experiments

Fundamental diagram of traffic flow

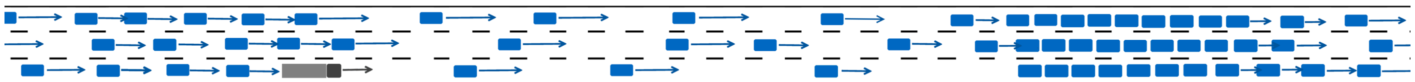


- 600 test runs on E4 in Nov 2015
- Traffic measurements from road units together with onboard sensors

Liang et al., 2016

Can controlled truck platoons be used to improve traffic conditions?

- Trucks act as bottlenecks moving in car traffic
- Regulate cars flowing into congested area



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

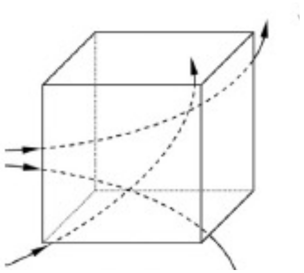
Cf., [Lebacque et al. 1998; Delle Monache & Goatin 2014]

Flows according to Euler and Lagrange

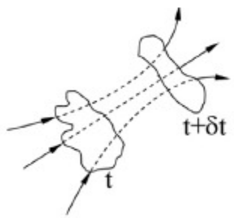
Leonhard Euler (1707-1783)

Joseph-Louis Lagrange (1736-1813)

Euler was looking at fluid motion focused on specific locations in the space through which the fluid flows as time passes.



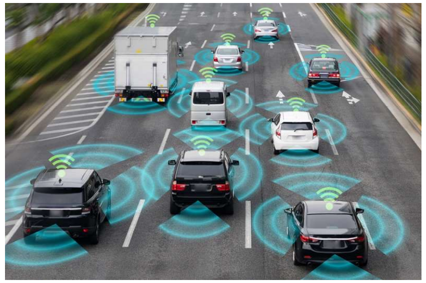
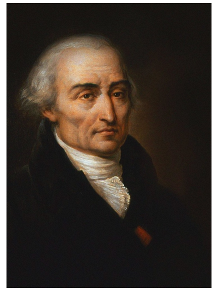
Lagrange was looking at fluid motion where the observer follows an individual fluid parcel as it moves through space and time



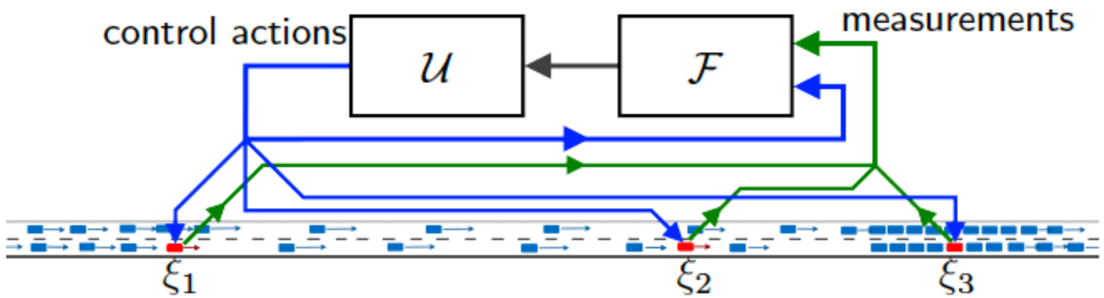
From Eulerian to Lagrangian traffic control



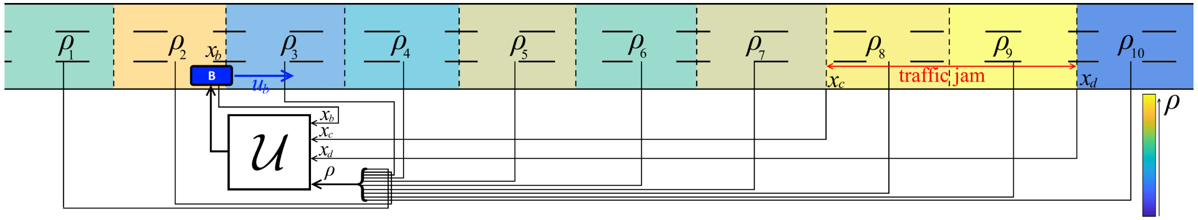
Leonhard Euler (1707-1783)
Stationary observer of the flow
Traffic control based on fixed infrastructure
High deployment costs and limited flexibility

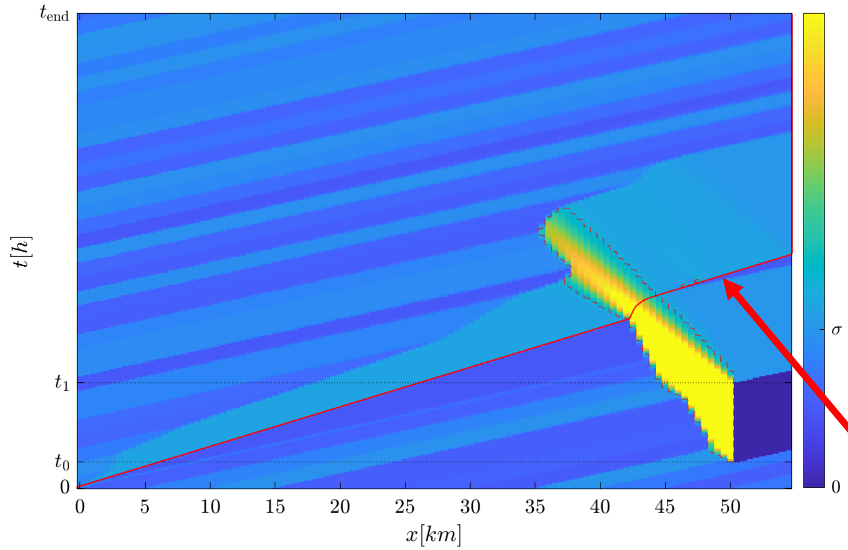
Joseph-Louis Lagrange (1736-1813)
Observers moves with the flow
Traffic control based on mobile sensors and actuators
Need for a new system theoretic foundation



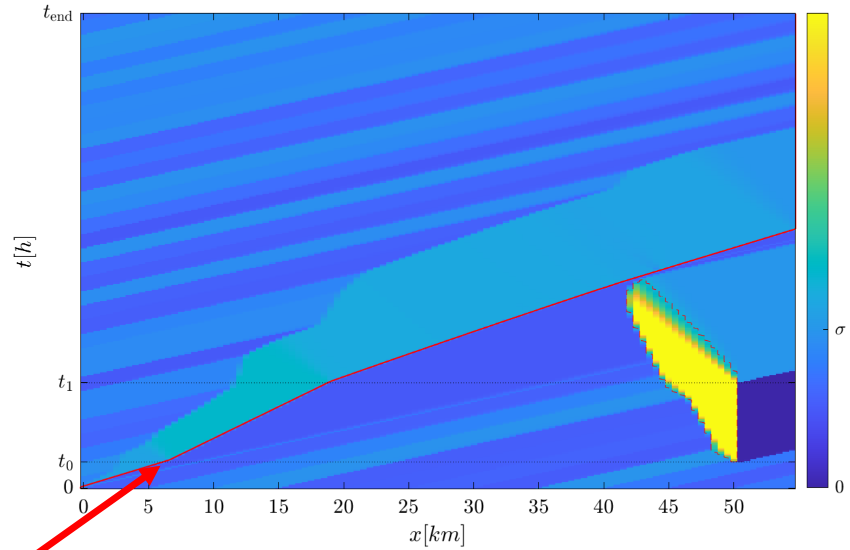
Control truck platoon velocity to dissipate traffic congestion



Without truck platoon control



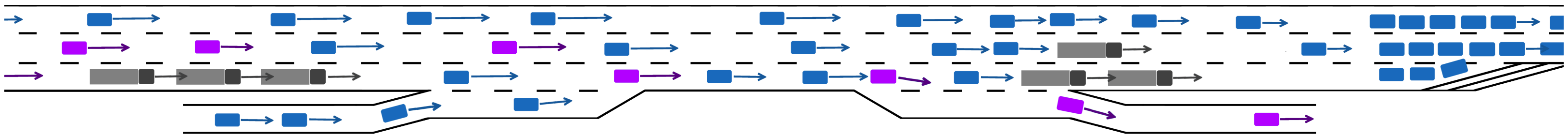
With truck platoon control



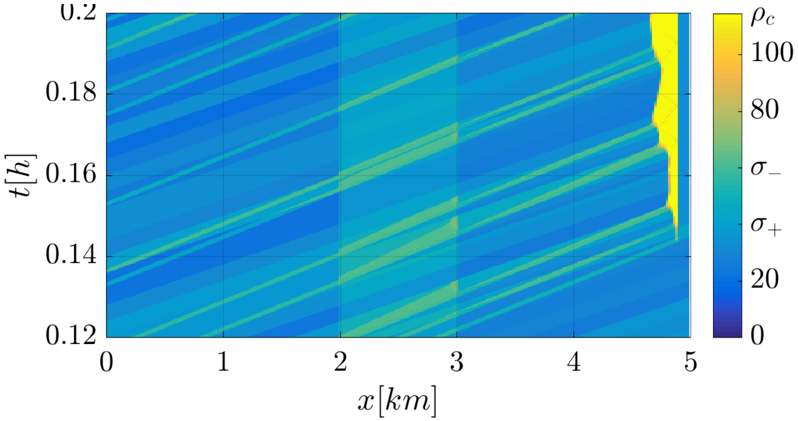
Truck platoon trajectory

Cicic and J, 2018

Truck platoon control reduces traffic congestion



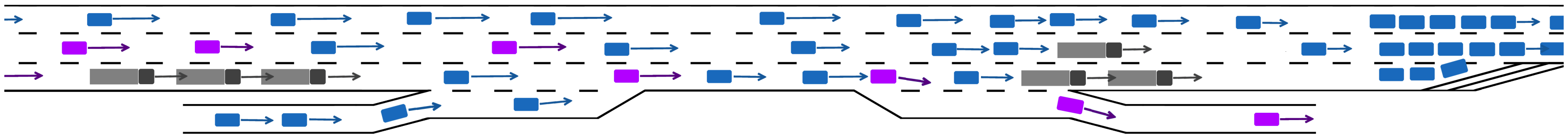
Without truck platoon control



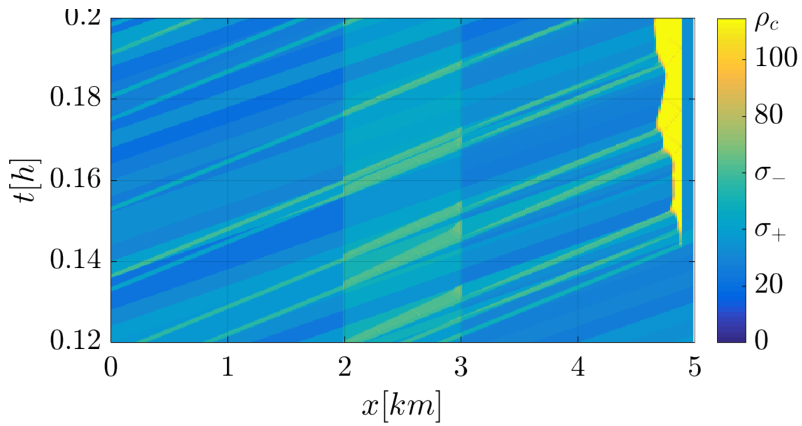
38% total travel time increase
due to traffic congestion

Cicic, Jin and J, 2019

Truck platoon control reduces traffic congestion

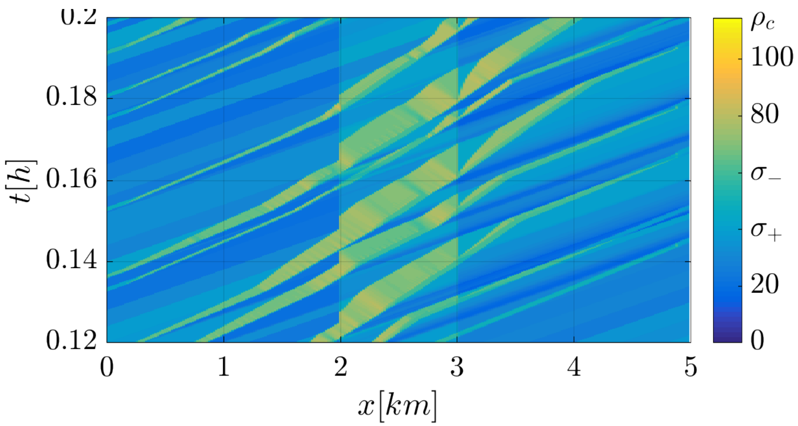


Without truck platoon control



38% total travel time increase
due to traffic congestion

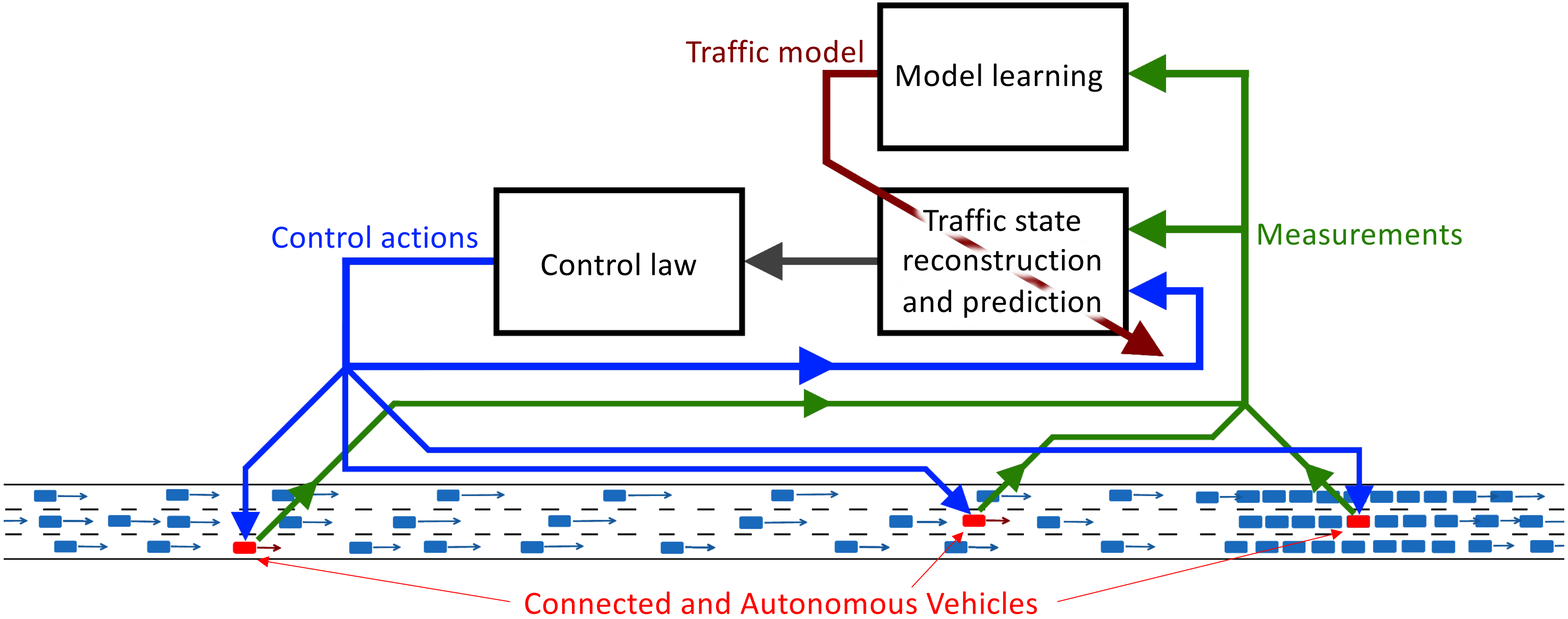
With truck platoon control



8% total travel time increase
due to traffic congestion

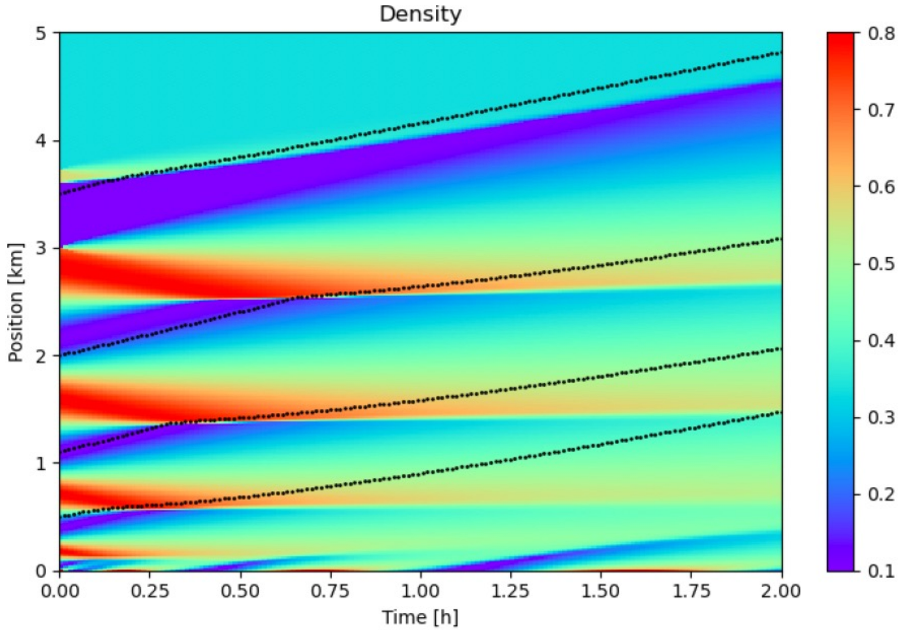
Cicic, Jin and J, 2019

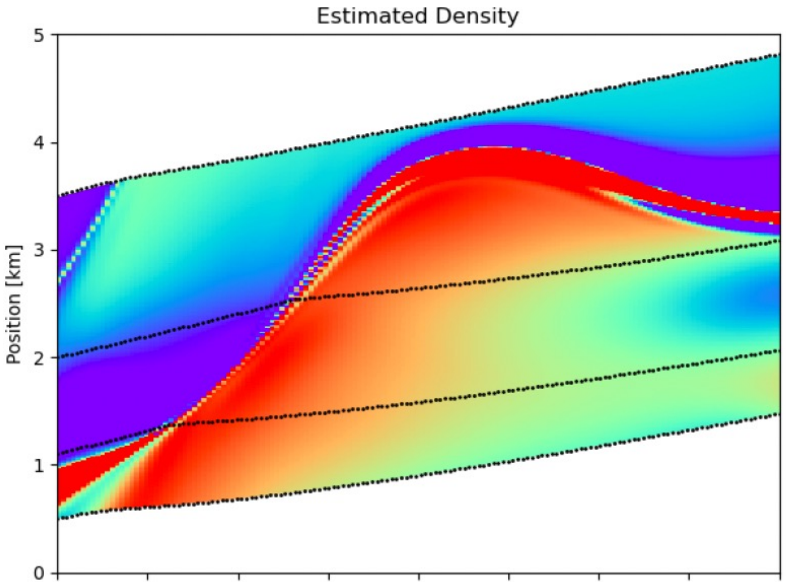
Lagrangian traffic control system

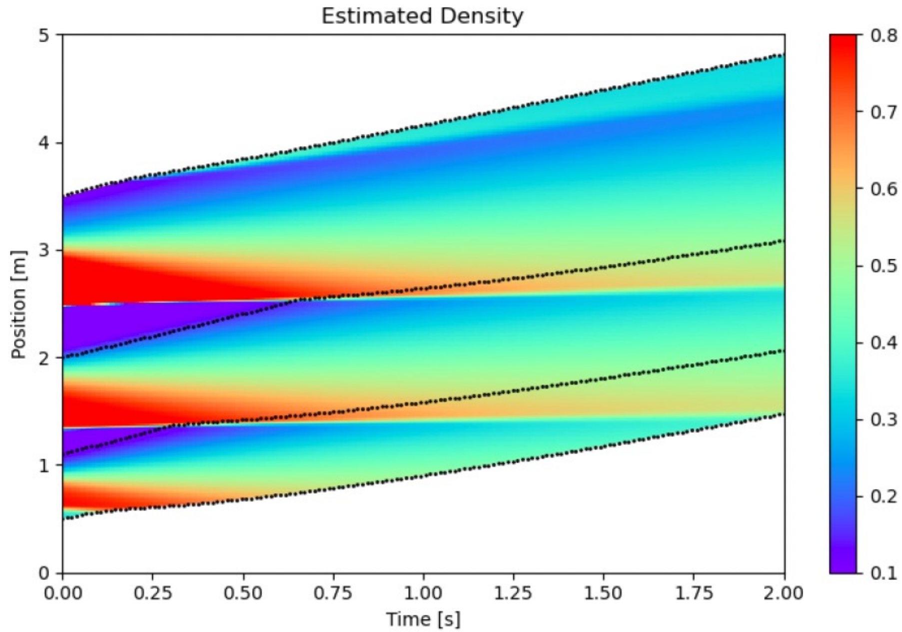


$$\frac{\partial \rho(x,t)}{\partial t} + \frac{\partial Q(\rho(x,t),x,t)}{\partial x} = 0$$

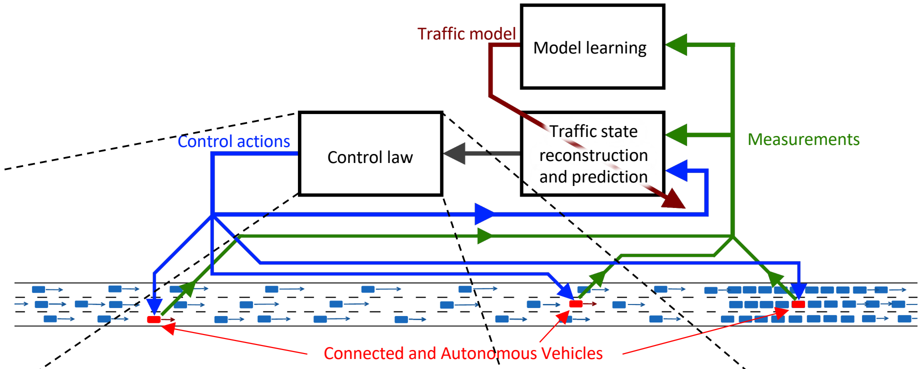
[Čičić., 2021]


Density
Position [km]
Time [h]


Estimated Density
Position [km]


Estimated Density
Position [m]
Time [s]

Control law

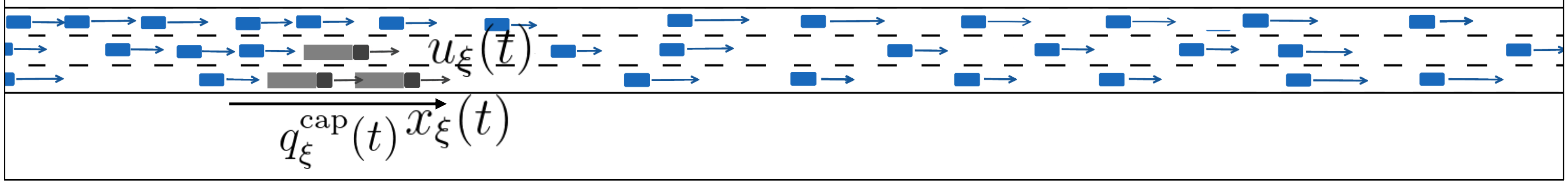


Control the traffic flow at the positions of available controlled vehicles

$$\underset{\substack{u_\xi(\cdot)\in[u^{\min},u^{\max}]\\ q_\xi^{\mathrm{cap}}(\cdot)\in[q^{\mathrm{lo}},q^{\mathrm{hi}}]}}{\text{minimize}} \quad \text{Total Time Spent}$$

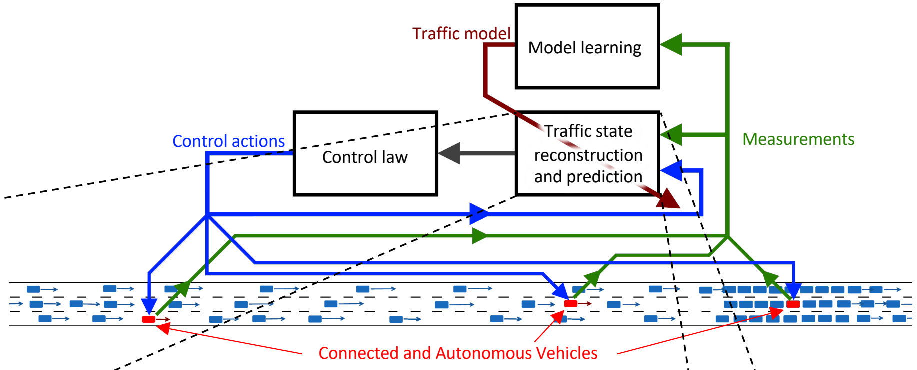
subject to traffic dynamics with moving bottlenecks

controlled vehicles dynamics and constraints

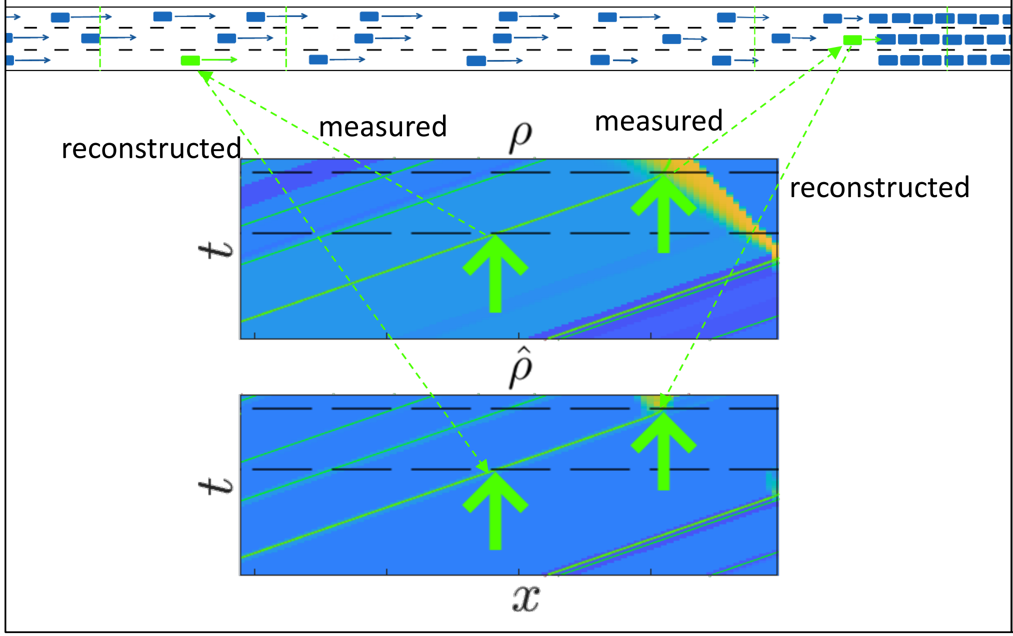


[Čičić., 2021]

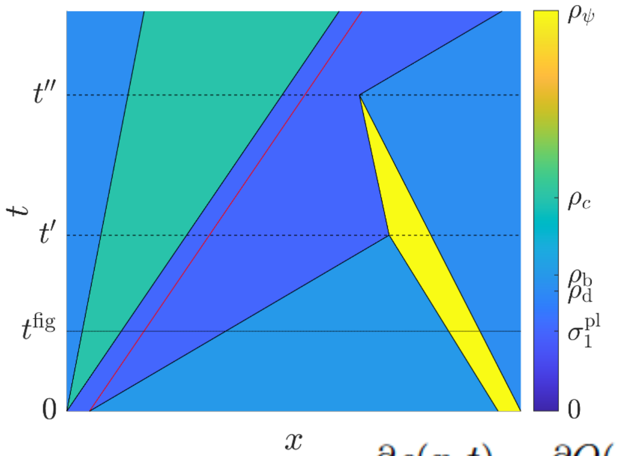
Traffic state reconstruction and prediction



- Use local traffic measurements to reconstruct the traffic state



- Traffic evolution prediction given applied control actions
  - Front-tracking Transmission System Model



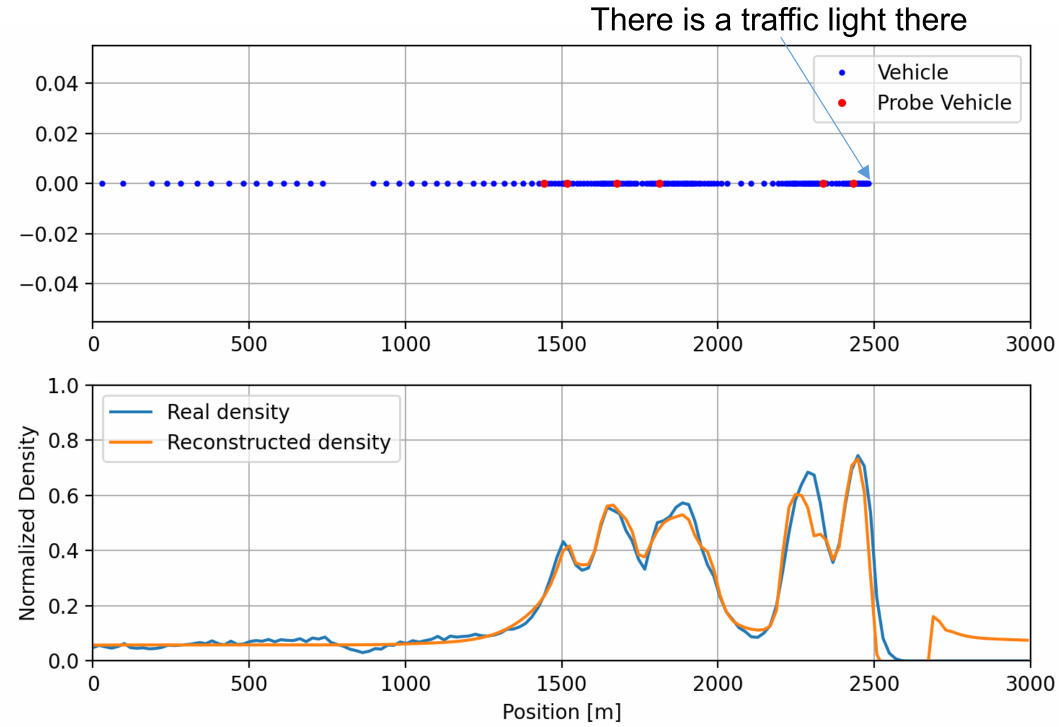
$$\frac{\partial \rho(x,t)}{\partial t} + \frac{\partial Q(\rho(x,t),x,t)}{\partial x} = 0$$

[Čičić., 2021]

State Reconstruction using Probe Data

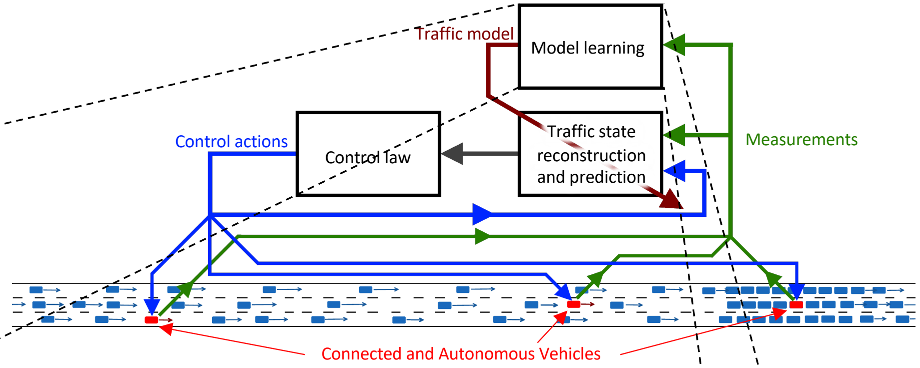
Microscopic simulation

Reconstruction algorithm

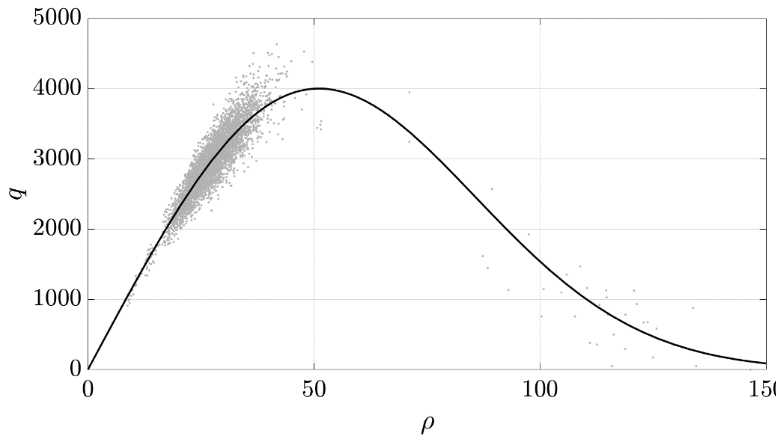


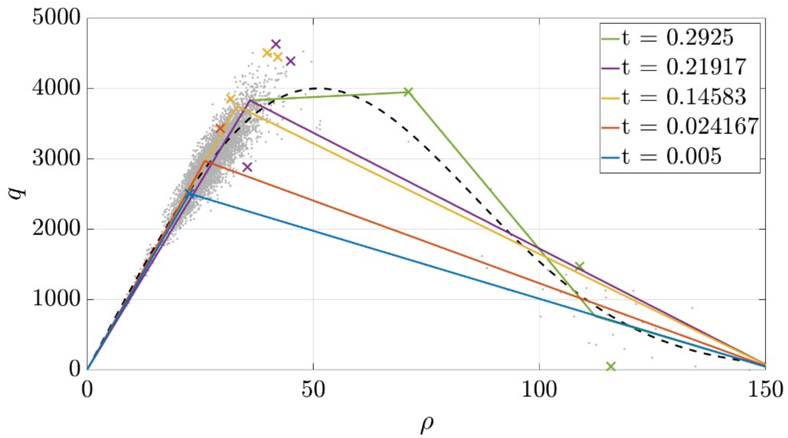
[Barreau et al., 2021]

Model learning



- Learn all flux functions using collected traffic measurements
  - Parametric, *batch* – assume a flux function form and minimize deviations from all measurements
  - Nonparametric, *stream* – piecewise linear flux function with nodes based on measurements as they become available



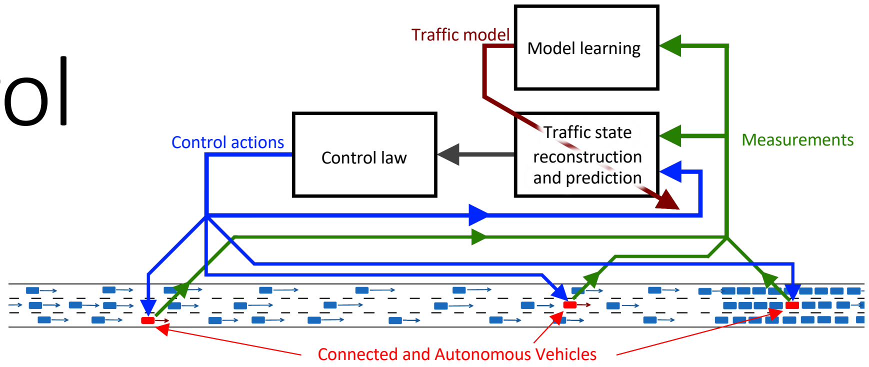


$$\frac{\partial \rho(x,t)}{\partial t} + \frac{\partial Q(\rho(x,t),x,t)}{\partial x} = 0$$

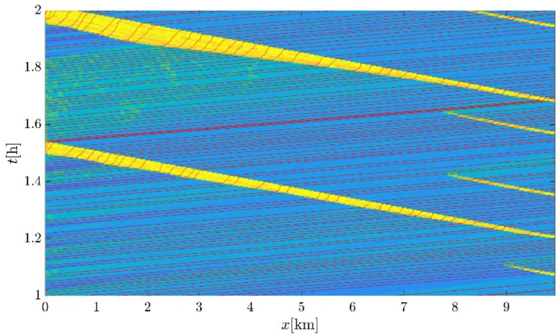
[Čičić, 2021]

Cf., physics-informed machine learning [M Raissi et al., 2019]

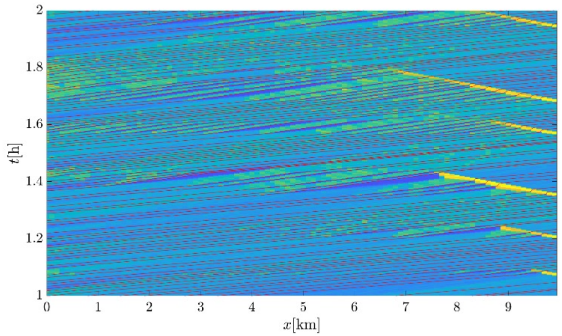
Evaluation of Lagrangian control



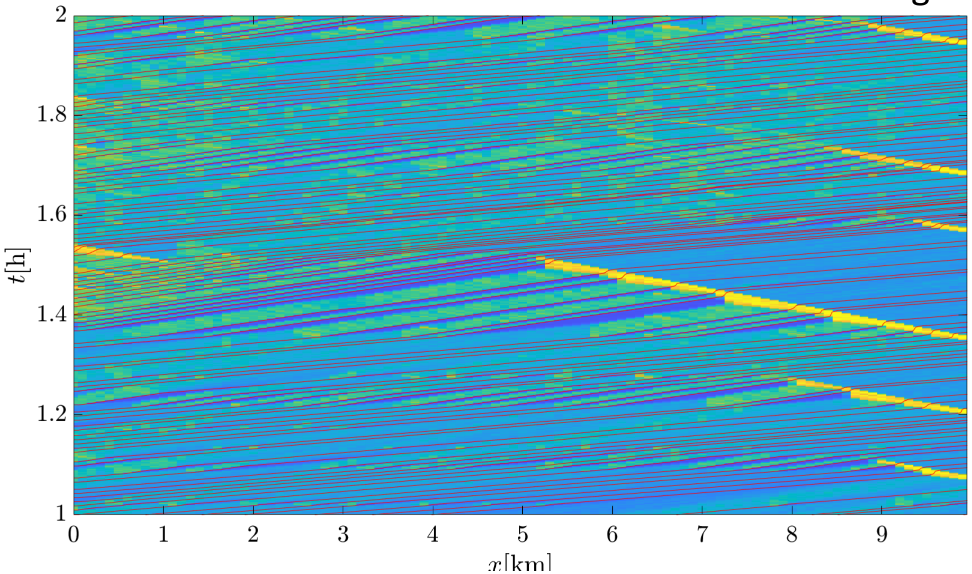
No control



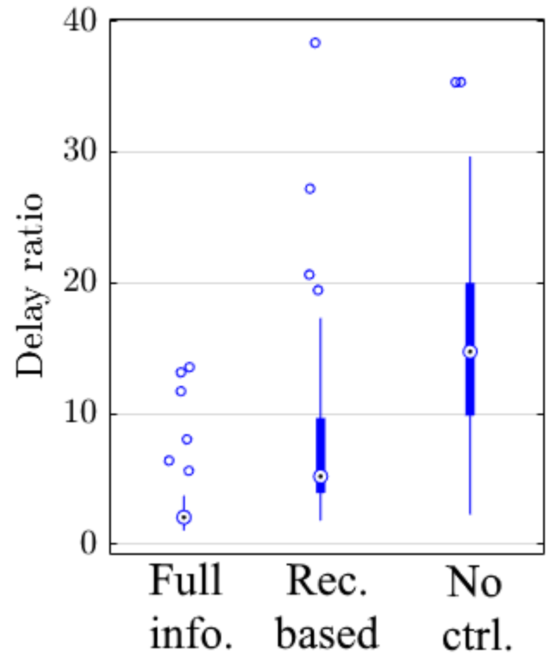
Full-information control



Reconstruction-based control with model learning

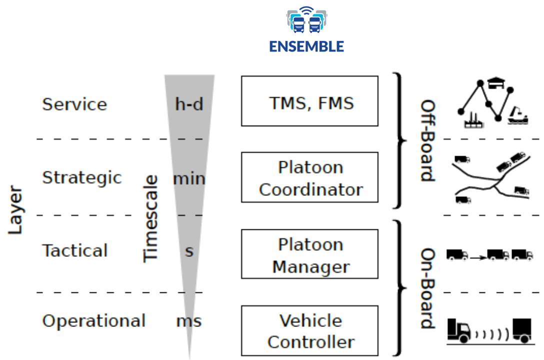


Travel time variations

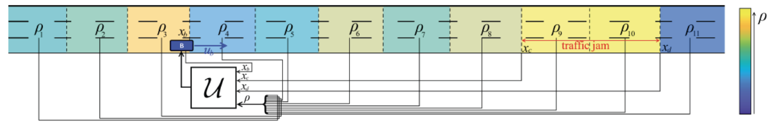


[Čičić., 2021]

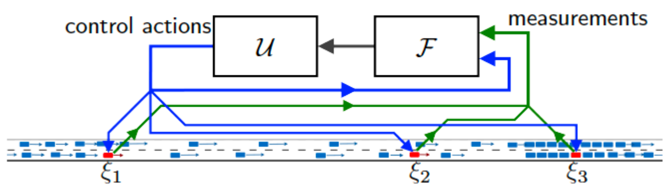
Conclusions

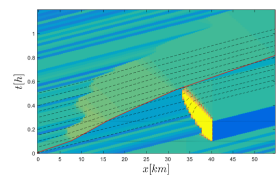


- Layered **architecture** for automated road freight transport enables significantly **lower energy and operation costs**
- Automated truck platoons to **reduce traffic congestion**
- **Platoons** acting as probe vehicles (**sensors**) and moving bottlenecks (**actuators**)



- **Traffic state reconstruction** based on physics-informed machine learning





- **Related work** on safe autonomy, data privacy, market mechanisms

people.kth.se/~kallej

Bibliography (2008-2018)

Available at http://people.kth.se/~kallej/publication.html

Overviews

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