Cyber-physical Control of Transport Systems

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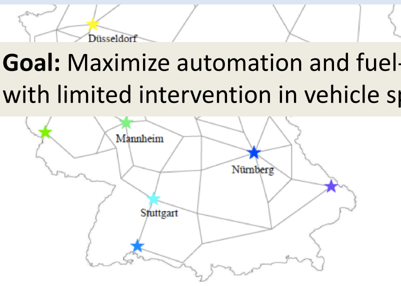
The Problem

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

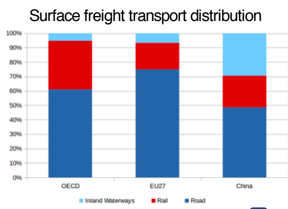
Goal: Maximize automation and fuel-saving cooperations with limited intervention in vehicle speed, route, and timing



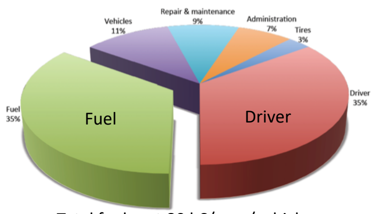
Demands from Goods Road Transportation

- 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

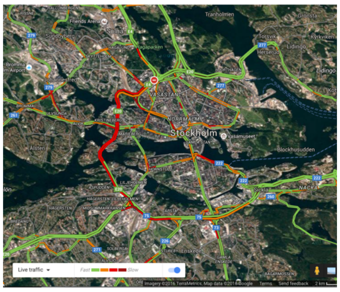
H. Ludanek, CTO, Scania (2014)

- 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

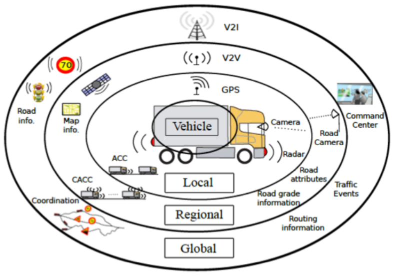
A. Mai, Dir. Connected Vehicle, Cisco (2016)

Technology Push

Real-time traffic information

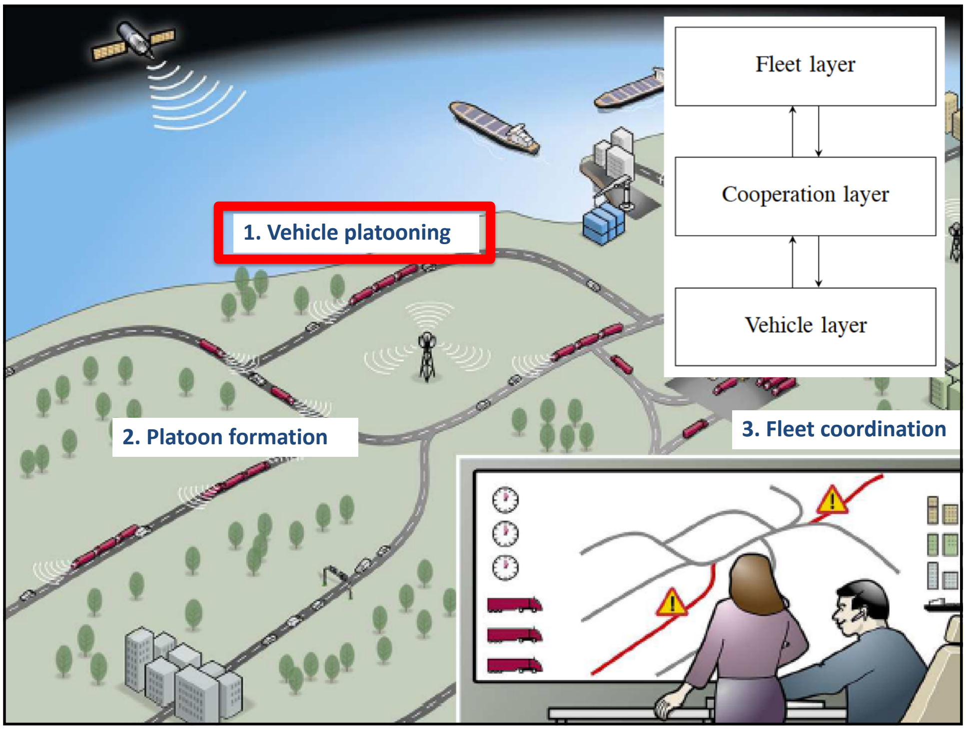


Sensor and communication technology



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

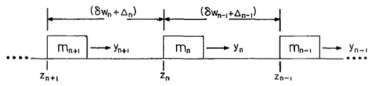


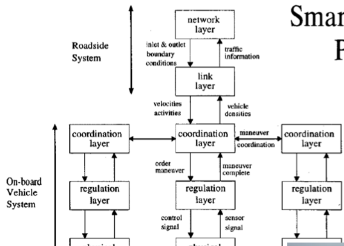
Fig. 1. Vehicles moving in a string.

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

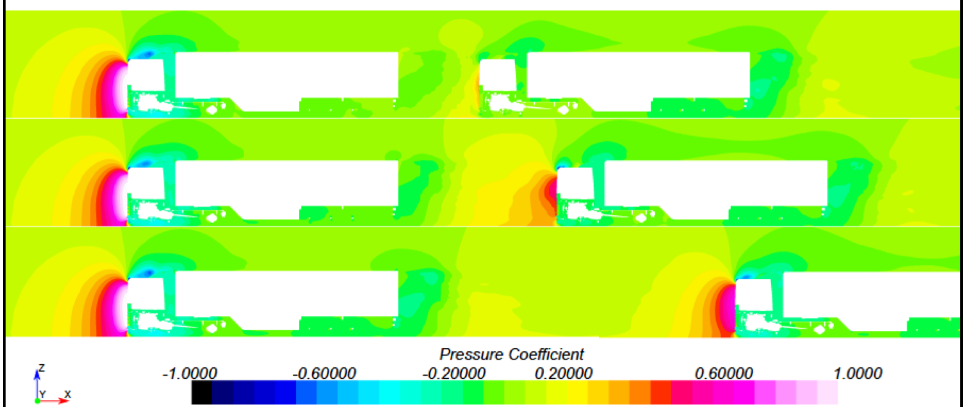


Scania

Swedish success stories

Volvo

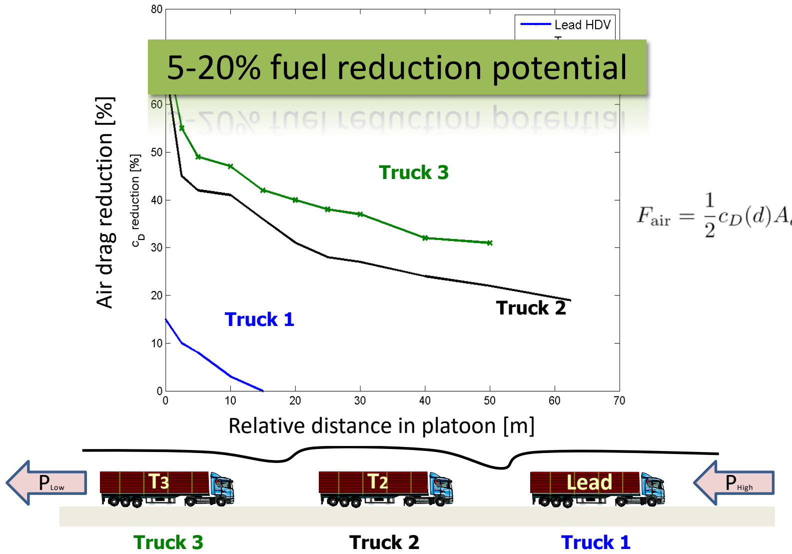
The Physics



Norrby (2014), Liang (2016)

Air Drag Reduction in Truck Platooning

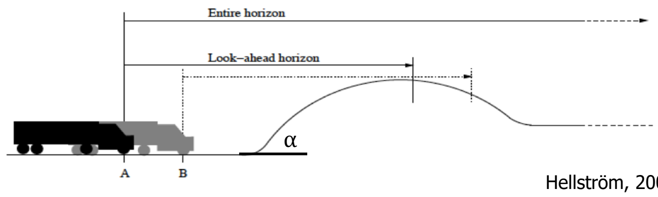
5-20% fuel reduction potential



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

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

Receding Horizon Cruise Control for Single Vehicle



Hellström, 2007

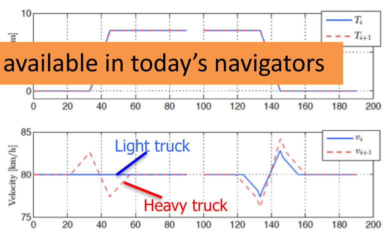
Adjust driving force to **minimize fuel consumption based on road topology** info:

The total fuel consumption over time T is:

$$f = \int^T \frac{\delta(t)}{\ldots} v(t)\Big(m\frac{\mathrm{d}v(t)}{\mathrm{d}t} + \frac{1}{2}\rho_a A_a c_D v^2(t)\phi(d(t)) \ldots + mgc_r\cos\alpha + mg\sin\alpha\Big)\mathrm{d}t$$

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

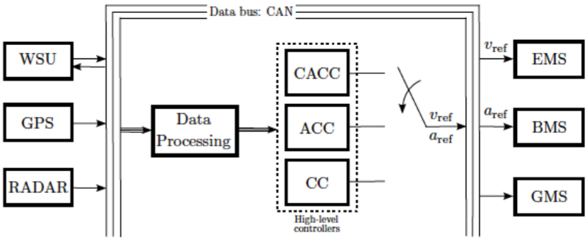
Alam et al., 2011

Vehicle System Architecture

Data from other vehicles

Own position and velocity

Pos from vehicle ahead

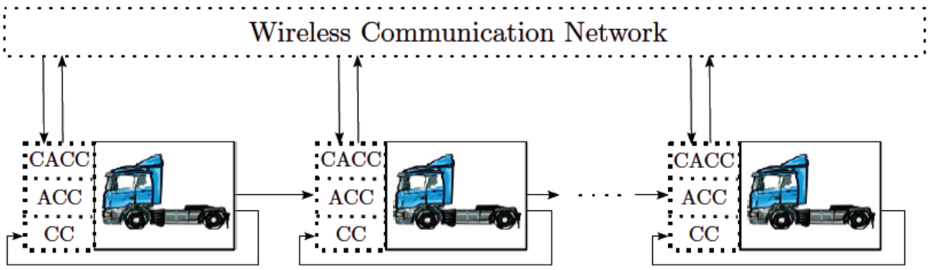


CACC – Collaborative adaptive cruise control
ACC – Adaptive cruise control
CC – Cruise control

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

Alam et al., 2014

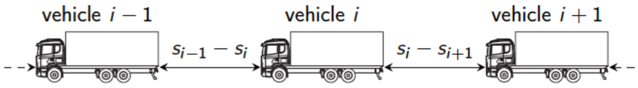
Platoon System Architecture



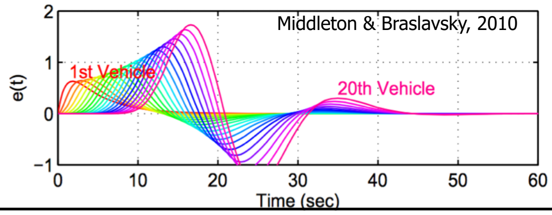
CACC – Collaborative adaptive cruise control
ACC – Adaptive cruise control
CC – Cruise control

Alam et al., 2014

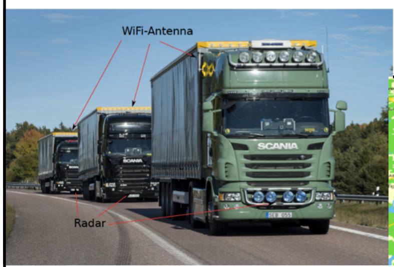
How to Control Inter-vehicular Spacings?

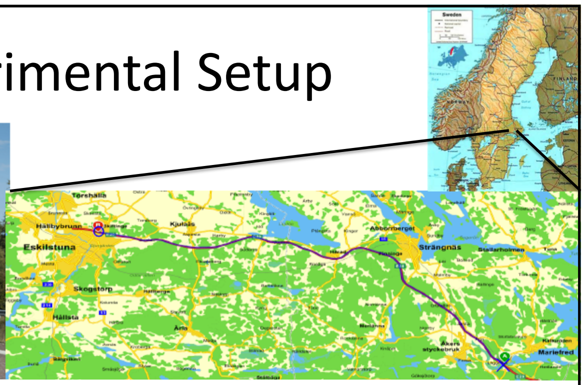


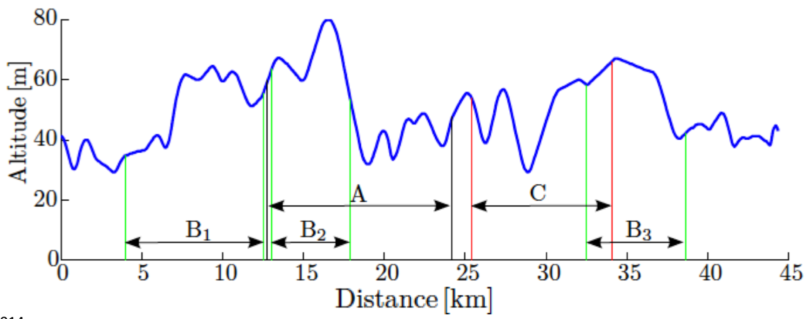
- Limited sensing and inter-vehicle communication suggests **distributed** control strategy
- Important to attenuate disturbances: **string stability**
- Extensively studied problem in ideal environments
  - E.g., Levine & Athans (1966), Peppard (1974), Ioannou & Chien (1993), Swaroop et al.(1994), Stankovic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



Experimental Setup

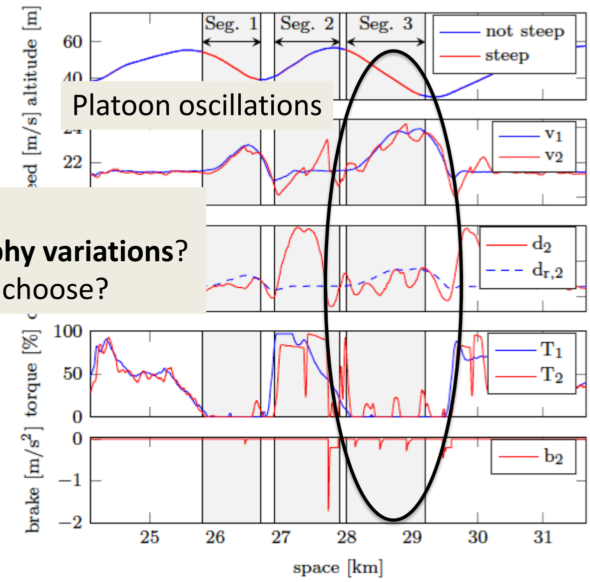






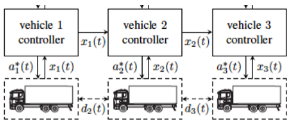
Alam, 2014

Experimental Results



Challenge

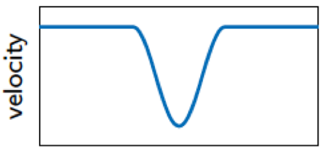
How to handle **topography variations**?
Which **spacing policy** to choose?

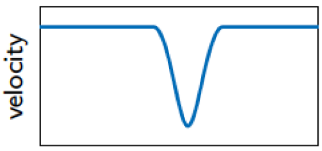


Alam, 2014

Spacing Policies

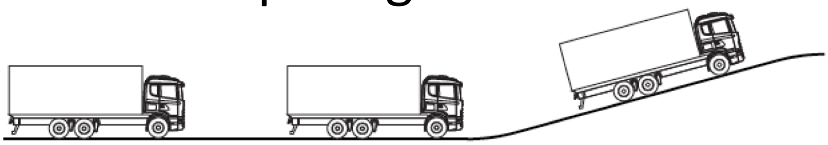
Constant spacing: $s_{\text{ref},i}(t) = s_{i-1}(t) - d$





Besselink & J, 2017

Spacing Policies



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

Besselink & J, 2017

Spacing Policies

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

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

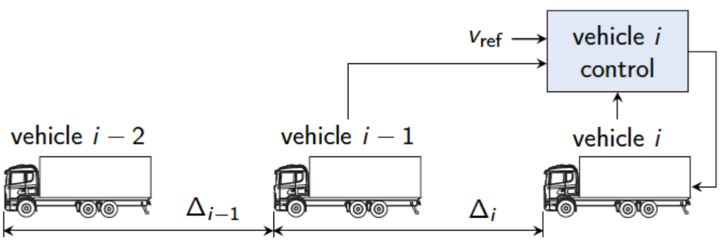
Constant Time Gap Spacing Policy

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

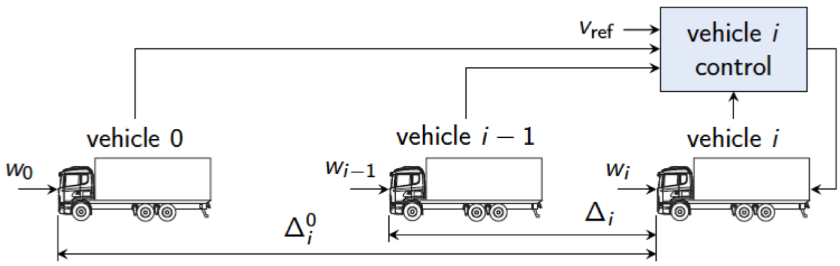
Besselink & J, 2017

Control objectives

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

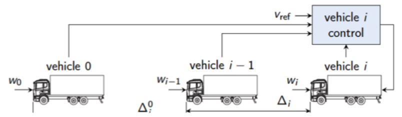
Timing error with $0 \leq \kappa_0 < 1$, $\kappa > 0$ and velocity error e_i

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



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 $\kappa_0 > 0$

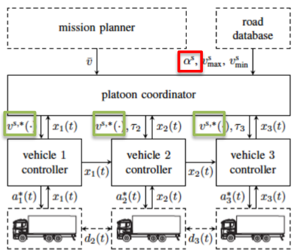
Properties

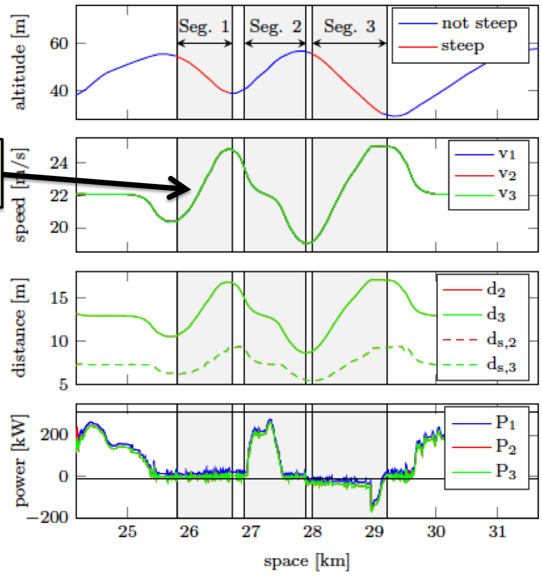
- Class of decentralized controllers
- Definition of the timing error is crucial
- Inclusion of leader information necessary for string stability

Besselink & J, 2017

Simulations with Platoon Coordinator and Look-ahead Road Grade Information

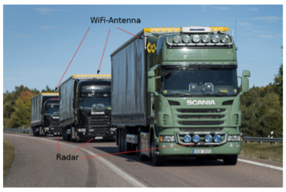
Successful tracking of common platoon velocity reference



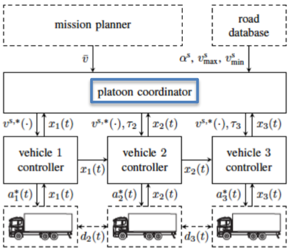


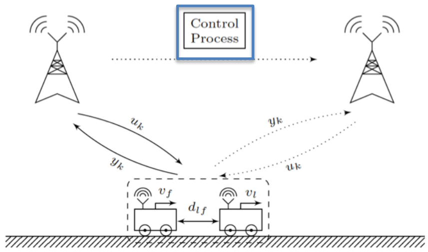
Turri et al., 2015

Cloud-based Implementation of Platoon Coordinator



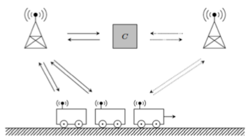
- Platoon coordinator generates common velocity reference: $v_i(t) \to v_{\mathrm{ref}}(s_i(t))$,
- Can be computed in the cellular system
- Requires new handover scheme for control computations between base stations





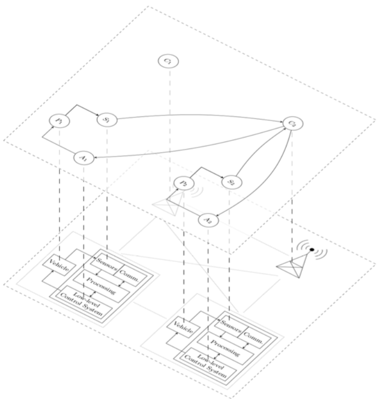
van Dooren et al., 2017

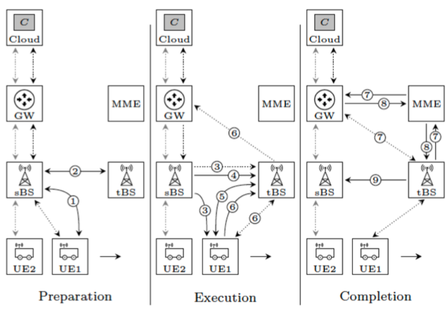
Controller Code Handover Supporting Vehicle Platooning



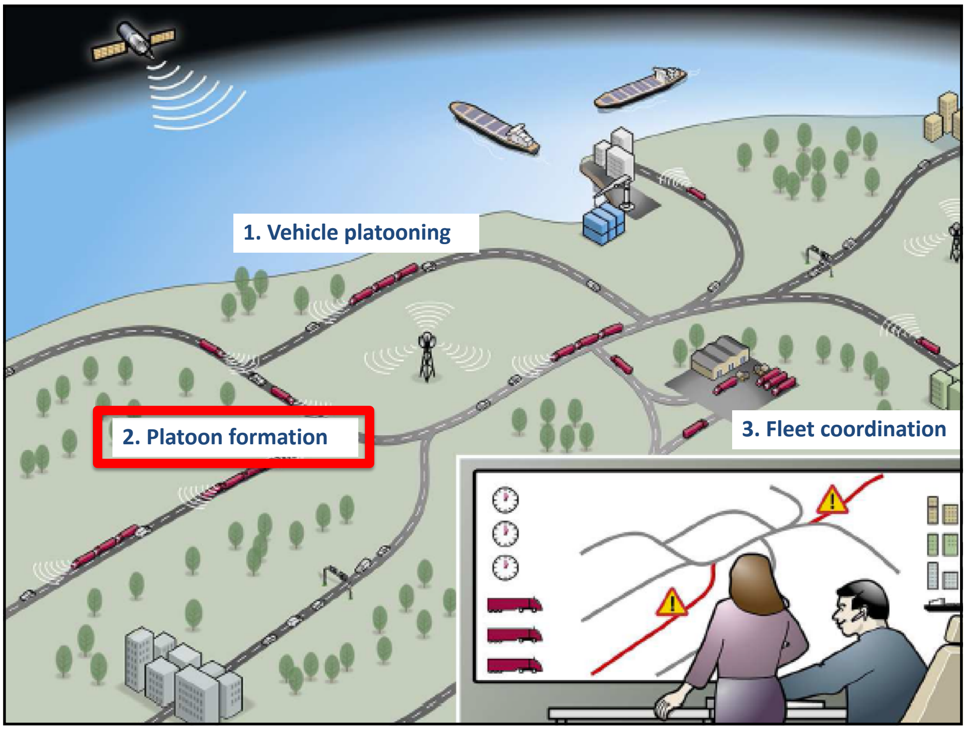
Control computations move within cellular network under guaranteed control performance

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



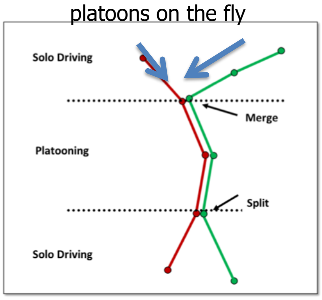


van Dooren et al., 2017, 2018

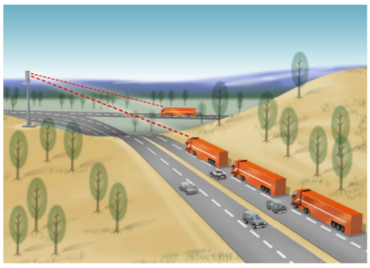


Platoon Formation

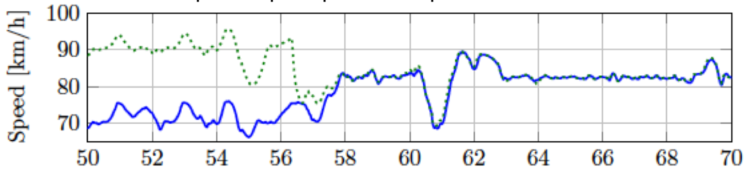
Merge and split vehicle platoons on the fly



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



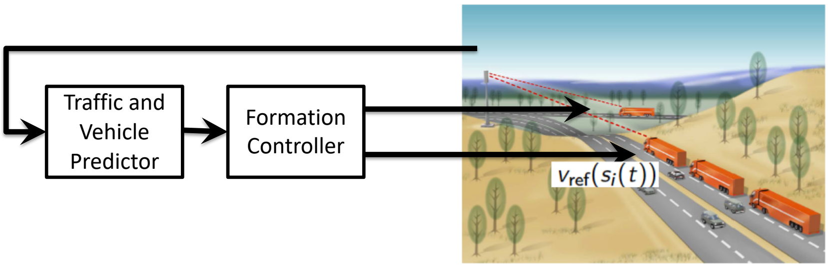
Optimal speed profiles for platoon formation



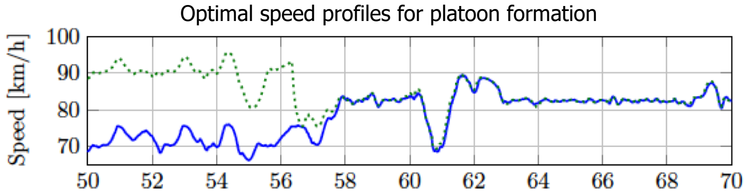
Liang et al., 2016

Platoon Formation

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



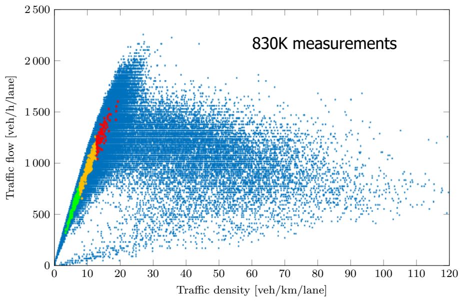
Optimal speed profiles for platoon formation



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

Platoon Formation Experiments

Fundamental diagram of traffic flow



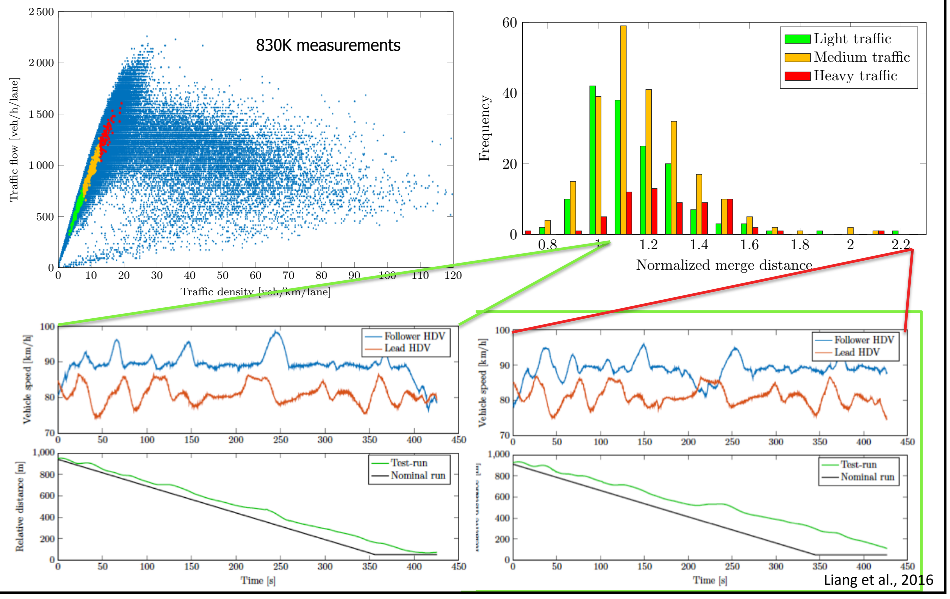
- 600 test runs on E4 in Nov 2015
- Traffic measurements from road units together with onboard sensors

Liang et al., 2016

Traffic Influence on Platoon Formation

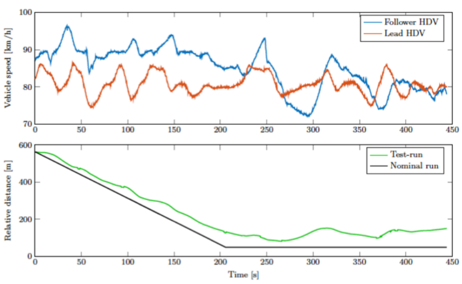
Fundamental diagram of traffic flow

Distribution of merge distances

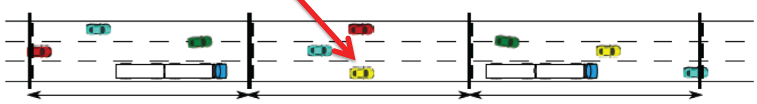


Liang et al., 2016

Persistent Driver Phenomena



Persistent driver blocking platoon formation



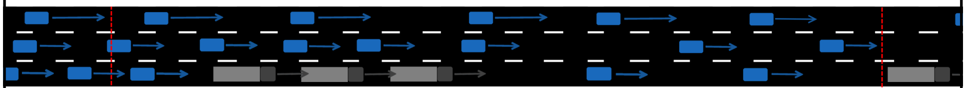
How to predict driver decisions for the control of truck platoons? E.g., Stefansson, 2018

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



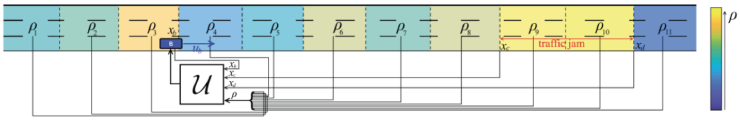
Discretization of the Lighthill-Whitham-Richards PDE model [Lebacque, 1996]

Evolution of **traffic density** in cell i: $\rho_i(t+1) = \rho_i(t) + \frac{T}{L}(q_{i-1}(t) - q_i(t))$

Traffic outflow from cell i: $q_i(t) = \min(V\rho_i(t), V\sigma, W(P - \rho_{i+1}(t))$

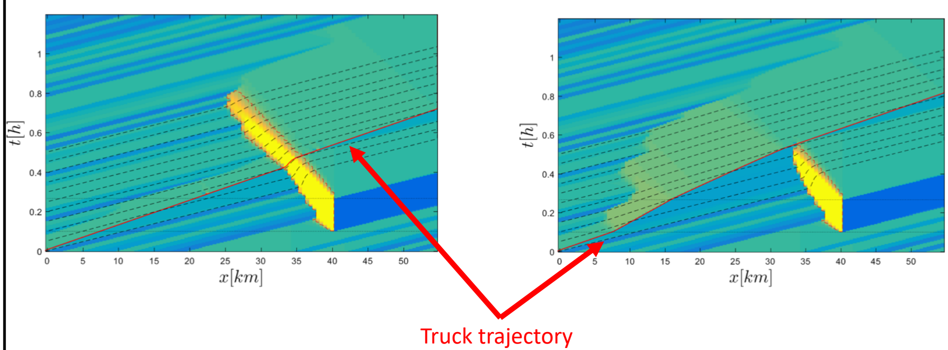
Lin et al., 2018; Cicic and J, 2018

Control truck velocity to dissipate congestion based on traffic densities

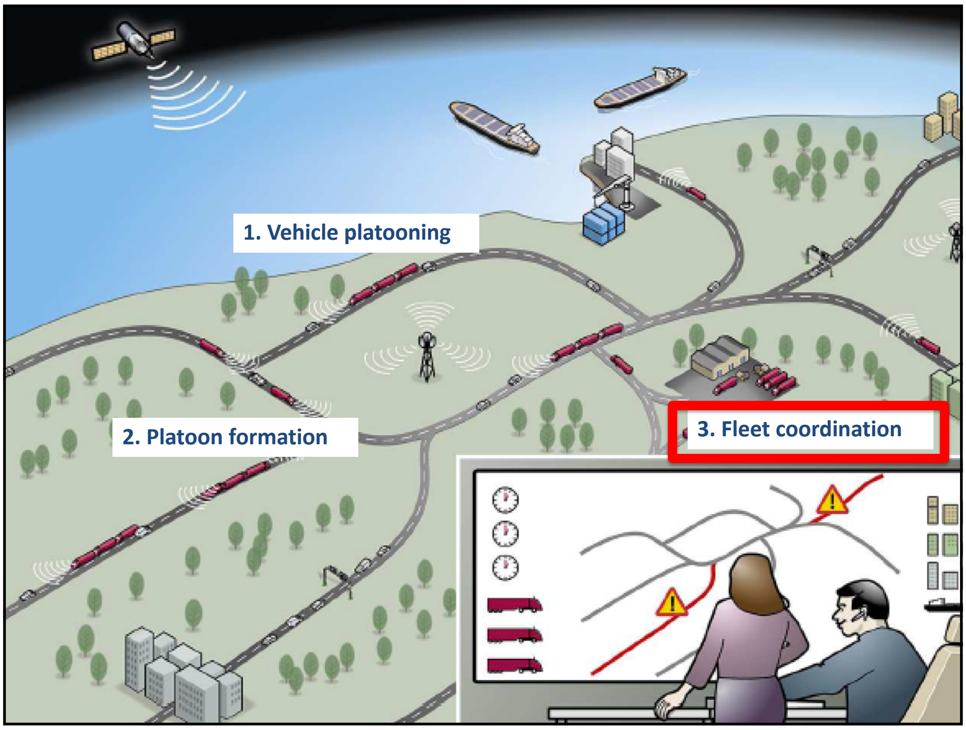


Traffic density **without** truck control

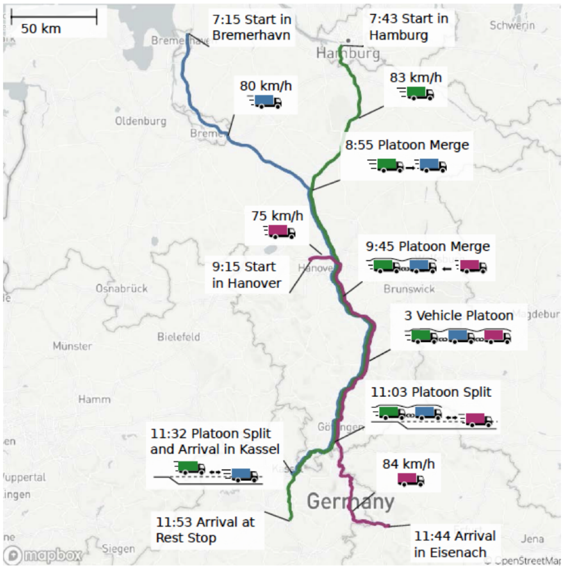
Traffic density **with** truck control



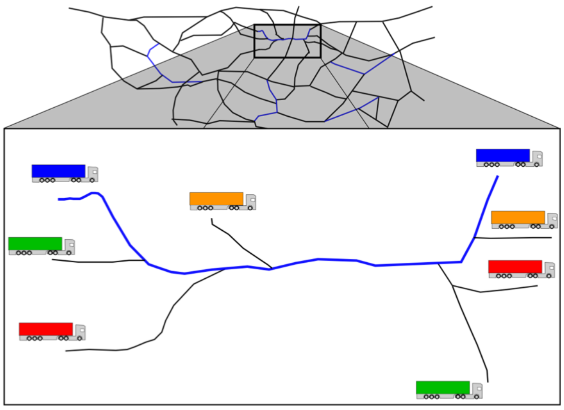
Cicic and J, 2018



The platoon matching problem



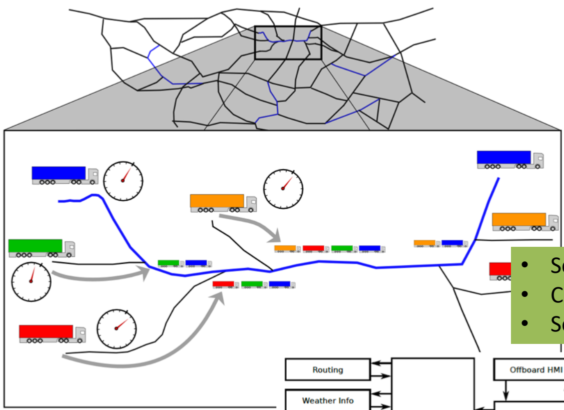
How to coordinate platoon formation?



Platoon coordination
Shortest path to destination given for each truck
1. Select some **trucks** as leaders, with fixed schedules

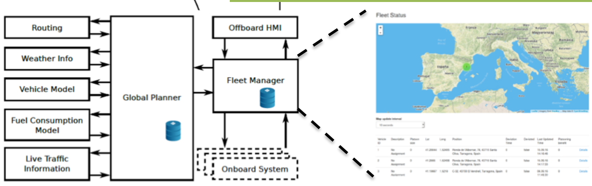
van de Hoef et al., 2015

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

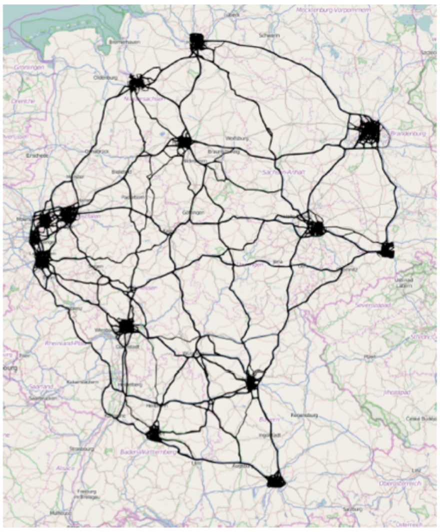
- Scales to large fleets and networks
- Cloud implementation
- Sep 2016 Stockholm-Barcelona demo



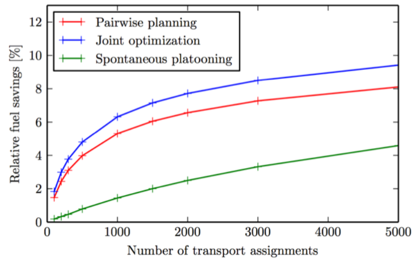
van de Hoef et al., 2015

How does platooning benefit from scale?

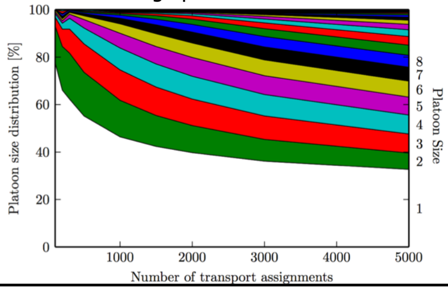
Randomly generated transport assignments



How many vehicles are needed for significant fuel savings?



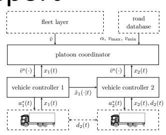
How large platoons will evolve?



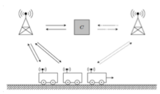
Liang et al., 2016

Conclusions

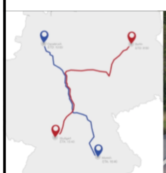
- **Control architecture** for cooperative road freight transport
  - Automated vehicle match-making and platoon formation
  - Platoon control over V2V and V2I cellular communication
  - Integrated platoon coordinator and cruise-controller



- **Disturbance string stability** 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?



people.kth.se/~kallej

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

Bibliography

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

Overviews

- A. Keimer, N. Laurent-Brouty, F. Farokhi, H. Signargout, V. Cvetkovic, A. M. Bayen, and K. H. Johansson, Integration of information patterns in the modeling and design of mobility management services. Proceedings of IEEE, 2018.
- B. Besselink, V. Turri, S.H. van de Hoef, K.-Y. Liang, A. Alam, J. Martensson, and K. H. Johansson, Cyber-physical control of road freight transport. Proceedings of IEEE, 104:5, 1128-1141, 2016.
- K.-Y. Liang, S.H. van de Hoef, H. Terelius, V. Turri, B. Besselink, J. Martensson, and K. H. Johansson, Networked control challenges in collaborative road freight transport. European Journal of Control, 30, 2-14, 2016.

Platoon and vehicle controls

- B. Besselink and K. H. Johansson, String stability and a delay-based spacing policy for vehicle platoons subject to disturbances. IEEE Transactions on Automatic Control, 2017.
- V. Turri, B. Besselink, and K. H. Johansson, Cooperative look-ahead control for fuel-efficient and safe heavy-duty vehicle platooning. IEEE Transactions on Control Systems Technology, 2017.
- V. Turri, B. Besselink, and K. H. Johansson, Gear management for fuel-efficient heavy-duty vehicle platooning, IEEE CDC, Las Vegas, NV, USA, 2016.
- A. Alam, B. Besselink, V. Turri, J. Martensson, and K. H. Johansson, Heavy-duty vehicle platooning for sustainable freight transportation. IEEE Control Systems Magazine, Dec, 35-56, 2015.
- B. Besselink and K. H. Johansson, Control of platoons of heavy-duty vehicles using a delay-based spacing policy, IFAC Workshop on Time Delay Systems, Ann Arbor, MI, USA, 2015.
- A. Alam, J. Martensson, and K. H. Johansson, Experimental evaluation of decentralized cooperative cruise control for heavy-duty vehicle platooning. Control Engineering Practice, 38, 11-25, 2015.
- A. Alam, A. Gattami, K. H. Johansson, and C. J. Tomlin, Guaranteeing safety for heavy duty vehicle platooning: Safe set computations and experimental evaluations. Control Engineering Practice, 24, 33-41, 2014.
- V. Turri, B. Besselink, J. Mårtensson, and K. H. Johansson, Look-ahead control for fuel-efficient heavy-duty vehicle platooning, IEEE CDC, Los Angeles, CA, USA, 2014.

Bibliography (cont'd)

- A. Alam, J. Martensson, and K. H. Johansson, Look-ahead cruise control for heavy duty vehicle platooning, International IEEE Conference on Intelligent Transportation Systems, The Hague, The Netherlands, 2013.
- A. Al Alam, A. Gattami, and K. H. Johansson, An experimental study on the fuel reduction potential of heavy duty vehicle platooning, IEEE ITSC, Madeira Island, 2010.

Platoon formation

- M. Cicic, K.-Y. Liang, and K. H. Johansson, Platoon merging distance prediction using a neural network vehicle speed model, IFAC World Congress, Toulouse, France, 2017.
- K.-Y. Liang, J. Mårtensson, and K. H. Johansson, Heavy-duty vehicle platoon formation for fuel efficiency. IEEE Transactions on Intelligent Transportation Systems, 17:4, 1051-1061, 2016.
- K.-Y. Liang, J. Martensson, and K. H. Johansson, Experiments on platoon formation of heavy trucks in traffic, IEEE ITSC, Rio de Janeiro, Brazil, 2016.
- J.P.J. Koller, A. Grossmann Colin, B. Besselink, and K. H. Johansson, Fuel-efficient control of merging maneuvers for heavy-duty vehicle platooning, IEEE Intelligent Transportation Systems Conference, Las Palmas de Gran Canaria, Spain, 2015.
- K.-Y. Liang, Q. Deng, , J. Martensson, X. Ma, and K. H. Johansson, The influence of traffic on heavy-duty vehicle platoon formation, IEEE Intelligent Vehicles Symposium, Seoul, Korea, 2015.
- K.-Y. Liang, J. Martensson, and K. H. Johansson, When is it fuel efficient for a heavy duty vehicle to catch up with a platoon? IFAC AAC, Tokyo, Japan, 2013.

Platoon assignments and coordination

- S. van de Hoef, K. H. Johansson, and D. V. Dimarogonas, Fuel-efficient en route formation of truck platoons. IEEE Transactions on Intelligent Transportation Systems, 19:1, 102-112, 2018.
- S. van de Hoef, K. H. Johansson, and D. V. Dimarogonas, Efficient dynamic programming solution to a platoon coordination merge problem with stochastic travel times, IFAC World Congress, Toulouse, France, 2017.
- S. van de Hoef, K. H. Johansson, and D. V. Dimarogonas, Computing feasible vehicle platooning opportunities for transport assignments, IFAC Symposium on Control in Transportation Systems, Istanbul, Turkey, 2016.

Bibliography (cont'd)

- S. van de Hoef, K. H. Johansson, and D. V. Dimarogonas, Coordinating truck platooning by clustering pairwise fuel-optimal plans, IEEE Intelligent Transportation Systems Conference, Las Palmas de Gran Canaria, Spain, 2015.
- J. Larson, K.-Y. Liang, and K. H. Johansson, A distributed framework for coordinated heavy-duty vehicle platooning. IEEE Transactions on Intelligent Transportation Systems, 16:1, 419-429, 2015.
- S. van de Hoef, K. H. Johansson, and D. V. Dimarogonas, Fuel-optimal centralized coordination of truck-platooning based on shortest paths, American Control Conference, Chicago, IL, USA, 2015.
- K.-Y. Liang, J. Martensson, and K. H. Johansson, Fuel-saving potentials of platooning evaluated through sparse heavy-duty vehicle position data, IEEE Intelligent Vehicles Symposium Dearborn, MI, USA, 2014.
- J. Larson, C. Kammer, K.-Y. Liang, and K. H. Johansson, Coordinated route optimization for heavy-duty vehicle platoons, International IEEE Conference on Intelligent Transportation Systems, The Hague, The Netherlands, 20

Economic and logistic consequences

- H. Terelius and K. H. Johansson, On the optimal location of distribution centers for a one-dimensional transportation system, IEEE CDC, Las Vegas, NV, USA, 2016.
- H. Terelius and K. H. Johansson, An efficiency measure for road transportation networks with application to two case studies, IEEE CDC, Osaka, Japan, 2015.
- F. Farokhi and K. H. Johansson, A study of truck platooning incentives using a congestion game. IEEE Transactions on Intelligent Transportation Systems, 16:2, 581-595, 2015.
- F. Farokhi, K.-Y. Liang, and K. H. Johansson, Cooperation patterns between fleet owners for transport assignments, IEEE Multi-Conference on Systems and Control, Sydney, Australia, 2015.
- F. Farokhi and K. H. Johansson, Using piecewise-constant congestion taxing policy in repeated routing games, SIAM Conference on Control and Its Applications, Paris, France, 2015.
- F. Farokhi and K. H. Johansson, Investigating the interaction between traffic flow and vehicle platooning using a congestion game, IFAC World Congress, Cape Town, South Africa, 2014.
- F. Farokhi and K. H. Johansson, A game-theoretic framework for studying truck platooning incentives, International IEEE Conference on Intelligent Transportation Systems, The Hague, The Netherlands, 2013.

Bibliography (cont'd)

Road grade estimation

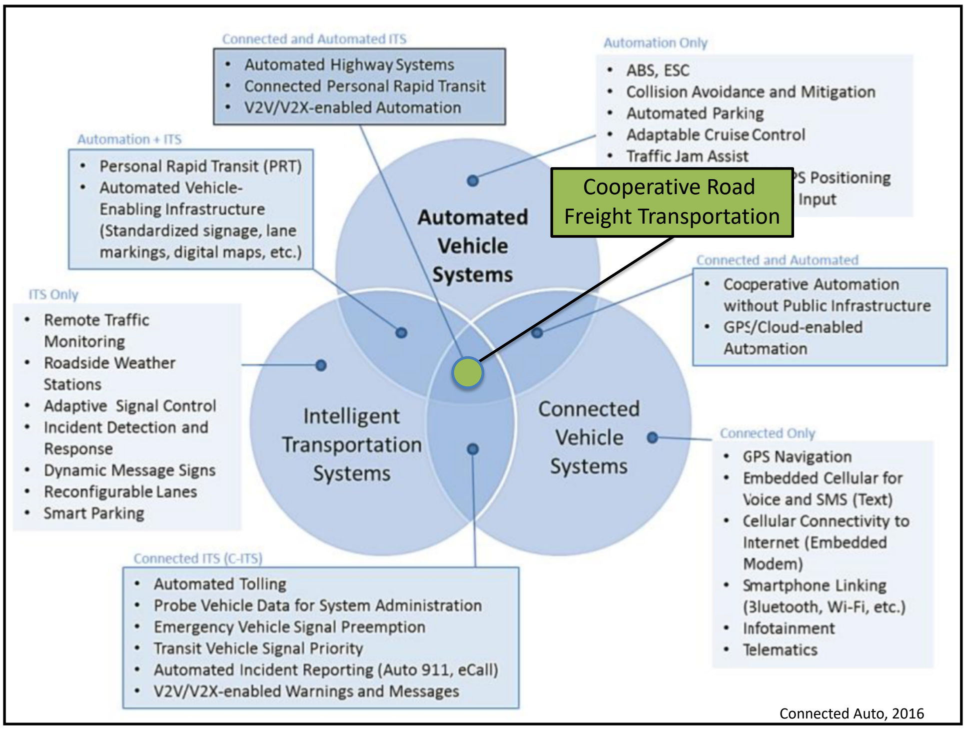
- P. Sahlholm, A. Gattami, and K. H. Johansson, Piecewise linear road grade estimation, SAE World Congress, Detroit, MI, USA, 2011.
- P. Sahlholm and K. H. Johansson, Road grade estimation for look-ahead vehicle control using multiple measurement runs. Control Engineering Practice, 18:11, 1328-1341, 2010.
- P. Sahlholm and K. H. Johansson, Segmented road grade estimation for fuel efficient heavy duty vehicles, IEEE CDC, Atlanta, GA, USA, 2010.
- P. Sahlholm and K. H. Johansson, Road grade estimation for look-ahead vehicle control, IFAC World Congress, Seoul, Korea, 2008.

Controller handover

- D. van Dooren, S. Schiessl, A. Molin, J. Gross, and K. H. Johansson, Safety analysis for controller handover in mobile systems, IFAC World Congress, Toulouse, France, 2017.
- D. van Dooren, G. Fodor, J. Gross, and K. H. Johansson, Performance analysis of controller handover schemes, Manuscript in preparation, 2018

Vehicle platooning impact on traffic

- L. Jin, M. Cicic, S. Amin, and K. H. Johansson, Modeling the impact of vehicle platooning on highway congestion: a fluid queuing approach, ACM Workshop on Hybrid Systems: Computation and Control, Porto, Portugal, 2018


Connected and Automated ITS
• Automated Highway Systems
• Connected Personal Rapid Transit
• V2V/V2X-enabled Automation
Automation Only
• ABS, ESC
• Collision Avoidance and Mitigation
• Automated Parking
• Adaptable Cruise Control
• Traffic Jam Assist
S Positioning
Input
Automation + ITS
• Personal Rapid Transit (PRT)
• Automated Vehicle-Enabling Infrastructure (Standardized signage, lane markings, digital maps, etc.)
Cooperative Road Freight Transportation
Automated Vehicle Systems
Connected and Automated
• Cooperative Automation without Public Infrastructure
• GPS/Cloud-enabled Automation
ITS Only
• Remote Traffic Monitoring
• Roadside Weather Stations
• Adaptive Signal Control
• Incident Detection and Response
• Dynamic Message Signs
• Reconfigurable Lanes
• Smart Parking
Intelligent Transportation Systems
Connected Vehicle Systems
Connected Only
• GPS Navigation
• Embedded Cellular for Voice and SMS (Text)
• Cellular Connectivity to Internet (Embedded Modem)
• Smartphone Linking (Bluetooth, Wi-Fi, etc.)
• Infotainment
• Telematics
Connected ITS (C-ITS)
• Automated Tolling
• Probe Vehicle Data for System Administration
• Emergency Vehicle Signal Preemption
• Transit Vehicle Signal Priority
• Automated Incident Reporting (Auto 911, eCall)
• V2V/V2X-enabled Warnings and Messages
Connected Auto, 2016