

Interactions Between Human-driven Vehicles and Automated Truck Platoons

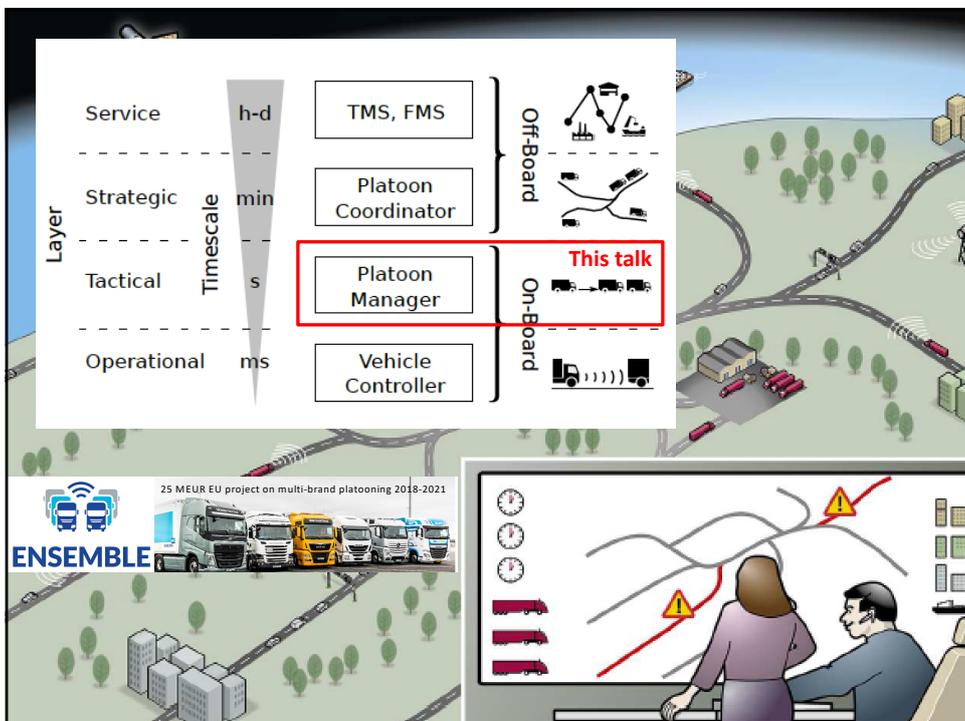
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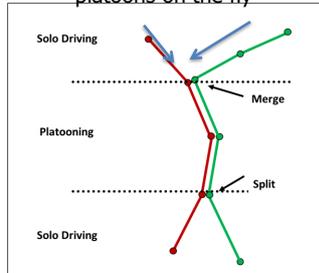



Workshop on Control for Networked Transportation Systems
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Platoon Formation

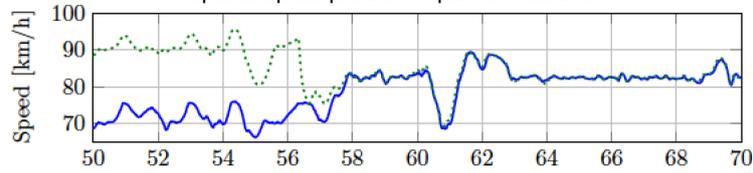
Merge and split vehicle platoons on the fly



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



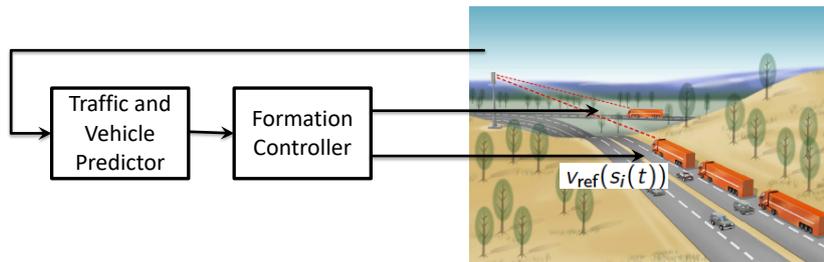
Optimal speed profiles for platoon formation



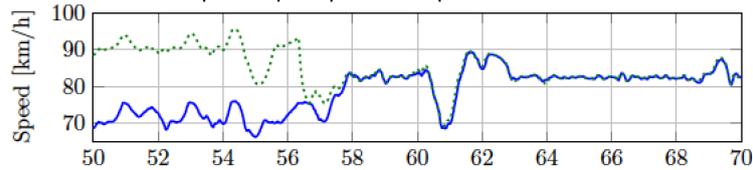
Liang et al., 2016

Platoon Formation

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

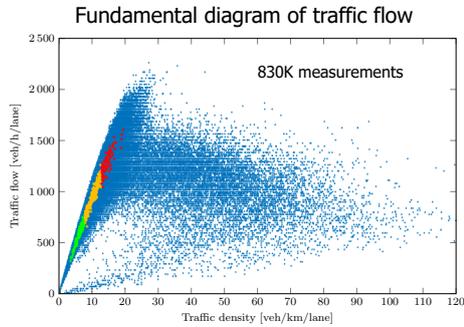


Optimal speed profiles for platoon formation



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

Catch-up phase

Merge point
 $\chi_1(\tau_m) = \chi_2(\tau_m)$

Platooning phase

Final split point
 $\chi_1(\tau_f) = \chi_2(\tau_f) = \chi_f$

minimize $\int_0^{\tau_m} (v_1(\tau)^3 + v_2(\tau)^3) d\tau + \phi \int_{\tau_m}^{\tau_f} v_p(\tau)^3 d\tau$

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

Catch-up phase

Platooning phase

Split

t [h]

x [km]

c density

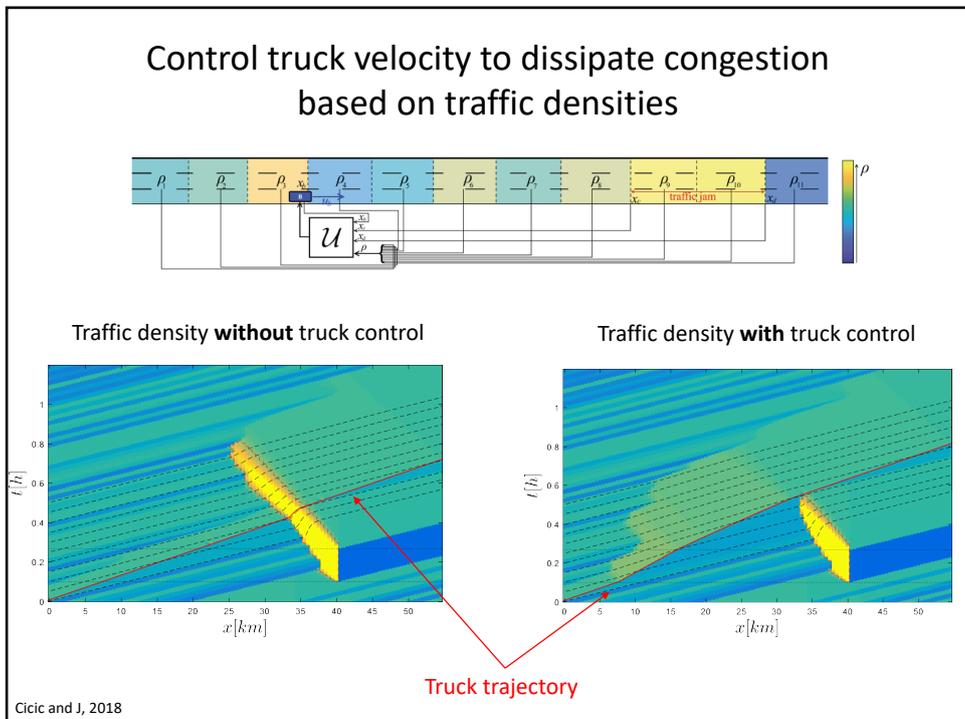
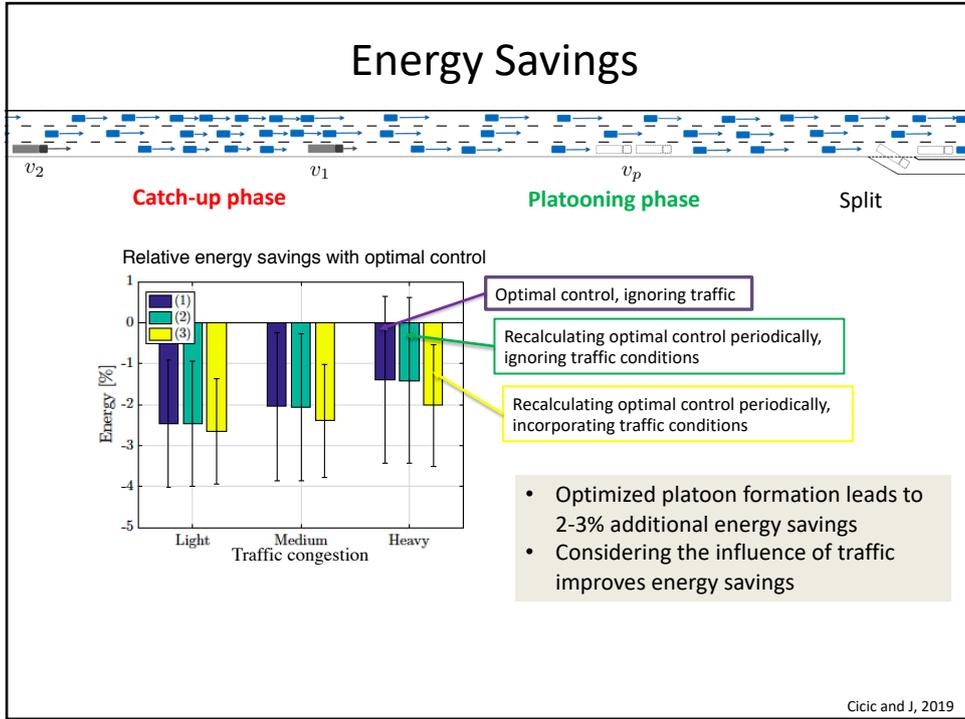
Fuel-optimal merge point

Merge point with traffic

Merge point without traffic

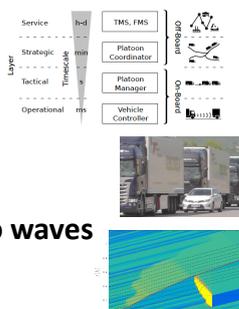
- Slowing down lead vehicle causes heavier traffic for follower vehicle
- Fuel consumption reduced for proposed controller despite later merging

Cicic and J, 2019



Conclusions

- **Automated and integrated road freight transport**
 - Optimized vehicle match-making and platoon formation
 - Platoon control over V2V and V2I cellular communication
 - Integrated platoon coordinator and cruise-controller
- **Platoon formation optimization with traffic**
- **Control automated platoons to reduce stop-and-go waves**
- **Ongoing:** Incentives, pricing, privacy, legislation,...



ENSEMBLE multi-brand platooning H2020 project 2018-2021



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

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And many other collaborators



Bibliography

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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. Cacic, 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