Large-scale and Networked Control of Automated Freight Transport

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IPAM Workshop on Autonomous Vehicles, Feb 25-Mar 1, 2019

Acknowledgments

Assad Alam, Scania
Kuo-Yun Liang, Scania
Per Sahilholm, Scania

Bart Besselink, U Groningen
Farhad Farokhi, U Melbourne
Sebastian van de Hoef, HERE
Jeff Larson, Argonne NL
Håkan Terelius, Google

Li Jin, NYU
Saurabh Amin, MIT

Mladen Cicic
Dirk van Dooren
Frank Jiang
Alexander Johansson
Ehsan Nekouei
Valerio Turri
Jonas Mårtensson
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)*

- 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

Real-time traffic information

Sensor and communication technology

Electric highways

Vehicle platooning and automated driving
Control of Vehicle Platoons

- PATH platoon demo San Diego 1997
- Scania
- Volvo
- Swedish success stories

The Physics

Norrby (2014), Liang (2016)
Air Drag Reduction in Truck Platooning


Vehicle System Architecture

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

Middleton & Braslavsky, 2010
Experimental Setup

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

Experimental Results
Spacing Policies

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

Besselink & J, 2017
Spacing Policies

**Constant headway:** 
\[ s_{\text{ref},i}(t) = s_{i-1}(t) - d - hv_i(t) \]

**Constant time gap:** 
\[ s_{\text{ref},i}(t) = s_{i-1}(t - \Delta t) \]
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:**

\[ v_i(t) \rightarrow v_{\text{ref}}(s_i(t)), \quad s_i(t) \rightarrow s_{i-1}(t - \Delta t) \]

Disturbance String Stability

**Platoon dynamics**

\[
\begin{align*}
\dot{x}_0 &= f(x_0, 0, w_0), \\
\dot{x}_i &= f(x_i, x_{i-1}, w_i), \quad i \in \mathbb{I}_N \setminus \{0\}
\end{align*}
\]

**Definition.** The platoon dynamics is disturbance string stable if there exist functions \( \bar{\beta} \in \mathcal{K} \mathcal{L} \) and \( \bar{\sigma} \in \mathcal{K}_\infty \) such that, for all \( N \in \mathbb{N} \),

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

**Theorem.** Let each vehicle satisfy, for some \( \beta \in \mathcal{K} \mathcal{L}, \gamma, \sigma \in \mathcal{K}_\infty \),

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

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

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

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

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

Control Design

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

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

Theorem. For any vehicle controller that achieves, for some functions $\beta_0 \in \mathcal{KL}$, $\sigma_0 \in \mathcal{K}_\infty$, $|\delta_i(s)| \leq \beta_0(|\delta(s_0)|, s - s_0) + \sigma_0(\|\bar{w}_i\|_{[s_0, s]})$

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

Cloud-based Implementation of Platoon Coordinator

- Platoon coordinator generates common velocity reference: $v(t) \rightarrow v_{ref}(s(t))$
- Can be computed in the cellular system
- Requires new handover scheme for control computations between base stations
Controller Code Handover Supporting Vehicle Platooning

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

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

van Dooren et al., 2017, 2018
Liang et al., 2016
Platoon Formation

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

- Traffic and Vehicle Predictor
- Formation Controller

Optimal speed profiles for platoon formation

Platoon Formation Experiments

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

Fundamental diagram of traffic flow

830K measurements

Li et al., 2016; Cicic et al., 2017
Traffic Influence on Platoon Formation

Fundamental diagram of traffic flow

Distribution of merge distances

Persistent Driver Phenomena

Persistent driver blocking platoon formation

How to predict driver decisions for the control of truck platoons? [Stefansson et al., 2019]

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]

\[
\rho_i(t + 1) = \rho_i(t) + \frac{T}{L} (q_{i-1}(t) - q_i(t))
\]

\[
q_i(t) = \min (V\rho_i(t), V\sigma_i, W(P - \rho_{i+1}(t)))
\]

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

Control truck velocity to dissipate congestion based on traffic densities

Traffic density without truck control

Traffic density with truck control

Truck trajectory

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

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

- **Platoon control** 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?

Bibliography

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

**Overviews**

**Platoon and vehicle controls**
- 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.
Bibliography (cont’d)


Platoon formation

- 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


Bibliography (cont’d)


Economic and logistic consequences

- 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.
Bibliography (cont’d)

Road grade estimation
- 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, G. Fodor, J. Gross, and K. H. Johansson, Performance analysis of controller handover schemes, Manuscript in preparation, 2018

Vehicle platooning impact on traffic