Cooperative Road Freight Transport: Opportunities and Challenges in Networking and Control

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The Problem

How to efficiently transport goods between cities over a highway network?

Characteristics

• 2,000,000 heavy trucks in EU over fixed road network
  - 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 fuel- and labor-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

- 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)*

**Surface freight transport distribution**

- Truck corresponds to 1.0 tUSD, relatively large
- 24% of long haulage trucks run empty
- 57% average load capacity

*H. Ludanek, CTO, Scania (2014)*

**Total fuel cost** 80 k€/year/vehicle

*Schittler, 2003; Scania, 2012*
Technology Push

Real-time traffic information

Sensor and communication technology

Electric highways

Vehicle platooning and automated driving

Elväg Gävle
1. Vehicle platooning

2. Platoon formation

3. Fleet coordination
Control of Vehicle Platoons

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.

Smart Cars on Smart Roads: Problems of Control
Pravin Varaiya, Fellow, IEEE

PATH platoon demo San Diego 1997

Swedish success stories

Scania

Volvo
The Physics

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

5-20% fuel reduction potential

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

Receding Horizon Cruise Control for Single Vehicle

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

Require knowledge of road grade $\alpha$, not freely available in today’s navigators.

Implemented as velocity reference change in adaptive cruise controller.

Alam et al., 2011
Distributed Road Grade Estimation

RMS Road Grade Error

Aggregated $N=10, 100, 1000$ profiles of lengths 50 to 500 km

Sahlholm, 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
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
Experimental Setup

Alam, 2014
Experimental Results

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

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

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

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

\[ v_i(t) \rightarrow v_{\text{ref}}(s_i(t)), \]

\[ s_i(t) \rightarrow s_{i-1}(t - \Delta t) \]

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 $e_i$

$$\delta_i(s) = (1 - \kappa_0)\Delta_i(s) + \kappa_0\Delta_i^0(s) + \kappa e_i(s)$$
Simulations with Platoon Coordinator and Look-ahead Road Grade Information

Successful tracking of common platoon velocity reference

Turri et al., 2015
Edge Cloud Implementation of Platoon Coordinator

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

van Dooren et al., 2017
Controller Code Handover Supporting Vehicle Cooperation Scenarios

Control computations move within cellular network under guaranteed control performance

- Proposed new handover schemes for 5G
- Coordinate handover of multiple users simultaneously to support multi-vehicle control
1. Vehicle platooning

2. Platoon formation

3. Fleet coordination
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

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

Fundamental diagram of traffic flow

830K measurements
Traffic Influence on Platoon Formation

Fundamental diagram of traffic flow

Distribution of merge distances

830K measurements

Liang et al., 2016
Persistent Driver Phenomena

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 how traffic congestion (queue length) depend on the fraction of platooned vehicles $\eta$ and their inter-vehicle distance $h$?

**Average queue length derived from stochastic fluid queue model**

- Vehicle platooning can improve traffic behavior
- Optimal control of platoons from infrastructure

Jin et al., 2018
1. Vehicle platooning

2. Platoon formation

3. Fleet coordination
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. Pairwise compute timing adjustments
3. Joint optimization of velocities

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

• **Layered 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

• **Automation** enabled by **multiple networking infrastructures**

• **Ongoing studies**
  – Global vs local objectives: Pricing? Social optimum?
  – Fair sharing of data under conflicting objectives?
  – Predicting human decisions in multi-vehicle scenarios?

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Overviews


Platoon and vehicle controls


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Controller handover


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Vehicle platooning impact on traffic

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