Networked Control Challenges in Collaborative Road Freight Transport

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The Problem

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

Characteristics
• Large distributed control system with no real-time coordination today
• 2 000 000 heavy trucks in EU (400 000 in Germany) over fixed road network
• A few large and many small fleet owners with heterogeneous truck fleets
• Tight delivery deadlines and high expectations on reliability

Approach: Maximize fuel-saving collaborations 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
- 45% of all freight transport is on roads
- Emissions increased by 21% for 1990-2009


- 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)

Life cycle cost for European heavy-duty vehicle

Schiiller, 2003; Scania, 2012

Total fuel cost 80 k€/year/vehicle

Fuel

Non-fuel costs
Technology Push

Real-time traffic information

Sensor and communication technology

Electric highways

Vehicle platooning and autonomous driving

Outline

1. Vehicle platooning

2. Platoon formation

3. Fleet coordination
Control of Vehicle Platoons

IEEE TRANSACTIONS ON AUTOMATIC CONTROL, VOL. 3, NO. 3, JANUARY 1958

On the Optimal Error Regulation of a String of Moving Vehicles

W. S. LEVINE, SENIOR MEMBER, IEEE, AND M. ATTIA, MEMBER, IEEE

Fig. 3. Vehicles moving in a string.

PATH platoon demo San Diego 1997

Scania

Volvo

Swedish success stories
The Physics

Norrby (2014), Liang (2016)

Air Drag Reduction in Truck Platooning

Receding Horizon Cruise Control for Single Vehicle

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

The total fuel consumption over time $T$ is:

$$\int_0^T \frac{1}{2} m(v(t))^2 \left( F_{mg} - F_b - F_{ad}(v, d) - F_f(\alpha) - F_g(\alpha) \right) dt$$

$$= F_{mg} - F_b - \frac{1}{2} \rho A_v v^2 \phi(d)$$

$$- mg e \cos \alpha - mg \sin \alpha$$

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

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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

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

**Experimental Setup**
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: $s_{\text{ref,}i}(t) = s_{i-1}(t) - d - hv_i(t)$

Besselink & J, 2015
Spacing Policies

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

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 objectives:
- \( v_i(t) \to v_{\text{ref}}(s_i(t)) \),
- \( s_i(t) \to s_{i-1}(t - \Delta t) \)

Besselink & J, 2015
Simulations with Platoon Coordinator and Look-ahead Road Grade Information

Evaluation of Energy Efficiency

CC: First vehicle runs conventional cruise controller, second keeps fixed time gap
LAC: First vehicle runs look-ahead cruise controller, second keeps fixed time gap
CLAC: Vehicles run new cooperative look-ahead control with platoon coordinator
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
Traffic Influence on Platoon Formation

- Platoon formation of two trucks under various traffic conditions
- 600 test runs on E4 in Nov 2015
- Traffic measurements from road units together with onboard sensors

Traffic Influence on Platoon Formation

Fundamental diagram

Distribution of merge distances

Liang, 2016
Persistent Driver Phenomena

1. Vehicle platooning

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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 platoon benefits scale?

Randomly generated transport assignments

How many vehicles are needed for significant fuel savings?

- Preplanned platooning
- Joint optimization
- Spontaneous platooning

How large platoons will evolve?

Feasibility Study Based on Real Truck Data

- Position snapshot May 14 2013
- 7,634 Scania trucks
- 500,000 km² in Europe

- Positions sampled every 10 min
- Trajectories of 14 trucks

- 875 long-haulage trucks over European region
- Trucks close in time and space (<r m) could adjust speed to platoon and then save 10% fuel during platooning

Liang et al., 2016

Larson et al., 2013
Spontaneous vs Coordinated Platooning

Paths of 1,773 trucks
Trucks within 100 m from another truck

Spontaneous vs Coordinated Platooning

Adjust truck departure times

<table>
<thead>
<tr>
<th>Time interval</th>
<th>Fuel saved*</th>
<th>Platooning rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 min</td>
<td>0.68%</td>
<td>13.25%</td>
</tr>
<tr>
<td>10 min</td>
<td>1.19%</td>
<td>22.41%</td>
</tr>
<tr>
<td>15 min</td>
<td>1.64%</td>
<td>30.26%</td>
</tr>
<tr>
<td>30 min</td>
<td>2.74%</td>
<td>47.58%</td>
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<tr>
<td>1 hr</td>
<td>4.31%</td>
<td>68.07%</td>
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<tr>
<td>2 hr</td>
<td>5.94%</td>
<td>83.23%</td>
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<tr>
<td>3 hr</td>
<td>6.87%</td>
<td>89.93%</td>
</tr>
<tr>
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<td>8.06%</td>
<td>95.67%</td>
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<tr>
<td>12 hr</td>
<td>8.85%</td>
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</tr>
<tr>
<td>24 hr</td>
<td>9.37%</td>
<td>99.38%</td>
</tr>
</tbody>
</table>

Coordinated departure times enable much more platooning

Liang et al., 2014
Conclusions

• **Large potential for networked control in road transport systems**
  – Real-time control over mobile wireless networks

• **Integrated cooperative driving for goods transportation**
  – High-level optimization and scheduling of transport
  – Low-level control and coordination of truck platoons

• **Open problems**
  – Global vs local objectives: Who owns the performance metric? Pricing?
  – Real-time cloud computing: Vehicle control from infrastructure?

• **Large-scale testing and evaluations**

http://people.kth.se/~kallej