Cooperative Driving for Road Goods Transportation: Optimization and Control

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The 33rd Chinese Control Conference, July 28-30, 2014, Nanjing

Plenary preparation at Mount Tai with CCC 2014 General Chairman
Acknowledgments

Assad Alam
Kuo-Yun Liang
Per Sahlholm

Jonas Mårtensson
Jeff Larson
Valerio Turri
Bart Besselink
Farhad Farokhi
Ather Gattami

The transportation system is a cyber-physical control system
Mainly without global control and optimization
New information technology has dramatic potentials
Demands from Goods Road Transportation

- Transport sector consumes 1/3 of EU energy
- 45% of all freight transport is on roads
- Road transport accounts for 20% of CO₂ emissions
- Emissions increased by 21% for 1990-2009


Life cycle cost for European heavy-duty vehicle

- 24% of long haulage trucks run empty
- 57% average load capacity

Dr. H. Ludanek, CTO, Scania

Total fuel cost 80 k€/year/vehicle

Schitter, 2003; Scania, 2012

Technology Push

Sensor and communication technology
Real-time traffic information
Vehicle platooning and semi-autonomous driving

Koutsopoulos et al., 2010
**Control of Vehicle Platoons**

*IEEE Transactions on Automatic Control, Vol. 36, No. 7, July 1991*

On the Optimal Error Regulation of a String of Moving Vehicles

W. B. LEVINE, STUDENT MEMBER, IEEE, AND M. ATHANS, MEMBER, IEEE

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**PATH platoon demo San Diego 1997**

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**Smart Cars on Smart Roads: Problems of Control**

Fritz Vazquez, Fellow, IEEE

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**Heavy-Duty Vehicle Platooning**

*Rapport on vehicle platooning developed by KTH and Scania (Oct, 2011)*

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**VIDEO**

PhD student Assad Alam on *Discovery Channel* (Jan, 2012)
The Physics

Air Drag Reduction in Truck Platooning

Outline

- Introduction
- Architecture for fuel-optimized goods transport
- Cruise control for vehicle platoons
- Optimized transport planner
- Humans in the loop
- Conclusions

Fuel-Optimized Goods Transport

- Goods transported between cities over highway network
- 2 000 000 heavy trucks in European Union (400 000 in Germany)
- 19 000 000 light+medium+heavy trucks in China
- Large distributed control systems with no real-time coordination today

Goal: Maximize total amount of platooning with limited intervention in vehicle speed and route

Larson et al., 2013
Functional Architecture for Goods Transport

- Transport Planner
- Platoon Coordinator
- Vehicle and Inter-Vehicle Controller

VIDEO

Alam et al., 2012
Off- and On-board Computing

Off-board transport planner
• Monitor trucks and traffic
• Choose routes to maximize platooning
• Replan due to new trucks, weather, changing traffic conditions, etc

On-board platoon coordinator
• Coordinate platoon creation, merge, split etc
• Optimize platoon speed
• Interact with cruise controllers

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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:

$$f = \int_0^T \delta(t) \left( \frac{1}{\cos \alpha} f_\text{ref} \right) dt + mg v_x \cos \alpha + mg \sin \alpha$$

Require knowledge of road grade $\alpha$, not 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

Alam et al., 2014
Collaborative Adaptive Cruise Control

- How to jointly minimize fuel consumption for a platoon of vehicles?
  - Keep small relative distances or close to individual optimal trajectories?
  - Uphill and downhill segments; heavy and light vehicles

Dynamics of vehicle $i$ depend on distance $d_{i-1,i}$ to vehicle i-1:

$$
\frac{dv_{i-1,i}}{dt} = v_{i-1,i} - v_i
$$

$$
\frac{dm_{i-1,i}}{dt} = F_{\text{engine}}(a_i, \omega_{wi}) - F_{\text{friction}} - F_{\text{drag}}(v_{i-1,i}, d_{i-1,i})
$$

$$
= k_{T_i} (\delta_i, \omega_{wi}) - F_{\text{friction}} - k_{f,i} f(d_{i-1,i})
- k_{i} \cos \alpha_i - k_{i} \sin \alpha_i
$$

Alam et al., 2013

Experimental Evaluation

Alam, 2014
Hilly roads generate platoon disturbances

May impose fuel-inefficient braking commands

Compensated by feedforward communication of road topology and vehicle commands

**Functional Architecture for Goods Transport**

Alam, 2014

Alam et al., 2012
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When and where to create platoons?

Goal: Maximize total amount of platooning with limited intervention in vehicle speed and route

Larson et al., 2013
Platoon merge and split

Heavy-duty vehicle traffic without platooning

Merge and split platoons at highway intersections

Only vehicles that are relatively close in space and time platooning

Larson et al., 2013

Distributed optimization of platooning

Heavy-duty vehicle traffic without platooning

With platooning

Predictive control decisions at road intersections on whether it is beneficial for a vehicle to catch up another vehicle at next intersection

Larson et al., 2013
Numerical evaluations

2-5% deployment enough for substantial benefit

Fuel saved vs total no of vehicles

- German road network with 300 trucks
- Random starting points and destinations
- 500 experiments

Larson et al., 2013

Infrastructure for data collection

Data base for data analysis

T_s=10 min

C200 Vehicle data
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>13.22%</td>
</tr>
<tr>
<td>10 min</td>
<td>1.19%</td>
<td>22.41%</td>
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<tr>
<td>15 min</td>
<td>1.64%</td>
<td>30.26%</td>
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<tr>
<td>30 min</td>
<td>2.74%</td>
<td>47.58%</td>
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<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>
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<td>3 hr</td>
<td>6.87%</td>
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<td>8.85%</td>
<td>98.38%</td>
</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

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- **Humans in the loop**
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Stockholm-Zwolle (1,300 km) 24/7 Testing

Evaluation studies
- Platooning in real traffic
- Fuel reductions and safety
- Driver acceptance
- Public acceptance

How willing are drivers to platoon?

- Jan-Apr 2013 experimental evaluation
- Drivers in the loop with advanced ACC (radar etc)
- Encouraged but not enforced to platoon
- Notable fuel reductions
Conclusions

- **Architecture 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?
  - Local computing vs communication: When do it in the Cloud?
  - Safety-critical systems: How guarantee real-time?

- **Large-scale testing and evaluations**

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