Optimizing Cooperative Driving for Road Goods Transportation

Karl H. Johansson
ACCESS Linnaeus Center & Electrical Engineering
KTH Royal Institute of Technology, Sweden

Dept of Electrical and Electronic Engineering, The University of Hong Kong, Aug 4, 2015

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Assad Alam
Kuo-Yun Liang
Per Sahlholm

Jonas Mårtensson
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Cyber-Physical Systems Roadmap, German National Academy of Science and Engineering, 2011

The transportation system is a large networked system
Mainly without global control and optimization
New information technology has dramatic potentials

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

_Eurostat (2011), EU Transport (2014)_

Life cycle cost for European heavy-duty vehicle

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

_Dr. H. Ludanek, CTO, Scania_

Schittler, 2003; Scania, 2012
Technology Push

Sensor and communication technology

Real-time traffic information

Vehicle platooning and semi-autonomous driving

Control of Vehicle Platoons

PATH platoon demo San Diego 1997
Heavy-Duty Vehicle Platooning

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

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

Zwolle, Netherlands, Feb 9, 2015
Demo for Dutch Minister of Infrastructure and the Environment Ms Schultz van Haegen

The Physics

Liang (2014)
Air Drag Reduction in Truck Platooning

10% fuel reduction potential

\[ F_{\text{air}} = \frac{1}{2} c_D \rho A v^2 \]


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
- 19,000,000 light+medium+heavy trucks in China
- 2,000,000 heavy trucks in European Union (400,000 in Germany)
- 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

Alam et al., 2012
Global and Local Control Systems

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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:

$$ f = \frac{1}{2} \int_0^T \delta(t) \left( \frac{1}{\cos\beta} \frac{d}{dt} \phi(t) \right) dt + mgc\cos\alpha + mg \sin\alpha $$

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

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Distributed Road Grade Estimation

**RMS Road Grade Error**

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

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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 vs. 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 $i-1$:

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

$$m_i \frac{dv_i}{dt} = F_{out}(\delta_i, \omega_u) - F_{\text{brake}} - F_{\text{steering}}(v_i, d_{i-1,i}) - F_{\text{roll}}(\alpha_i) - F_{\text{group}}(\alpha_i)$$

$$= k'_i T_e(\delta_i, \omega_u) - F_{\text{tire}} - k'_i \delta_i f_i (l_{i-1,i}) - k'_i \cos \alpha_i - k'_i \sin \alpha_i$$

Alam et al., 2013

Look-ahead Control for Fuel-efficient and Safe Vehicle Platooning

- Platoon coordinator
  - Minimize $\sum_i \text{task}_i$ subject to
  - Non-linear HDVs model
  - Constraints on state and input
  - Constraint on average speed
  - Same speed profile for all HDVs

- Vehicle $i$ controller
  - Minimize deviation from reference profile subject to
  - Linear HDV model
  - Constraints on state and input
  - Safety constraint
  - Soft constraint on braking
Experimental Evaluation

Experiments **without** Platoon Coordinator and Look-ahead Road Grade Information

Turri et al., 2015
Simulation with Platoon Coordinator and Look-ahead Road Grade Information

Turri et al., 2015

Evaluation of Energy Efficiency

CC: First vehicle runs conventional cruise controller, second tries to keep fixed time gap
LAC: First vehicle runs instead look-ahead cruise controller, second still keeps fixed time gap
CLAC: Vehicles run cooperative look-ahead control with platoon coordinator

Turri et al., 2015
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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 platoon

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

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

Fuel saved compared to shortest path

2-5% deployment enough for substantial benefit

Fuel saved vs total no of vehicles

Larson et al., 2013

Infrastructure for data collection

Platooning - Evaluation

Data base for data analysis

C200 Vehicle data

\( T_s = 10 \text{ min} \)
Feasibility Study Based on Real Truck Data

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

- 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
- Benefits:
  - r = 0.2 km: 78 trucks platooned, 0.16% savings
  - r = 1 km: 241 trucks platooned, 0.38% savings
  - r = 5 km: 778 trucks platooned, 1.2% savings

Larson et al., 2013

Spontaneous vs Coordinated Platooning

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

Liang et al., 2014
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>15.22%</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>
</tr>
<tr>
<td>1 hr</td>
<td>4.31%</td>
<td>68.07%</td>
</tr>
<tr>
<td>2 hr</td>
<td>5.94%</td>
<td>83.23%</td>
</tr>
<tr>
<td>3 hr</td>
<td>6.87%</td>
<td>89.93%</td>
</tr>
<tr>
<td>6 hr</td>
<td>8.06%</td>
<td>95.67%</td>
</tr>
<tr>
<td>12 hr</td>
<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

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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

Scania Transport Lab
Internal haulage company
20 trucks, 360,000 km/year
75 trailers, 92% loaded
65 drivers, 40 h work/week
Technological and Physical Complexity

Cyber-Physical Systems

Human and Social Complexity

Multi-Layer Dynamic Network Models

Cognitive & Human

Optimization & Control

Information & Communication
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
Hilly roads generate platoon disturbances

May impose fuel-inefficient braking commands

Compensated by feedforward communication of road topology and vehicle commands
Information Propagation in Platoons

- Platooning vehicles need common information on:
  - **Dynamics**: vehicle mass, platoon references etc
  - **States**: velocity, acceleration etc
  - **Actions**: breaking, disturbances etc
- Varying urgency and time constants
- Existing vehicle-to-vehicle communication is based on broadcasting protocols for traffic warnings etc

- How synchronize information in a network with guaranteed performance despite changing topology?

When is it Fuel Efficient for a Heavy-Duty Vehicle to Catch Up with a Platoon?

Liang et al., 2013
The role of plant model information

Inter-vehicle distances $d_{12}$ and $d_{23}$ are locally controlled through vehicle torques $u_i$

$$
\begin{bmatrix}
  v_1(t) \\
  d_{12}(t) \\
  v_2(t) \\
  d_{23}(t) \\
  v_3(t)
\end{bmatrix} =
\begin{bmatrix}
  -g_1/m_1 & 0 & 0 & 0 & 0 \\
  0 & 1 & 0 & -1 & 0 \\
  0 & 0 & -g_2/m_2 & 0 & 0 \\
  0 & 0 & 0 & 1 & 0 \\
  0 & 0 & 0 & 0 & -g_3/m_3
\end{bmatrix}
\begin{bmatrix}
  v_1(t) \\
  d_{12}(t) \\
  v_2(t) \\
  d_{23}(t) \\
  v_3(t)
\end{bmatrix} +
\begin{bmatrix}
  w_1(t) \\
  w_2(t) \\
  w_3(t) \\
  w_4(t) \\
  w_5(t)
\end{bmatrix}
\begin{bmatrix}
  -g_1/m_1 & 0 & 0 & 0 & 0 \\
  0 & 1 & 0 & -1 & 0 \\
  0 & 0 & -g_2/m_2 & 0 & 0 \\
  0 & 0 & 0 & 1 & 0 \\
  0 & 0 & 0 & 0 & -g_3/m_3
\end{bmatrix}
\begin{bmatrix}
  v_1(t) \\
  d_{12}(t) \\
  v_2(t) \\
  d_{23}(t) \\
  v_3(t)
\end{bmatrix} +
\begin{bmatrix}
  b_1/m_1 & 0 & 0 & 0 & 0 \\
  0 & b_2/m_2 & 0 & 0 & 0 \\
  0 & 0 & b_3/m_3 & 0 & 0 \\
  0 & 0 & 0 & b_4/m_4 & 0 \\
  0 & 0 & 0 & 0 & b_5/m_5
\end{bmatrix}
\begin{bmatrix}
  u_1(t) \\
  u_2(t) \\
  u_3(t) \\
  u_4(t) \\
  u_5(t)
\end{bmatrix}
$$

How does knowledge of the vehicle mass $m_i$ influence performance?

Motivating Example Revisited

- Regulating inter-vehicle distances $d_{12}$ and $d_{23}$

$$
\begin{bmatrix}
  v_1(t) \\
  d_{12}(t) \\
  v_2(t) \\
  d_{23}(t) \\
  v_3(t)
\end{bmatrix} =
\begin{bmatrix}
  -g_1/m_1 & 0 & 0 & 0 & 0 \\
  0 & 1 & 0 & -1 & 0 \\
  0 & 0 & -g_2/m_2 & 0 & 0 \\
  0 & 0 & 0 & 1 & 0 \\
  0 & 0 & 0 & 0 & -g_3/m_3
\end{bmatrix}
\begin{bmatrix}
  v_1(t) \\
  d_{12}(t) \\
  v_2(t) \\
  d_{23}(t) \\
  v_3(t)
\end{bmatrix} +
\begin{bmatrix}
  w_1(t) \\
  w_2(t) \\
  w_3(t) \\
  w_4(t) \\
  w_5(t)
\end{bmatrix}
\begin{bmatrix}
  -g_1/m_1 & 0 & 0 & 0 & 0 \\
  0 & 1 & 0 & -1 & 0 \\
  0 & 0 & -g_2/m_2 & 0 & 0 \\
  0 & 0 & 0 & 1 & 0 \\
  0 & 0 & 0 & 0 & -g_3/m_3
\end{bmatrix}
\begin{bmatrix}
  v_1(t) \\
  d_{12}(t) \\
  v_2(t) \\
  d_{23}(t) \\
  v_3(t)
\end{bmatrix} +
\begin{bmatrix}
  b_1/m_1 & 0 & 0 & 0 & 0 \\
  0 & b_2/m_2 & 0 & 0 & 0 \\
  0 & 0 & b_3/m_3 & 0 & 0 \\
  0 & 0 & 0 & b_4/m_4 & 0 \\
  0 & 0 & 0 & 0 & b_5/m_5
\end{bmatrix}
\begin{bmatrix}
  u_1(t) \\
  u_2(t) \\
  u_3(t) \\
  u_4(t) \\
  u_5(t)
\end{bmatrix}
$$

- Find a saddle point of $J(\Gamma, \alpha) = \|T_{sw}(s; \Gamma, \alpha)\|_\infty$ when $\alpha = [m_1, m_2, m_3] \in [0.5, 1.0]_3$ and $\Gamma$ belongs to the set of polynomials of $\alpha_i$, $i = 1, 2, 3$, up to the second order.

$$
\inf_{\Gamma \in \mathcal{A}} \sup_{\alpha \in \mathcal{A}} J(\Gamma, \alpha) = \inf_{\Gamma \in \mathcal{A}} \sup_{\alpha \in \mathcal{A}} \|T_{sw}(s; \Gamma, \alpha)\|_\infty
$$

Farokhi & J., 2013
Motivating Example Revisited

Control Design with Local Model Information
\[ \max_{\alpha \in A} \|T_{\pi w}(s; \Gamma^{\text{local}}, \alpha)\|_{\infty} = 4.7905 \]

Control Design with Limited Model Information
\[ \max_{\alpha \in A} \|T_{\pi w}(s; \Gamma^{\text{limited}}, \alpha)\|_{\infty} = 3.5533 \]

Control Design with Full Model Information
\[ \max_{\alpha \in A} \|T_{\pi w}(s; \Gamma^{\text{full}}, \alpha)\|_{\infty} = 3.3596 \]

Farokhi & I, 2013

Visualization and demonstration of future transportation in Smart Mobility Lab

- Autonomous toy trucks equipped with V2V and V2I communication
- Indoor GPS, real-time traffic information and dynamic road network
- Reach-out activities to industrial and political leadership, high school students etc

Apr 29, 2013
General Motors vision 76 years ago
“Automatic radio control”