Optimizing Cooperative Driving for Road Goods Transportation

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

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General Motors vision 75 years ago
"Automatic radio control"

- 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

- Transport sector consumes 1/3 of EU energy
- 45% of all freight transport is on roads
- Road transport accounts for 20% of CO$_2$ emissions
- Emissions increased by 21% for 1990-2009

**Eurostat (2011), EU Transport (2013)**

Life cycle cost for European heavy-duty vehicle

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

*Dr. H. Ludanek, CTO, Scania*

Technology Push

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

**SchiAler, 2003; Scania, 2012**

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

PATH platoon demo San Diego 1997

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

Heavy-Duty Vehicle Platooning

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)
• 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
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:

$$f = \int_0^T \delta(t) \left( \frac{1}{\rho} \cos \alpha \cos \phi(t) \right) \frac{dv(t)}{dt} dt + mg e \cos \alpha + mg \sin \alpha$$

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

$$\frac{mv}{dt} = F_{mg} - F_b - F_{ad}(v, d) - F_\alpha(\alpha) - F_b(\alpha)$$

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

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

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

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 $i-1$:

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

$$m_i \frac{dv_i}{dt} = F_{\text{eng}}(\delta_i, \omega_{\text{e}}) - F_{\text{brake}} - F_{\text{drag}}(v_i, d_{i-1,i})$$

$$= k_i T_e(\delta_i, \omega_{\text{e}}) - F_{\text{brake}} - k_i^T f_i(d_{i-1,i})$$

$$- k_i^v \cos \alpha_i - k_i^\theta \sin \alpha_i$$

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 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 platoon

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
Numerical evaluations

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

2-5% deployment enough for substantial benefit

Fuel saved vs total no of vehicles

- Larson et al., 2013

Infrastructure for data collection

Data base for data analysis

C200 Vehicle data

T_s=10 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

Coordinated departure times enable much more platooning

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- **Humans in the loop**
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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
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