How to Control Road Traffic Using Automated Truck Platoons

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The Problem

How to efficiently transport goods over a highway network?

**Characteristics**
- 2,000,000 heavy long-haulage trucks in EU
  - 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 automation and fuel-saving cooperations with limited intervention in vehicle speed, route, and timing

Why focus on fuel and automation?

*Life cycle cost* for European heavy-duty vehicle

- Total fuel cost 80 k€/year/vehicle

Schittler, 2003; Scania, 2012
11/21/20

25 MEUR EU project on multi-brand platooning 2018-2021

The Physics

Norrby (2014), Liang (2016)

Air Drag Reduction in Truck Platooning

5-20% fuel reduction potential

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

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

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**Experimental Setup**

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Alam, 2014
Experimental Results

Challenge
How to handle topography variations? Which spacing policy to choose?

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:
\[ v_i(t) \to v_{\text{ref}}(s_i(t)), \]
\[ s_i(t) \to s_{i-1}(t - \Delta t) \]
Simulations with **Platoon Coordinator** and **Look-ahead Road Grade Information**

Successful tracking of common platoon velocity reference

5G Cellular Implementation of **Platoon Coordinator**

- Platoon coordinator generates common velocity reference: $v_i(t) \rightarrow v_{ref}(s_i(t))$.
- Can be computed in the cellular system.
- New handover scheme for moving control computations between base stations.
Controller Code Handover Supporting Vehicle Platooning

- Proposed new handover schemes for 5G
- Support real-time control from edge cloud

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
Platoon Formation

Feedback control of merging point based on real-time vehicle state and traffic information

- Traffic and Vehicle Predictor
- Formation Controller

Optimal speed profiles for platoon formation

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
Platoon Formation Optimization

**Catch-up phase**

**Platooning phase**

**Split**

minimize \( v_1, v_2, v_p \in [v_{\text{min}}, v_{\text{max}}] \)

subject to

controlled vehicles dynamics and constraints

traffic dynamics with moving bottlenecks

Traffic dynamics represented by extending the Daganzo (1994) cell transmission model (CTM) to handle moving bottlenecks

Discretize Lighthill-Whitham-Richards PDE \( \frac{\partial \rho}{\partial t} + \frac{\partial Q}{\partial x} = 0 \) with truck platoon:

\[
\rho_i(t+1) = \rho_i(t) + \frac{T}{L} (q_{i-1}(t) - q_i(t))
\]

\[
q_i(t) = \min \left( V \rho_i(t), V \sigma, W(P - \rho_{i+1}(t)) \right)
\]

- \( \rho_i(t) \) – traffic density in cell \( i \)
- \( q_i(t) \) – traffic flow from cell \( i \) to cell \( i + 1 \)

Higher fuel consumption during the **catch-up phase**

Lower fuel consumption during the **platooning phase**

**Merge point** depends on velocities during the **catch-up phase**

**Final split point** is fixed to give desired average velocity
Slowing down lead vehicle causes heavier traffic for follower vehicle.
Fuel consumption reduced for proposed controller despite later merging.

Numerical Example

\[ v_1, v_2, v_p^2 \in [v_{\text{min}}, v_{\text{max}}] \]

- Optimum platoon formation leads to 2-3% additional energy savings.
- Considering the influence of traffic improves energy savings.
Can truck platooning be used to improve traffic conditions?

- Model truck platoons as bottlenecks moving in car traffic, cf., Lebacque et al. 1998; Delle Monache & Goatin 2014
- Restrict the traffic flow into the congested areas using controlled truck platoons

Discretize the Lighthill-Whitham-Richards PDE model and include truck platoons:

\[
\rho_i(t+1) = \rho_i(t) + \frac{T}{L} \left( q_{i-1}(t) - q_i(t) \right) \\
q_i(t) = \min \left\{ V \rho_i(t), V \sigma_i, W(P - \rho_{i+1}(t)) \right\}
\]

- \( \rho_i(t) \) – traffic density in cell \( i \)
- \( q_i(t) \) – traffic flow from cell \( i \) to cell \( i+1 \)

Stop-and-go wave dissipation

Upstream-propagating wave of slowed or stationary vehicles without an apparent bottleneck

Euler approach
- Control of vehicle flows, e.g., variable speed limits

[Hegeyi et al., 2008]

Lagrange approach
- Control of individual vehicles or platoons, e.g., connected automated vehicles

[Stern et al., 2018, Kreidieh et al., 2018, Čičić & J., 2018]
Control truck platoon velocity to dissipate congestion based on traffic densities

Traffic density without truck control

Traffic density with truck control

Truck platoon trajectory

Truck platoon control reduces traffic congestion

Without truck platoon control

38% total travel time increase due to traffic congestion
Truck platoon control reduces traffic congestion

Without truck platoon control

With truck platoon control

38% total travel time increase due to traffic congestion

8% total travel time increase due to traffic congestion

Stop-and-go wave dissipation based on state reconstruction

No control

Perfect information control

- What if perfect traffic state information is not available?
- Use reconstructed traffic state based on adaptively selected vehicle measurements
Stop-and-go wave dissipation based on state reconstruction

1. Probe vehicles detect congestion
2. More probe vehicles are activated to better reconstruct the congestion

[Čičić et al., 2020]
Stop-and-go wave dissipation based on state reconstruction

1. Probe vehicles detect congestion
2. More probe vehicles are activated to better reconstruct the congestion
3. Actuator vehicles dissipate the stop-and-go wave

4. Next actuator vehicle dissipates the congestion caused by the first one

[Čičić et al., 2020]
Conclusions

- **Automated road freight transport**
  - Integrated platoon coordinator and cruise-controller
  - Platoon control over V2V and V2I cellular communication
  - Automated vehicle match-making and platoon formation
- Leads to significantly **lower fuel and operation costs**
- Control automated platoons to **reduce traffic congestion**
- Platoons acting as probe vehicles (sensors) and moving bottlenecks (actuators)

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Matthieu Barreau poster ressentations at 11:50 (PT) on Learning-based Traffic State Reconstruction
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