Traffic Control using Automated Vehicles: Distributed Sensing, Actuation, and Learning

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S. Amin (MIT), L. Jin (SJT), A. Ferrara (Pavia) and many others
Growing relative importance of goods transport?
Why focus on fuel and automation for trucks?

**Life cycle cost** for European heavy-duty vehicle

- **Fuel**: 35%
- **Driver**: 35%
- **Repair & maintenance**: 9%
- **Administration**: 7%
- **Tires**: 3%
- **Vehicles**: 11%

Total fuel cost 80 k€/year/vehicle

Schittler, 2003; Scania, 2012
Control of Vehicle Platoons

On the Optimal Error Regulation of a String of Moving Vehicles

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

Fig. 1. Vehicles moving in a string.

Path platoon demo San Diego 1997

Scania

Volvo

Swedish success stories
Air Drag Reduction in Truck Platooning

Simulations with Platoon Coordinator and Look-ahead Road Grade Information

Successful tracking of common platoon velocity reference

Turri et al., 2015
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 (4G, 5G, 6G)
- New handover scheme for moving control computations between base stations

van Dooren et al., 2017
How to form platoons?
Platoon Formation

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

Optimal speed profiles for platoon formation

Liang et al., 2016; Cicic et al., 2017
Platoon Formation Experiments

- 600 test runs on E4 in Nov 2015
- Traffic measurements from road units together with onboard sensors

Liang et al., 2016
Can controlled truck platoons be used to improve traffic conditions?

- Trucks act as bottlenecks moving in car traffic
- Regulate cars flowing into congested area

Lin et al., 2018; Cicic and J., 2018

Cf., [Lebacque et al. 1998; Delle Monache & Goatin 2014]
Flows according to Euler and Lagrange

Euler was looking at fluid motion focused on specific locations in the space through which the fluid flows as time passes.

Lagrange was looking at fluid motion where the observer follows an individual fluid parcel as it moves through space and time.
From Eulerian to Lagrangian traffic control

Leonhard Euler (1707-1783)
Stationary observer of the flow
Traffic control based on fixed infrastructure
High deployment costs and limited flexibility

Joseph-Louis Lagrange (1736-1813)
Observers moves with the flow
Traffic control based on mobile sensors and actuators
Need for a new system theoretic foundation
Control truck platoon velocity to dissipate traffic congestion

Without truck platoon control

With truck platoon control

Truck platoon trajectory
Truck platoon control reduces traffic congestion

38% total travel time increase due to traffic congestion

Cicic, Jin and J, 2019
Truck platoon control reduces traffic congestion

Without truck platoon control

38% total travel time increase
due to traffic congestion

With truck platoon control

8% total travel time increase
due to traffic congestion

Cicic, Jin and J, 2019
Lagrangian traffic control system

\[ \frac{\partial \rho(x,t)}{\partial t} + \frac{\partial Q(\rho(x,t), x, t)}{\partial x} = 0 \]
Control law

Control the traffic flow at the positions of available controlled vehicles

\[
\begin{align*}
\text{minimize} & \quad \text{Total Time Spent} \\
& \quad u_\xi(\cdot) \in [u_{\text{min}}, u_{\text{max}}] \\
& \quad q^{\text{cap}}_\xi(\cdot) \in [q^{\text{lo}}, q^{\text{hi}}] \\
\text{subject to} & \quad \text{traffic dynamics with moving bottlenecks} \\
& \quad \text{controlled vehicles dynamics and constraints}
\end{align*}
\]

[Čičić., 2021]
Traffic state reconstruction and prediction

- Use local traffic measurements to reconstruct the traffic state

- Traffic evolution prediction given applied control actions
  - Front-tracking Transmission System Model

\[ \dot{\rho}_t \]

\[ \rho_{ct} \]

[Čičić., 2021]
State Reconstruction using Probe Data

Microscopic simulation

Reconstruction algorithm

There is a traffic light there

[Barreau et al., 2021]
• Learn all flux functions using collected traffic measurements

  • Parametric, *batch* – assume a flux function form and minimize deviations from all measurements

  • Nonparametric, *stream* – piecewise linear flux function with nodes based on measurements as they become available

\[
\frac{\partial \rho(x,t)}{\partial t} + \frac{\partial Q(\rho(x,t), x, t)}{\partial x} = 0
\]

Cf., physics-informed machine learning [M Raissi et al., 2019]
Evaluation of Lagrangian control

No control

Full-information control

Reconstruction-based control with model learning

Travel time variations

[Čičić., 2021]
Conclusions

• Layered architecture for automated road freight transport enables significantly lower energy and operation costs

• Automated truck platoons to reduce traffic congestion

• Platoons acting as probe vehicles (sensors) and moving bottlenecks (actuators)

• Traffic state reconstruction based on physics-informed machine learning

• Related work on safe autonomy, data privacy, market mechanisms

people.kth.se/~kallej
Bibliography (2008-2018)

Available at http://people.kth.se/~kallej/publication.html

Overviews


Platoon and vehicle controls


• B. Besselink and K. H. Johansson, Control of platoons of heavy-duty vehicles using a delay-based spacing policy, IFAC Workshop on Time Delay Systems, Ann Arbor, MI, USA, 2015.


Bibliography (cont’d)


**Platoon formation**


- K.-Y. Liang, J. Martensson, and K. H. Johansson, When is it fuel efficient for a heavy duty vehicle to catch up with a platoon? IFAC AAC, Tokyo, Japan, 2013.

**Platoon assignments and coordination**


Bibliography (cont’d)


Economic and logistic consequences


- F. Farokhi and K. H. Johansson, Investigating the interaction between traffic flow and vehicle platooning using a congestion game, IFAC World Congress, Cape Town, South Africa, 2014.

Bibliography (cont’d)

Road grade estimation

• P. Sahlholm, A. Gattami, and K. H. Johansson, Piecewise linear road grade estimation, SAE World Congress, Detroit, MI, USA, 2011.


• P. Sahlholm and K. H. Johansson, Road grade estimation for look-ahead vehicle control, IFAC World Congress, Seoul, Korea, 2008.

Controller handover


• D. van Dooren, G. Fodor, J. Gross, and K. H. Johansson, Performance analysis of controller handover schemes, Manuscript in preparation, 2018

Vehicle platooning impact on traffic

• L. Jin, M. Cicic, S. Amin, and K. H. Johansson, Modeling the impact of vehicle platooning on highway congestion: a fluid queuing approach, ACM Workshop on Hybrid Systems: Computation and Control, Porto, Portugal, 2018