Energy-Efficient Cooperative Adaptive Cruise Control (EECACC) for Cars & Commercial Vehicles

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Energy-Efficient CACC - Overview

1. Introduction to Predictive Energy Management

2. Traffic Light Assistant

3. Energy-Efficient Cooperative Adaptive Cruise Control
   a) Problem Overview
   b) Model Predictive Control
   c) Simulation Results
   d) Testbed Results

4. Summary & Conclusion
Introduction
Market Drivers / Customer Requirements

- **Accident free driving**
  active safety functions e.g. emergency braking, lane keeping assistant

- **Driver relief and comfort functions**
  e.g. parking assistant, adaptive cruise control

- **Connectivity**
  e.g. smart phone interaction, real time traffic information, V2X, cloud computing

- **Fuel/energy efficiency**
  e.g. EV driving range, Fuel saving by predictive functions and platooning

- **Operating cost**: Driver substitution as TCO argument at mainly transport & shared mobility business
Introduction
Predictive Energy Management Leveraging ADAS Data

COASTING ASSISTENT

TRAFFIC LIGHT ASSISTANT

ECO ROUTING

ADAS/AD HMI

PREDICTIVE ADAPTIVE CRUISE CONTROL

PREDICTIVE CHARGING

PREDICTIVE THERMAL MANAGEMENT

PREDICTIVE GEARSHIFT

Sources: www.AVL
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Traffic Light Assistant
Introduction to Traffic Light Assistants

Vehicles & traffic lights will communicate in future (starting now):
• Direct communication (or via centralized traffic management).
• Vehicle follow calculated (here generated on-board) velocity trajectory.

AVL’s concept development of 1st generation Traffic Light Assistant ca 2012. TLA relies on V2I communication, specifically from I2V.
Traffic Light Assistant
Traffic Light Assistant Functions for the Market

First Traffic Light Assistant (TLA) systems starting to be introduced e.g.:

• Continental performing testing with ‘Smart Traffic Light Assist (TLA)’. Field trials in Las Vegas & Regensburg. Shows very significant energy savings (9.5% average).

• Audi announces first vehicle to infrastructure (V2I) service in US with Traffic Light info. system. System available in 2017 on Q7, A4 & A4 Allroad.

Press release
Audi announces the first vehicle to infrastructure (V2I) service - the new Traffic light information system

- New traffic light information system communicates with municipal traffic signals to inform the driver when traffic lights turn from red to green.
- Traffic light information system is first step in vehicle to infrastructure (V2I) integration, set to launch in select cities before end of 2016.
- System will be available on select 2017 Audi Q7, A4 and A4 allroad models with Audi connect®

Press Release: AudiUSA

Powertrain Control by Connectivity – Chances, Architectures, Solutions
Friedrich Graf, Franz Pellkofer
Continental, Regensburg
CESA 4.0

Vdi Wissensforum Innovative antriebe | 23rd-24th November 2016
Traffic Light Assistant
Traffic Light Assistant Visualized (1/2)

- Use of V2I information to approach multiple Traffic Light (TL) scenario:
  - Goal: find most energy efficient way.
- Model Predictive Control (MPC) formulation:
  - Receding horizon approach.
  - Real-time optimization by cost fcn minimization & constraints.
Optimization problem:
\[
\min_{\tau=t}^{t+N_p} \sum \left( x(\tau), u(\tau) \right)
\]
S.T. \( g(x, u, t) \leq 0 \)
\( u(\tau) \in U, \quad x(\tau) \in X, \quad \tau = t, \ldots, t + N_p \)
\( x(\tau + 1) = Ax(\tau) + Bu(\tau), \quad \tau = t, \ldots, t + N_p - 1 \)

- Min. of Energy Consumption
- Constraints imposed by TL
- Constraints imposed by traffic
- Powertrain specific constraints

Traffic Light Assistant
Traffic Light Assistant Visualized (2/2)
Traffic Light Assistant
Results From Testing of AVL’s 1st Generation TLA

➢ Battery SoC considered as metrics of energy savings

➢ ‘Normal Driver’ controlled by reference simulated driver

<table>
<thead>
<tr>
<th>Energy Savings</th>
<th>Time Savings</th>
</tr>
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<tbody>
<tr>
<td>17%</td>
<td>3.8%</td>
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</table>
Traffic Light Assistant
Seamless Development of OpEneR Functions 2013

Reuse of office simulation environment for AVL InMotion testbed
Interactive Workshop (1/2)

Traffic Light Assistants (TLA) require digital communication of traffic light signal phase & timing (SPAT). Alternative (complementary or competitive) V2X (Vehicle-to-Anything) technologies are emerging, either based on cellular/mobile data communication, or via Dedicated Short Range Communication (DSRC).

**Which types of V2X do you think will be dominant in the short and long-term future?** Short-term cellular/mobile data or DSRC? Long-term both? In UK? In Europe? Worldwide?
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Energy-Efficient CACC – Problem Overview

What is Cooperative Adaptive Cruise Control?

**Cruise Control (CC):** Longitudinal speed control with set speed defined by human driver.

**Adaptive Cruise Control (ACC):** Adapts speed based on distance to & speed of preceding vehicle, e.g. measured using on-board sensors such as RADAR or Camera.

**Cooperative Adaptive Cruise Control (CACC):** ACC extension supported by communication with surrounding traffic & infrastructure, possibly also other data sources e.g. cyclists, pedestrians.
Energy-Efficient CACC – Problem Overview
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Energy-Efficient CACC – Problem Overview

Background

Vehicle following known path

Route contains altitude, curvature, traffic lights, ...

Includes time-dependent constraints such as traffic light signal phases

V2V / I2V

Vehicle-to-Vehicle (V2V)

Infrastructure-to-vehicle (I2V)

Holistic approach needed!
Holistic & full range predictive speed control strategy (CACC) including ego-vehicle & its static & dynamic powertrain characteristics, uses V2X derived RT traffic, infrastructure & route data.

Optimizes in real-time trade-off between energy efficiency, driver comfort & safety.
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Energy-Efficient CACC – MPC
Introduction to Model Predictive Control (1/2)

\[ u_{opt} = [u(0), u(1), \ldots, u(H_T)]^T \]

Optimal sequence of control inputs over prediction horizon \( H_T \)

* i.e. vehicle & driving environment

** Vehicle states, traffic light information, etc.
### Energy-Efficient CACC – MPC

**Introduction to Model Predictive Control (2/2)**

- **Predicts plant states** based upon optimal control signal & system equations.

- **Optimization problem solution.** Generation of optimal control signal. Only first element of that signal is forwarded to the plant. The rest is used in Prediction Module.

- **MPC optimizes future plant control trajectory** by minimizing a prescribed cost function subject to constraints.

\[
\begin{align*}
\text{Minimize} & \quad J(u, \hat{x}, \hat{y}, \ldots) \\
\text{Subject to} & \quad f(u, \hat{x}, \hat{y}, \ldots) \leq 0 \\
& \quad g(u, \hat{x}, \hat{y}, \ldots) = 0
\end{align*}
\]
Energy-Efficient CACC – MPC

Hybrid* Model Predictive Control (MPC) dynamically incorporates descriptions of upcoming traffic & road conditions as constraints in receding horizon.

- **Non-linear constraints** like energy consumption, gear shifts, full load, & road attributes (e.g. gradient, curvature) modelled.

- **eHorizon & V2X** used for better predictions of preceding traffic & infrastructure, including traffic lights, variable speed limits, delivery & bus stops.

*Note Hybrid here refers to modelling technique, not the powertrain type*
Energy-Efficient CACC – MPC
Alternative Hybrid MPC Cost Functions

Minimize
\[ J(u, \hat{x}, \hat{y}, \ldots) \]
Subject to
\[ f(u, \hat{x}, \hat{y}, \ldots) \leq 0 \]
\[ g(u, \hat{x}, \hat{y}, \ldots) = 0 \]

Cost function
Constraints

Acceleration (QP)
Quadratic projection of Fuel Consumption Map (QP)
Piecewise affine FCM (Hybrid)
Energy-Efficient CACC – MPC
Hybrid MPC Constraints

Discontinuities
e.g. gearshifting

Min. of convex function
or
Max. of concave function
e.g. full load curve

Multiple affine constraints
(no binary variables)

Propositional logic with binary variables

Separated regions
e.g. hybrid modes

Non-convex/concave functions
e.g. speed limits on route

Piecewise Affine (PWA)
approximation of nonlinear constraints

Max velocity

Inclination

Propositional logic with binary variables

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Energy-Efficient CACC – MPC
Traffic Light Constraints

Select Earliest Reachable Green Phases

Define Distance Boundaries Over Prediction Horizon
Energy-Efficient CACC – MPC
Traffic Constraints (1/5)

**Prediction Model**

<table>
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<tr>
<th>AR (Autoregressive) (v_{pr}, a_{pr})</th>
<th>V2X-Based Prediction</th>
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- **TL 1**: Predicted positions of preceding vehicle, including minimum headway distances/times ('hard' maximum positions)

- **TL 2**: Predicted positions of preceding vehicle, including minimum headway distances/times ('hard' maximum positions)

- **Ego vehicle**

- **Preceding vehicle**

- **Min Headway Time/Distance**

- **Max headway time/distance**

- 3 s

- 17 s

- \(H_T\)

- \(p_{pr}\)

- \(p_{TL}\)
Energy-Efficient CACC – MPC
Traffic Constraints (2/5)

Prediction Model

AR (Autoregressive) \((v_{pr}, a_{pr})\)
V2X-Based Prediction

\[ d_{pr} = 40 \text{ m} \]

\( A \) tunable distance from the preceding vehicle is allowed ('soft' minimum positions)

Min Headway Time/Distance
Max headway time/distance

Ego vehicle
Preceding vehicle

**TL 1**
**TL 2**

**TL 2**
**TL 1**

\[ p^{pr} \]

\[ p_T \]
Energy-Efficient CACC – MPC
Traffic Constraints (3/5)

Prediction Model

- AR (Autoregressive) \( (v_{pr}, a_{pr}) \)
- V2X-Based Prediction

3 s 17 s 17 s

\( H_T \)

Min Headway Time/Distance
Max headway time/distance

Ego vehicle
Preceding vehicle \( p^{pr} \)

\( p_{TL}^{TL} \)

The start of traffic light green phases should be targeted ('soft' minimum positions)
### Prediction Model

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- **Ego vehicle**
- **Preceding vehicle**

- **Min Headway Time/Distance**
- **Max headway time/distance**

- **TL 1**
- **TL 2**

The effective soft minimum positions are obtained by taking the minimum of all individual soft minimum positions.
Energy-Efficient CACC – MPC
Traffic Constraints (5/5)

**Prediction Model**

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3 s  17 s  \(H_T\)

\[ d_{pr} = 40 \text{ m} \]

Min/Max Positions over Prediction Horizon

MPC minimized trade-off between energy consumption & driveability (jerk) within this accepted area of positions
The MPC’s environmental model is updated using data from both map & V2I.

Behavior of preceding traffic is predicted using short-term predictions, possibly with V2V, also considering infrastructure.

MPC finds acceleration which minimizes tunable cost between energy consumption, travel time, & comfort/driveability.
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Energy-Efficient CACC – Simulation Results
Graz Route Simulation (Overview)

Typical energy savings of between 5% & 30% depending on scenario
**Energy-Efficient CACC – Simulation Results**

**Graz Route Simulation without Traffic**

*Energy savings: 25%* without traffic with no increase in travel time

* like most predictive functions, the benefits depend on the specific use case.
Energy-Efficient CACC – Simulation Results
Graz Route Simulation with Traffic

Energy savings: 16%* with traffic with no increase in travel time

* like most predictive functions, the benefits depend on the specific use case.
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2. Recap of V2X and Traffic Light Assistant
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Energy-Efficient CACC – Testbed Results
FFG TASTE Project

"Traffic Assistant Simulation and Testing Environment".
10.2015 – 06.2017

- Virtual test environment for ADAS, including real communication units.
- RT interaction / communication of traffic control infrastructure & cars.
- Specific testbed setting for specialized application.
- Testbed & Road testing with real vehicle & V2X units.
Energy-Efficient CACC – Testbed Results FFG TASTE Powertrain Testbed Setup (2/2)

- Seamless & concurrent development approach.
- Requirements, Control Functions & Test Cases first developed in pure office co-simulation (not shown).
- Later development moves to real-time Powertrain Testbed, with reuse of the Test Cases, & remaining system parts that must still be simulated.
Energy-Efficient CACC – Testbed Results
EECACC Test Results from Powertrain Testbed

Road with low traffic, and average traffic speed, real V2X disabled.
EECACC controlled test case achieves a lower fuel consumption by the end of the maneuver (measured real 25% diesel fuel consumption savings).
Both Reference and EECACC are able to cross the first traffic light under green phase, whereas for the second traffic light, the EECACC controlled vehicle performs a smoother deceleration.
When approaching the last traffic light, EECACC controller slightly reduces its travel speed and is able to effectively avoid the stop at the red traffic light.
Interactive Workshop (2/2)

If we have comprehensive knowledge about the future driving environment, significant energy consumption benefits can be achieved with basically the same vehicle & powertrain hardware.

**When will these functions reach the markets?** Some limited functions are already available in premium passenger cars & commercial vehicles. When will they become more mainstream?
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Summary & Conclusion

- Increasing interest in V2X communications to intelligently connect conventional & automated vehicles.
- V2X supported ADAS such as simple Traffic Light Assistants, now starting to be introduced in market.
- Efficiency, safety & convenience all benefit from optimized vehicle speed profiles.

- AVL’s Energy-Efficient Cooperative Adaptive Cruise Control (EECACC) reduces energy consumption by up to 30%* in simulated city scenario, 25% on testbed.
- EECACC considers the static layout, sizing & efficiency of powertrain, as well as the dynamic state (e.g. SoC, temperature) of powertrain, traffic ahead & traffic light signal, phasing & timing information.
- Benefits of EECACC extended to other powertrain functions e.g. hybrid powertrain mode selection.
- Seamless approach (office to testbed) facilitates dvpt. & validation of connected & predictive functions.

* like most predictive functions, the benefits depend on the specific use case.
Thank You

www.avl.com