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
4 Pillars of ADAS/AD Engineering Services

System Design
system engineering, use & test cases, architecture, component & function specification

Tailored Control & SW Development
concept & series development customer features, modification/adaptation

Advanced Predictive Functions
improving vehicle attributes e.g. energy or fuel efficiency

Calibration, Testing & Validation
derivative integration, optimization & assessment, testing from lab, XiL to road

Trusted Engineering Service Provider & Development Partner at ADAS & Autonomous Driving with long term references at several OEMs
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

Key importance
Introduction
Predictive Energy Management Leveraging ADAS Data
Introduction
Predictive Speed Control for Various CV OEM

**Aim:**
- Optimize vehicle speed over defined & relevant prediction horizon
- Criteria for optimization mainly fuel consumption & travel time

**Functionalities:**
- Predictive Cruise Control (PCC) adjusts speed to upcoming gradients
- Predictive Adaptive Cruise Control (PACC) if slower traffic ahead
- Eco-roll\(^*\) finds efficient mode (e.g. drive, coast, regeneration)
Drag Reduction in Platooning Operation
CFD Simulation
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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 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 Audi models this fall in the USA.
- 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
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:

\[
\text{min } \sum_{t=0}^{t+N_p} (x(t), u(t)) \\
\text{S.T. } \quad g(x, u, t) \leq 0 \\
\quad u(t) \in U, \quad x(t) \in X, \quad t = t, ..., t + N_p \\
\quad x(t + 1) = Ax(t) + Bu(t), \quad t = t, ..., t + N_p - 1
\]

- State variables, \( x \)
- Control variables, \( u \)
- Time, \( t \)
- Prediction horizon, \( N_p \)

- Min. of Energy Consumption
- Constraints imposed by TL
- Constraints imposed by traffic
- Powertrain specific constraints
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>
</thead>
<tbody>
<tr>
<td>17%</td>
<td>3.8%</td>
</tr>
</tbody>
</table>
Traffic Light Assistant
Seamless Development of OpEneR Functions 2013

Reuse of office simulation environment for AVL InMotion testbed
Traffic Light Assistant
Current Activities

• TLA results including latest EECACC to be published in more detail in early 2019
• AVL Traffic Light Assistant being enhanced & tested for major OEM
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 DSRC? Long-term both? In Sweden? 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

**Overview**

- **Vehicle following known path**

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

**Vehicle following** known path.

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

- **V2V / I2V**
- **Radar**

**Vehicle-to-Vehicle (V2V)**

- **Preceding vehicles**

**Infrastructure-to-vehicle (I2V)**

- **Traffic light 1**
- **Traffic light 2**
- **Traffic light 3**

**Includes time-dependent constraints such as traffic light signal phases**

**Holistic approach needed!**
Energy-Efficient CACC – Problem Overview

EECACC Overview

- **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.

![Diagram showing CACC components](image)

- **V2X (Vehicle to Anything)**
- **Vehicle-to-Vehicle (V2V)**
- **Vehicle-to-Infrastructure (V2I)**

- **Velocity** $v$
- **Acceleration** $a$
- **Road Inclination** $\theta$
- **Gear** $G$
- **Inertia, Drag, Rolling Res., Gravity**

Energy savings up to 30%

Energy Consumption Map computed Online in real-time Optimization
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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

- **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
\[ J(u, \dot{x}, \dot{y}, ...) \]
Subject to
\[ f(u, \dot{x}, \dot{y}, ...) \leq 0 \]
\[ g(u, \dot{x}, \dot{y}, ...) = 0 \]

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

Multiple affine constraints
(no binary variables)

Propositional logic with binary variables

Min. of convex function
or
Max. of concave function

e.g. full load curve

Non-convex/concave functions

e.g. speed limits, slopes on route

Separated regions

e.g. hybrid modes

A

B

Propositional logic with binary variables

Multiple affine constraints

Propositional logic with binary variables

\[
\begin{align*}
\min x \\
\text{s.t. } & x \geq a_1 + b_1 x \\
& x \geq a_2 + b_2 x \\
& \vdots
\end{align*}
\]

Max velocity

Inclination

Piecewise Affine (PWA) approximation of non-linear constraints
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

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

$3 \text{s}$
$p_{pr}$

Max headway time/distance

Min headway time/distance

Ego vehicle
Preceding vehicle $p_{pr}$

$H_T$

Predicted positions of preceding vehicle, including minimum headway distances/times (‘hard’ maximum positions)
Energy-Efficient CACC – MPC
Traffic Constraints (2/5)

Prediction Model

**AR (Autoregressive)**

\( v_{pr}, a_{pr} \)

**V2X-Based Prediction**

\[ p \]

\[ 3 \text{ s} \]

\[ 17 \text{ s} \]

\[ H_T \]

Min Headway Time/Distance

Max headway time/distance

Ego vehicle

Preceding vehicle

\( p_{pr} \)

\( p^T_L \)

\( d_{pr} = 40 \text{ m} \)

A tunable distance from the preceding vehicle is allowed (‘soft’ minimum positions)
Energy-Efficient CACC – MPC
Traffic Constraints (3/5)

**Prediction Model**

- **AR (Autoregressive)**
  \( (v_{pr}, a_{pr}) \)

- **V2X-Based Prediction**

3 s $\rightarrow$ 17 s $\rightarrow$ \( H_T \)

Min Headway Time/Distance

Max headway time/distance

Ego vehicle

Preceding vehicle

\( p^{TL}_T \)

\( p_T \)

\( p_{pr} \)

Start of traffic light green phases should be targeted ('soft' minimum positions)

TL 2

TL 1

\( H_T \)
Energy-Efficient CACC – MPC
Traffic Constraints (4/5)

Prediction Model

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

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

Prediction Model

<table>
<thead>
<tr>
<th>AR (Autoregressive) (v_{pr}, a_{pr})</th>
<th>V2X-Based Prediction</th>
</tr>
</thead>
</table>

Ego vehicle

\[ p_{TL} \]

Min Headway Time/Distance

Max headway time/distance

Preceding vehicle

\[ p_{pr} \]

Min/Max positions over prediction horizon

MPC minimized trade-off between energy consumption & comfort (e.g. jerks) within this accepted area of positions

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

\[ p_{MIN} \]

\[ p_{pr} \]

\[ p_{TL} \]
Energy-Efficient CACC – MPC
Overview of ECACC Control Architecture

MPC’s environmental model updated with data of 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 aspect)
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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:** 25.3% without traffic
Note: No increase in travel time

Adjustable travel time & driver comfortability
Energy-Efficient CACC – Simulation Results
Graz Route Simulation (With Traffic)

Energy savings: 16% with traffic
Note: No increase in travel time
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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 (1/2)
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.
▪ Efficiency, safety & convenience all benefit from optimized vehicle speed profiles.
▪ V2X supported ADAS features such as Traffic Light Assistant (TLA), now start to be introduced in market.
▪ 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 (SPAT).
▪ Benefits of EECACC extend to other powertrain functions e.g. gear, hybrid powertrain mode selection.
▪ Seamless approach (office to testbed) facilitates dvpt. & validation of connected & predictive functions.

* Like all predictive functions, the benefits depend on the specific use case.