AVL List GmbH (Headquarters)

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

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Energy-Efficient CACC - Overview

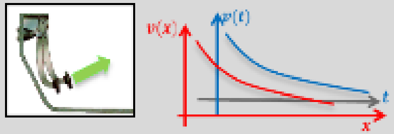
Introduction
Market Drivers / Customer Requirements

- **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

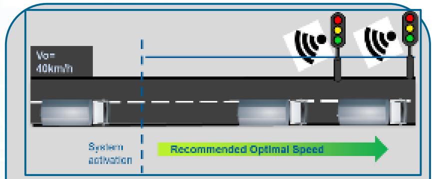
Key importance

- **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

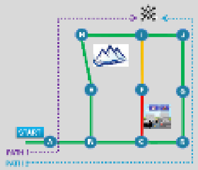
Introduction
Predictive Energy Management Leveraging ADAS Data



COASTING ASSISTENT

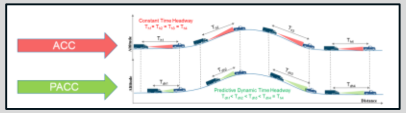


TRAFFIC LIGHT ASSISTANT

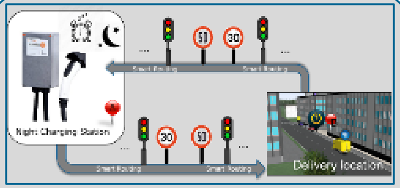


ECO ROUTING

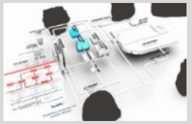
ADAS/AD HMI



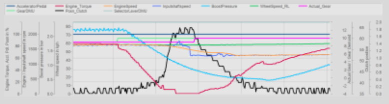
PREDICTIVE ADAPTIVE CRUISE CONTROL



PREDICTIVE CHARGING



PREDICTIVE THERMAL MANAGEMENT



PREDICTIVE GEARSHIFT

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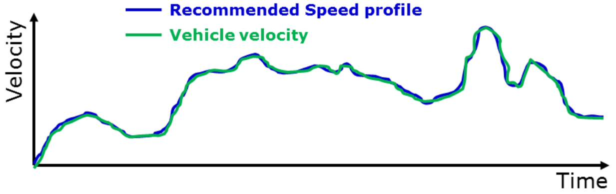
Traffic Light Assistant
Introduction to Traffic Light Assistants

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.

Centralized traffic management

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.

Powertrain Control by Connectivity – Chances, Architectures, Solutions

Friedrich Graf, Franz Pellkofer Continental, Regensburg CESA 4.0 Automotive Electronic Systems, Nov. 2016

Press release

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

August 15, 2016 | HERNDON, Virginia

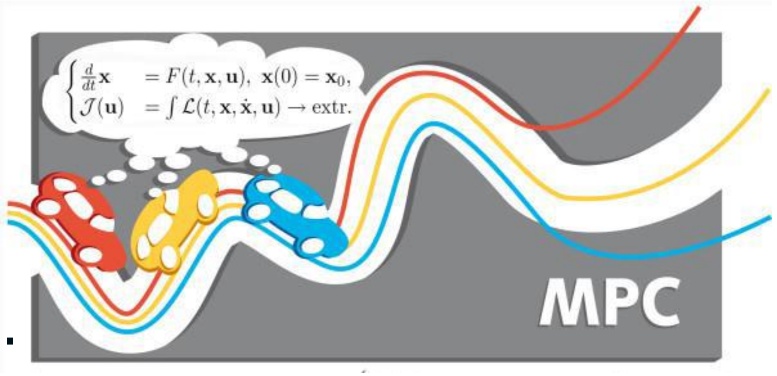
- New Traffic light information system communicates with municipal traffic signals to inform the driver when traffic lights turn from red to green.
- Traffic light information system is first step in vehicle to infrastructure (V2I) integration, set to launch in select smart cities this fall in the U.S.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

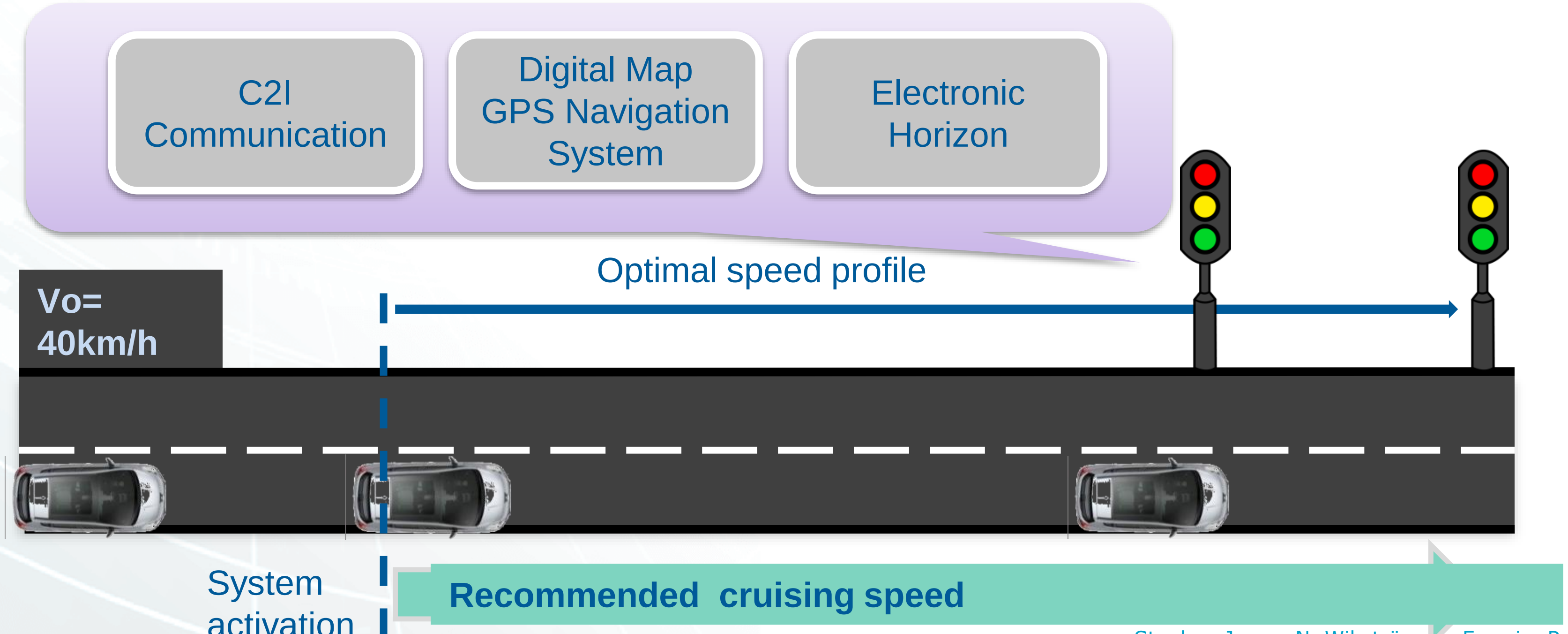
Press Release: AudiUSA

Vdi Wissensforum Innovative antriebe | 23rd- 24th November 2016

Traffic Light Assistant
Traffic Light Assistant Visualized (1/2)

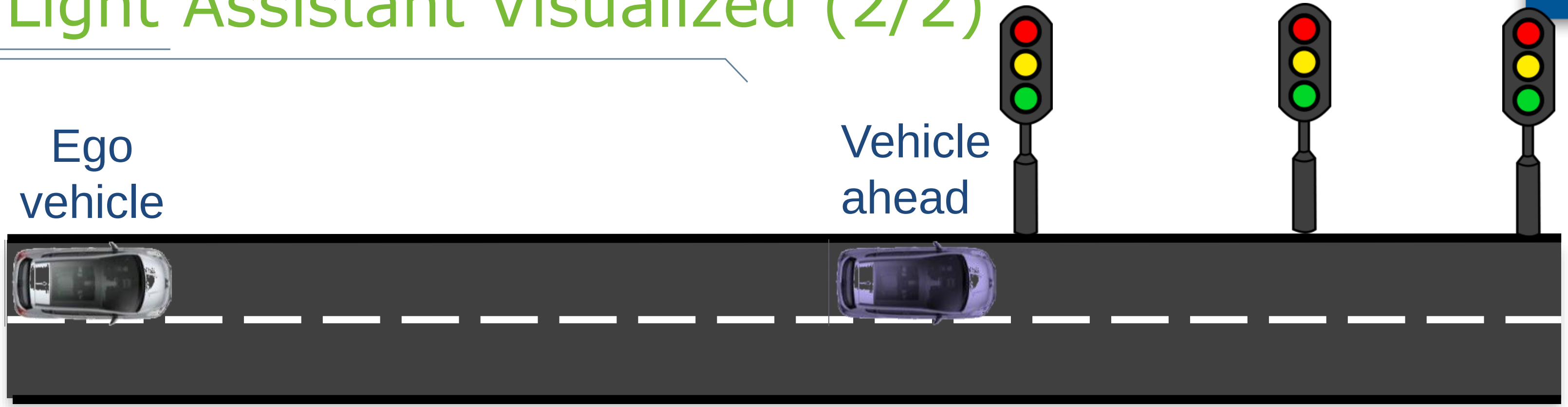
- Use of V2I information to approach multiple Traffic Light (TL) scenario:
  - Goal: find most energy efficient way.
- Model Predictive Control (MPC) formulation:
  - Receding horizon approach.
  - Real-time optimization by cost fcn minimization & constraints.



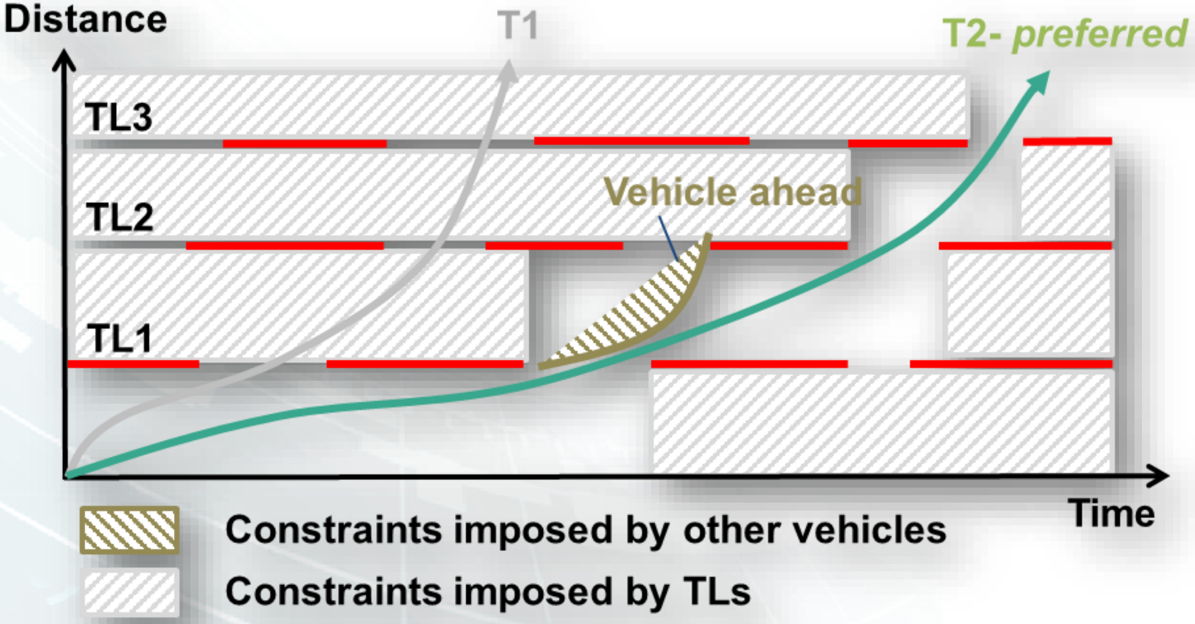


Traffic Light Assistant

Traffic Light Assistant Visualized (2/2)



Set of constraints imposed by Traffic Lights & traffic



Optimization problem:

$$min \sum_{\tau=t}^{t+N_p} (x(\tau), u(\tau))$$

$$\text{S.T.} \;\; g(x,u,t) \leq 0$$

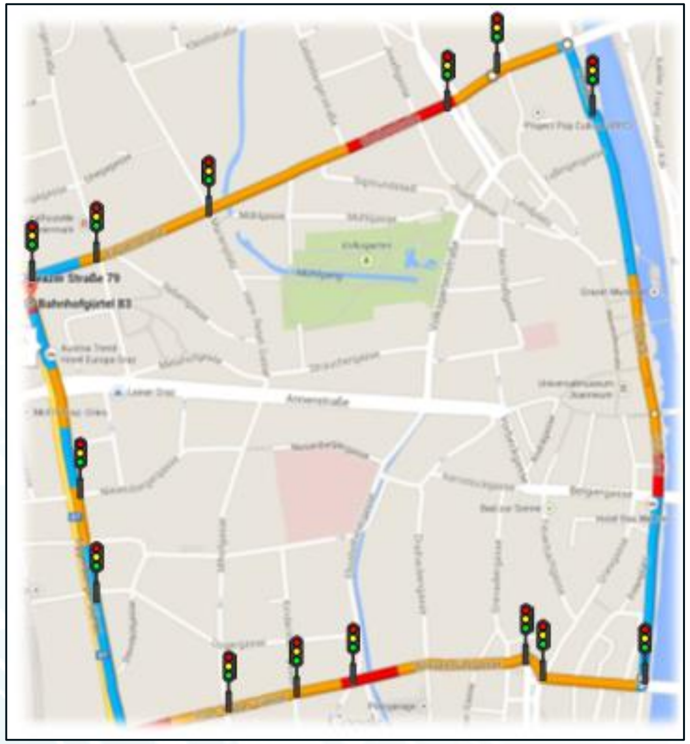
$$u(\tau) \in U, \quad x(\tau) \in X, \quad \tau = t, \ldots, t+N_p$$

$$x(\tau+1) = Ax(\tau) + Bu(\tau), \quad \tau = t, \ldots, t+N_p - 1$$

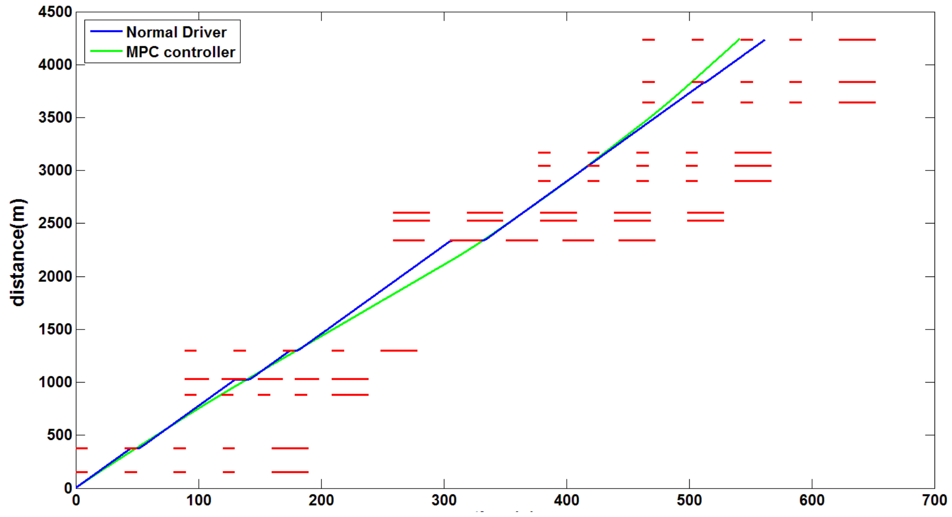
x: state variables, u: control variables, τ: time, N_p: prediction horizon

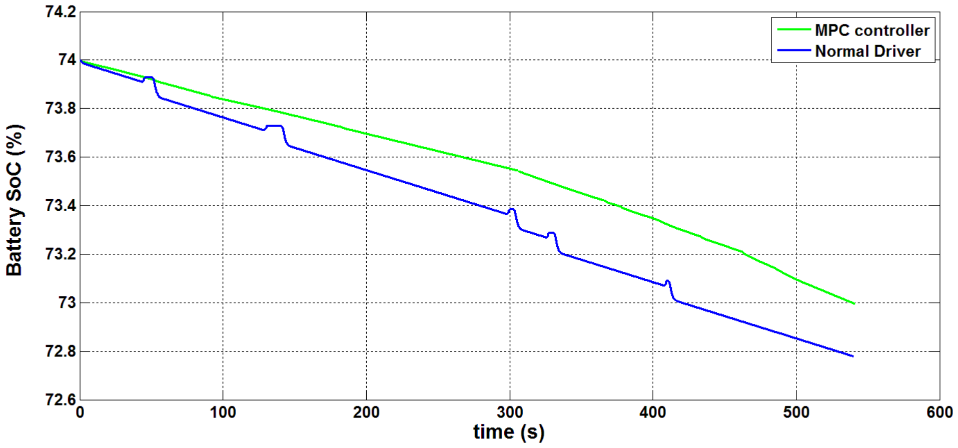
- Min. of Energy Consumption
- Constraints imposed by TL
- Constraints imposed by traffic
- Powertrain specific constraints

Traffic Light Assistant
Results From Testing of AVL's 1st Generation TLA



Energy Savings	Time Savings
17%	3.8%



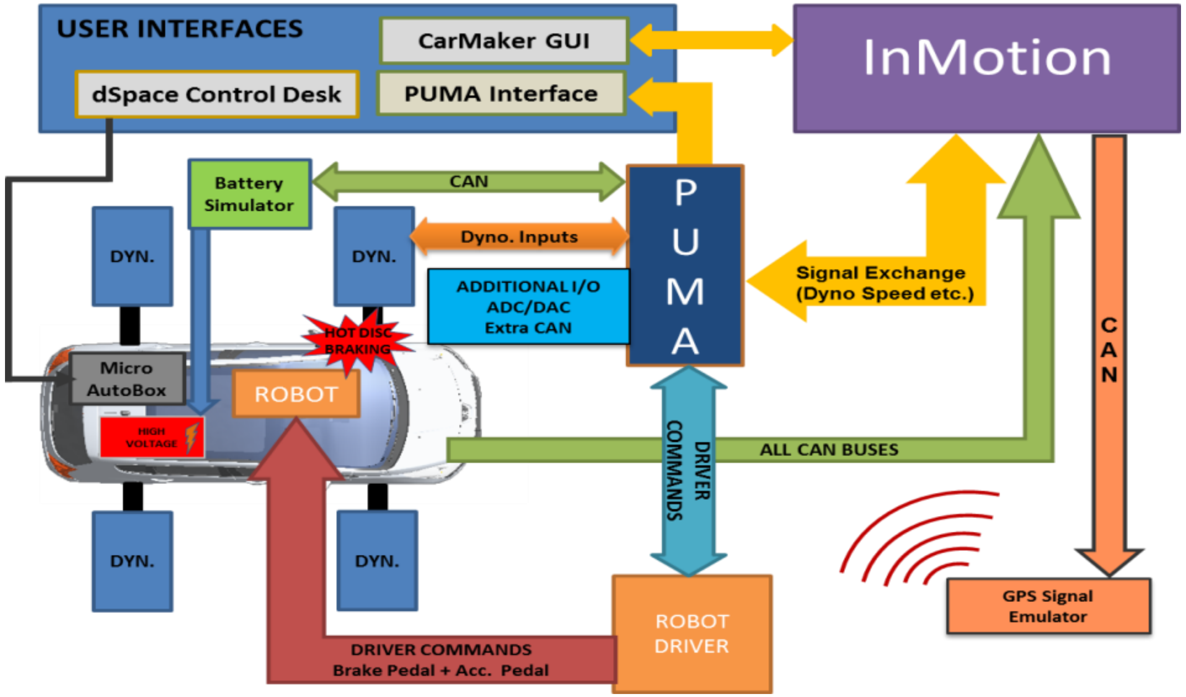


- ➢Battery SoC considered as metrics of energy savings
- ➢'Normal Driver' controlled by reference simulated driver

Traffic Light Assistant
Seamless Development of OpEneR Functions 2013

Reuse of office simulation environment for AVL InMotion testbed

Office → Lab → Testbed → Road

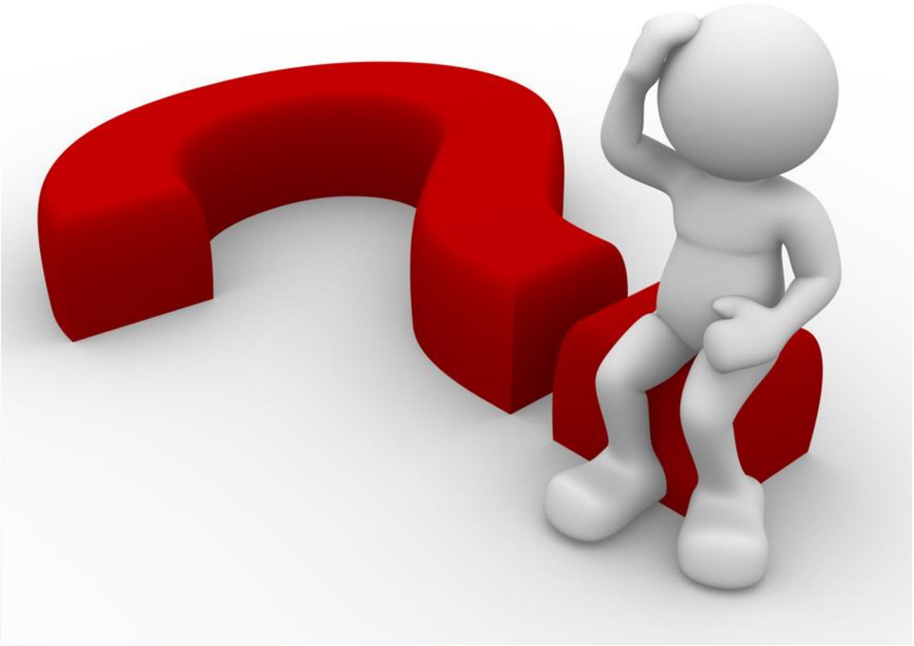


Interactive Workshop (1/2)

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?



Energy-Efficient CACC - Overview

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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.

Cruise Control (CC)

Image source: edmunds.com

Adaptive Cruise Control (ACC)

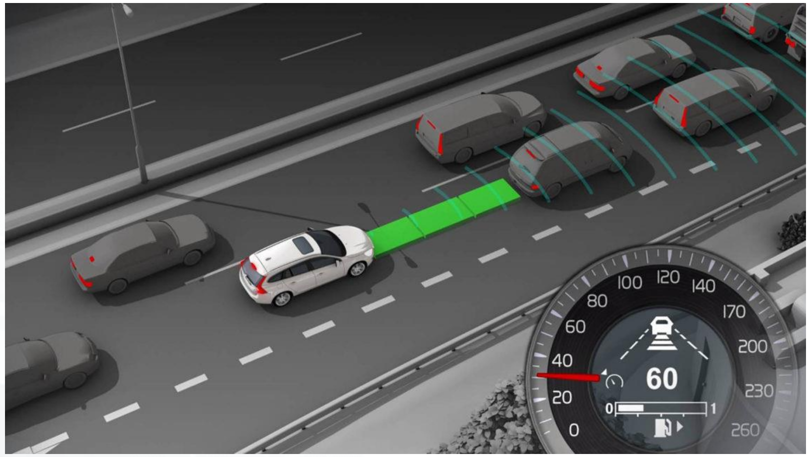

Image source: media.volvocars.com

Cooperative Adaptive Cruise Control (CACC)

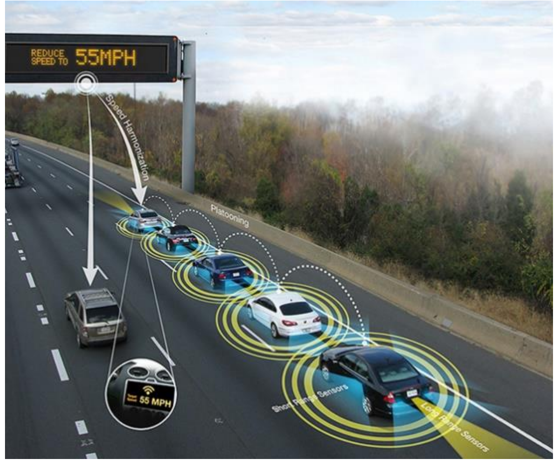

Image source: researchgate.net

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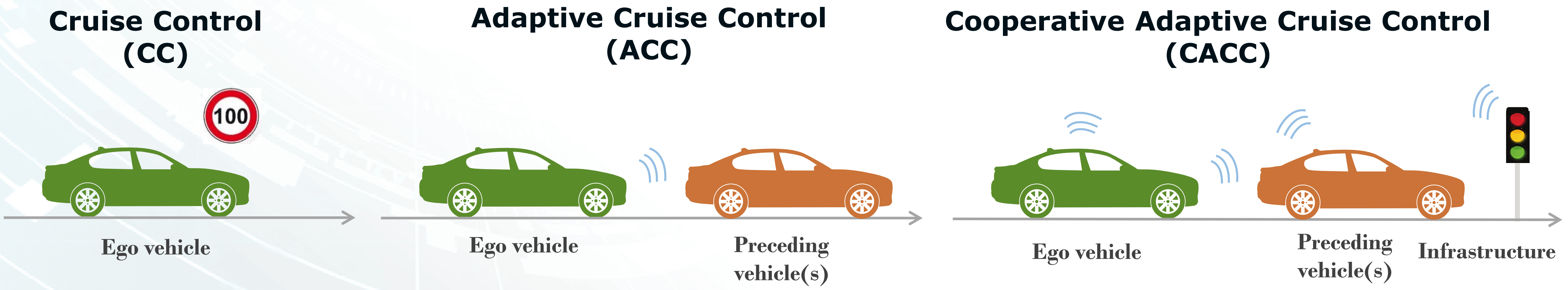
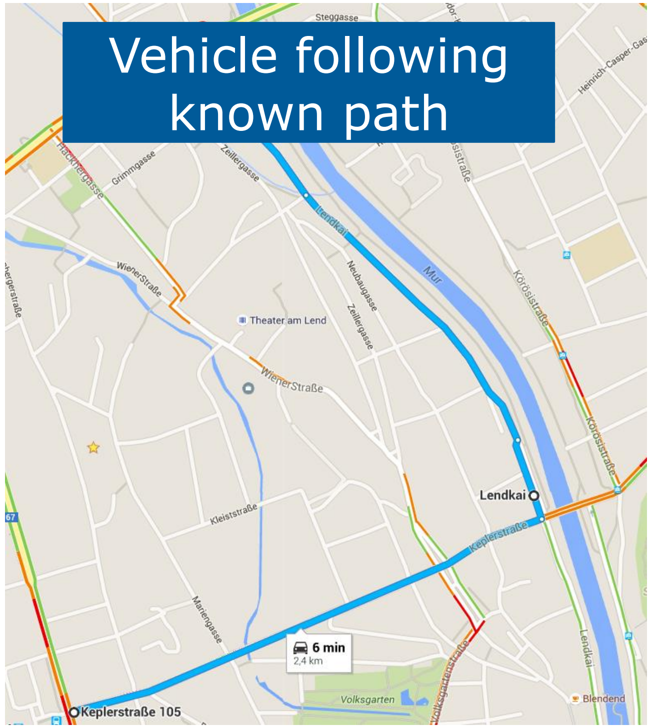
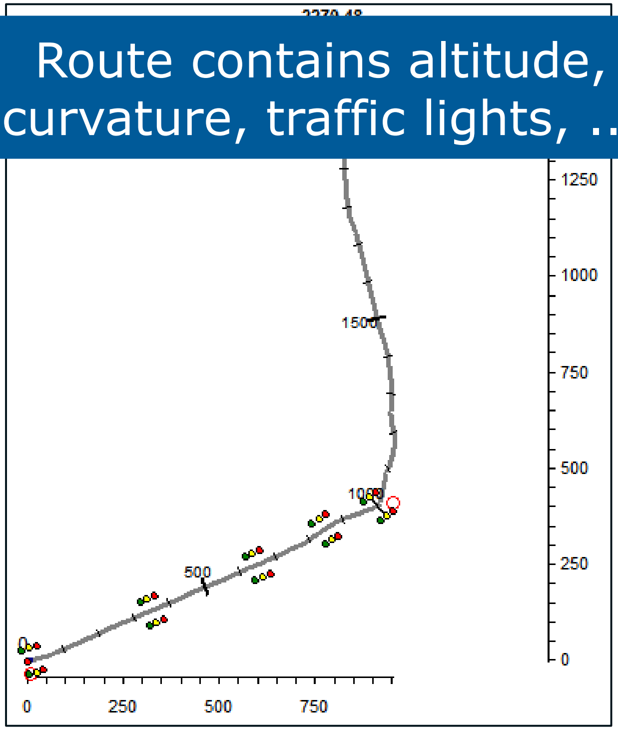


Energy-Efficient CACC – Problem Overview
Background

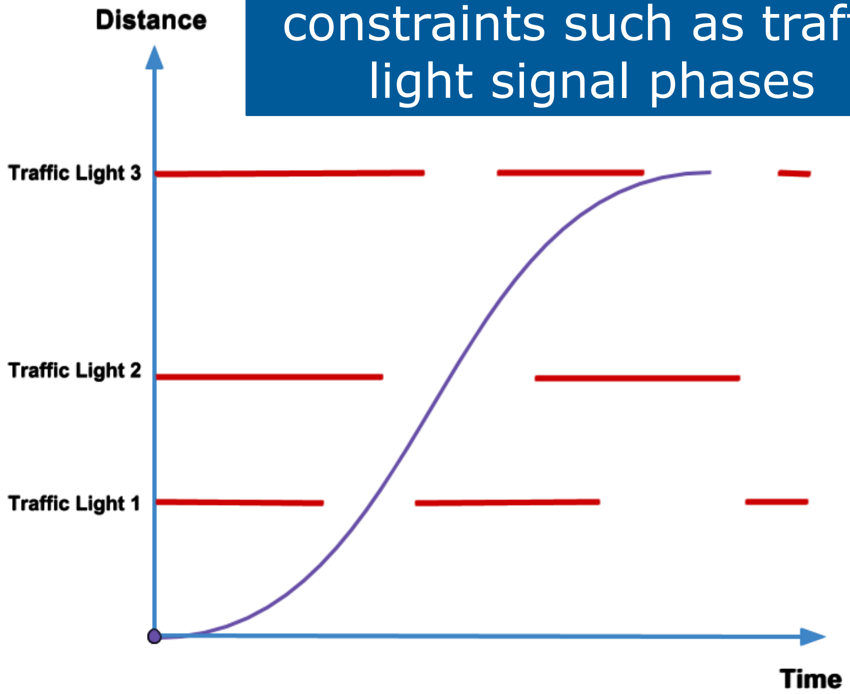
Vehicle following known path

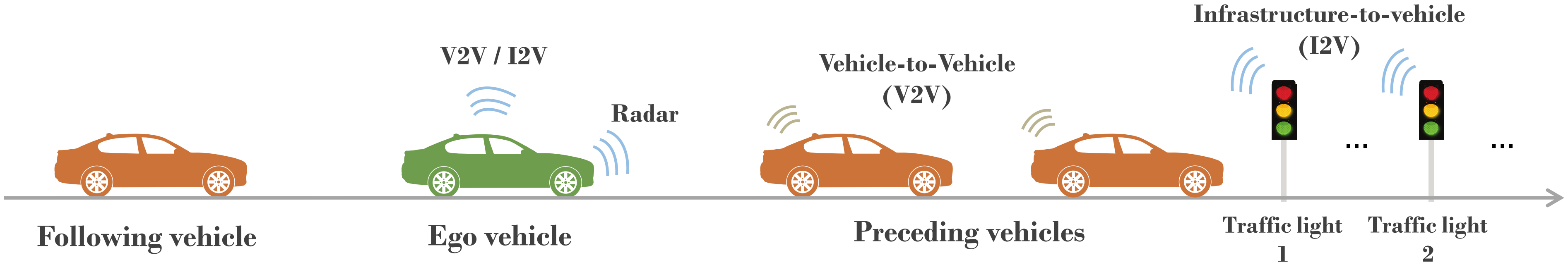


Route contains altitude, curvature, traffic lights, ...



Includes time-dependent constraints such as traffic light signal phases

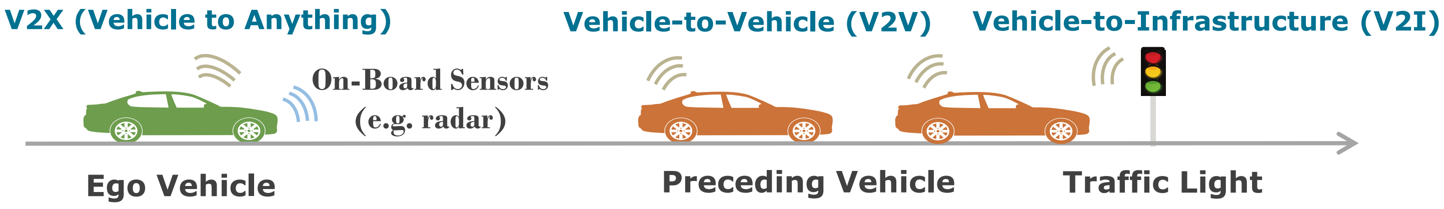




Holistic approach needed!

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.



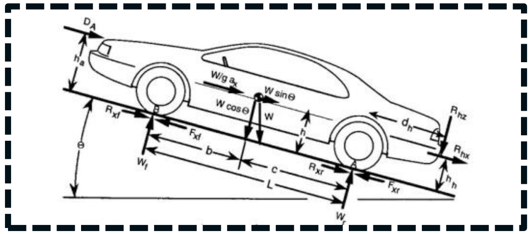
Velocity v

Acceleration a

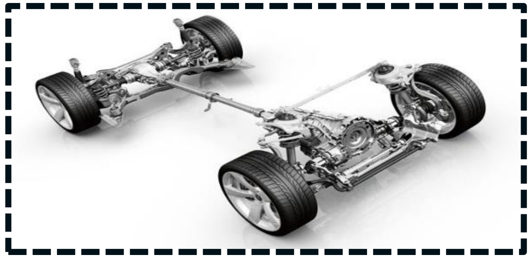
Road Inclination θ

Gear G

…

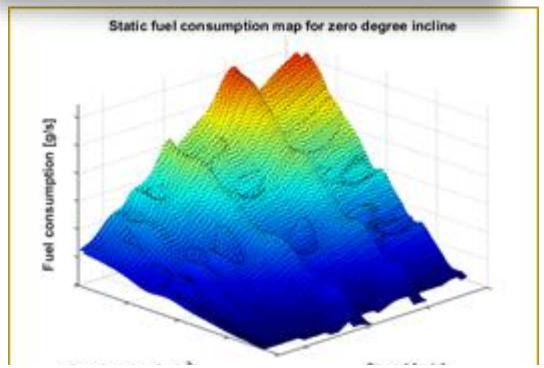


Inertia, Drag, Rolling Res., Gravity



Powertrain Model

Energy savings up to 30%



Energy Consumption Map computed Online in real-time Optimization

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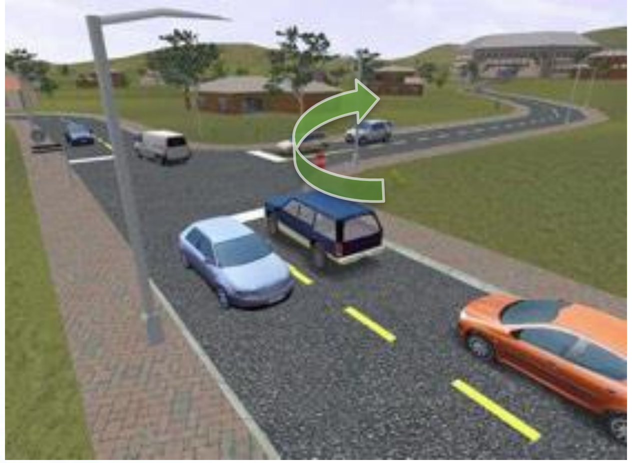
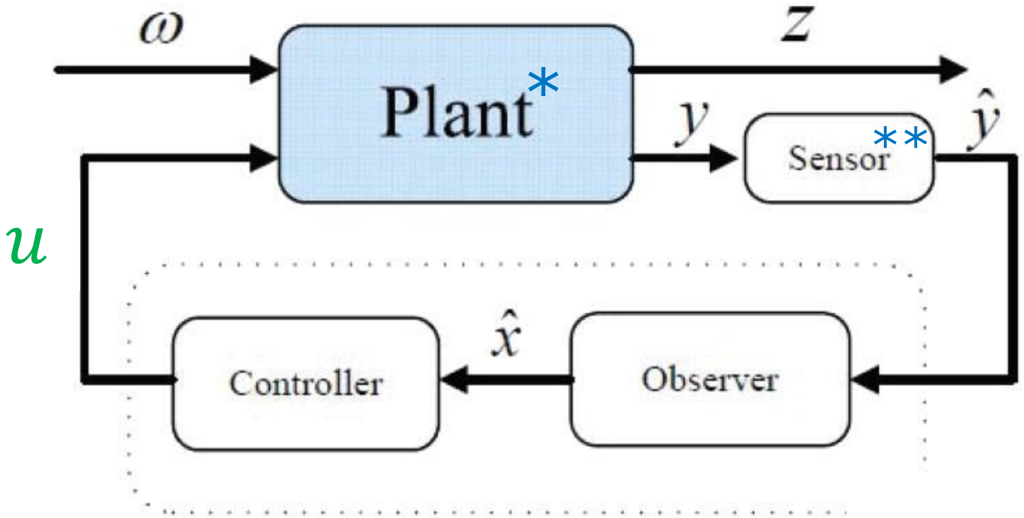
Energy-Efficient CACC – MPC
Introduction to Model Predictive Control (1/2)





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

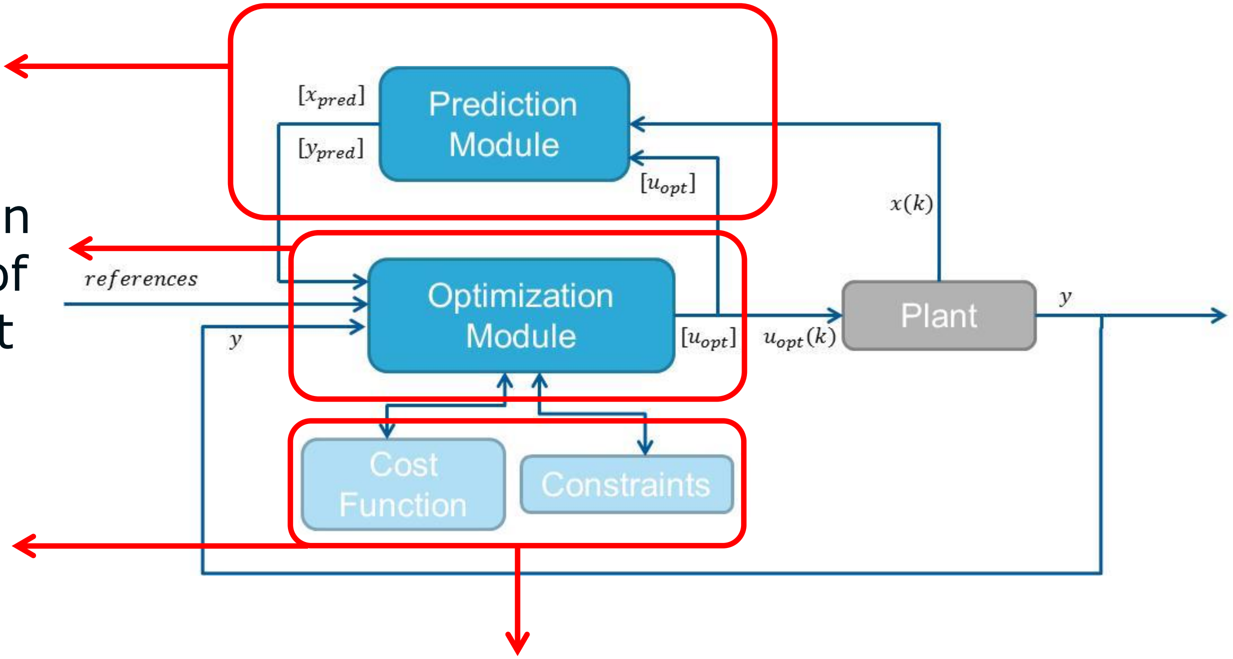
Optimal sequence of control inputs over prediction horizon H_T

* 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.



Minimize

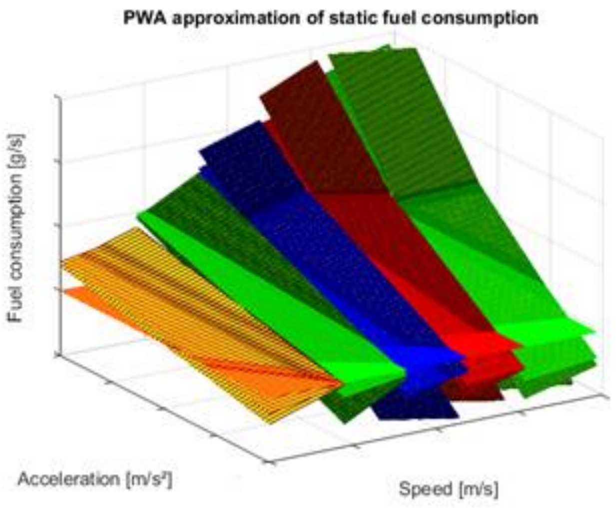
$$J(\boldsymbol{u}, \hat{\boldsymbol{x}}, \hat{\boldsymbol{y}}, \dots)$$

Subject to

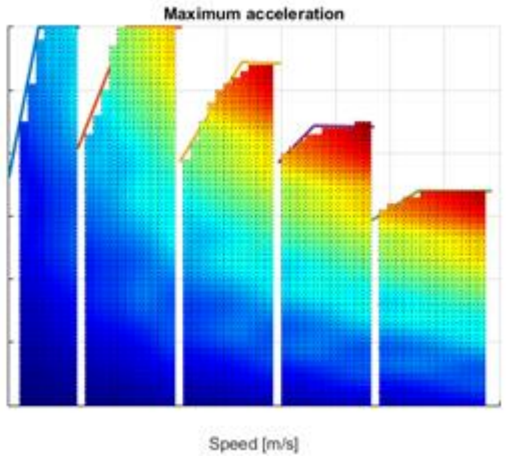
$$\boldsymbol{f}(\boldsymbol{u}, \hat{\boldsymbol{x}}, \hat{\boldsymbol{y}}, \dots) \leq 0$$
$$\boldsymbol{g}(\boldsymbol{u}, \hat{\boldsymbol{x}}, \hat{\boldsymbol{y}}, \dots) = 0$$

Energy-Efficient CACC – MPC
Hybrid Model Predictive Control

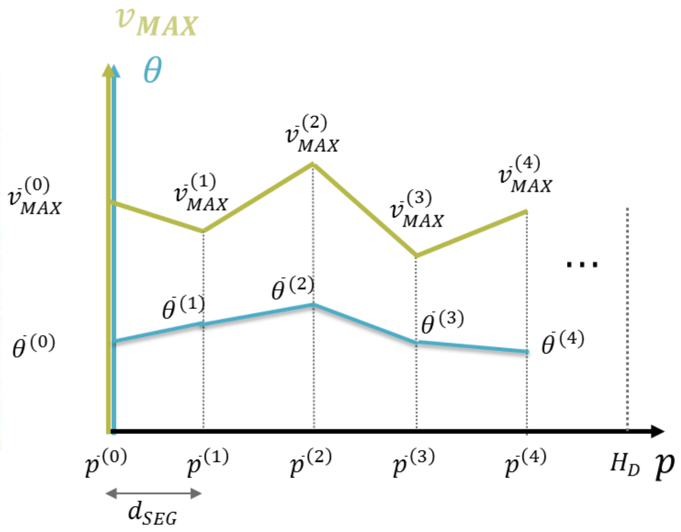
- **Hybrid* Model Predictive Control (MPC)** dynamically incorporates descriptions of upcoming traffic & road conditions as constraints in receding horizon.
- **Non-linear constraints** like energy consumption, gear shifts, full load, & road attributes (e.g. gradient, curvature) modelled.
- **eHorizon & V2X** used for better predictions of preceding traffic & infrastructure, including traffic lights, variable speed limits, delivery & bus stops.



Energy consumption map including gear shifting



Acceleration limits including road gradient



Road segmentation for topology, speed limits, etc.

*Note Hybrid here refers to modelling technique, not the powertrain type

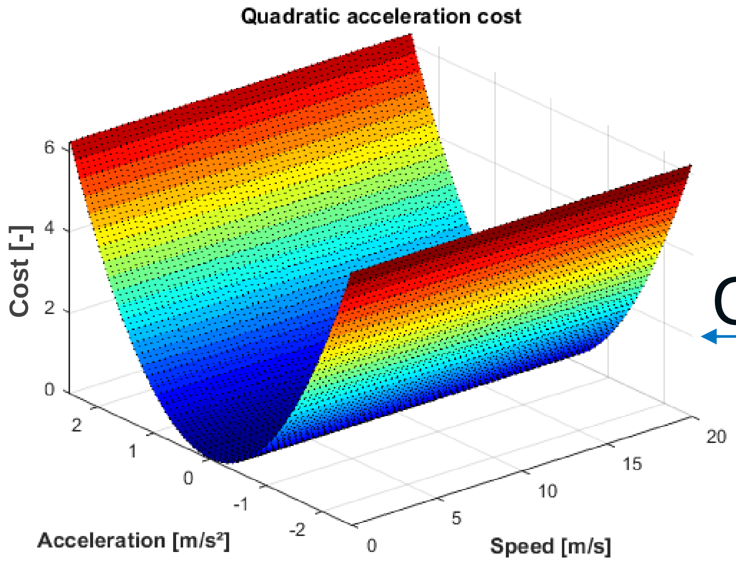
Energy-Efficient CACC – MPC
Alternative Hybrid MPC Cost Functions

Minimize

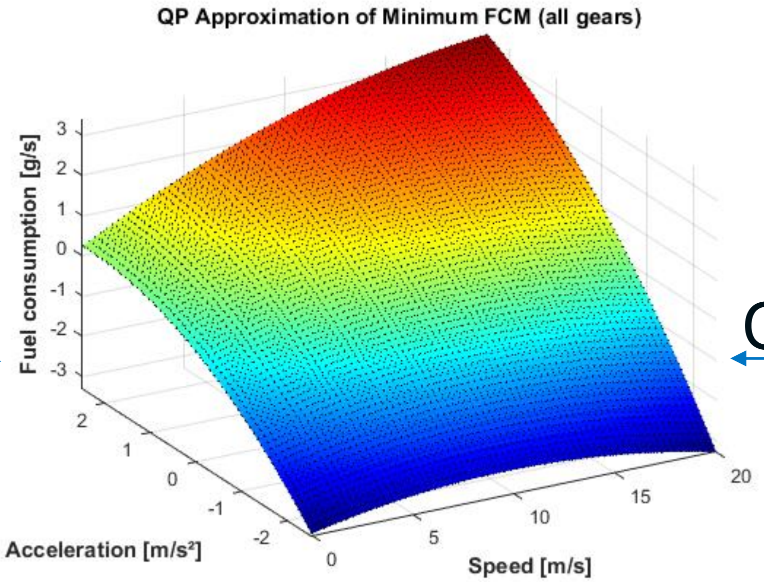
$$J(\boldsymbol{u}, \hat{\boldsymbol{x}}, \hat{\boldsymbol{y}}, \ldots)$$ → Cost function

Subject to

$$\boldsymbol{f}(\boldsymbol{u}, \hat{\boldsymbol{x}}, \hat{\boldsymbol{y}}, \ldots) \leq 0$$
$$\boldsymbol{g}(\boldsymbol{u}, \hat{\boldsymbol{x}}, \hat{\boldsymbol{y}}, \ldots) = 0$$ → Constraints



OR



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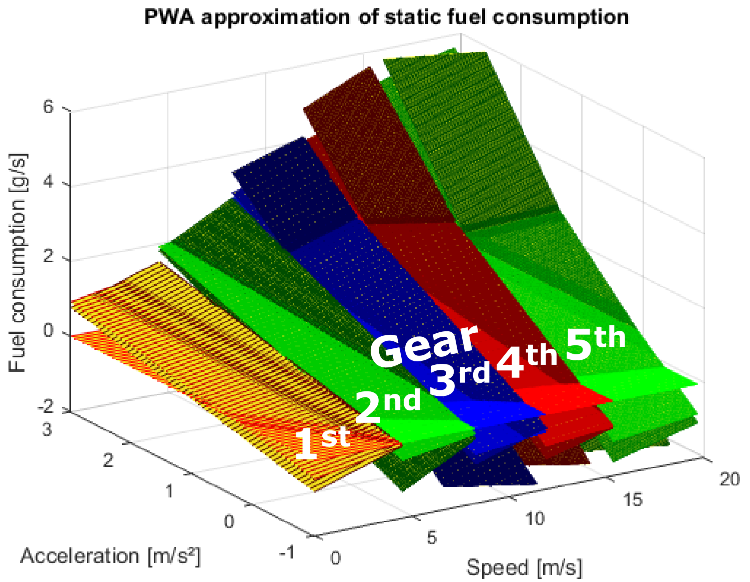


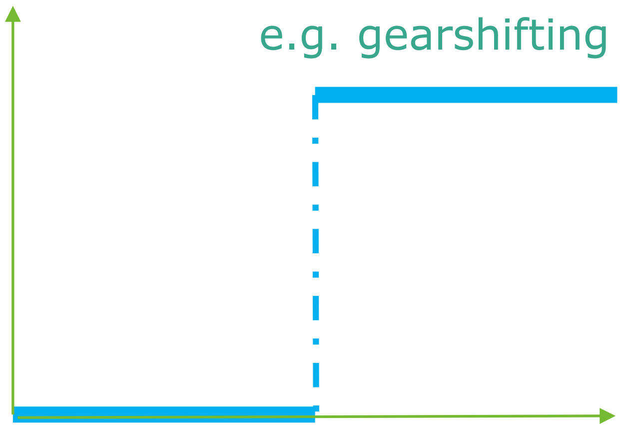
Acceleration (QP)

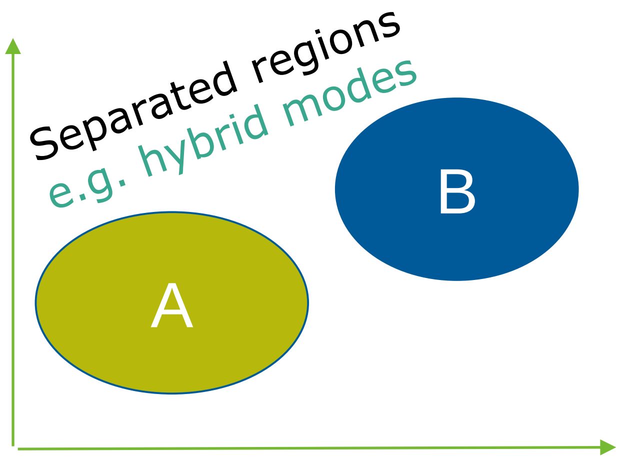
Quadratic projection of Fuel Consumption Map (QP)

Piecewise affine FCM (Hybrid)

Energy-Efficient CACC – MPC
Hybrid MPC Constraints

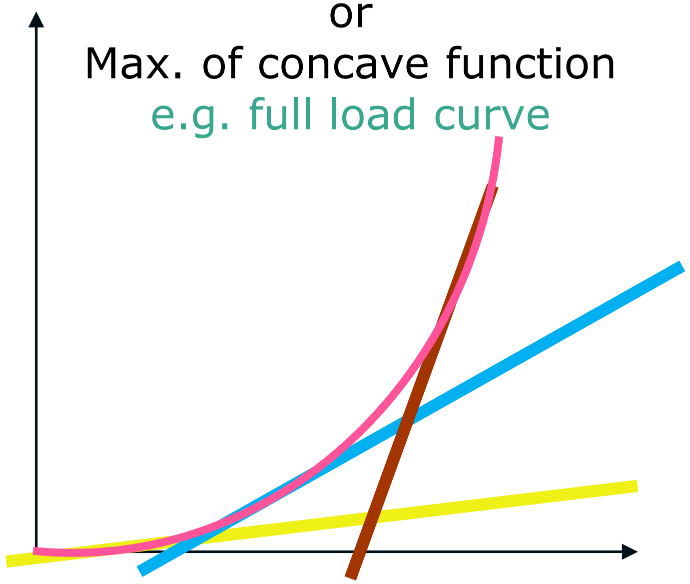
Discontinuities
e.g. gearshifting





Propositional logic with binary variables

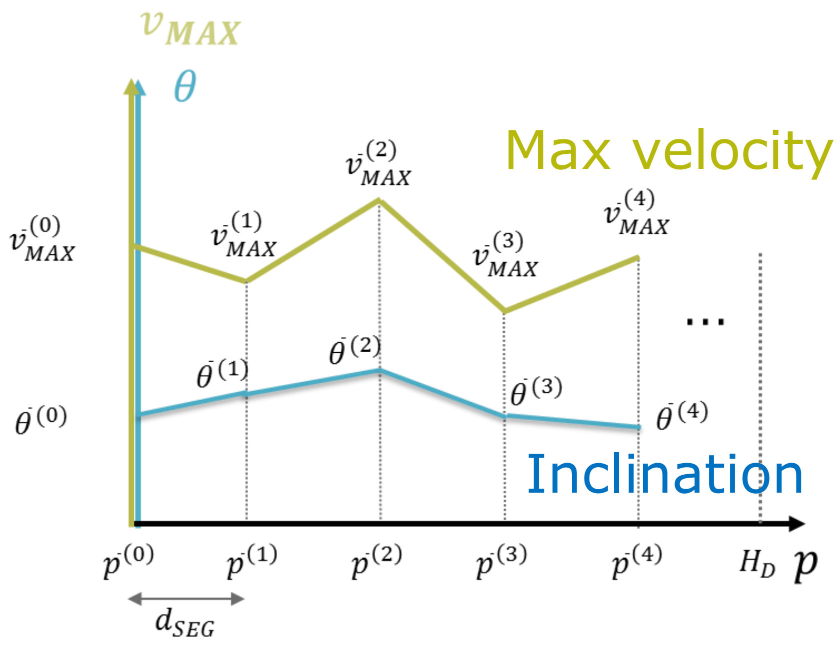
Min. of convex function
or
Max. of concave function
e.g. full load curve



Multiple affine constraints (no binary variables)

$$\min x$$
$$s.t\ x \geq a_1 + b_1 x$$
$$x \geq a_2 + b_2 x$$
…

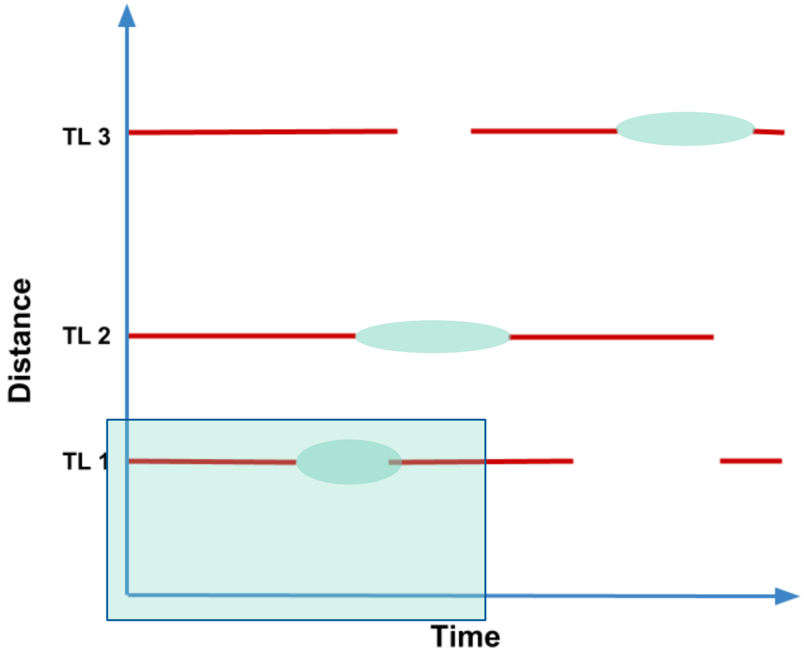
Non-convex/concave functions
e.g. speed limits on route

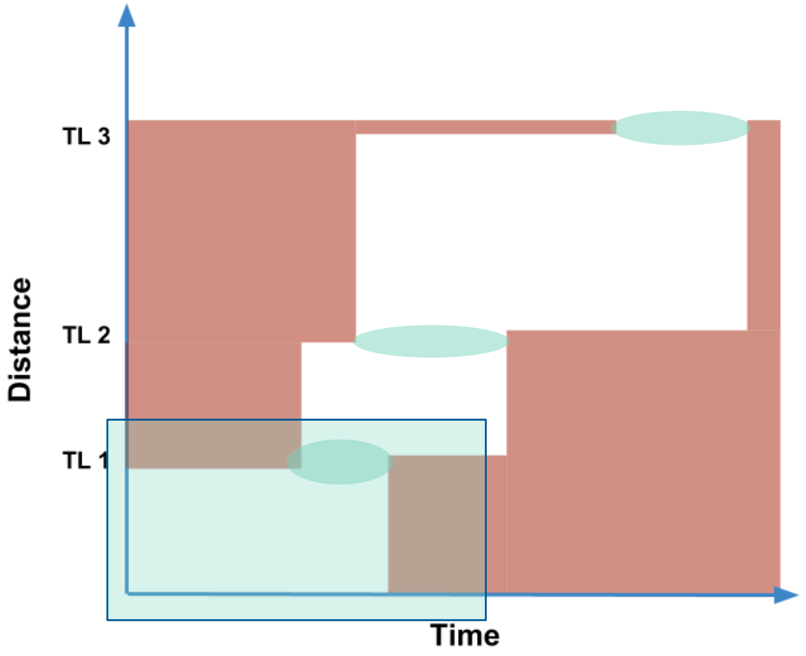


Piecewise Affine (PWA) approximation of nonlinear constraints

Energy-Efficient CACC – MPC
Traffic Light Constraints

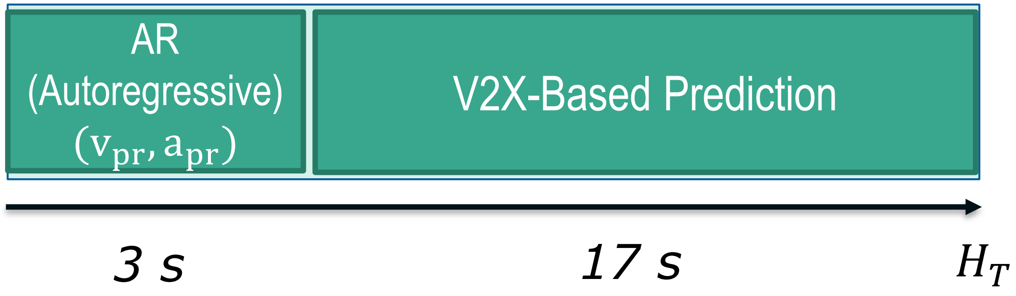
Select Earliest Reachable Green Phases → Define Distance Boundaries Over Prediction Horizon

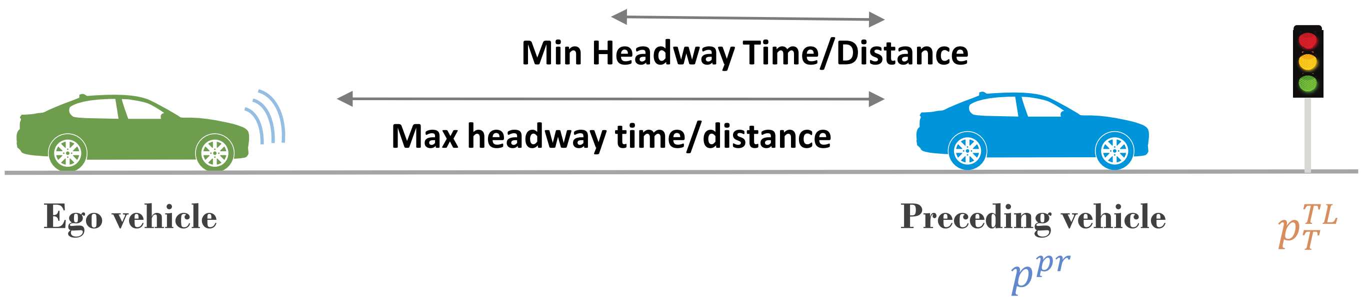


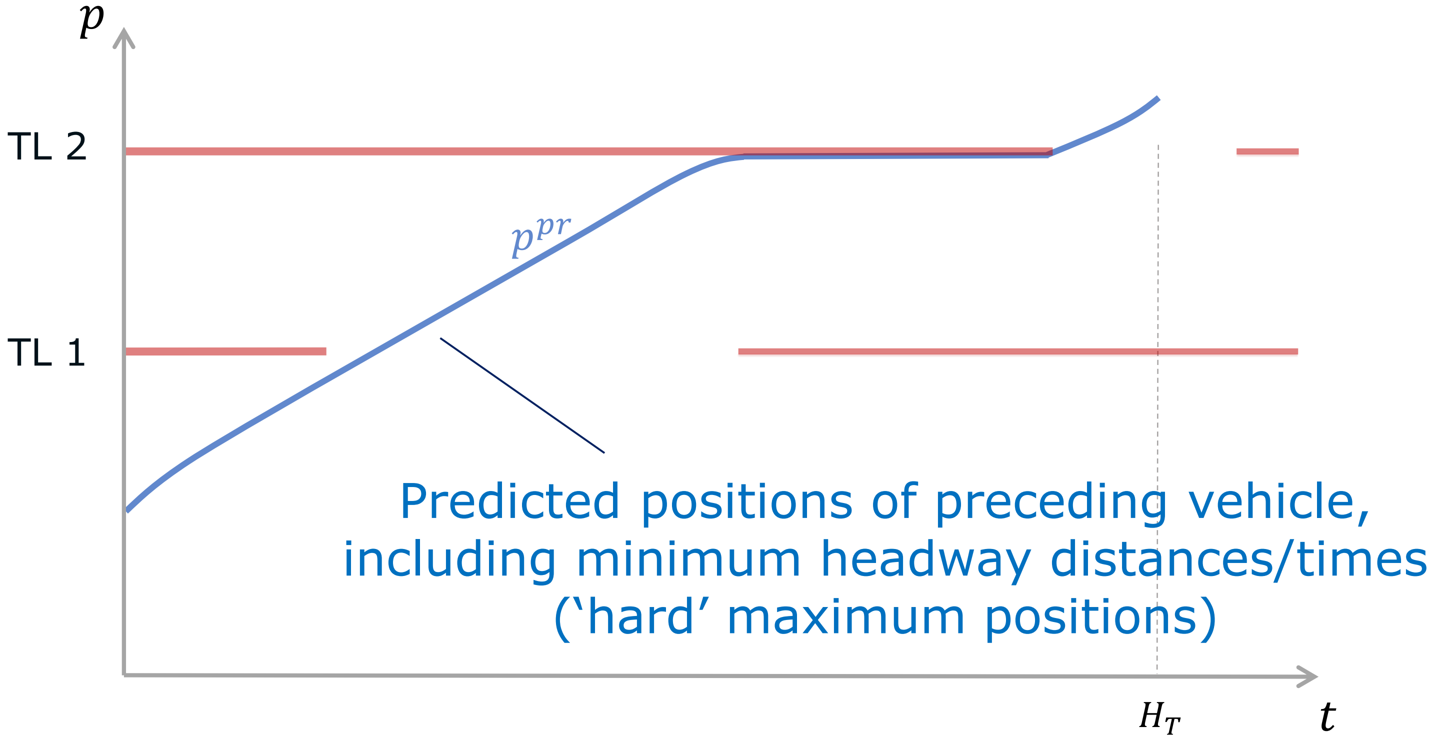


Energy-Efficient CACC – MPC
Traffic Constraints (1/5)

Prediction Model

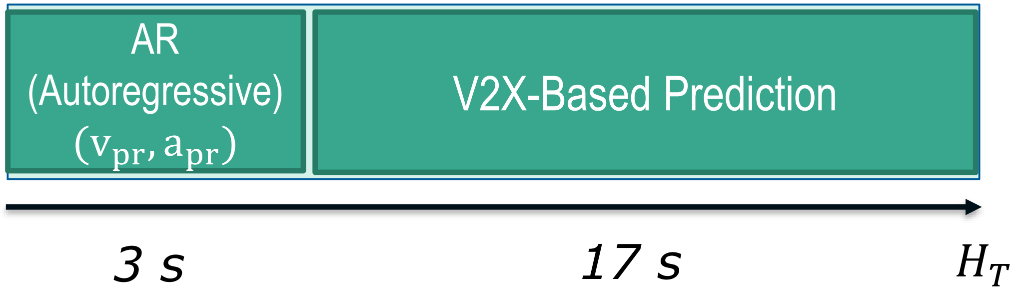


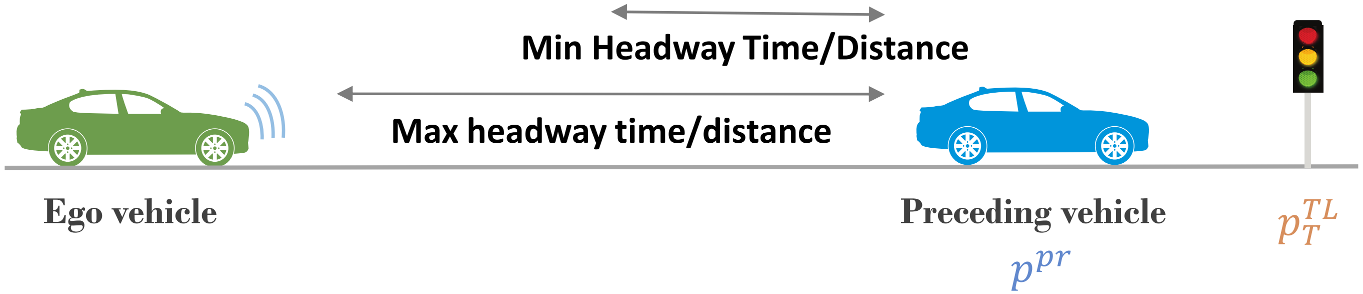


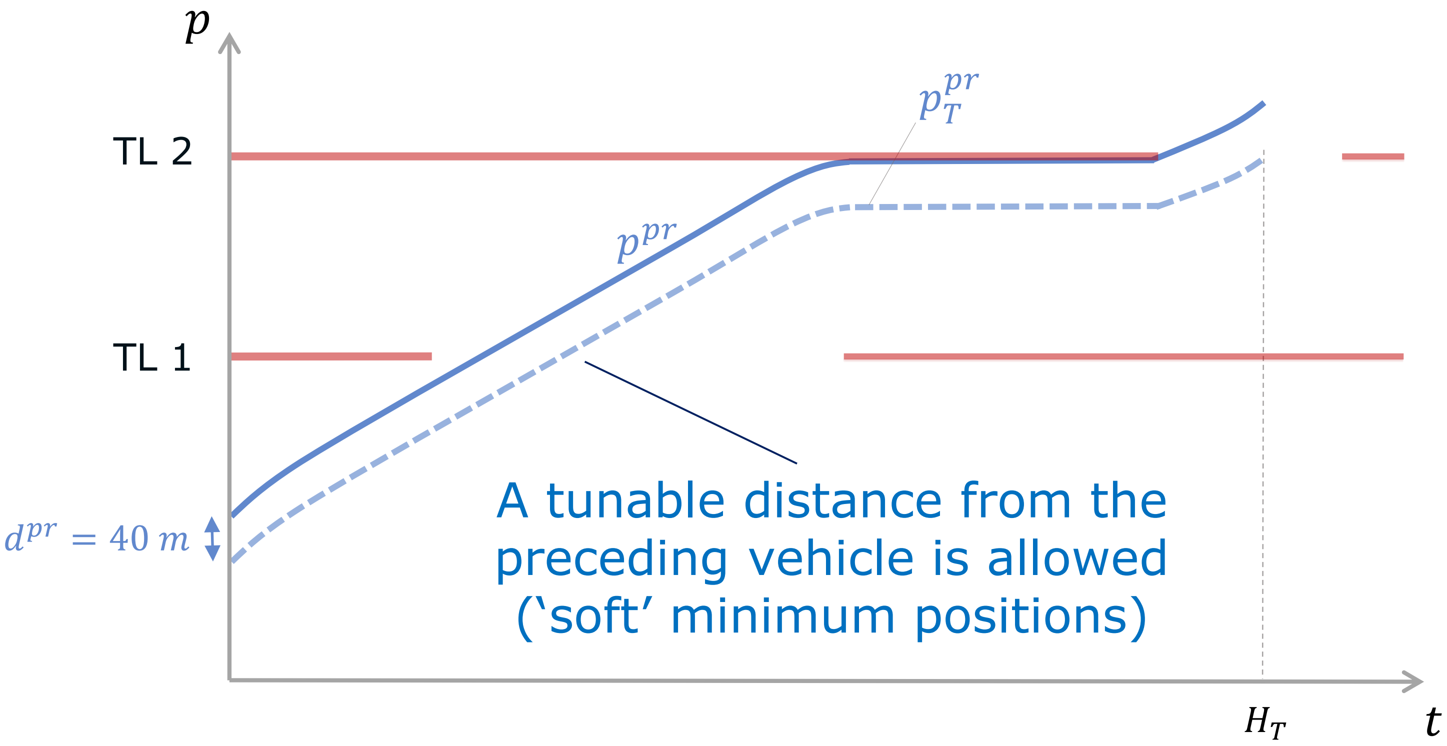


Energy-Efficient CACC – MPC
Traffic Constraints (2/5)

Prediction Model

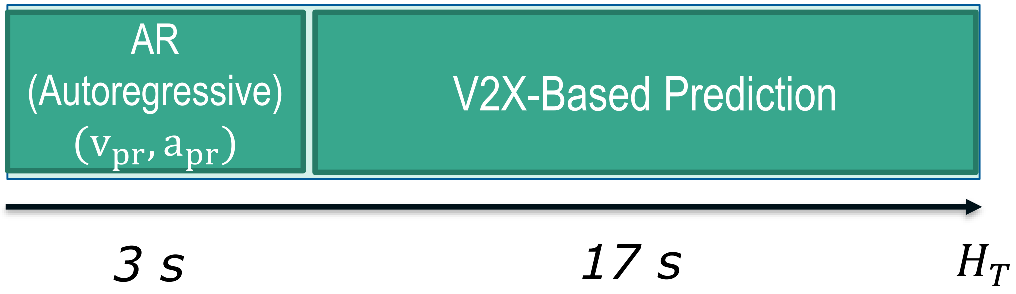


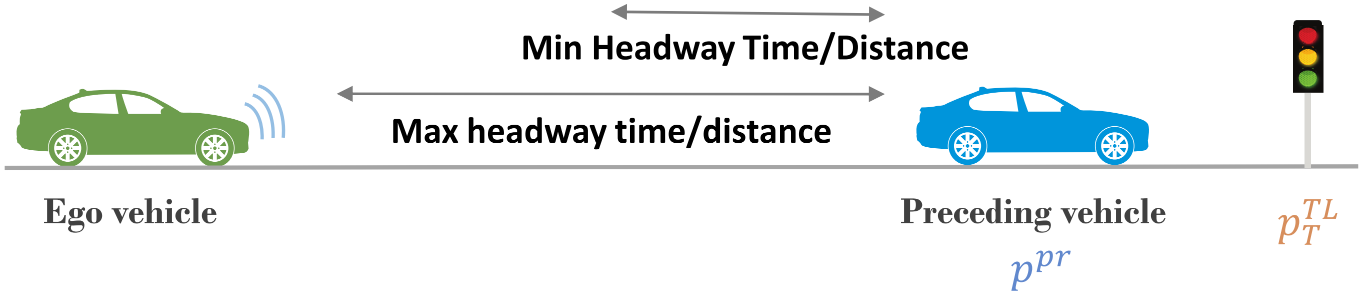


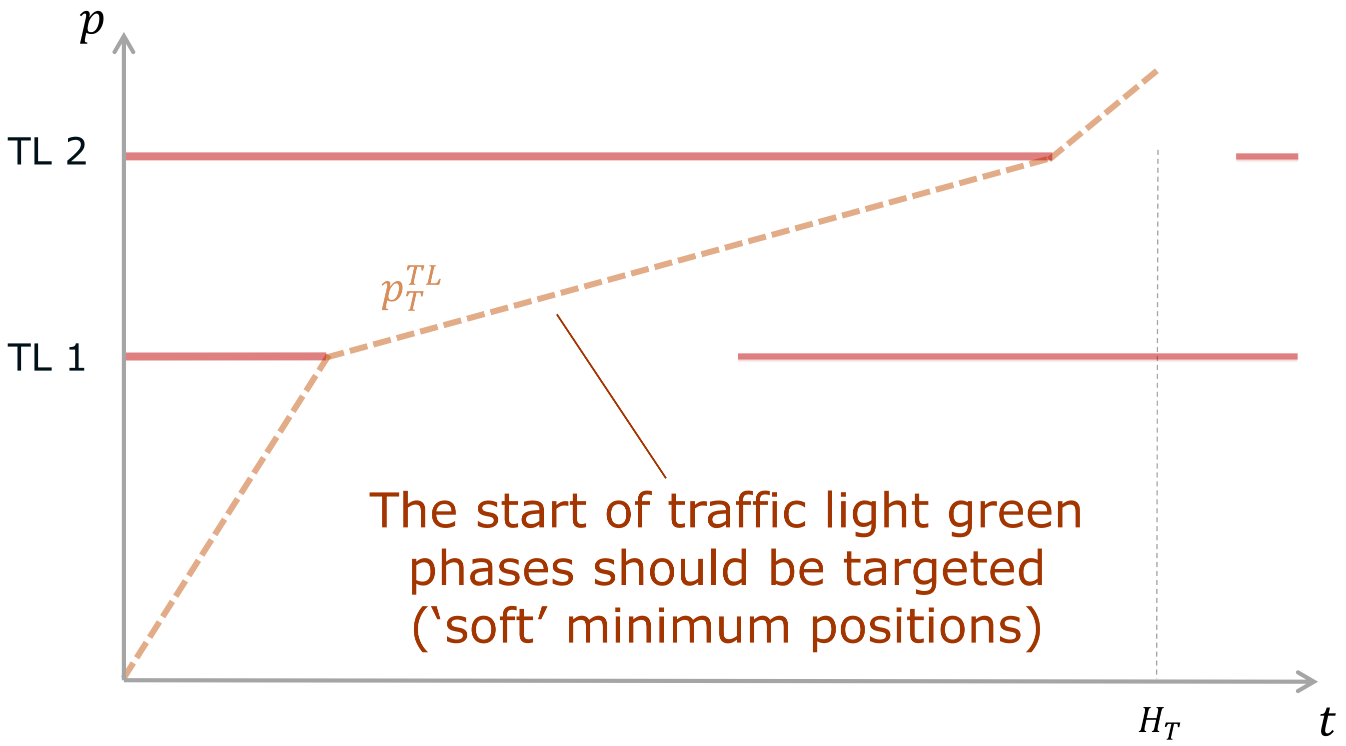


Energy-Efficient CACC – MPC
Traffic Constraints (3/5)

Prediction Model



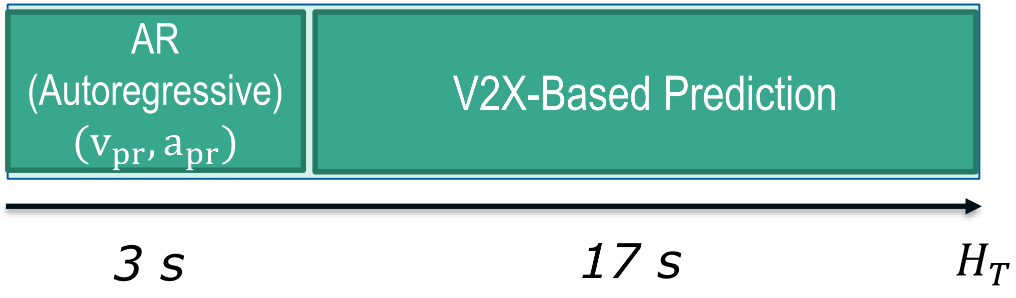


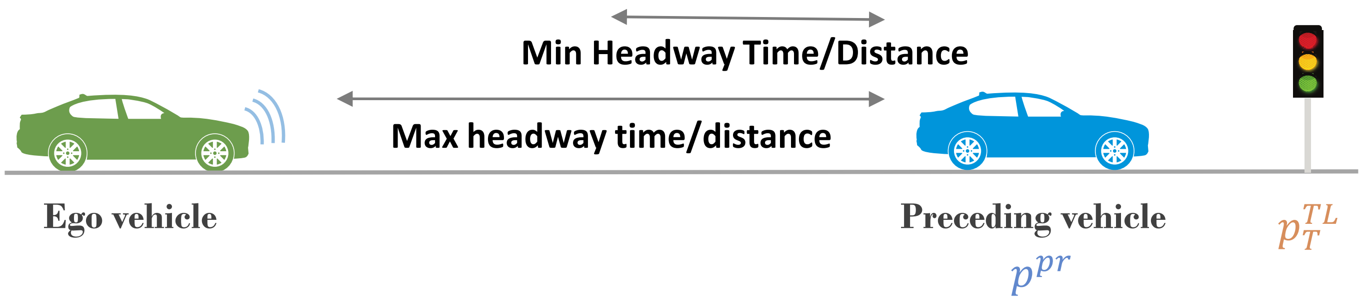


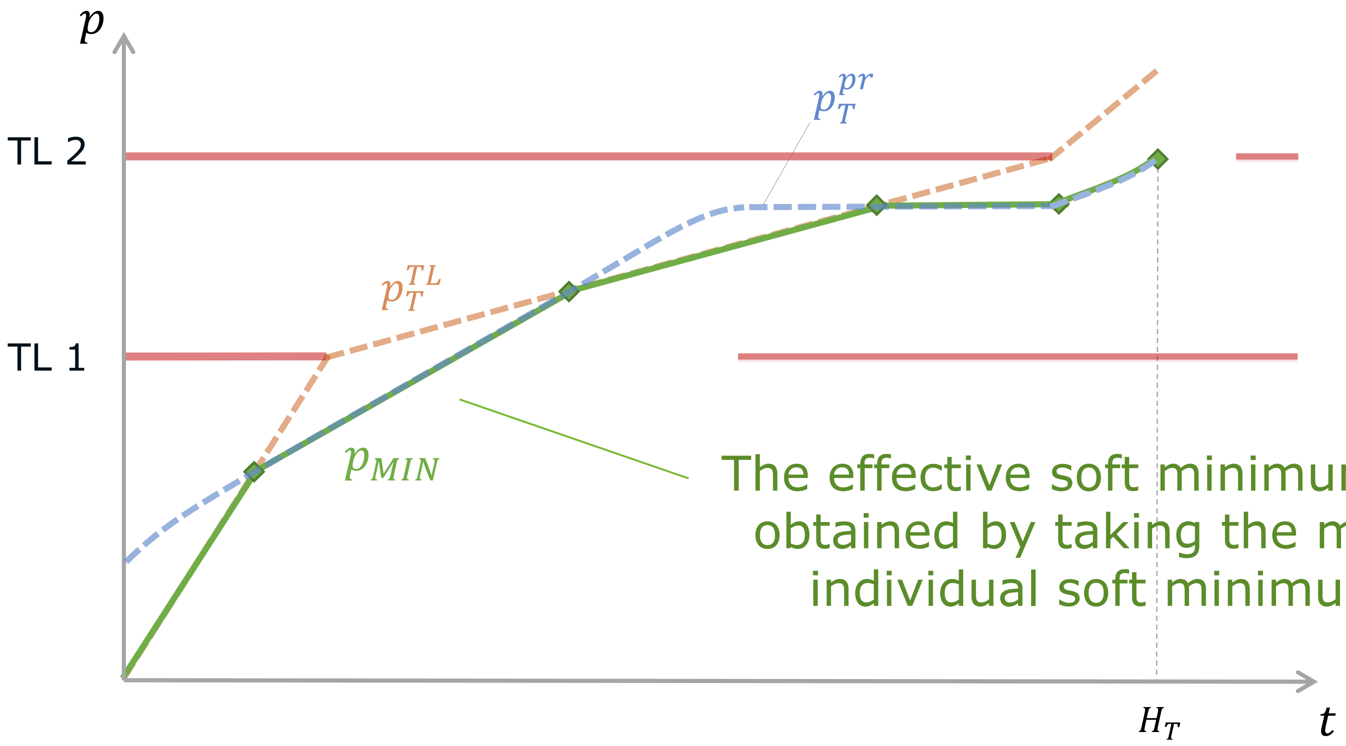
The start of traffic light green phases should be targeted (‘soft’ minimum positions)

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

Prediction Model



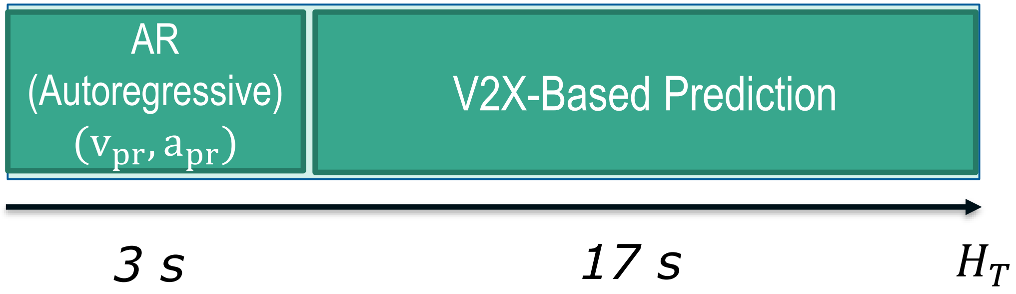


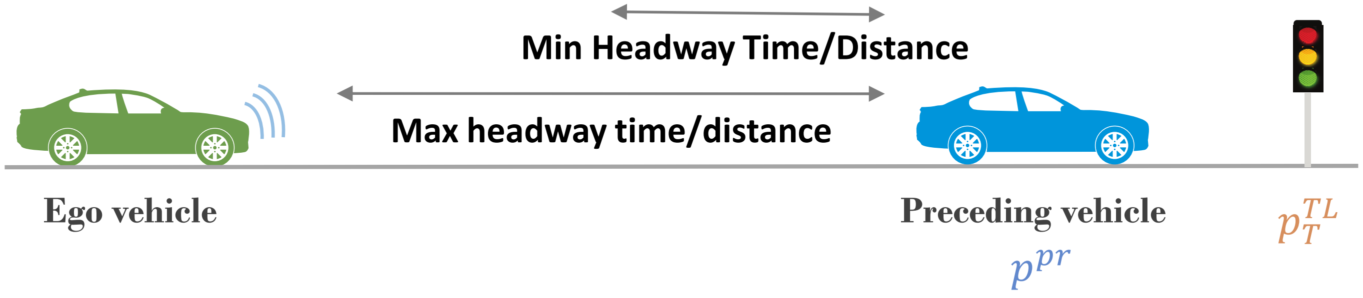


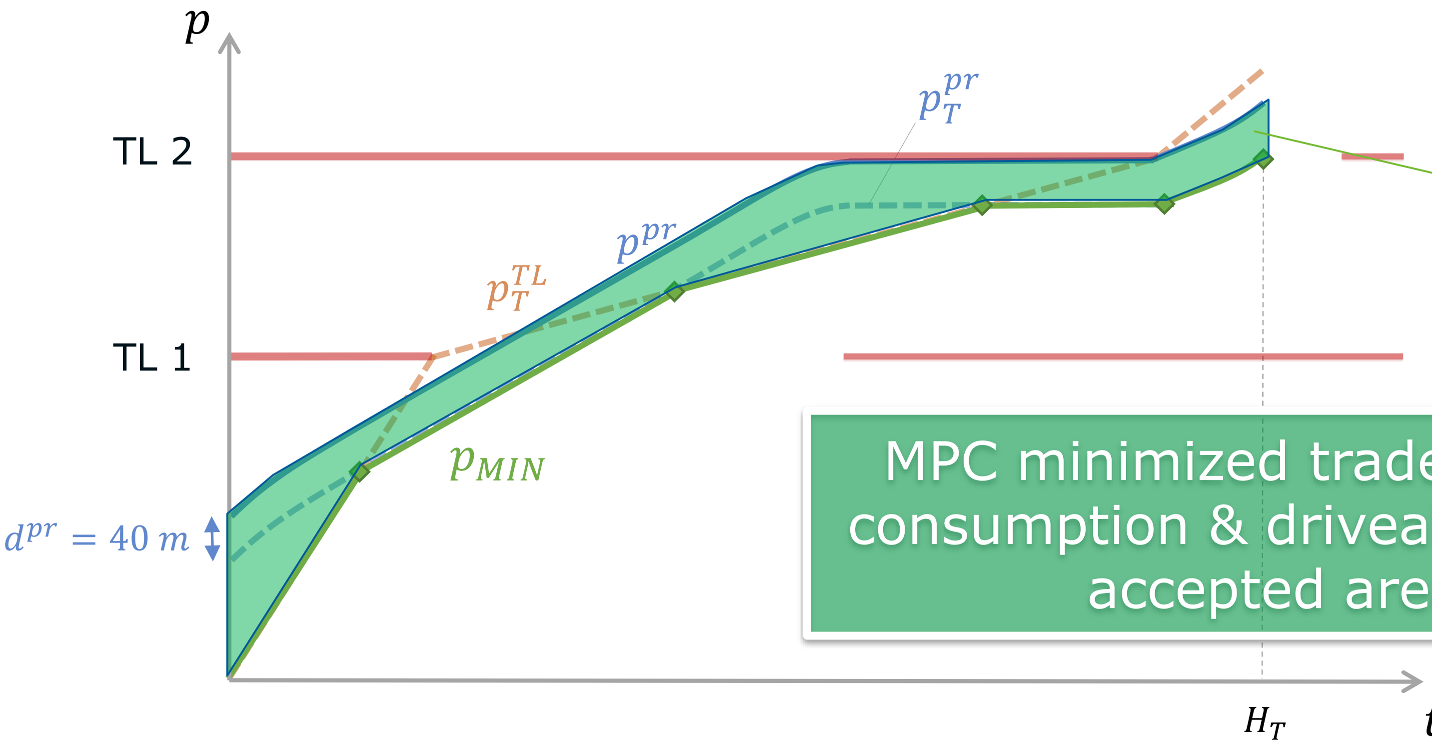
The effective soft minimum positions are obtained by taking the minimum of all individual soft minimum positions

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

Prediction Model



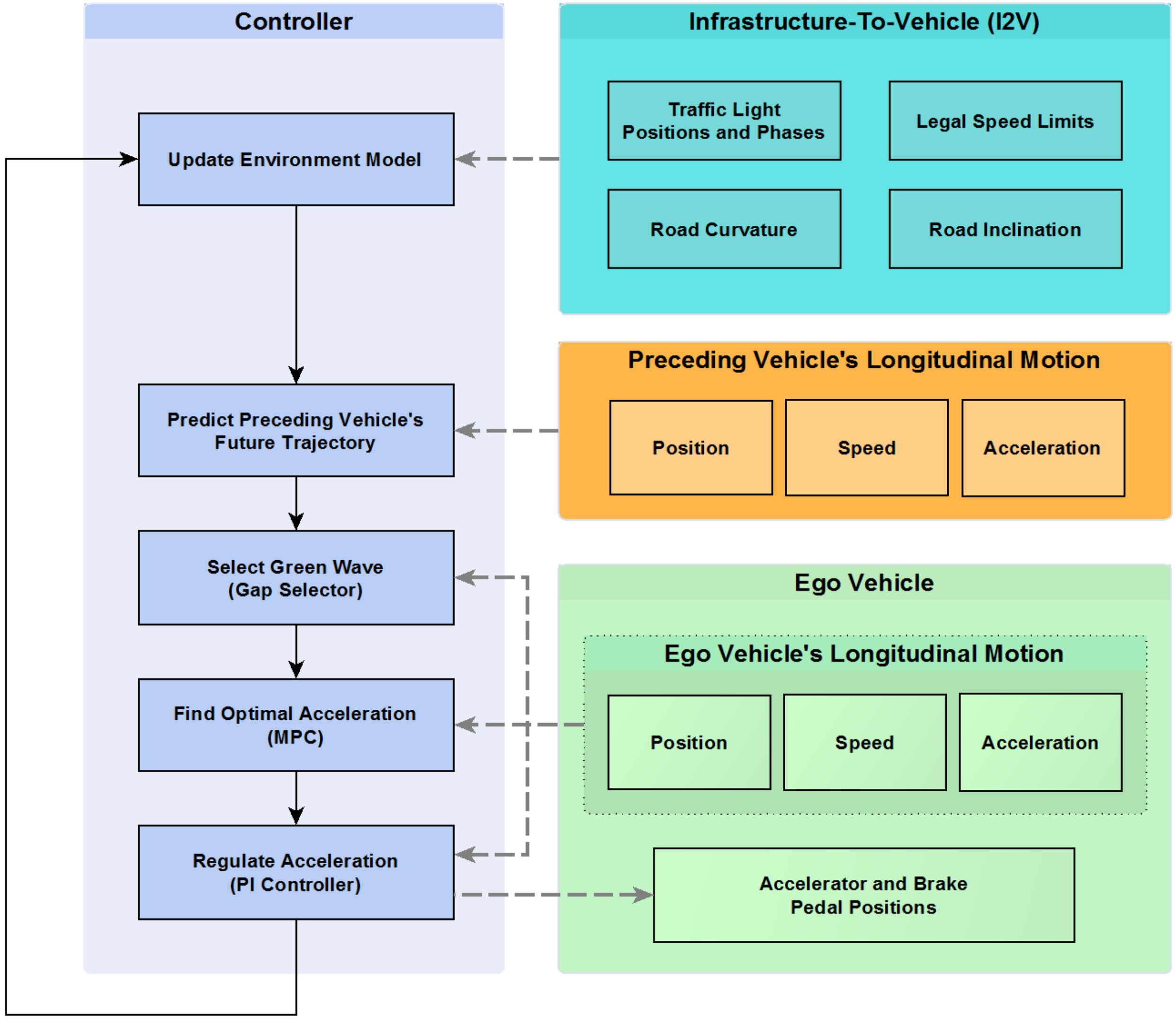




Min/Max Positions over Prediction Horizon

MPC minimized trade-off between energy consumption & driveability (jerk) within this accepted area of positions

Energy-Efficient CACC – MPC
Overview of ECACC Control Architecture



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

Energy-Efficient CACC - Overview

Energy-Efficient CACC – Simulation Results
Graz Route Simulation (Overview)

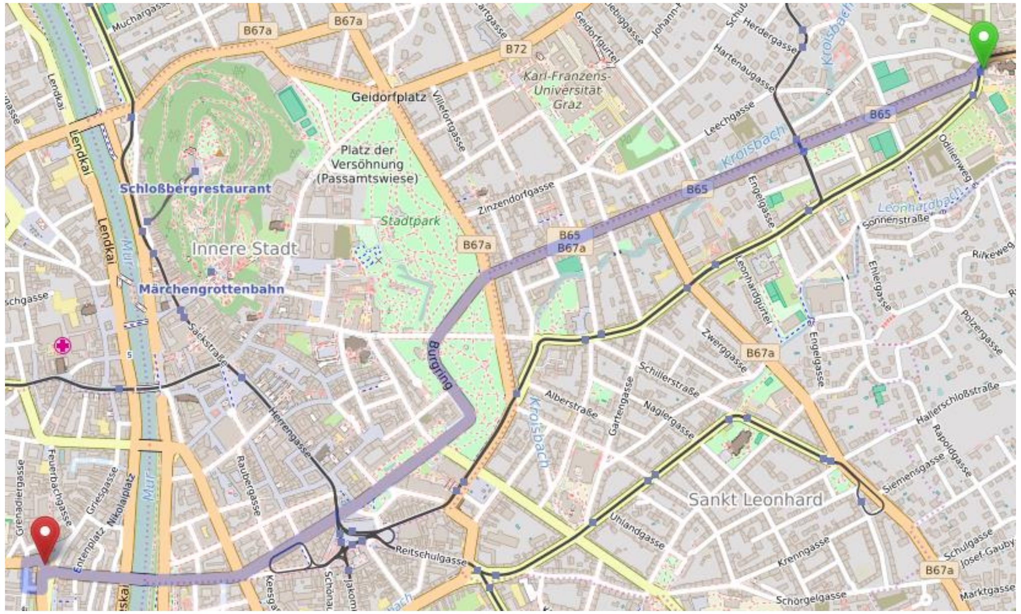
EECACC
- *Vehicle & Powertrain Model*
- *Road Model*
- *Surrounding Traffic Model*

MATLAB SIMULINK

Vehicle & Powertrain Plant

Environment

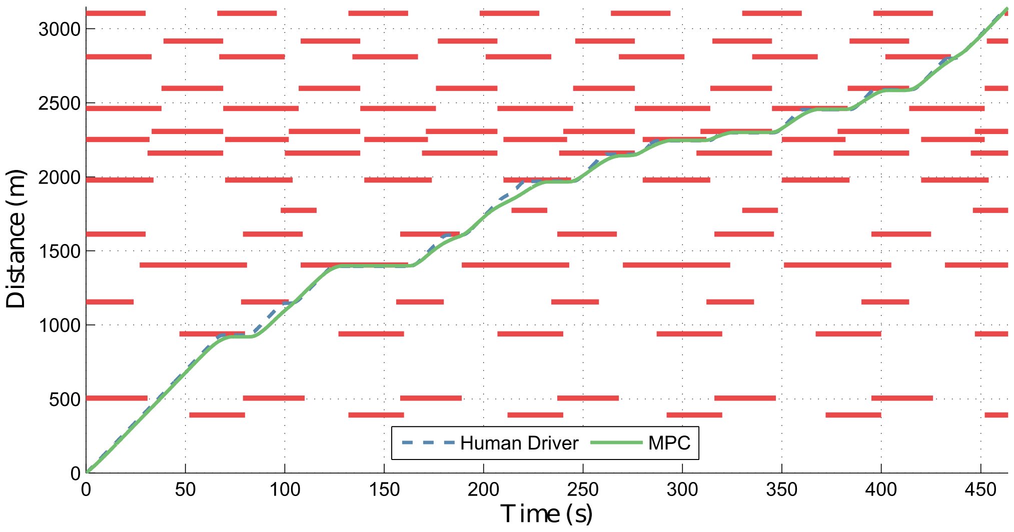
Traffic Lights
Road Description
Surrounding Traffic

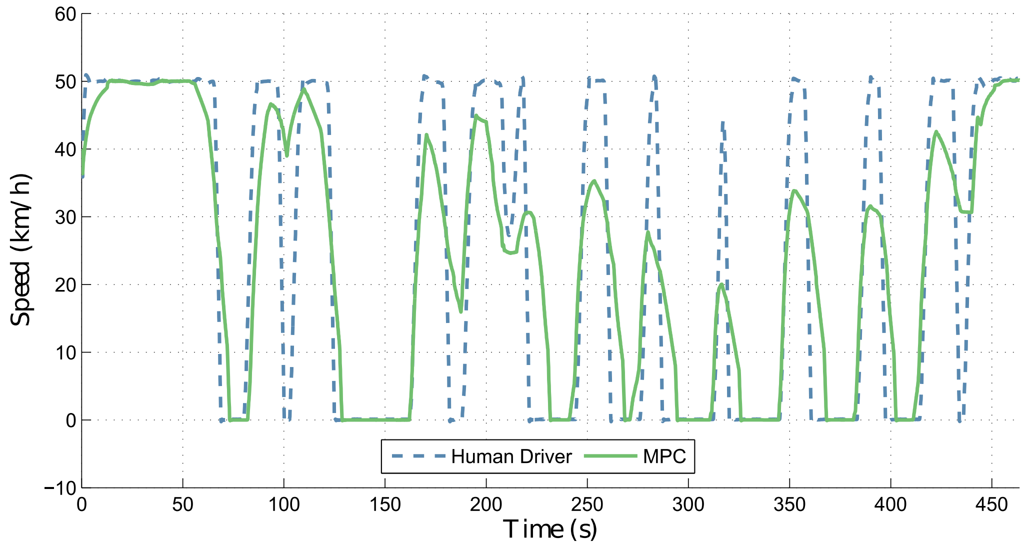


Hilmteichstraße 1 – Griesplatz 1

Typical energy savings of between 5% & 30% depending on scenario

Energy-Efficient CACC – Simulation Results
Graz Route Simulation **without** Traffic



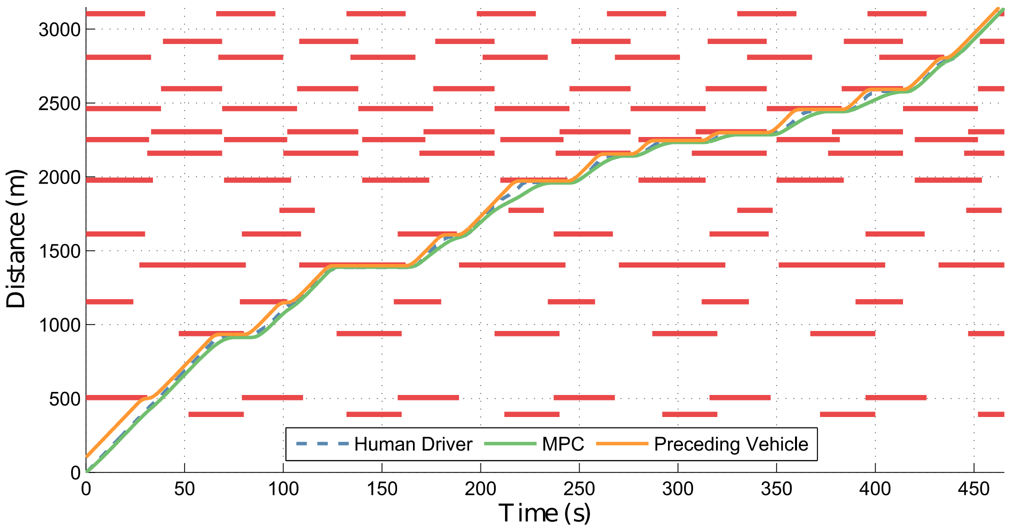


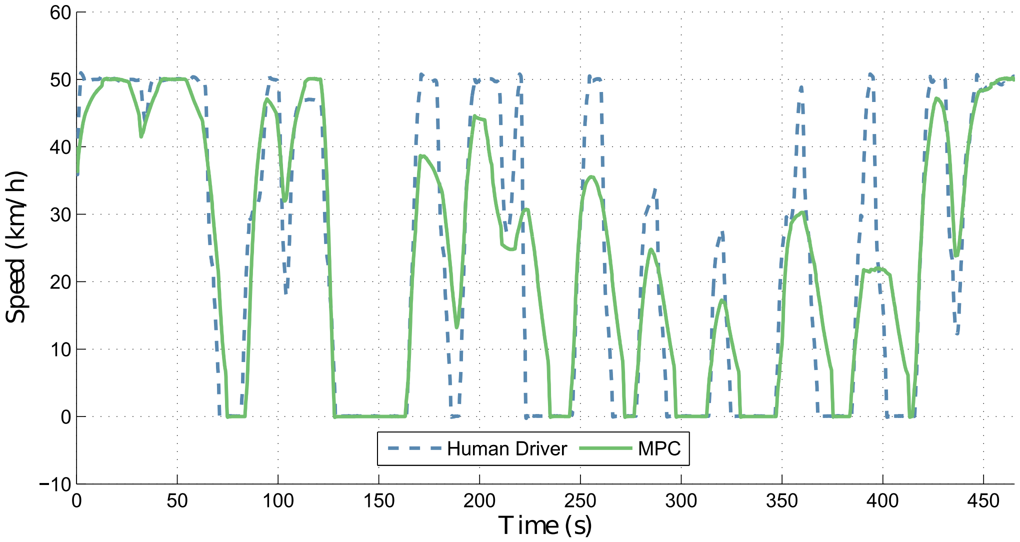
Energy savings: 25%* without traffic
with no increase in travel time

Adjustable travel time & driveability

* 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

Adjustable travel time & driveability

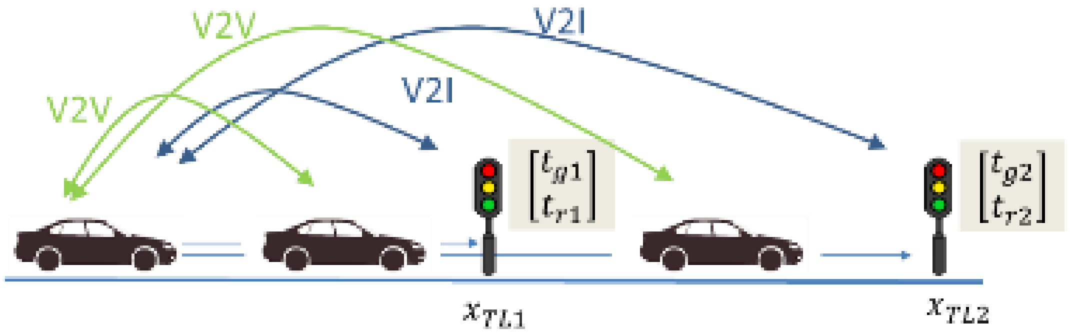
* like most predictive functions, the benefits depend on the specific use case.

Energy-Efficient CACC - Overview

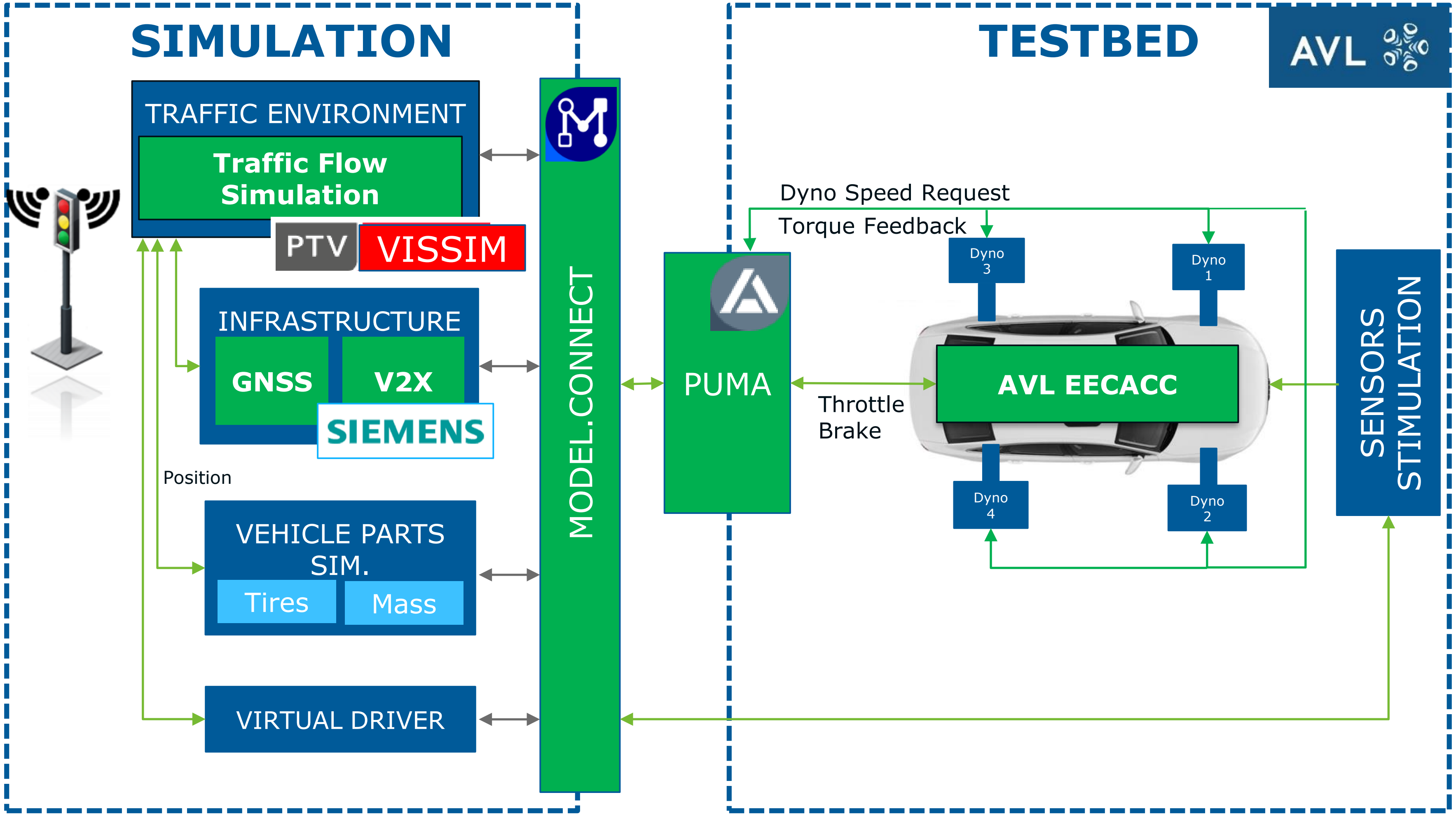
Energy-Efficient CACC – Testbed Results
FFG TASTE Project

"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.

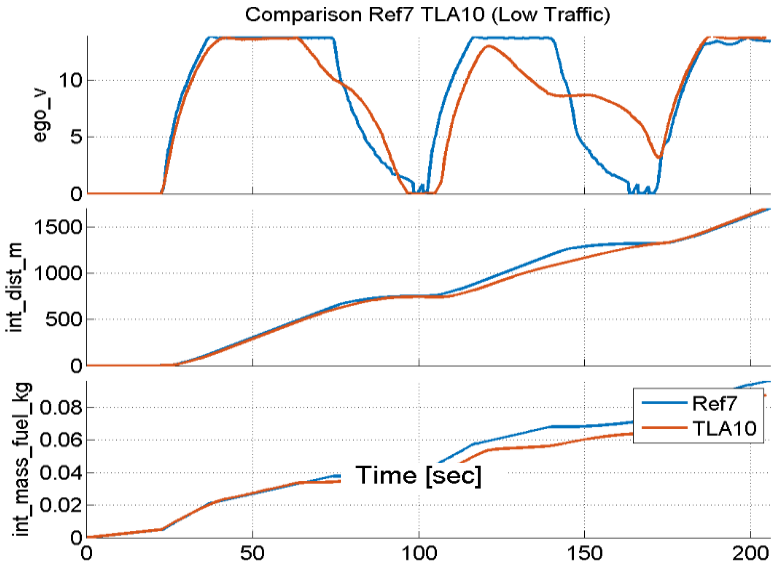
Energy-Efficient CACC – Testbed Results
EECACC Test Results from Powertrain Testbed

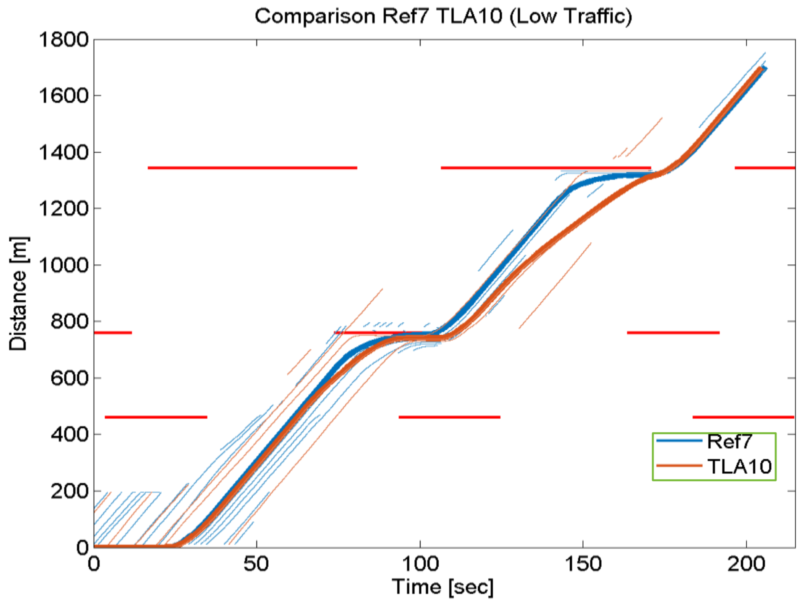
Road with low traffic, and average traffic speed, real V2X disabled.

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?

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

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

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