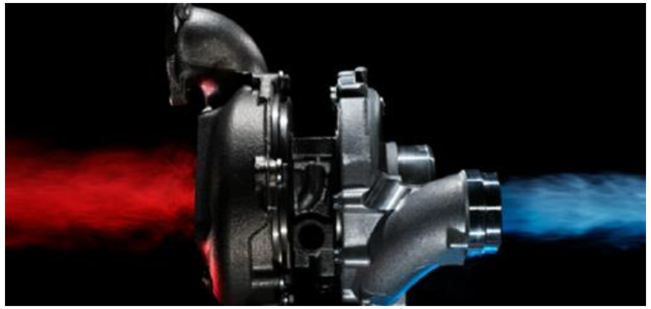

2021-09-09

NMPC FRAMEWORK FOR AUTOMOTIVE

Daniel Youssef

Garrett
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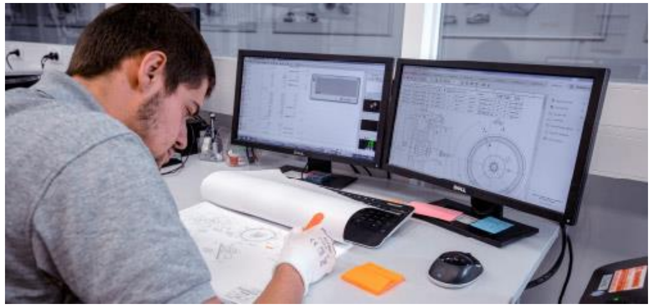
Agenda



COMPANY INTRODUCTION

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Garrett technology growth strategy

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CORE TURBO

Continuous differentiated innovation

- 60+ years of technology leadership and product innovation
- Highly-engineered products deeply integrated with customers
- Broadest portfolio across vehicle segments

ELECTRIFICATION & SOFTWARE

Next generation of technology leadership

- Extending strong turbo foundation into electric boosting
- Expanding portfolio for electrified vehicles
- Differentiated software solutions for connected vehicles

PIPELINE

Advanced technology for new unmet customer needs

- Novel solutions for electrified, connected and autonomous vehicles
- Building on our strong customer intimacy and collaboration

Focus on advanced technology for difficult industry challenges

Garrett Connected Vehicle Software

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Structural Complexity	Unsolved Challenges	New Garrett Solutions

Internal Combustion Engine
aftertreatment + E-boosting + . . .

+

Electrified Powertrain
hybridization + battery SOC/SOH + . . .

+

Autonomy
sensors + actuations + . . .

+

Connected
threat surfaces + updates + . . .

Optimize complex systems

Validate for real-world

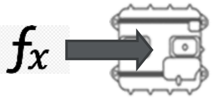
Ensure in-use compliance

Detect health degradation

Diagnose accurately

Differentiate fault vs. hack

Advanced Control
Algorithms & Health Indicators
- industrial process controls



- 25+ patents
- MPC in production
- Boost Ctrl SOP 2021

IVHM*
Fault Modeling, Diagnostic Reasoning & Prognostics
- aircraft health management

- 25+ patents
- JA6268 author
- SOP 2020

Cyber Security
Intrusion Detection & Diagnostic
- industrial security management

- Tier1 integrated
- 40+ proprietary algorithms
- SOP 2021

*integrated vehicle health management

New Challenges Require New Technologies for Control, Health and Security Management

Garrett Advanced Control Products

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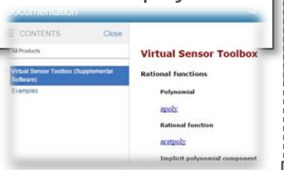
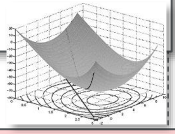
Modelling → Parameters estimation → Model validation → Control design → Calibration → Deployment

Virtual Sensor Toolbox is a generic symbolic toolbox to develop robust and physics-based models for real-time applications running at ECUs. ★

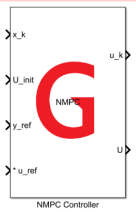


Quadratic Programming solvers with strong CPU and RAM optimization. ★



Caltool is a generic web-based calibration tool to deploy complex model-based calibration processes. ★

NMPC Framework is a toolbox to develop Nonlinear Model Predictive controllers with real-time capability at ECUs.



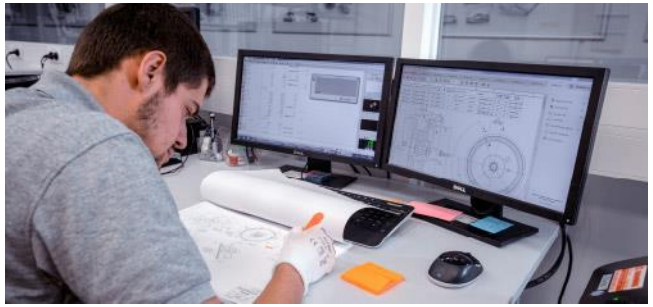
Virtual engine mass flow estimator is a tool suitable to replace a Venturi tube and allowing air path diagnostic. The final physics-based model runs real-time in embedded platforms. ★

OnRAMP Design Suite is a tool with GUI to design optimal multivariable control algorithms based on switched Linear Model Predictive Control. It significantly reduces development time for real time MPC design and deployment. ★

Energy Management Framework is a set of model-based design oriented tools for developing various predictive energy management solutions with application not only in HEV/EVs.

Mathbox is a user ready rapid prototyping ECU that enables fast and efficient development of advanced control (e.g. NMPC) and diagnostic systems from initial concept to production. The system is also suitable for fast data logging.

★ In mass production



MODEL PREDICTIVE CONTROL INTRODUCTION

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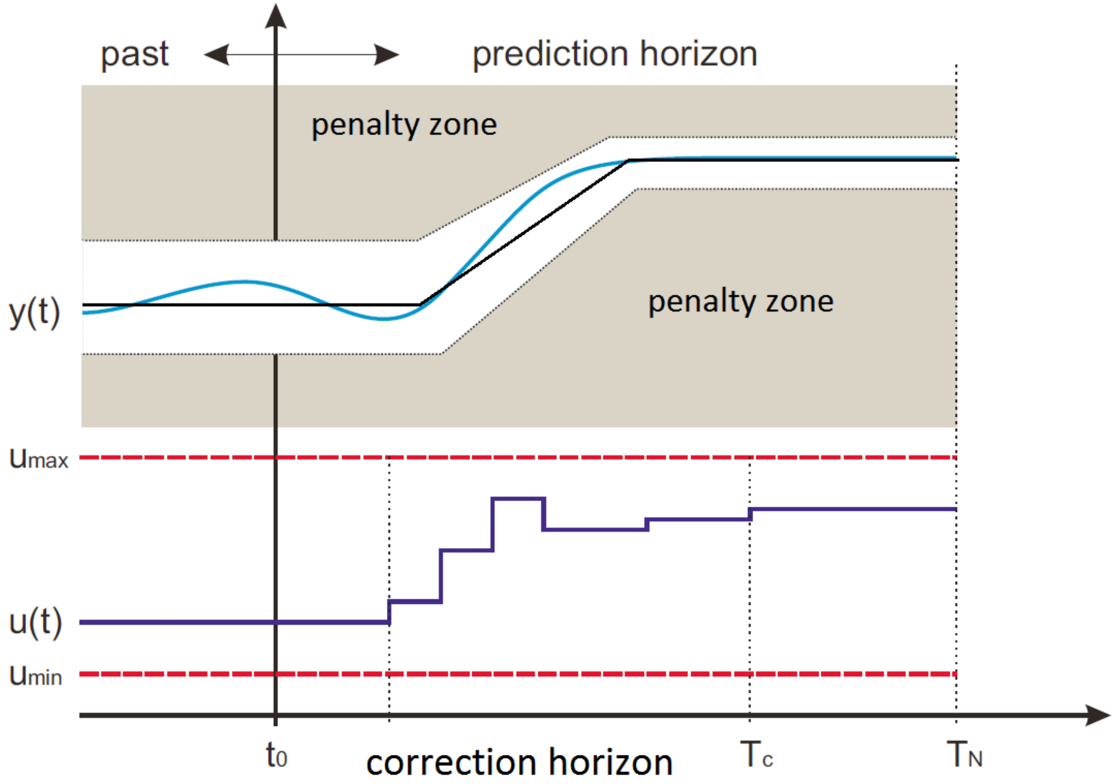
What is Model Predictive Control?

Model Predictive Control is a technology that optimizes performance of systems with many actuators, sensors and objectives in order to get the best possible performance of the controlled system.



What is Model Predictive Control (MPC)?

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Multiple performance objectives – fuel economy, emission, driveability

MATCH

Multi-objective optimization-based technology

Complex systems with many actuators, sensors and constraints

MATCH

Designed to control and optimize multivariable constrained systems

Connectivity is becoming a standard

MATCH

“Preview information” is embedded in the core

Calibration effort for emerging technologies – to be fast on the market

MATCH

Model-based approach with high level of automation

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Model Predictive Control

Leading MPC Solution for Automotive Applications

NMPC FRAMEWORK

Nonlinear MPC Framework - Introduction

Problem Statement

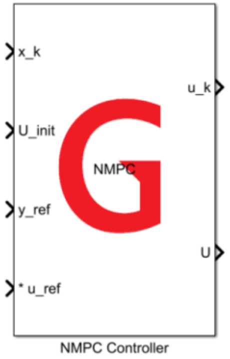
- Nonlinear dynamic system to be optimized
- Known / estimated preview information utilization (references, limits, disturbances, …)
- Model parameters variability (ageing)
- CPU / Memory Limitations **(~200MHz @128kB RAM)**

Solution

- Full **Nonlinear** Model Predictive Controller
- Time-varying preview of references, limits, disturbances, …
- Highly efficient real-time optimizer + memory optimization

Benefits

- Reaching full potential of the system optimization
- Reduction of calibration time and code complexity
  - Systematic preference and **model-based** calibration
  - Systematic handling of preview information
  - Systematic handing of system limits
- Unified multi-domain approach



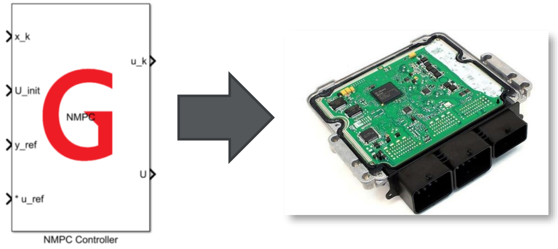
NMPC

Model Based Design – General Workflow

NMPC Framework

Modeling	Control Design	Deployment & Execution
• Model definition	• Definition of control problem • System limitations definition • Preview information definition	• Deployment to Matlab / Simulink • Code generation

$$
\begin{aligned}
f^*_{\mathsf{MPC}_{reg}}(\tilde{\boldsymbol{x}}(k)) \triangleq \quad \min_{\boldsymbol{u}(k),\ldots,\boldsymbol{u}(k+N-1)} \quad & \frac{1}{2}\boldsymbol{x}(k+N)^T\boldsymbol{P}\boldsymbol{x}(k+N) + \\
& \frac{1}{2}\sum_{i=1}^{N-1}\boldsymbol{x}(k+i)^T\boldsymbol{Q}\boldsymbol{x}(k+i) + \frac{1}{2}\sum_{i=0}^{N-1}\boldsymbol{u}(k+i)^T\boldsymbol{R}\boldsymbol{u}(k+i), \\
\text{s.t.} \quad & \boldsymbol{x}(k+1+i) = \boldsymbol{A}\boldsymbol{x}(k+i) + \boldsymbol{B}\boldsymbol{u}(k+i),\ i = 0,\ldots,N-1 \\
& \boldsymbol{u}(k+i) \in \widetilde{\Omega},\ i = 0,\ldots,N-1, \\
& \boldsymbol{x}(k) = \tilde{\boldsymbol{x}}(k), \qquad \text{(1a)}
\end{aligned}
$$



Benefits of NMPC Framework

- System interaction / limitation
- MIL/SIL validation enabler

- Preference-based calibration (**systematic**)
- Flexibility while still systematic (math is behind the scene)

- Model-based Design
  - Maintenance cost reduction
  - Code reuse optimization
- CPU/Memory Optimal Solver

NMPC Utilizes Model and Preview to Provide System Optimization

Nonlinear Model Predictive Control Framework - Overview

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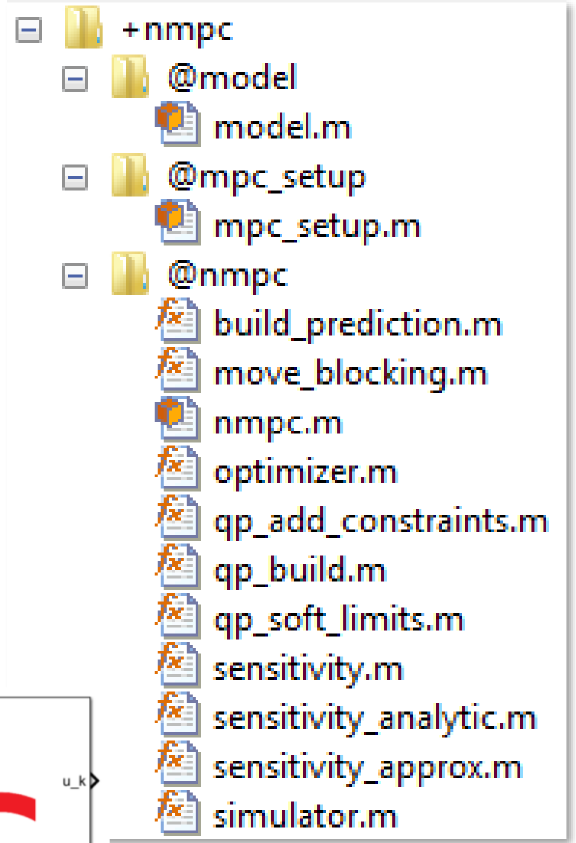
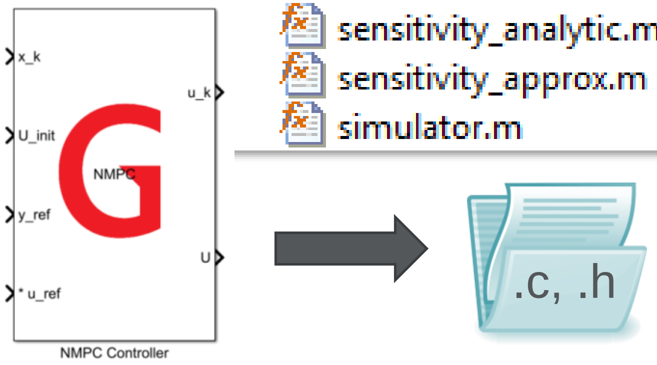
- Matlab / Simulink based Object Oriented Toolbox
- Continuous / Discrete-time models support
  - Internal / external parameters
- Straightforward formulation of MPC control problem
  - Definition of model and sensitivities (anonymous, external functions)
  - Defining the control goals (tracking for actuators and output references, actuator increment and value, output limits, ratio difference, ratio tracking), linear + quadratic norms
  - Hard and soft constraints
- Others
  - Support of preview information
  - Systematic controller design and system performance evaluation in simulation
  - Support of multiple QP solvers for best performance and memory footprint
  - Can be exported to Simulink and code generated from it
  - **Single precision** floating point logic





Model Predictive Control - Typical Workflow

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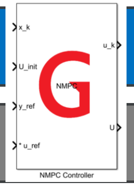
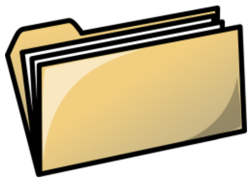
NMPC Framework



Offline

On-line



MPC
Problem Setup

Cost Function Builder

Constraints Builder

$$\frac{1}{2}\mathbf{x}^{\mathrm{T}}Q\mathbf{x} + \mathbf{c}^{\mathrm{T}}\mathbf{x}$$

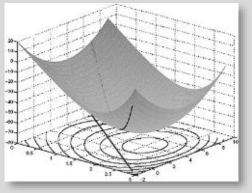
$$A\mathbf{x} \preceq \mathbf{b},$$

QP Problem

Q

c

QP Problem Data



QP Solver

NMPC Framework – High Level Overview

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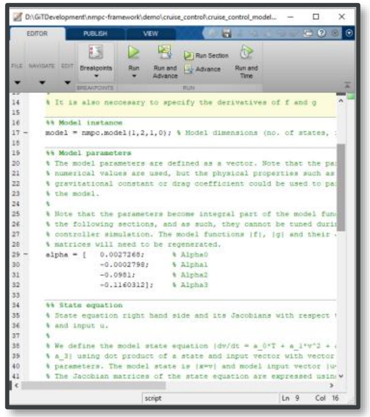
Modeling → Control Design → Deployment & Execution

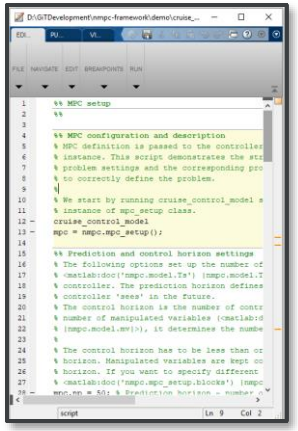
NMPC Model

Definition of model functions
Dynamics, outputs and Jacobians
Support of numerical Jacobians



NMPC Setup

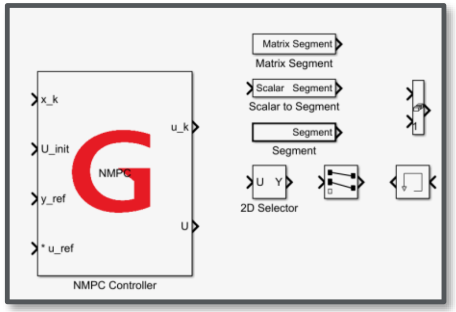
Cost function definition
Linearization type (LTI/LTV)
Preview information settings
(S)QP solver settings

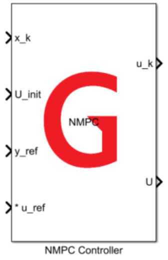


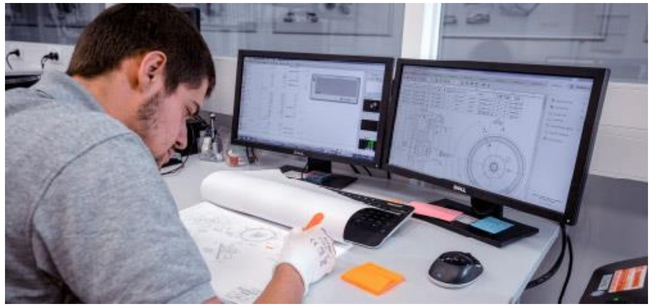
NMPC deploy_system

Matlab + Simulink Interfaces
External model parameters
External cost function weights
Export of model / input predictions
Interpreted / Code generation targets

Simulink Library







USE CASES

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Use Case – Predictive Cruise Control Example – How To

Longitudinal Vehicle dynamics*

*SAE 2016-01-0155

$$\frac{dv}{dt} = \alpha_1 T + \alpha_2 v^2 + \alpha_3 \phi + \alpha_4$$

Modeling

```
>>nx = 1; m = 1, p = 1; model = nmpc.model(nx, m, p,0);
>>model.f = @(x,u,r) [u(1), x^2, u(2), 1]*alpha; % Acceleration [ms^(-2)]
>>model.dfdx = @(x,u,r) 2*x*alpha(2); % Derivatives of f w.r.t. x
>>model.dfdu = @(x,u,r) [alpha(1), alpha(3)]; % Derivatives of f w.r.t. u
>>model.g = @(x,u,r) x; % Velocity [ms^(-1)]
>>model.dgdx = @(x,u,r) 1; % Derivatives of g w.r.t. x
>>model.dgdu = @(x,u,r) [0, 0]; % Derivatives of g w.r.t. u
>>model.mv = 1; % Engine torque [Nm]
>>model.dv = 2; % Road grade [%]
>>model.Ts = 0.1; % Sampling period
```

Controller Design

```
>>mpc = nmpc.mpc_setup(); % create instance of NMPC
```

Prediction Horizon Settings

```
>>mpc.np = 50; % Prediction horizon - number of steps into future
```

Constraints

```
>>mpc.u_lb = 0 * ones(1,mpc.np); % limitation of inputs
>>mpc.u_ub = 400 * ones(1,mpc.np); % limitation of inputs
```

Cost function

```
>>mpc.R_du = 0.005 * ones(1,mpc.np); % drivability
>>mpc.y_tr = [1]; % Index of output – vehicle speed
>>mpc.Q_r = 500 * ones(1,mpc.np); % tracking of vehicle speed ref.
>>mpc.preview = 1; % Use reference preview
```

Execution

```
>> my_nmpc = nmpc.nmpc(model,mpc); % Setup object for run
>> [U,y_pred,~] = my_nmpc.control(x0,U,YREF,[],u_lb,u_ub, y_min,y_max);
```

Deployment to Simulink

```
my_nmpc.control.deploy_system(‘pcc’); % Deploy to Simulink for codegen
```

Use Case – Predictive Cruise Control for Hybrid Vehicle

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Predictive Cruise Control (PCC)

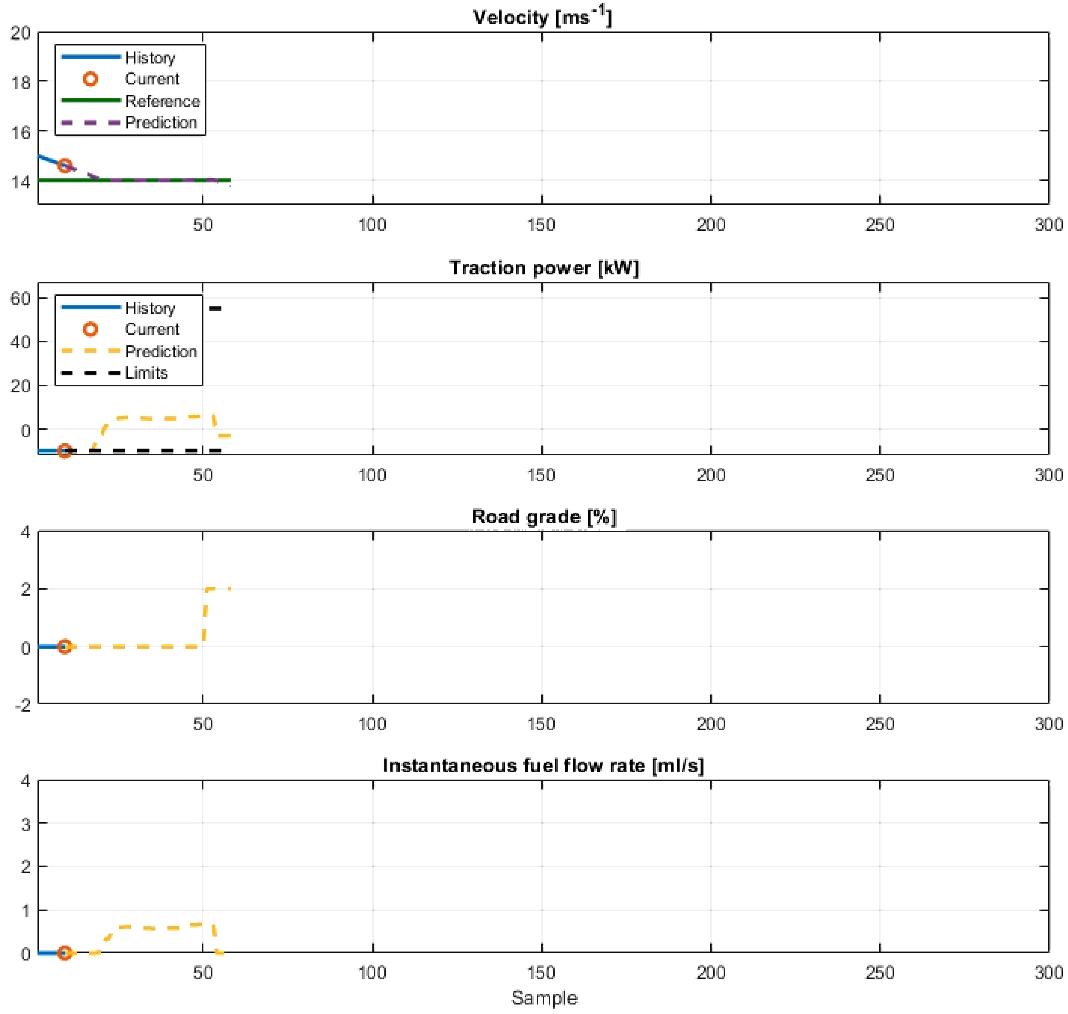
- Find optimal traction power to propel vehicle at the **reference velocity** while respecting driver's comfort, speed limits, minimum/maximum power, and safe distance from the lead vehicle

Objective

- Utilize horizon preview
  - Road grade, road curvature, speed limits
- Smooth changes of traction power request
- Best fuel economy

Problem formulation

- Defined in power/energy domain
- Scalable to any vehicle configuration



Up to 11% Fuel Economy Benefit demonstrated in vehicle*

* SAE 2017-01-0090

NMPC Framework vs. Other Solutions

PCC (SAE 2016-01-0155) with preview with N = 40 , Ts = 500ms

	NMPC Framework	MPC Toolbox (LTV)	MPC Toolbox + External Solver + 3rd Party Solver	External Solver 3rd Party Solver
CPU*	1.1 ms	-	14.7 ms (~14x)	6.2 ms (~6x)
RAM	4.4 kB (0.5 kB stack)	136 kB (+10kB stack) (~30 x)	92 kB (+1 kB stack) (~20x)	131 kB (+1 kB stack) (~30x)
Logic	single	single	double	double
Cost function	Wide range of practical cost function terms	Limited	Limited	Generic
Feedthrough Support	yes	no	no	yes
Blocking	Different for each actuator	Fixed, Interpolated	Fixed, Interpolated	Not directly

* factor of 25 used for compute the PC->ECU time

Summary

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Garrett's NMPC Framework

- Matlab / Simulink based Toolbox
- Easy-to-use practical tool for design and deployment of **NMPC for Automotive**
  - Low CPU time
  - Low memory footprint

Next Steps

- Adding of GUI and Extended Kalman filter functionality
- RAM memory optimization
- Interface for Matlab MPC Toolbox?

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