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## Investigations on a Hybrid Energy Storage System for an All-wheel Driven Motorcycle

EVS 2017

## Motivation

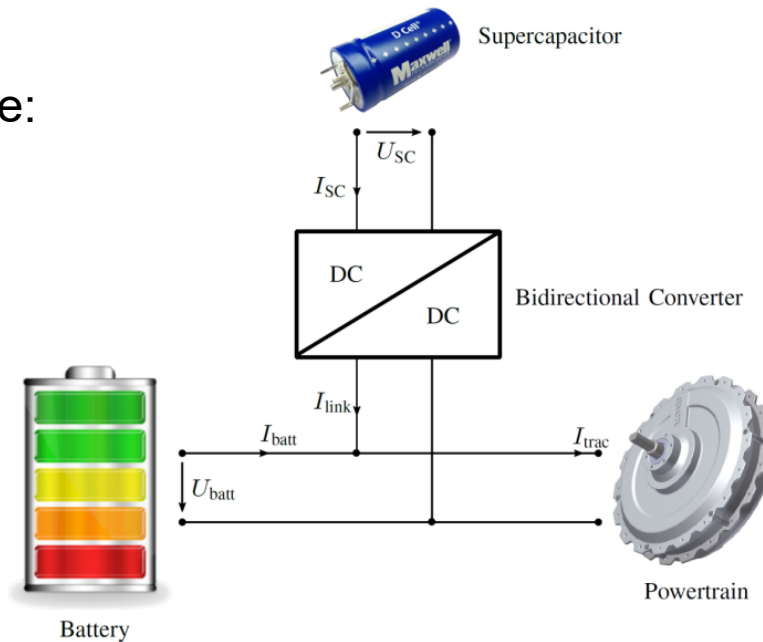


- All-wheel driven motorcycle with passive hybrid energy storage system (HESS)<sup>1</sup>

<sup>1</sup>M. Baumann, M. Buchholz, and K. Dietmayer. "A two-wheel driven power train for improved safety and efficiency in electric motorbikes," *Electric Vehicle Symposium (EVS 29)*, 2016.

## Motivation: HESS Architecture

- Passive HESS: Directly connected, no control strategy is needed
- Semi-active HESS: One converter is needed as well as a control strategy
- Fully-active HESS: Two converter, high costs but also high degree of freedom
- Semi-active HESS architecture:  
→ good trade-off between costs and performance



# Overview

Motivation

System Modeling and Identification

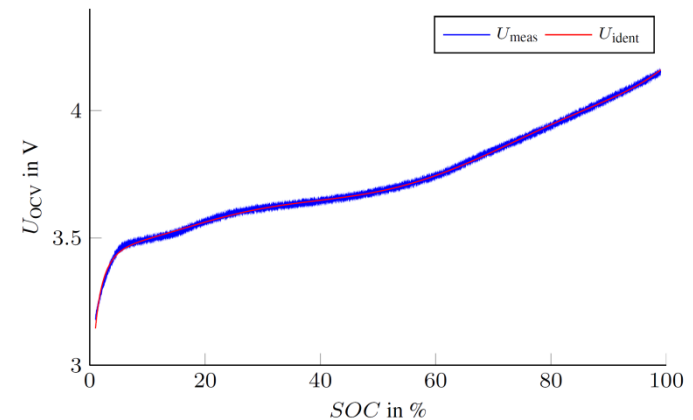
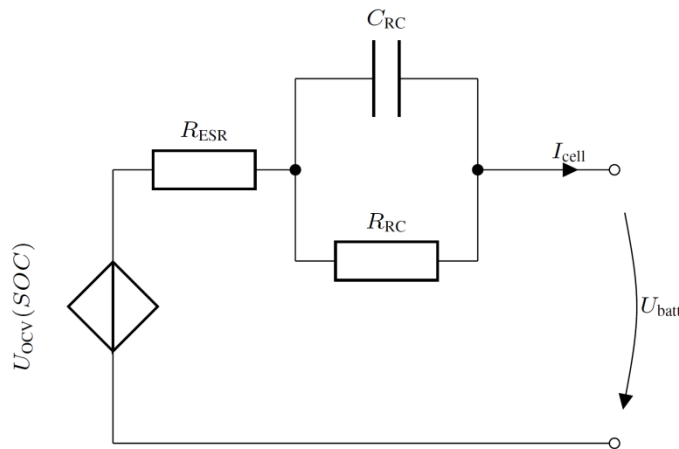
Control Strategy and Observer

XiL Test

Conclusion

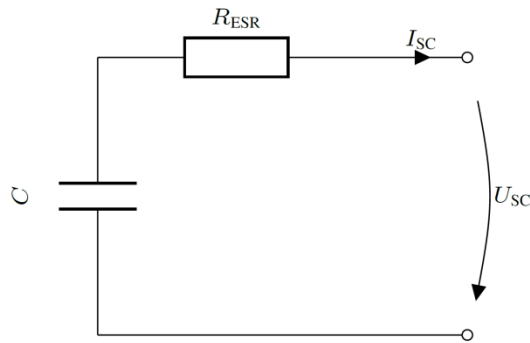
## System Modeling: Battery

- Battery: 1<sup>st</sup> order RC model (classical Thevenin model)
  - Ohmic resistor for internal resistance
  - RC element for dynamic behavior
  - Voltage source depends on actual state of charge



## System Modeling: Supercapacitor and DC/DC Converter

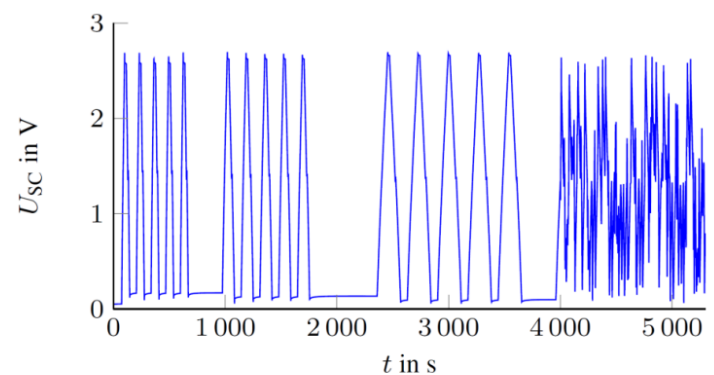
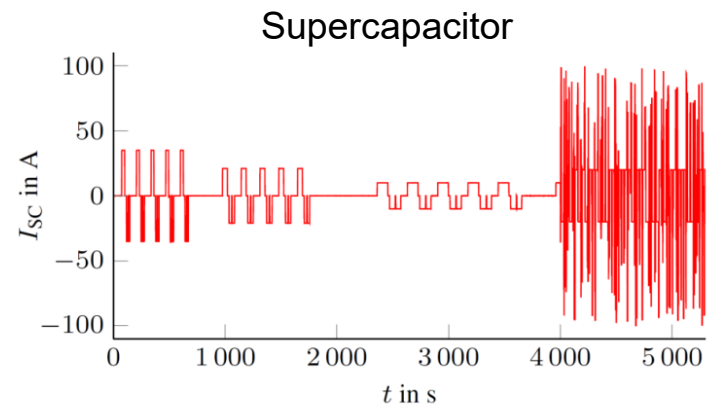
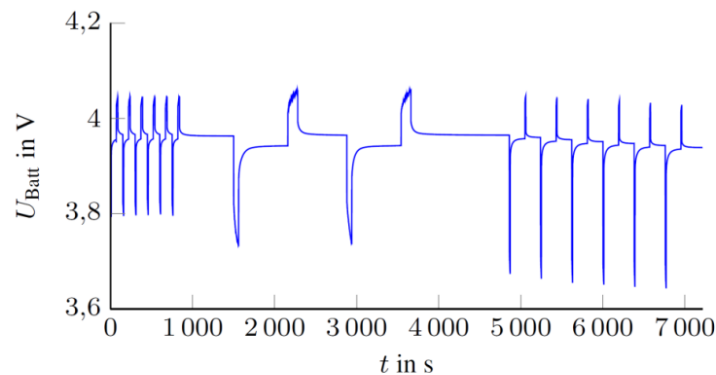
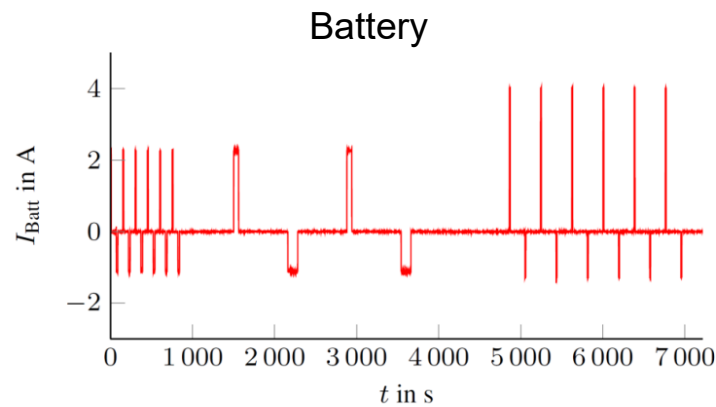
- Supercapacitor: RC model



- DC/DC converter: Static system model
  - Very fast time constants compared to battery and supercapacitor
  - Delivers current according to external set point
  - Sign of current defines energy flow

## System Identification: Battery Model and Supercapacitor

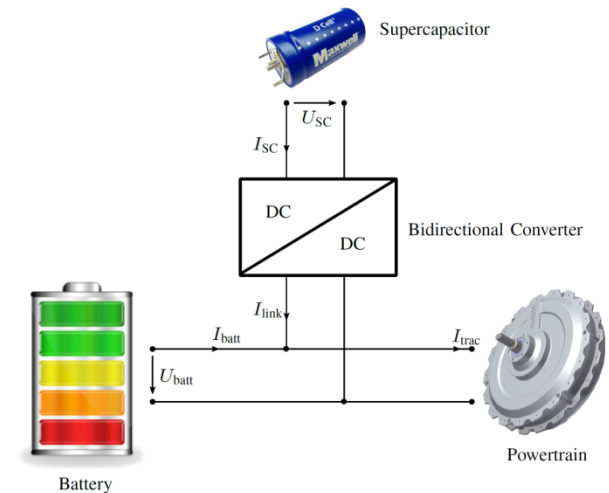
- Identification data:



- Identification results:  $RMSE_{\text{Batt}} = 3,6 \text{ mV}$  and  $RMSE_{\text{SC}} = 5,0 \text{ mV}$

## Control Strategy

- Goals:
  - Protecting battery from damaging currents
  - Recuperating as much as possible of braking energy
  - Enhancing batteries lifetime
- Starting point:
  - Non-linear model of semi-active HESS
- Assumption:
  - Power profile predictable over reasonable horizon



## Control Strategy

- States  $\mathbf{x} = [U_C, U_{RC}]^T$ , input  $u = I_{SC}$  and disturbance  $z = P_{\text{trac}}$
- Optimal control problem:

$$\begin{aligned} \min_{\bar{u}(t)} \quad & J(\mathbf{x}_k, \bar{u}) = \int_{t_k}^{t_k+T} l(\bar{\mathbf{x}}(t), \bar{u}(t), \bar{z}(t)) \, dt \\ \text{s.t.} \quad & \dot{\bar{\mathbf{x}}}(t) = \mathbf{f}(\bar{\mathbf{x}}, \bar{u}, \bar{z}), \bar{\mathbf{x}}(t_k) = \mathbf{x}_k, \\ & \bar{u}(t) \in [I_{SC}^-, I_{SC}^+] \end{aligned}$$

- Cost function:

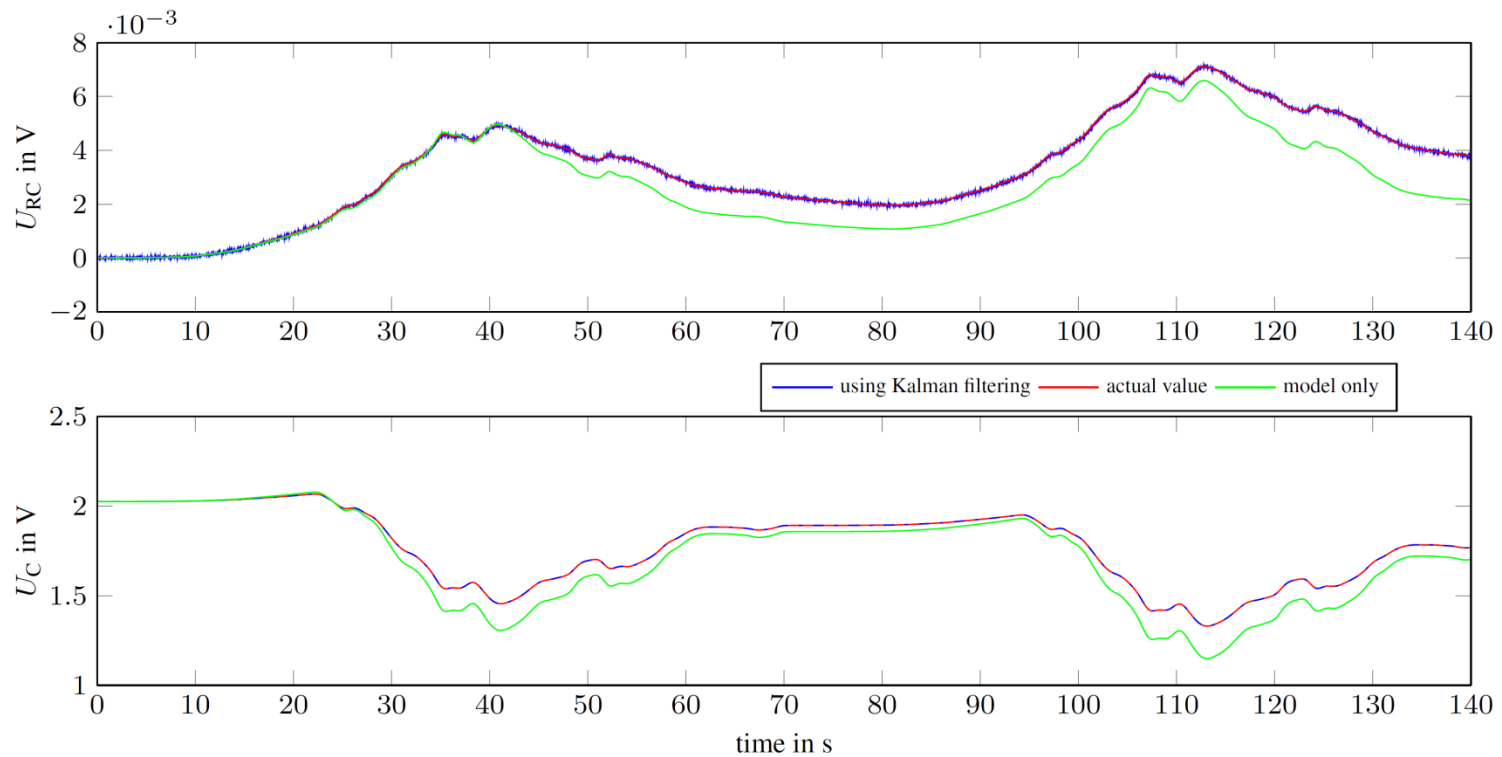
$$\begin{aligned} l(\mathbf{x}, u, z) = & \gamma_1 I_{\text{batt}}^2 + \gamma_2 ((R_{\text{loss}} + N_{\text{cap}} R_{\text{ESR, cap}}) u^2 + R_{\text{ESR, batt}} I_{\text{batt}}^2) \\ & + \gamma_3 f_{\text{pen}}(\text{SOC}_{\text{batt}}, \text{SOC}_{\text{batt}}^+, \text{SOC}_{\text{batt}}^-) + \gamma_4 f_{\text{pen}}(U_{SC}, U_{SC}^+, U_{SC}^-) \\ & + \gamma_5 f_{\text{pen}}(I_{\text{batt}}, I_{\text{batt}}^+, I_{\text{batt}}^-) + Ru^2 + \mathbf{x}_\delta^T \mathbf{Q} \mathbf{x}_\delta \end{aligned}$$

- Real-time Solver: Open-source software GRAMPC<sup>2</sup>

<sup>2</sup>B. Käpernick and K. Graichen. "The gradient based nonlinear model predictive control software GRAMPC," *European Control Conference (ECC)*, IEEE, 2014.

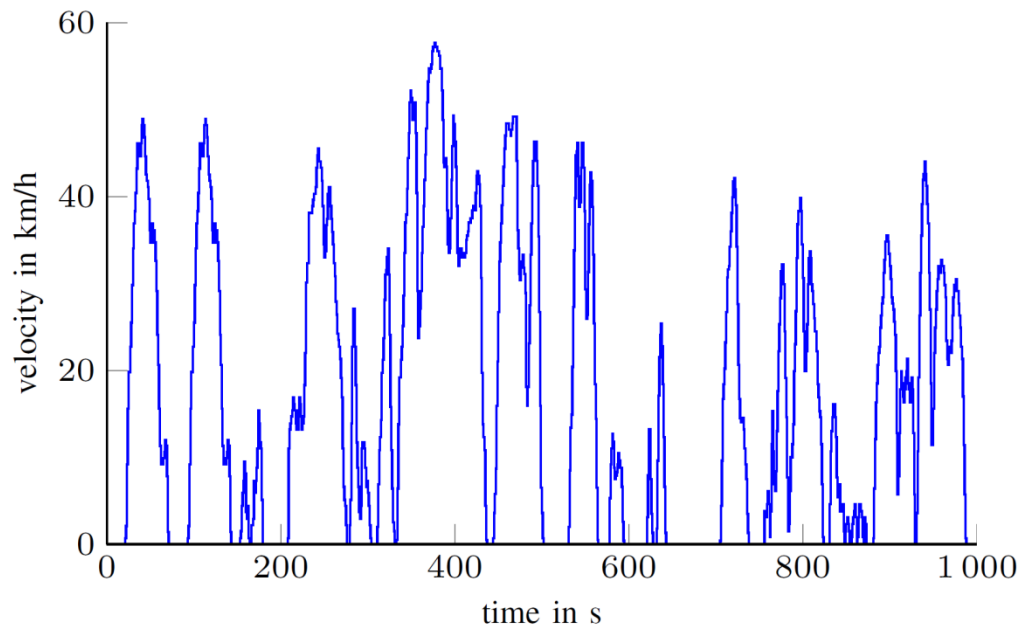
## Observer: Unscented Kalman Filter

- Compensation of model inaccuracies by model alignment with measured outputs
- Observation of non-measurable states:



## XiL Test: Scenario

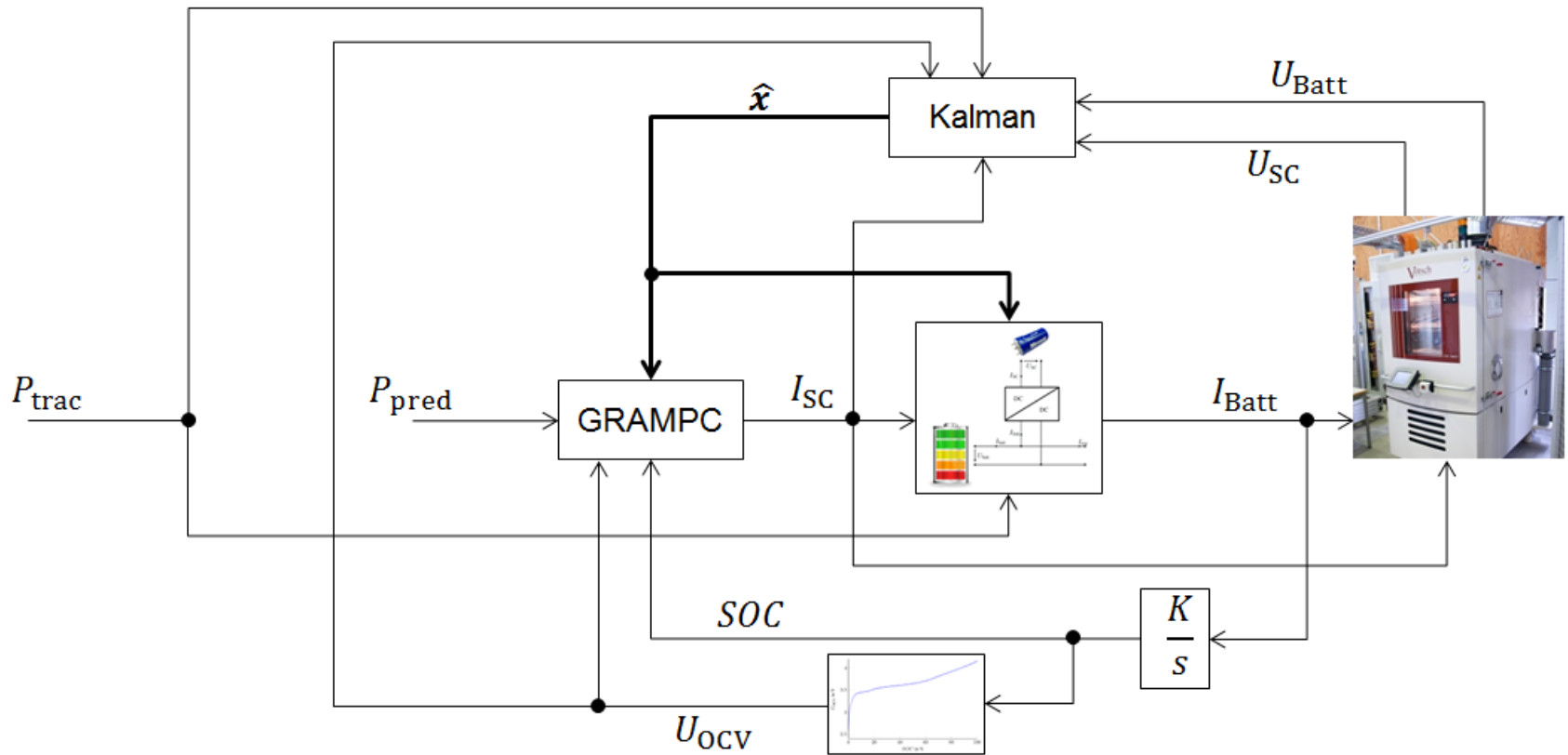
- Urban part of the ARTEMIS<sup>3</sup> driving cycle



- Based on parameters of the all wheel driven motorcycle translated into a power profile

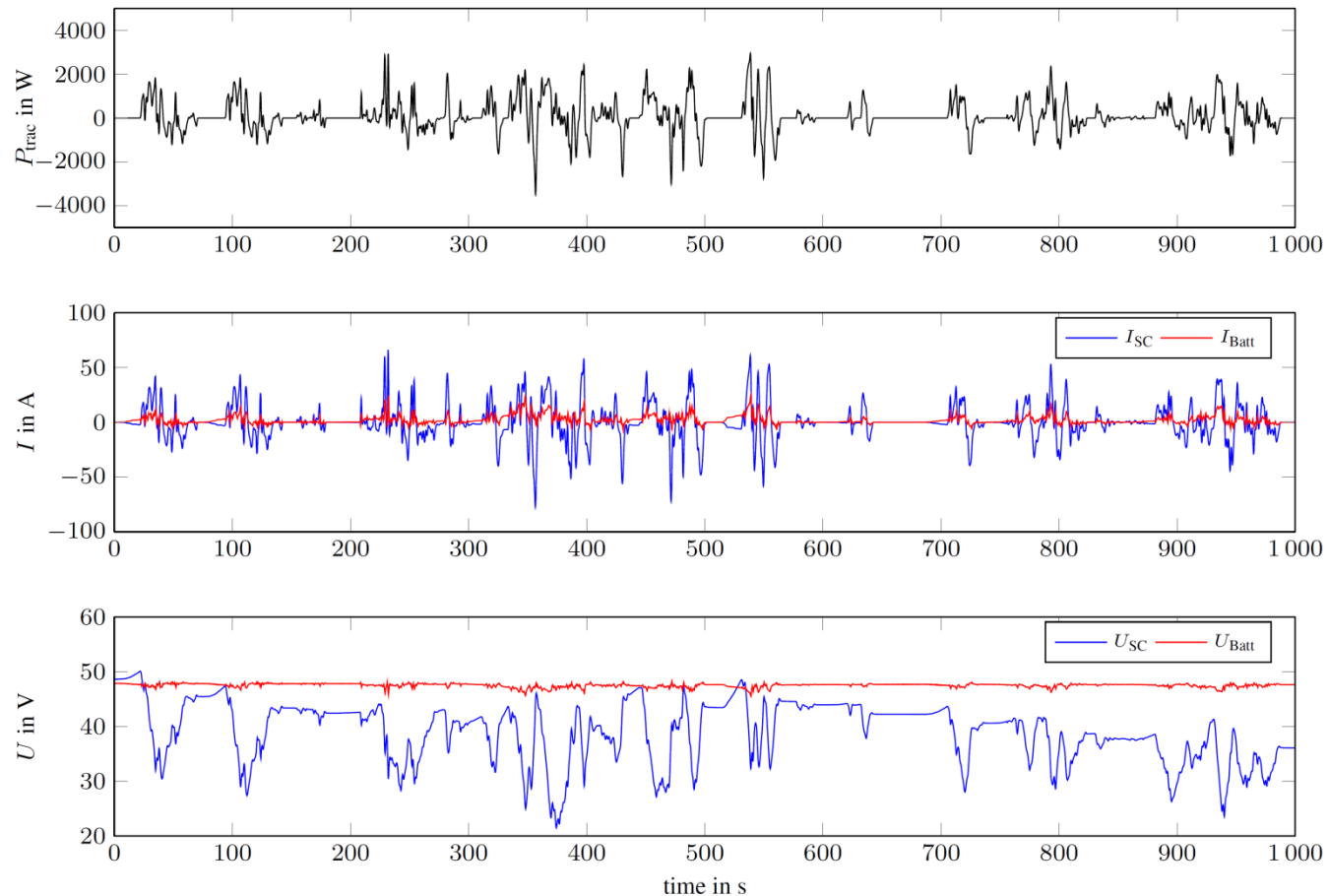
<sup>3</sup>M. André, "The ARTEMIS European driving cycles for measuring car pollutant emissions," *Science of The Total Environment*, 2004.

## XiL Test: Set-up



- Real battery cells and supercapacitors under test

## XiL Test: Results



- Power demand successfully mastered using the semi-active HESS
- Compliance of battery current limits

## Conclusion

- Real-time model of a semi-active HESS based on measurements of the real system
- Real-time model predictive control strategy (online optimization!) on rapid-prototyping electronic control unit (ECU)
- Very good XiL test results based on ARTEMIS driving cycle

## Future Work

- Analyze effects of uncertain power prediction and its horizon length
- Integration of DC/DC converter in test vehicle



**Thank you for your attention!**

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