FKFS
RESEARCH IN MOTION.

High precision time series regression

for Automotive Powertrain Development & More

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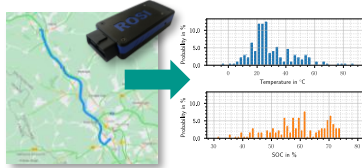
Introduction: Our use-case
From Measurement to AI-based Digital Twins

Vehicle

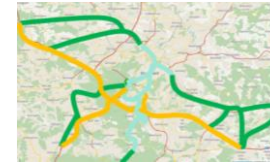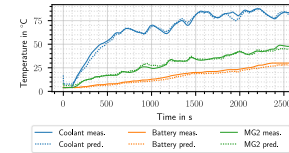**Measurement Data**

AI Model of Powertrain

Digital Twin Instance

Virtual Test Drive

- Route
- Speed Profile
- Traffic Situation
- Weather

Digital Twin Instance

Analysis

- Investigate test drives that are not included in the training data
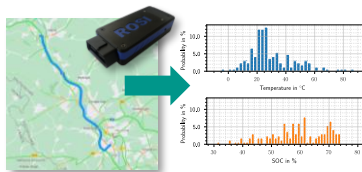- Investigate control strategies

Sources: https://www.ford.de/fahrzeuge/ford-galaxy

Introduction: Our use-case

From Measurement to AI-based Digital Twins

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Vehicle

Measurement Data

AI Model of Powertrain

AI

Digital Twin Instance

- **What are the challenges?**
- **What are the special issues in the powertrain?**

- highly automated process@FKFS
- training duration ~16h
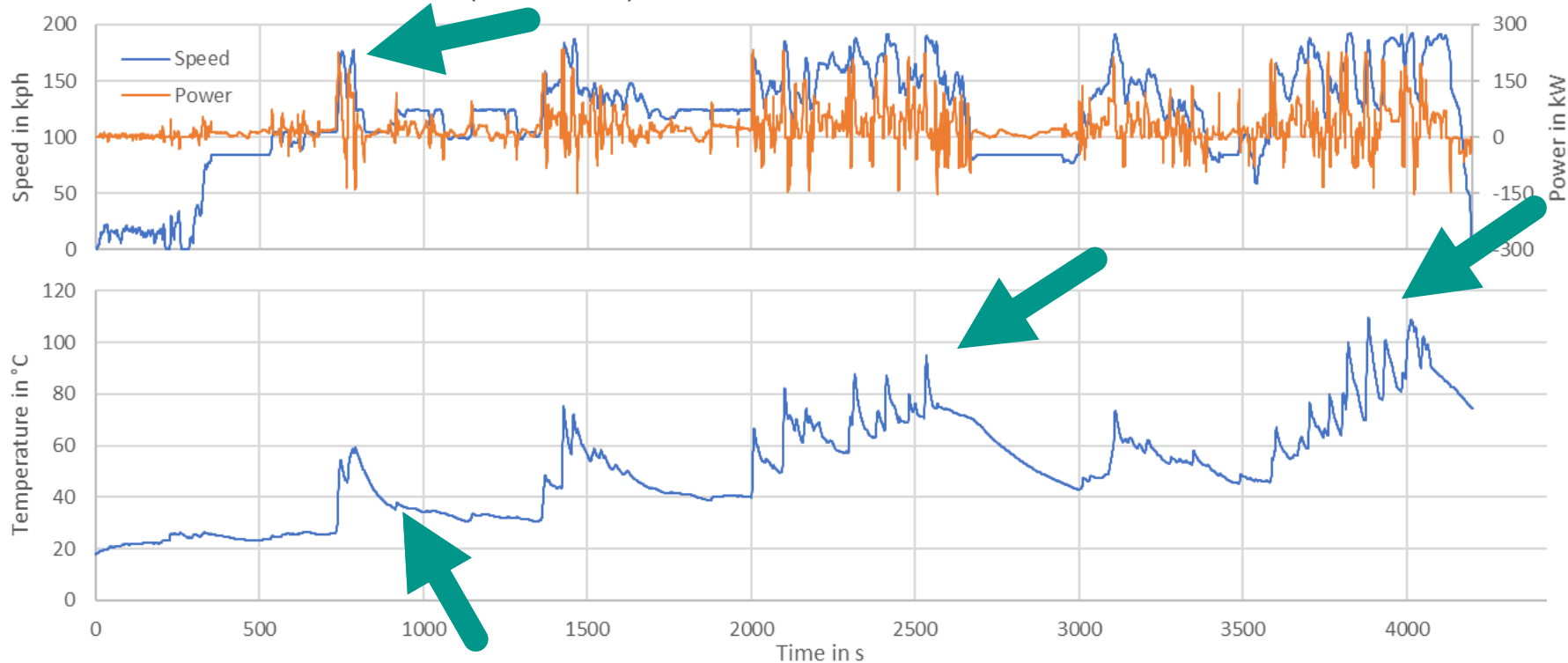- 14x RTX3080/3090 @ FKFS
- cloud services possible

Sources: https://www.ford.de/fahrzeuge/ford-galaxy

Example

E-Motor: Temperature of stator

BMW i4 eDrive 40 (G26)
EESM (rear), max. 250 kW/430 Nm

Profile: München – Illertissen (135 km, 4 °C)

Sources: https://www.press.bmwgroup.com/deutschland/article/detail/T0333329DE/der-erste-bmw-i4

Example
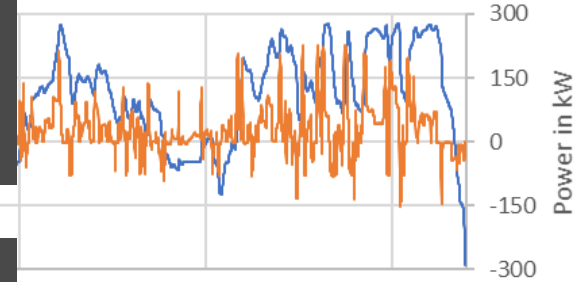
E-Motor: Temperature of stator

BMW i4 eDrive 40 (G26)

Typical task:
- AI-based temperatur model
  T = f(T_Start, t, v(t), P(t), ...)
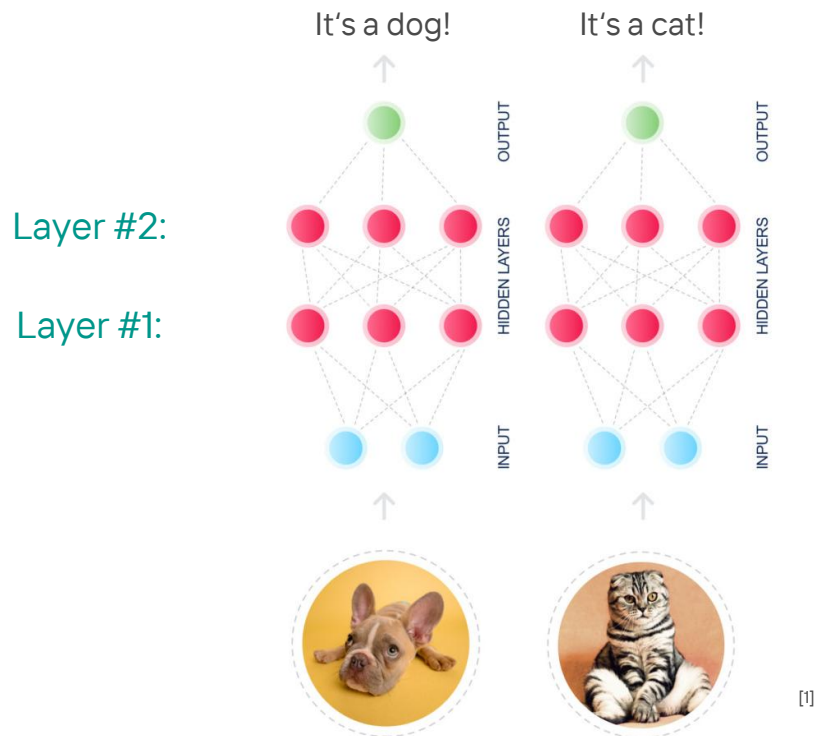- ... time series regression

Challenges
- Time dependencies are crucial
- High precision is crucial
- Inertias (mechanical, thermal, chemical, fluid) with different time scales are characteristic of the powertrain

Introduction: Typical Neuronal Networks
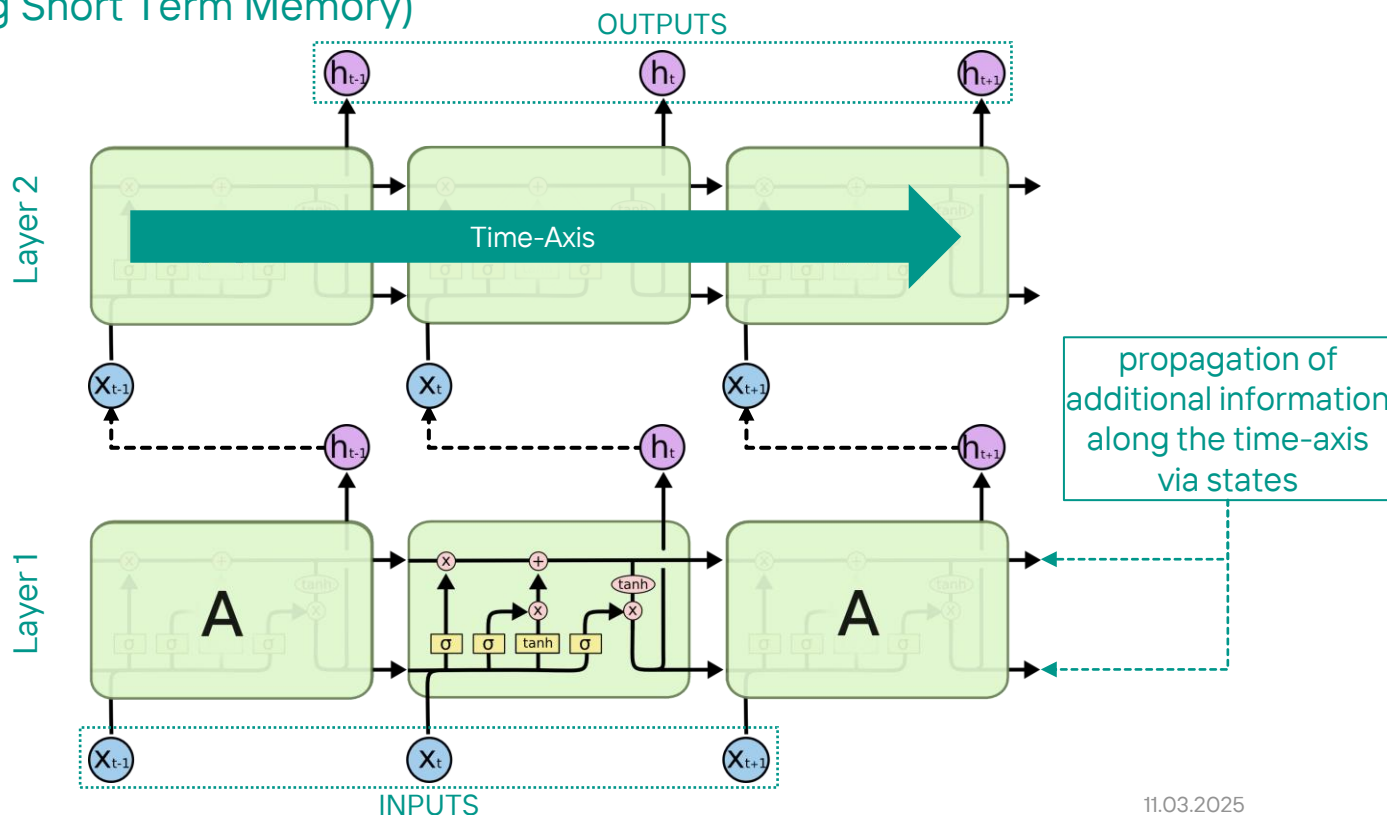## Example: Image Recognition

It's a dog!   It's a cat!

OUTPUT

Layer #2:

HIDDEN LAYERS

Layer #1:

INPUT

[1]

CNN and dense NN are stateless:

the prior experience has no influence on the outcome

[1] https://nix-united.com/wp-content/uploads/2021/02/Image-1-1024x683.jpg

Time-Series Regression

LSTM (Long Short Term Memory)

Time-Series Regression

Our approach: LSTM networks (Long Short Term Memory)

Strenghts:

- Memory of previous timesteps via states
  - long- and short term memory
- Ability to forget irrelevant information
- Very high simulation speed > 100x RT

Challenges:

- Initialization of states is non-trivial
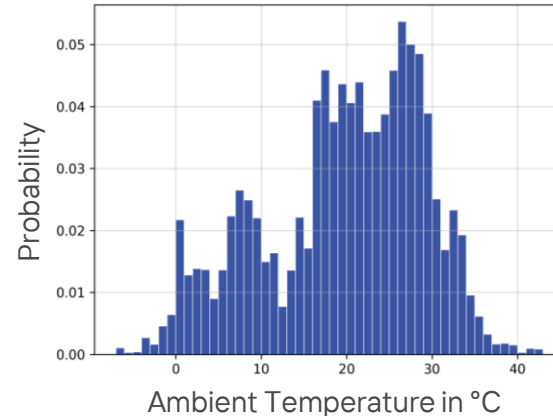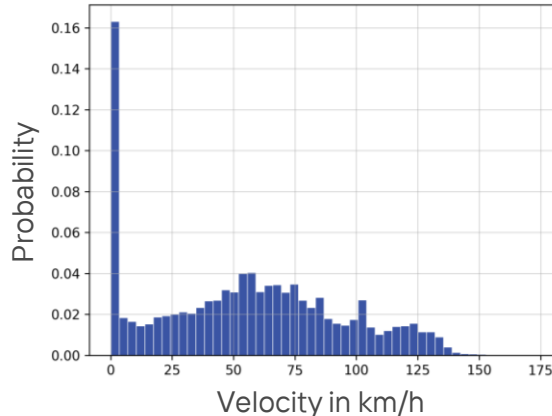- Error accumulation over time
- Good training strategies necessary
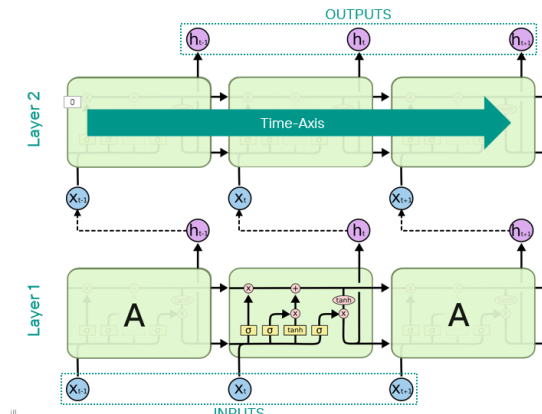
Demonstrator Project
Ford Galaxy FHEV

- Test vehicle is rented and unmodified

- Data-logging via OBD2-port

- Only openly available control unit signals are utilised (no OEM support)
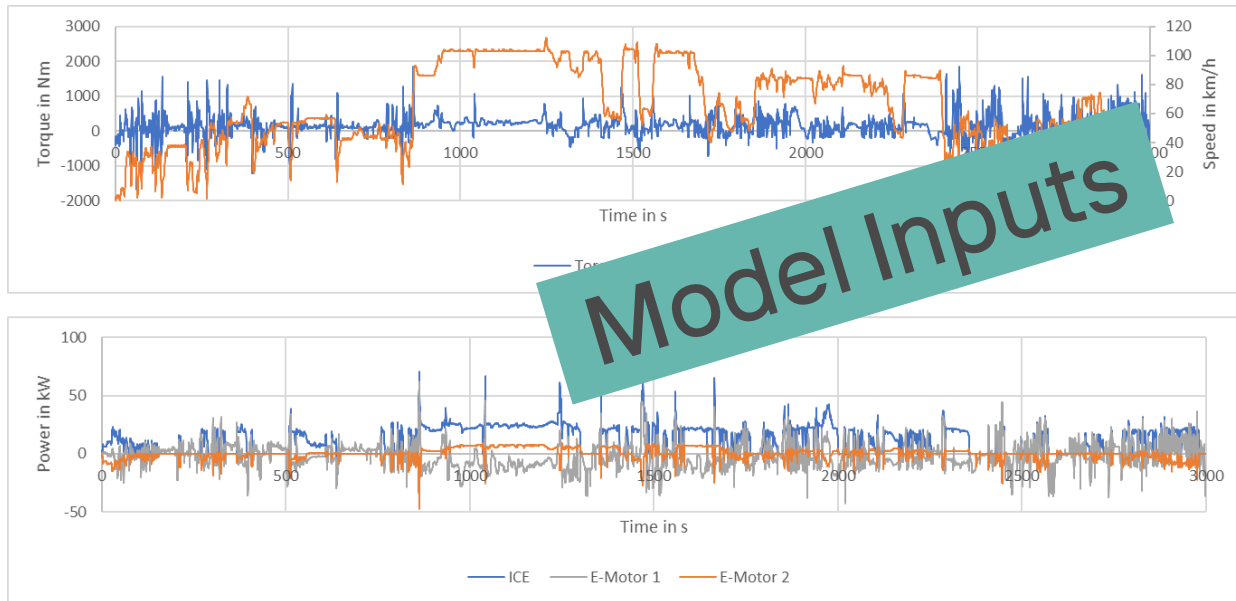
- 160 cycles covering over 7400 km

Source: https://www.ford.de/fahrzeuge/ford-galaxy

Results

Temperature Model of Battery and E-Motor

Profile: Montecchio – San Gimignano (108 km, 27 °C)

Ford Galaxy Hybrid:

- 1x ICE, 2x E-Motor

- 7400 km of real world driving

- Random data split:
  20% test, 30% validation,
  50% training

Model Inputs

ICE   E-Motor 1   E-Motor 2

Sources: https://www.ford.de/fahrzeuge/ford-galaxy

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Results: Ford Galaxy Hybrid
Temperature Model

Data Scientist: that looks too good. That's overfitting.
Engineer: no, that's "test data". And that's the accuracy we need in engineering.
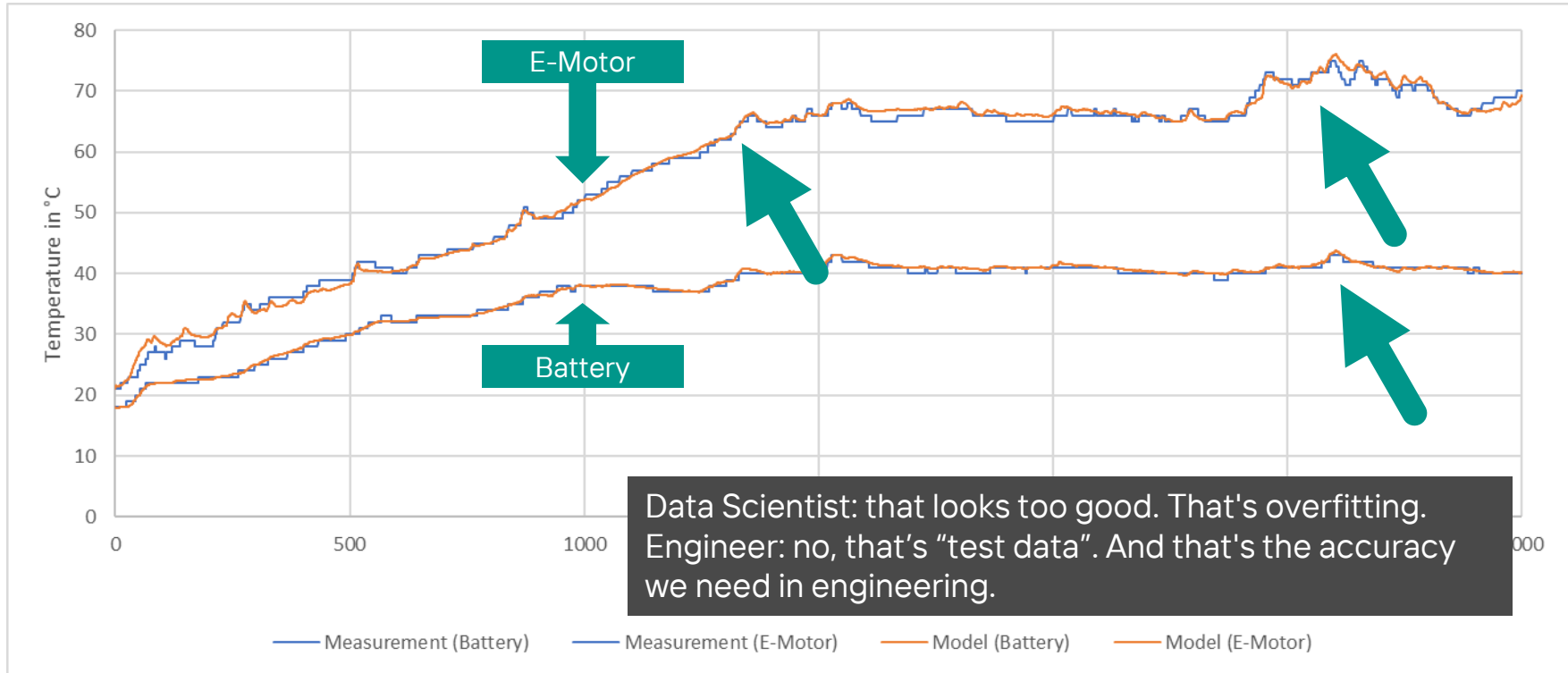
Results: Ford Galaxy Hybrid
Temperature Model

Bissone (I) -> Montecchio (I)

Battery

E-Motor

22.500 s = 6,25 h
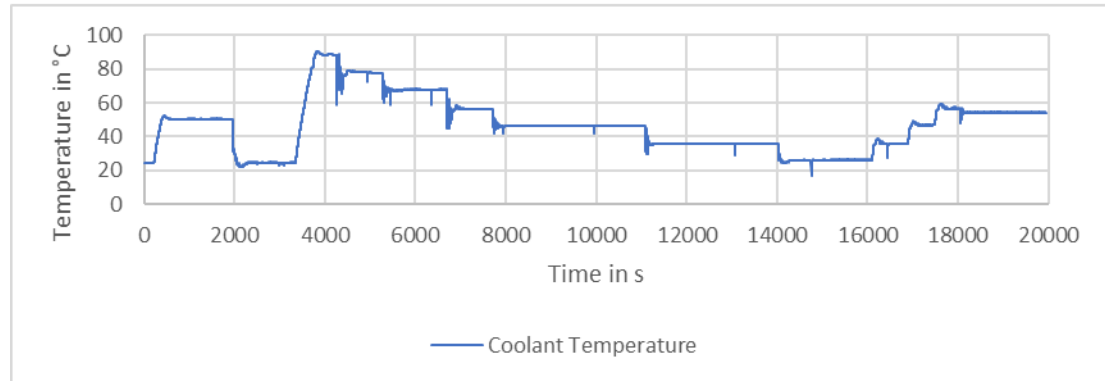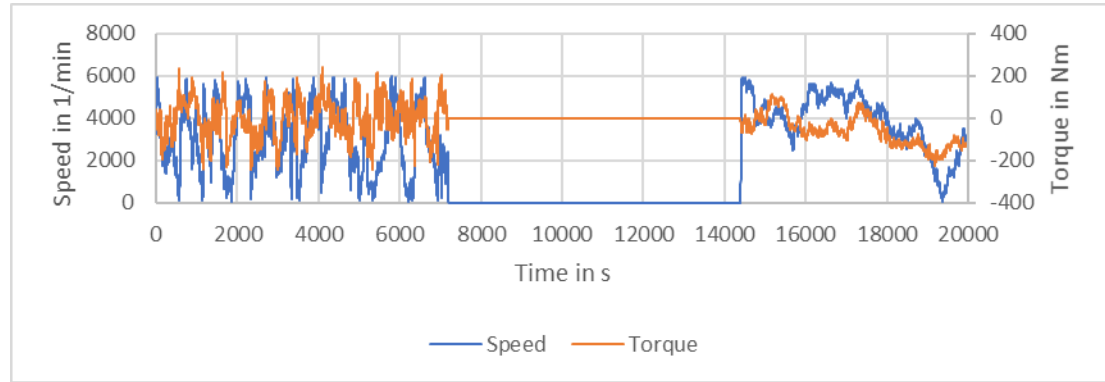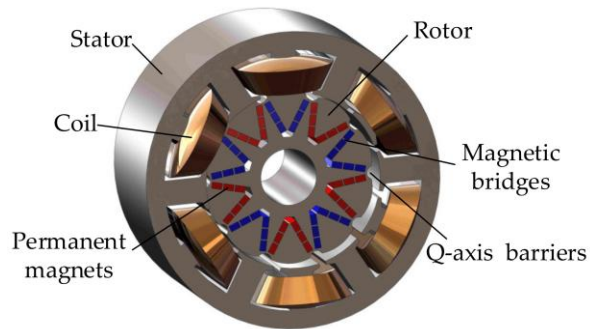-> 225.000 Timesteps (!!)
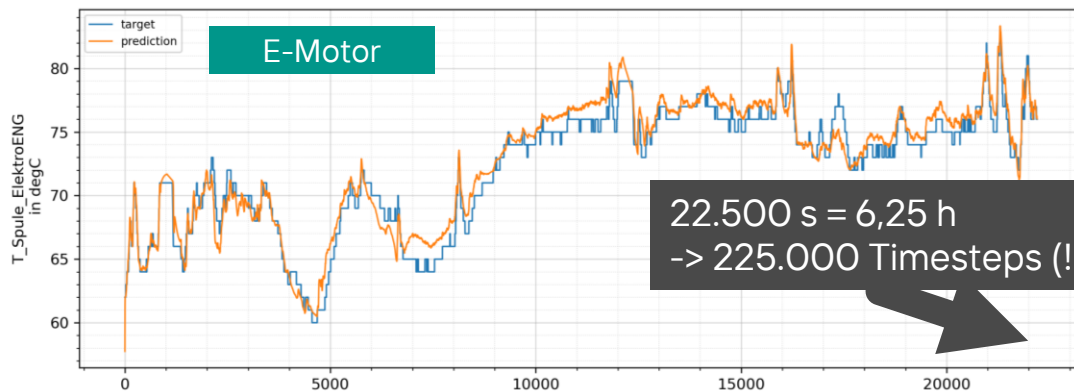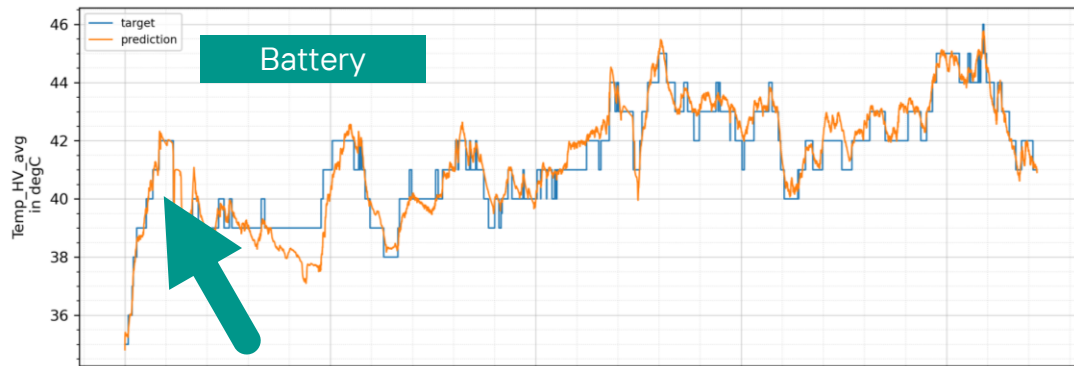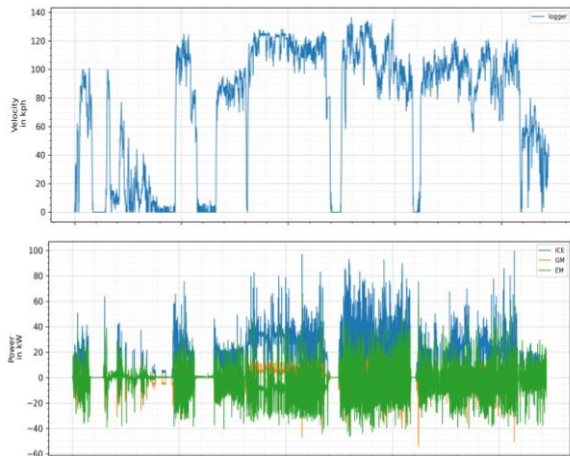
Results: BMW i4 eDrive 40

Temperature Model (E-Motor)
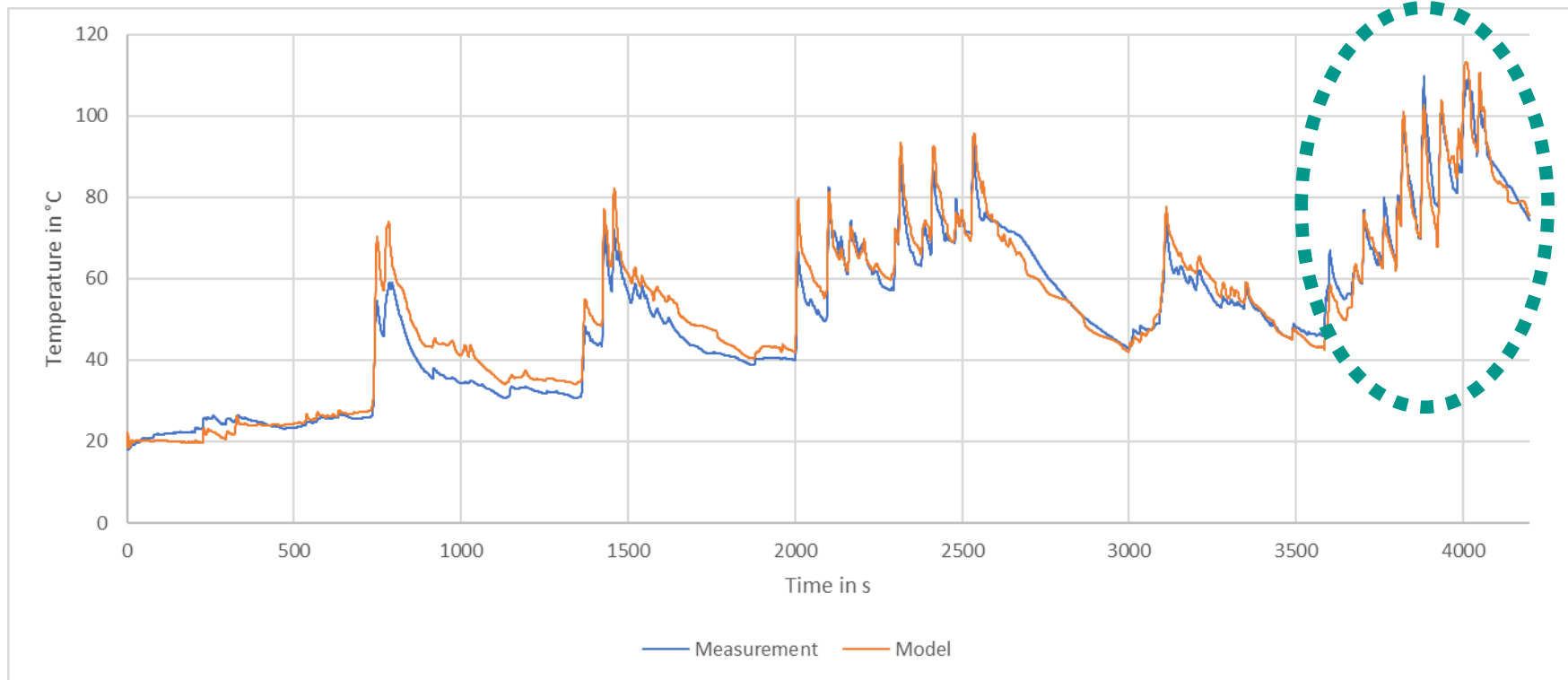
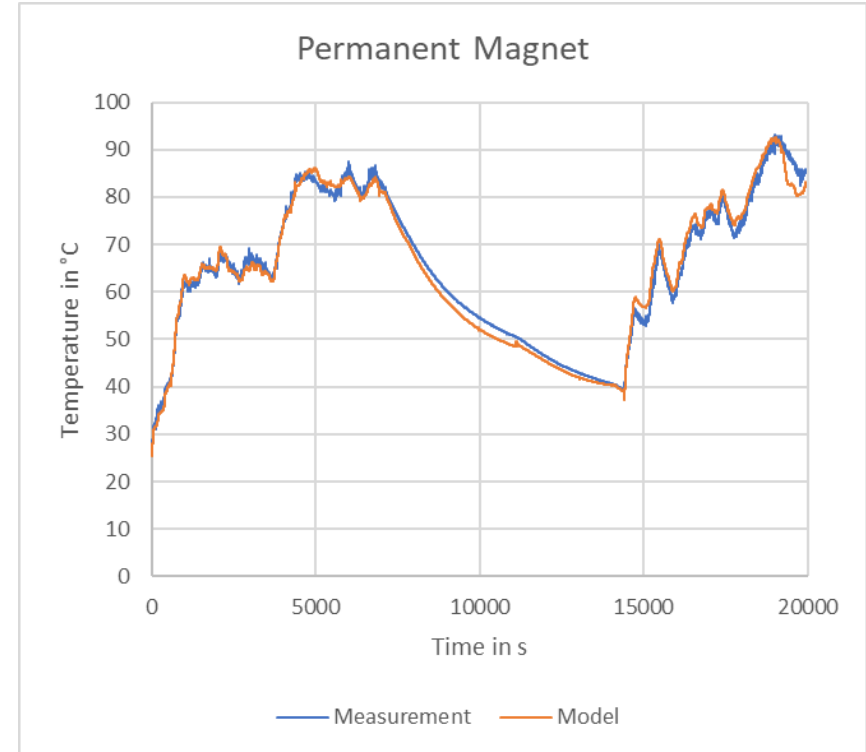# Results: Training on dynamic test bench data
Overview

- Permanent Magnet Synchronous Motor (PMSM)

- max. 32 kW

- matches with the prototype of a German OEM

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Results: Training on dynamic test bench data
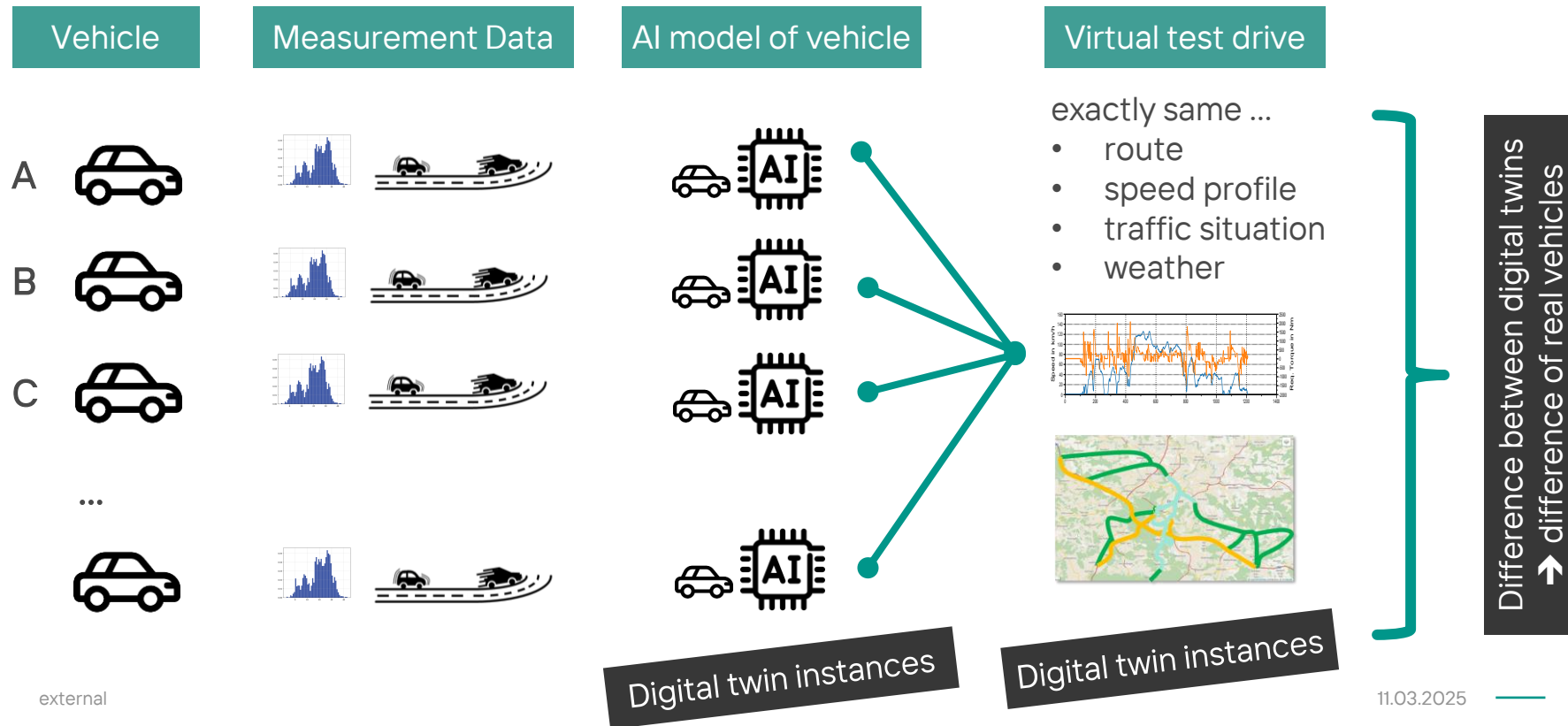## Temperature Model

Conclusion

Digital twins based on measurement data & AI

- Very high accuracy is achievable

- Models can be trained in ~16 hours (high degree of automation)

- Very high simulation speed 100 – 10.000x faster than real-time

- Expert knowledge on the network architecture of recurrent neural networks and on the handling of their internal memory states necessary

- Expert knowledge of the domain is crucial: very few model inputs to enable "learning" of the physics.

Other Use-Case: fleet measurements

New approach to analyse real word driving data

High prediction quality of the Digital Twin is crucial for this application

Vehicle	Measurement Data	AI model of vehicle	Virtual test drive

exactly same ...
- route
- speed profile
- traffic situation
- weather

A

B

C

...

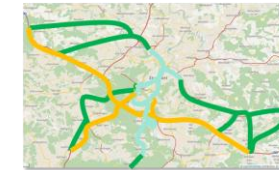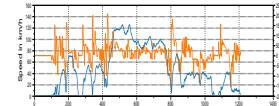Digital twin instances

Digital twin instances

Difference between digital twins
↑ difference of real vehicles

Other Use-Case: Analysis of aging effects
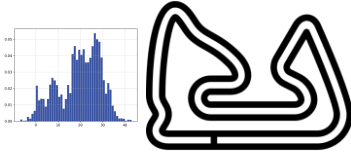## Based on real world driving data

Other use-case: Motorsports

Motorsports: Racing strategy and laptime optimization based on Digital Twins

Vehicle	Measurement Data	AI model of vehicle	Virtual test drive

Digital twin

- laptime simulation
- 10.000x faster than RT

Digital twin

FKFS is proud to be AI partner of GM motorsports

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Thank you for your attention.

Dr.-Ing.
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