IEEE-PEMC 2024

Pilsen, Czech Republic, Europe

MODULAR DIGITAL TWIN PLATFORM FOR ELECTRICAL DRIVETRAINS

Linked Projects

eBRT2030 ZEFES HiEFFICIENT

Speakers:

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LECTURERS' INFORMATION

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ELECTROMOBILITY RESEARCH CENTRE

ELECTROMOBILITY RESEARCH HUB IN EUROPE

EFFICIENT POWER ELECTRONICS, POWERTRAIN & ENERGY SOLUTIONS RESEARCH GROUP

15+

EU funded projects

40+

Members

4

Top-Notch Labs

5

Research Tracks

Brussels, Belgium

SHORT INTRODUCTION OF MOBI-EPOWERS

EPOWERS RESEARCH GROUP EFFICIENT POWER ELECTRONICS, POWERTRAIN & ENERGY SOLUTIONS

Power Electronics

- Charging Systems
- Inverters & multi-level converters
- DC/DC converters & Active Front-End (AFE)
- Battery Management Systems

Electrical Machines

- Design and Optimization
- System Control
- Performance Assessment

Smart Green Grid Solutions

- Design Optimization
- (Control) Energy Management

Vehicle Powertrains

- Powertrain Co-design optimization
- Integrated EMS for Plug-in/Hybrid/Electric Vehicles
- Multi-level and ECO-EMS strategies

Digital Twin & Reliability

- Technology and Prototype Validation in Relevant Environment
- Fully Proofed Technology, Operational System and Manufacturing

TUTORIAL CONTENT

Introduction to Digital Twin Platform for EVs [Presenter: Omar Hegazy]

- Introduction to E-drivetrain Architecture and Digital twin for EVs
- Requirements and Challenges for Implementing Digital Twins in Automotives
- Future Developments and Emerging Trends in Digital Twin Technology

Part I: Digital Twin: Performance and Efficiency [Presenter: Mohamed El Baghdadi]

- Virtual Models for design
- Virtual Models for Control and Management strategy
- Virtual Models Parameterization and Calibration
- Virtual Models transition towards Digital Twin Concept

Part II: Digital Twin: Lifetime and Safety [Presenter: Sajib Chakraborty]

- Digital Twin Context for Lifetime and Safety
- Model-based Reliability Estimation
- Online Prognostics and Health Management (PHM)

Conclusions and Future Outlooks [Presenter: Omar Hegazy]

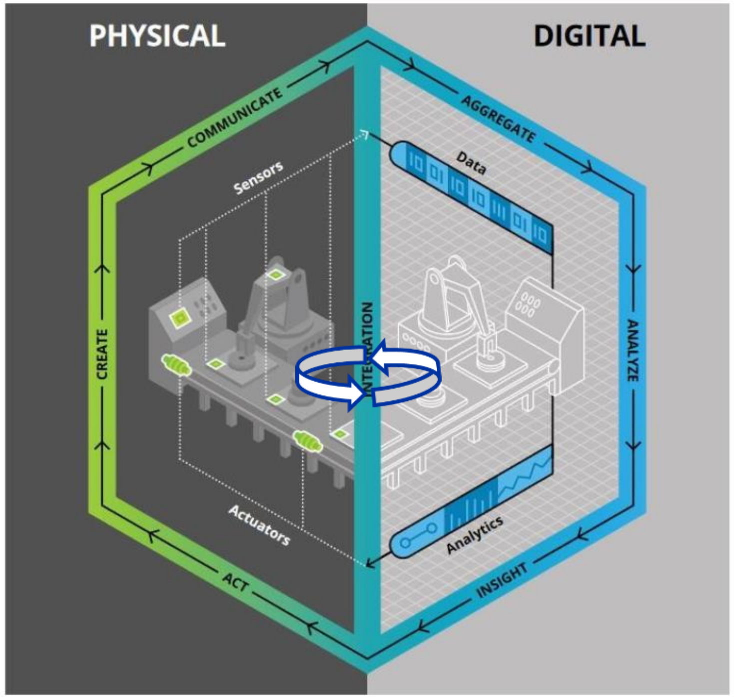
WHAT DOES CHATGPT REFER TO AS A DIGITAL TWIN??

Source: *OpenAI. (2024)*

DEFINING A DIGITAL TWIN

- What is Digital Twin?

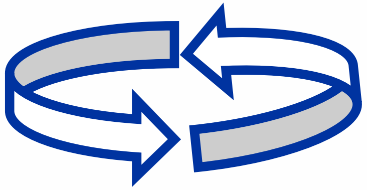
"a virtual representation of a physical system (and its associated environment and processes) that is updated through the exchange of information between the physical and virtual systems." [Digital Twin: Generalization, characterization and implementation]



[Digital Twins in the Automotive Industry: The Road toward Physical-Digital Convergence (mdpi.com)]

Digital Twin Characteristics

Physical Reality
- Physical system
- Physical environment
- Physical processes



Virtual Reality
- Virtual simulation and data-driven model
- System states and parameters
- Virtual system
- Virtual process

Connectivity to exchange information
- Physical-to-virtual connection
- Information fusion
- Virtual-to-physical connection

SOME DEFINITIONS: VERIFICATION/VALIDATION/EVALUATION /ASSESSMENT

Validation:
The assurance that a product, service, or system meets the needs of the customer and other identified stakeholders.

Verification:
The evaluation of whether or not a product, service, or system complies with a regulation, requirement, specification, or imposed condition.

Evaluation:
The combination of software or testing to determine the value of a piece of technology or approach given various defined Key Performance Indicators (KPIs).

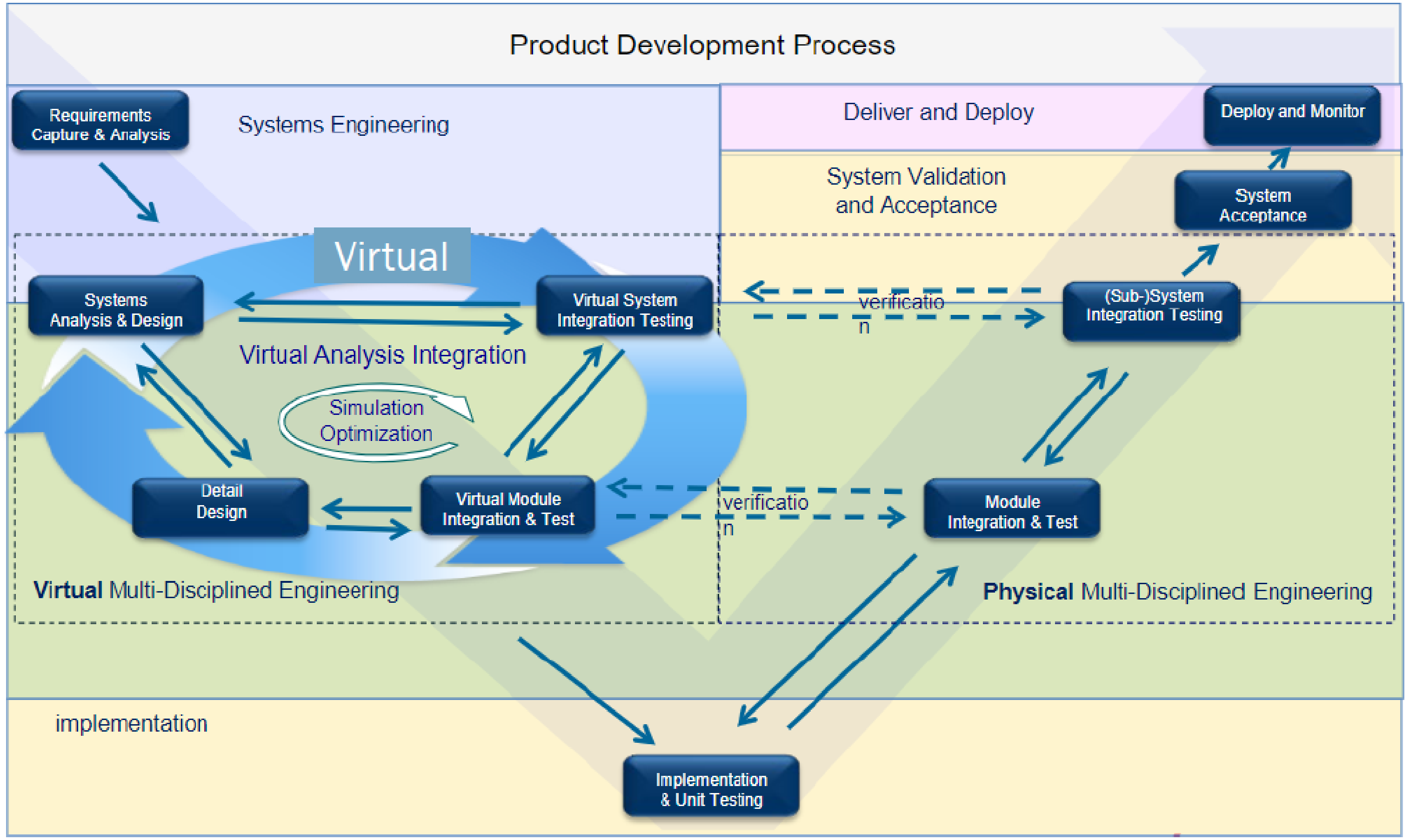
Assessment:
The broader evaluation of a piece of technology or approach compared with other existing and theoretical approaches, given both defined and undefined Key Performance Indicators (KPIs).

X-IN-THE-LOOP AND V&V DEVELOPMENT PROCESS

Model-in-the-Loop (MiL):
The functional testing to abstract the behaviour of a system so that the model can be used to test, simulate and verify itself. Often for control development.

Software-in-the-Loop (SiL):
The testing of a compiled software component, wherein the loop comprises of a simulated system.

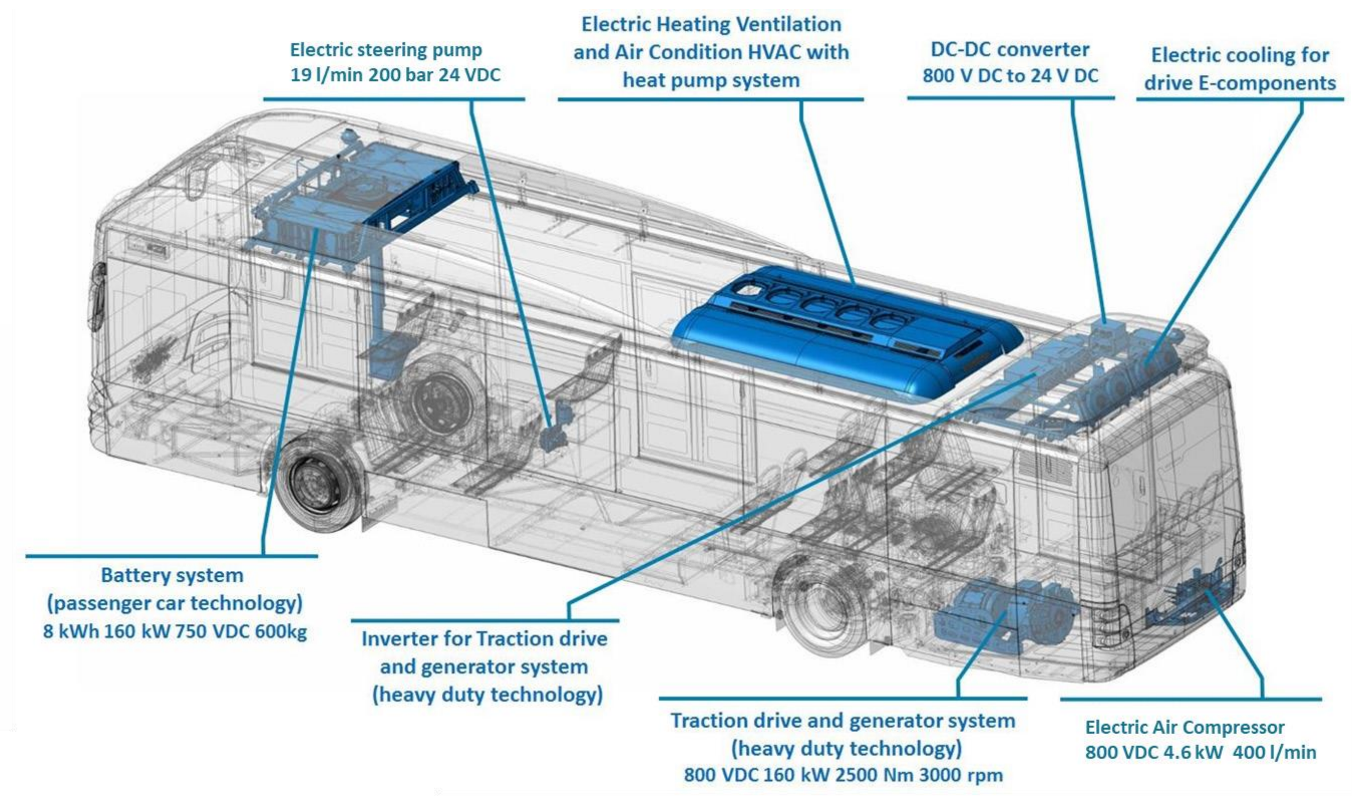
Hardware-in-the-Loop (HiL):
The testing of a single component, wherein the loop comprises of a simulated system. Controller (PIL) can be part of the hardware or separate (see HDH HILS).



Source: *TNO Lecture on Digital Twin (May 2024)*

Introduction to Digital Twin Platform for EVs

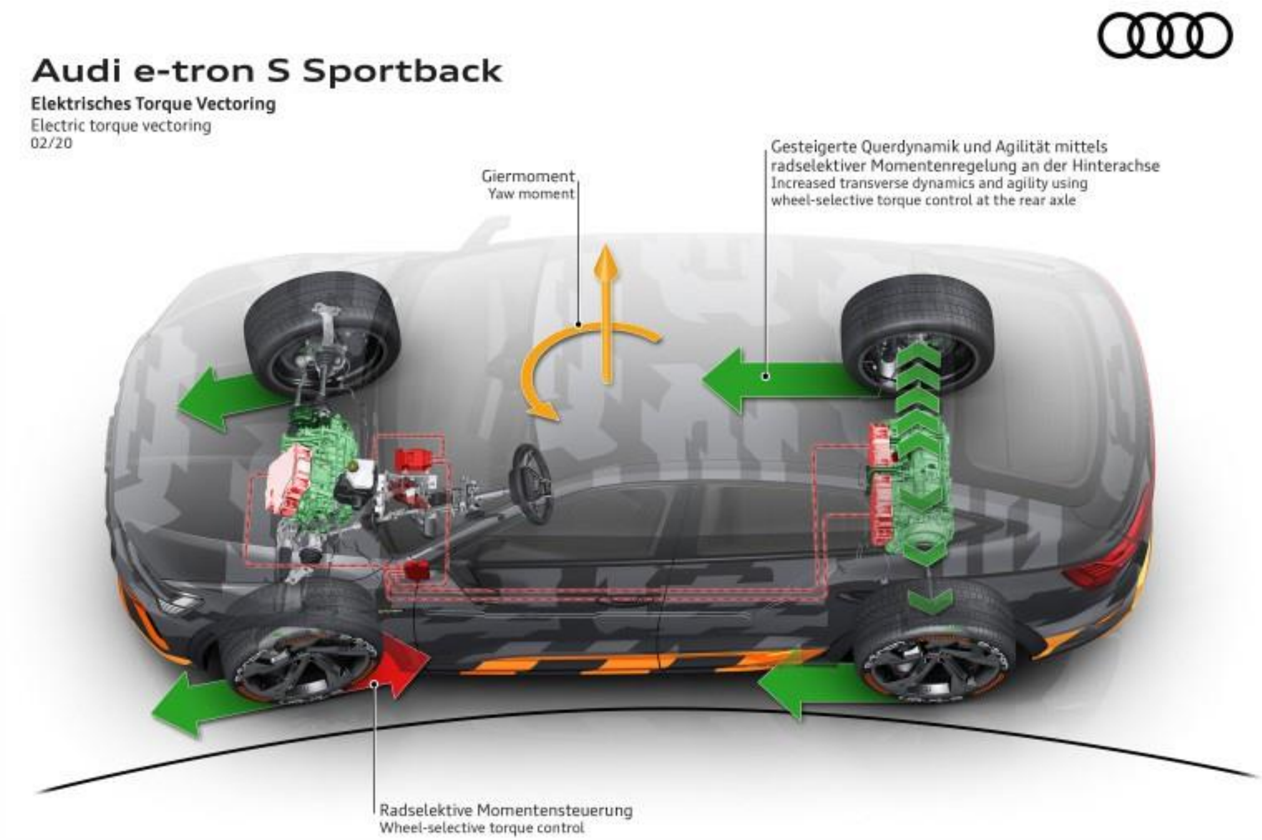
INTRODUCTION TO E-DRIVETRAIN ARCHITECTURE



Electric Vehicle Powertrain (Heavy duty)

Powertrain of the new eBus (courtesy: MAN Lion's City Hybrid SHS A37)

INTRODUCTION TO E-DRIVETRAIN ARCHITECTURE



Electric Vehicle Powertrain (Light duty)

Source: https://audiclubna.org/etron/2020/02/21/in-detail-audi-e-tron-s-and-e-tron-s-sportback/

INTRODUCTION TO E-DRIVETRAIN COMPONENTS

Components of Electric Vehicle Powertrain

Electrical subsystems
- DC/DC converter
- Inverter
- On-board Charger

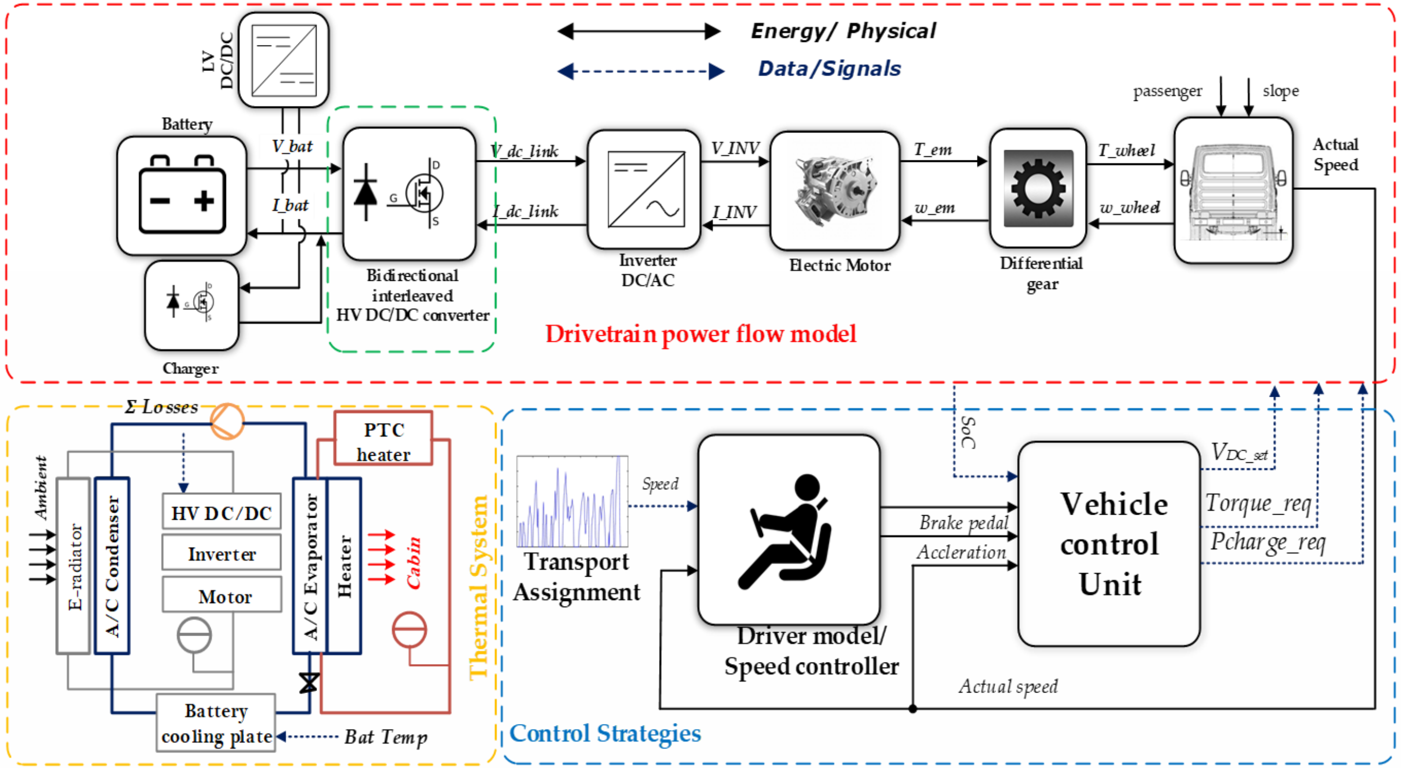
Mechanical subsystems
- Gear and transmission
- Vehicle Chassis, wheels
- Friction brakes

Electromechanical subsystems
- Electric motor

Electrochemical subsystems
- Battery
- Supercapacitor

Thermal subsystems
- HVAC
- Radiator
- PTC heater

Control subsystems
- Driver
- Energy management system



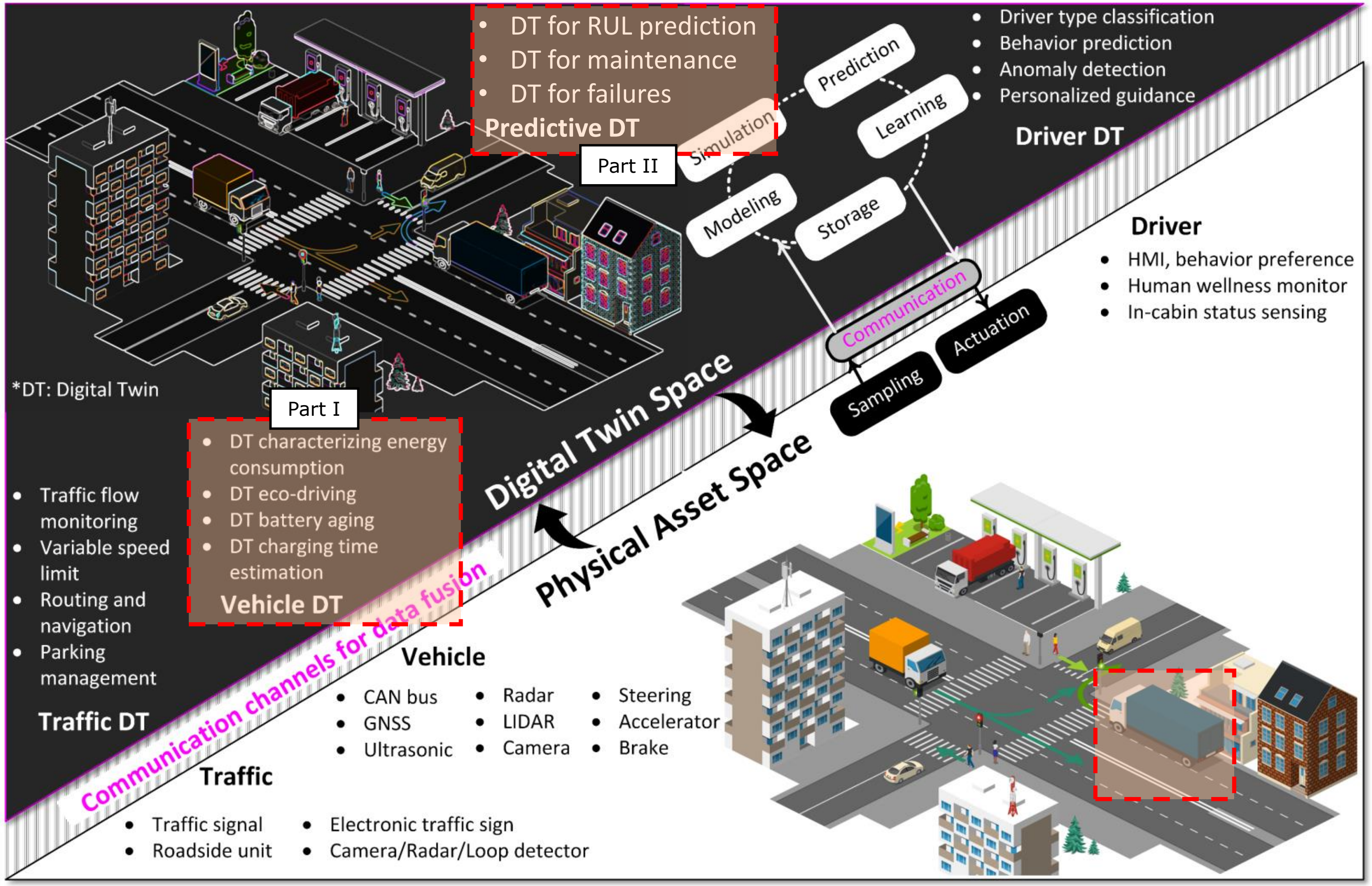
The figure illustrates an example of a forward-facing electric vehicle powertrain

INTRODUCTION TO E-DRIVETRAIN DIGITAL TWIN

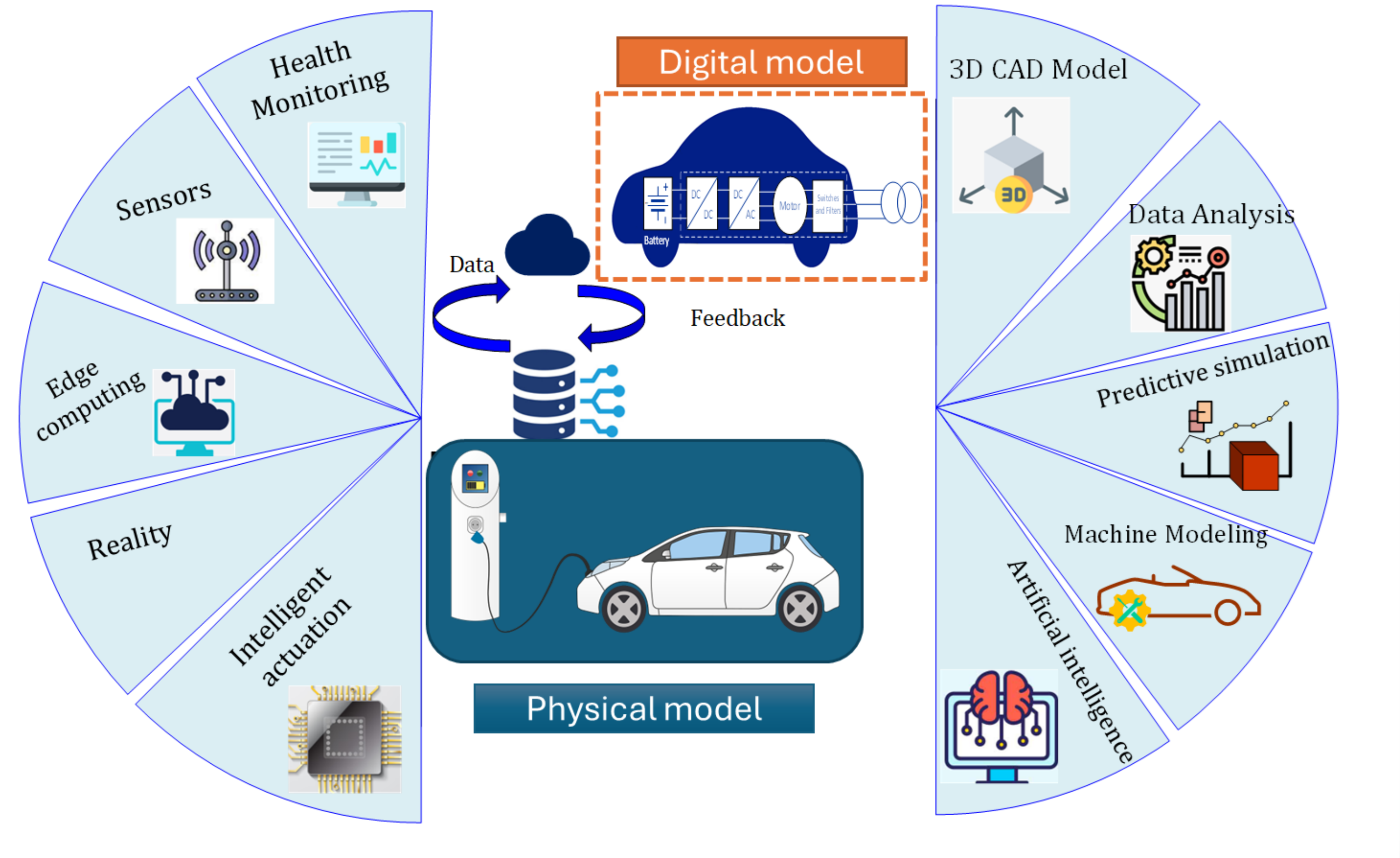
- **Digital Twin:**
  - Dynamic virtual model of an existing physical asset

- **Digital Twin technologies:**
  - Virtual Models
  - Machine Learning
  - Artificial Intelligence (AI)
  - Internet of Things (IoT)

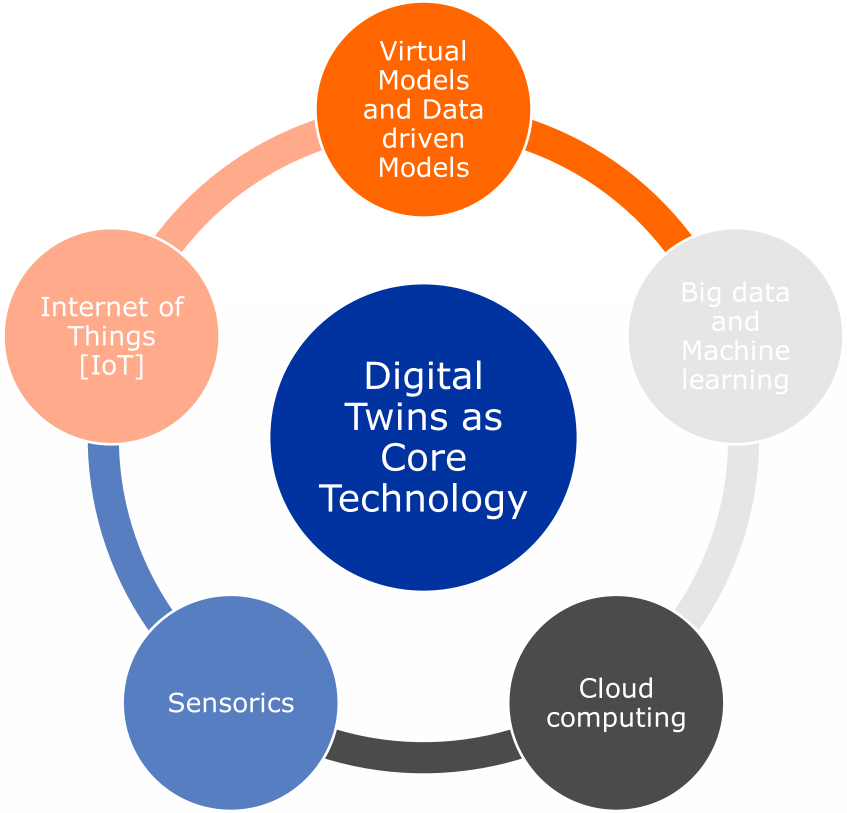
- **Digital Twin spaces:**
  - Digital space
  - Physical space
  - Communication:
    - Sampling →
      { storage
      modeling → simulation
      prediction → learning }
    - → Actuation



AUTOMOTIVE DIGITAL TWIN- ECOSYSTEM

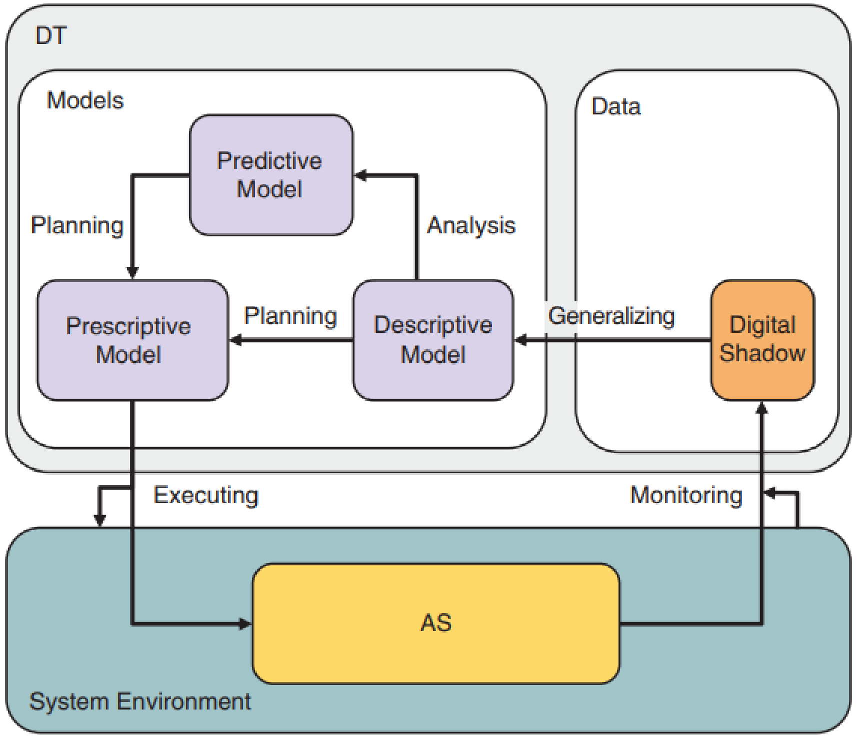


Source: Towards the future of smart electric vehicles: Digital twin technology



Components and Enablers for DT

DIGITAL TWIN – GENERIC MODEL



Descriptive model: current or past aspects of the system
Predictive model: analysis, simulation and machine learning
Prescriptive model: description of the system to be realized

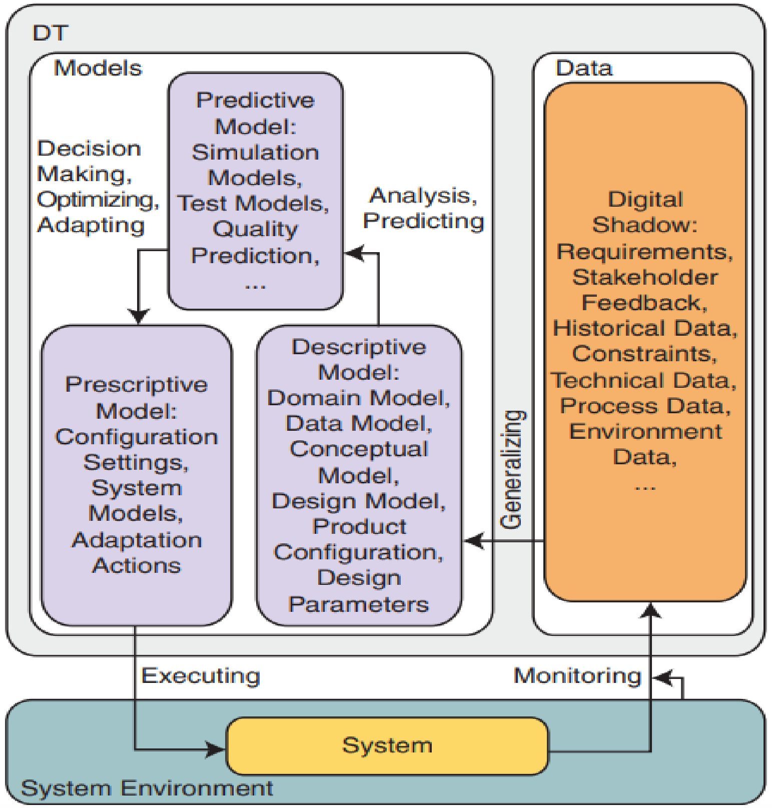
The conceptual framework for DTs based on Model and data

Source: Conceptualizing Digital Twins

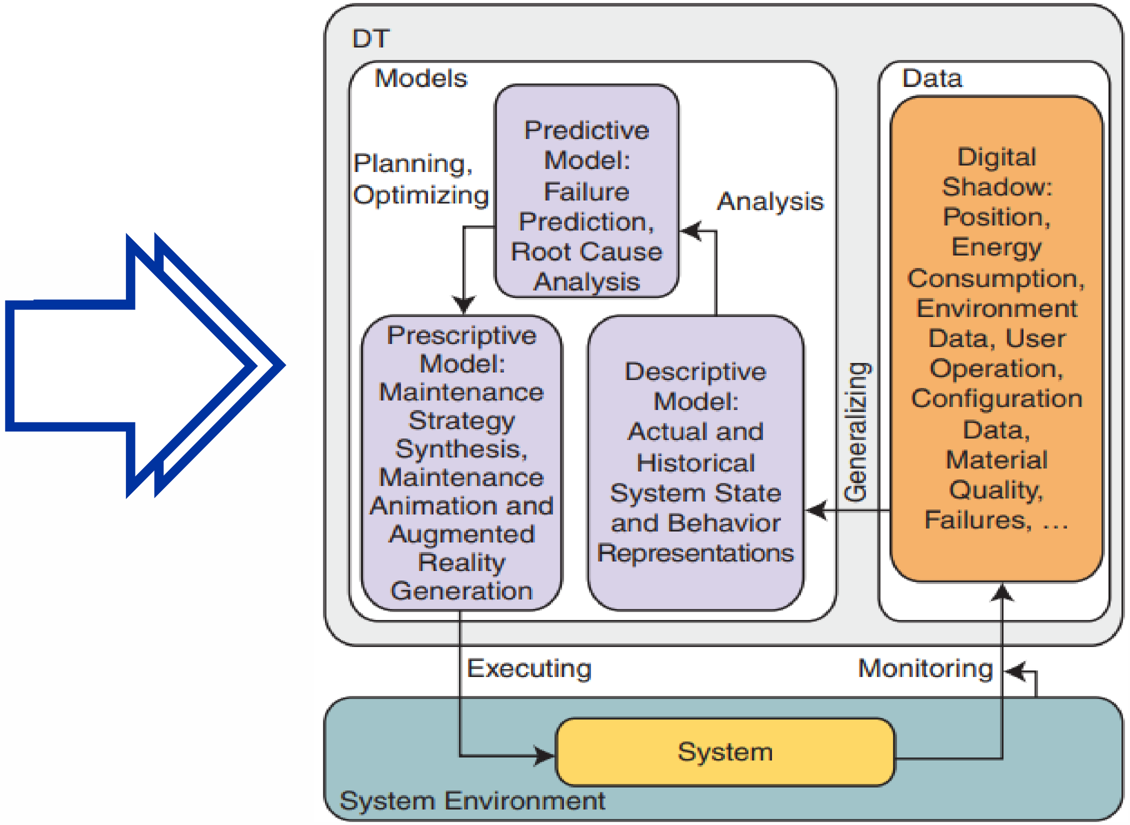
DT = DgiitalTwin
AS=Actual System

DEDICATED DIGITAL TWIN - MODEL

Part I:DT for Design



Part II: DT for Lifetime



Generic DT conceptual framework representing different DT applications

Source: Conceptualizing Digital Twins

DIGITAL TWINS → REQUIREMENTS

Robust Communication Protocols
- In vehicle communication
- Edge ←→ Cloud communication

Multi-Fidelity Modelling
- Different Objective → Different Computational Requirement
- Mathematical, AI, ML driven Modelling

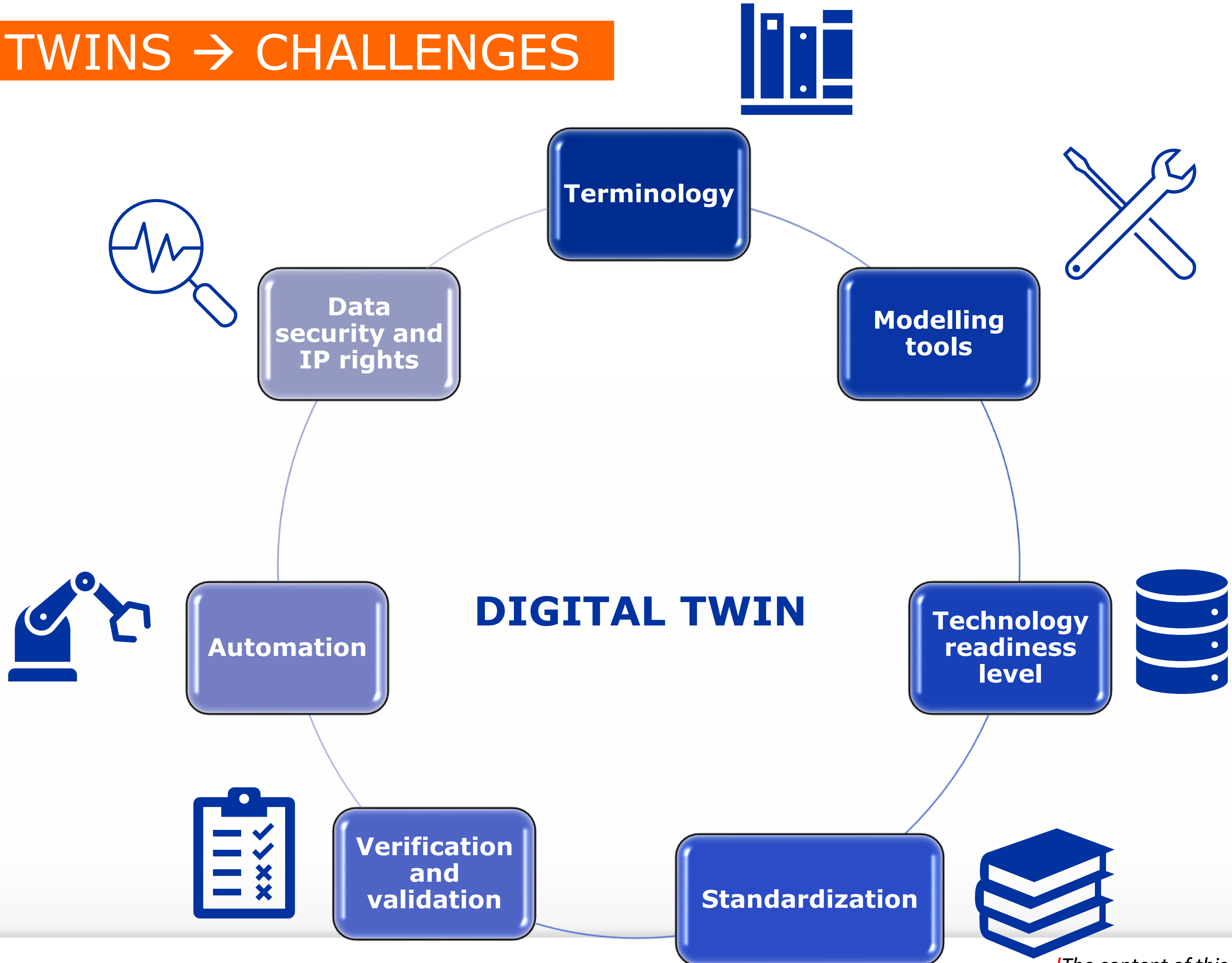
Cyber Security
- Security concern increases with high connectivity
- Secure communication

Real-time Data Acquisition and Edge Computing
- Advanced sensors and analog circuit design
- Data Processing and model deployment on the edge device

OEM Usability and Cost Efficiency
- Design with an objective
- Long term fleet level planning

Cloud Computing
- Digital Twin service deployment
- Fleet Level management
- User interface

DIGITAL TWINS → CHALLENGES



FUTURE TRENDS IN DIGITAL TWIN

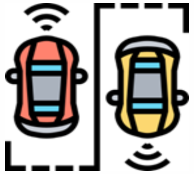
- **Full coverage via DT** from components layer to fleet management layer

- An **open standard** for digital twining

- **Predictive Maintenance** and Diagnostics

- AI and Machine Learning driven **Hybrid Modelling Techniques**

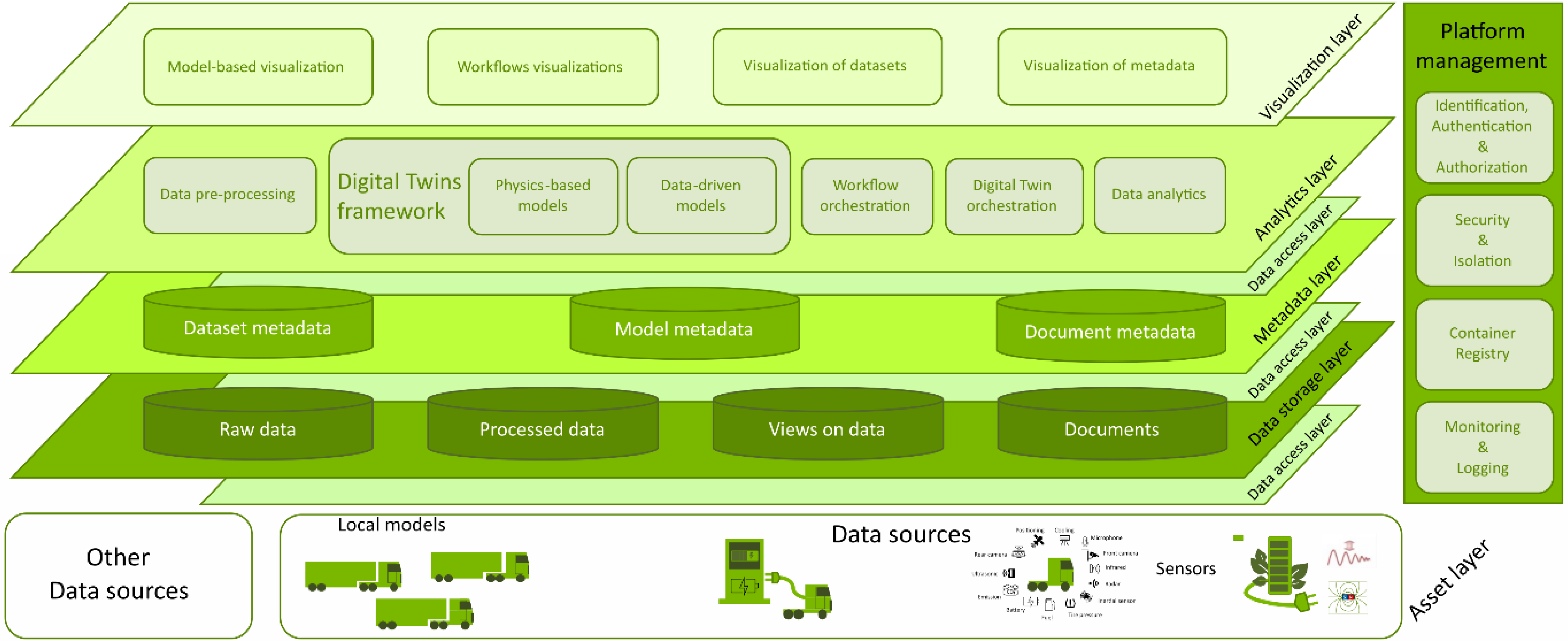
- Advanced and Safe Components Management Systems



- Integration of DT to Autonomous Driving Systems

- Better lifecycle management of vehicles
- **Fleet Management** for OEMs

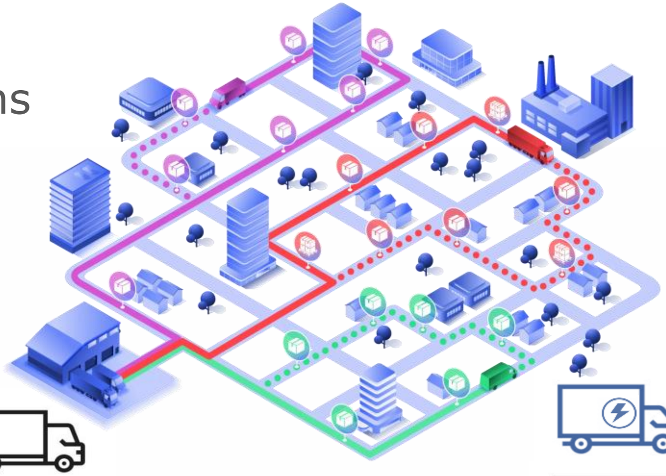
DIGITAL TWINS → EMERGING TRENDS

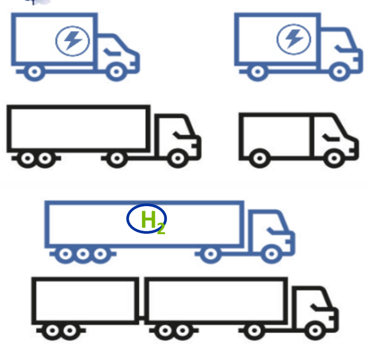


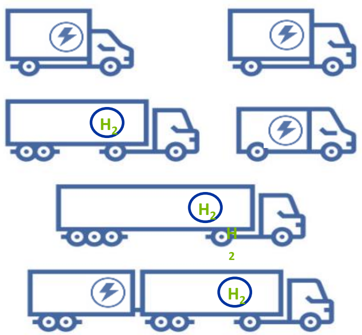
Modular and Multi-layer Secured Digital Twin Orchestration

DIGITAL TWINS → EMERGING TRENDS

- An upscaling analysis with the first generation of vehicles
- Assess future fleet scenarios
  - vehicles
  - restrictions
  - volumes
  - locations







Part I: Offline Digital Twin: Performance and Efficiency

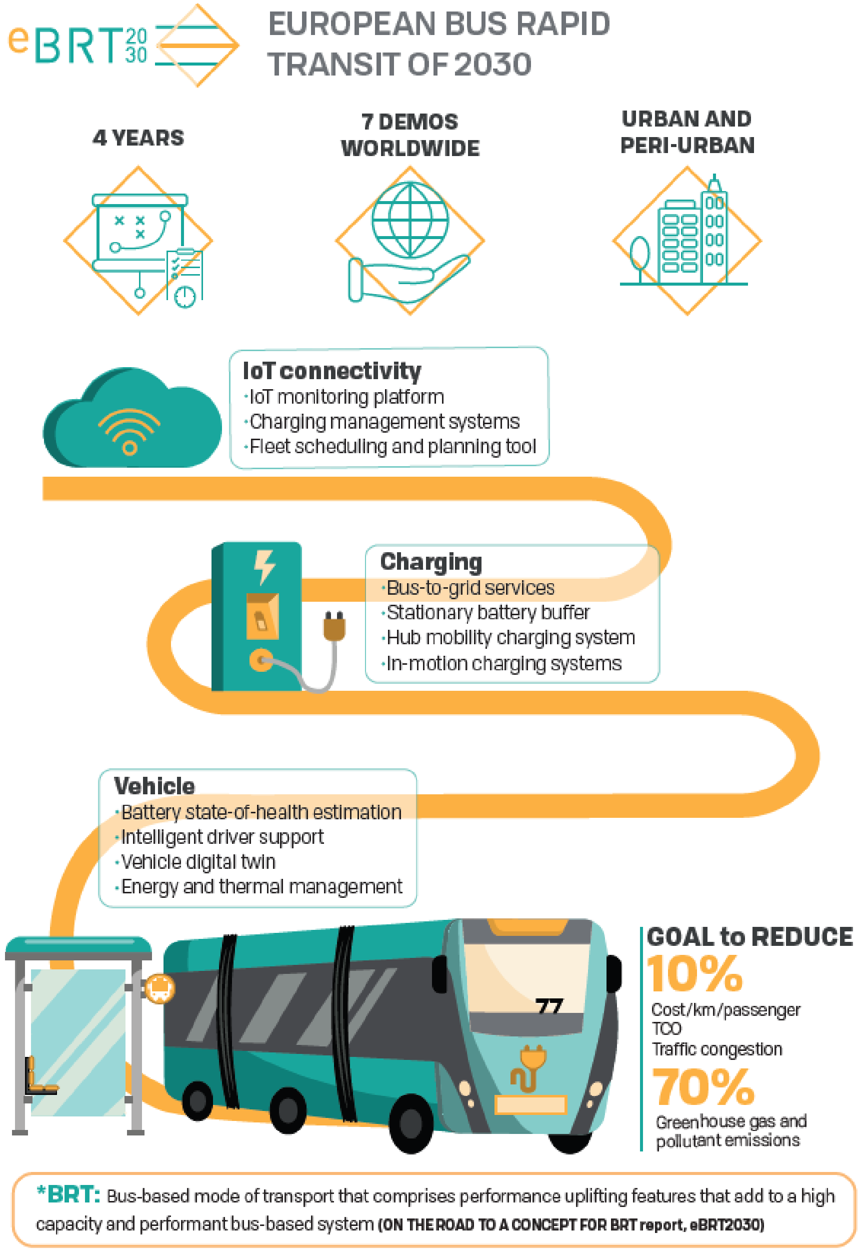
EBRT 2030 PROJECT

- **Project overall duration: 48 months**
- **Start date: 1/1/2023**
- **Total person month: 2823**
- **EU Grant: 22 776 213,57**
- **49 partners** (OEMs, Suppliers, Tech Providers, PTOs/PTAs, Research and networks) **-** Management:
  - Strategic and overall operational Coordinator: **UITP**
  - Technical Manager: **VUB** (MOBI-EPOWERS RG)

Grant Number: 101095882

EU-funded project and major milestone in electric mobility that seeks to **support sustainable urban transport by proposing innovative solutions for electric Bus Rapid Transit (BRT)**

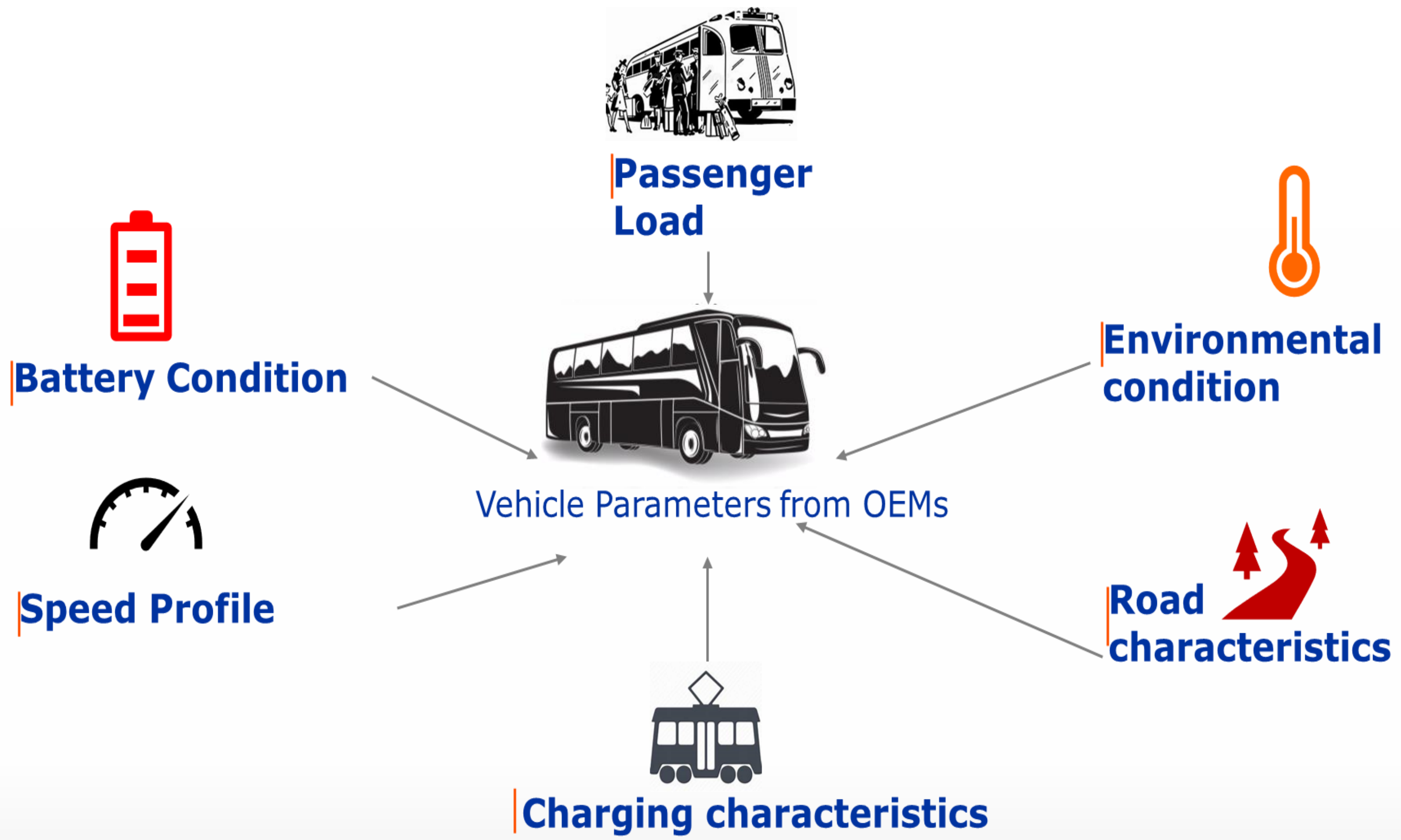
Visit: [Home - eBRT2030]



ELECTRIC BUS VIRTUAL MODEL

SIMULATION FRAMEWORK

- Low-Medium fidelity scalable powertrain model simulation
- Uses:
  - Testing energy-saving (ECO) strategies
  - Testing control strategies
  - Infrastructure sizing
  - Component sizing
  - Bus fleet scheduling
  - Optimization
- Outputs:
  - TCO (€/km)
  - LCA (kg/km of COx, NOx, PMx)
  - Energy requirement (kWh/km)
  - Grid load (kWh)



ELECTRIC BUS VIRTUAL MODEL

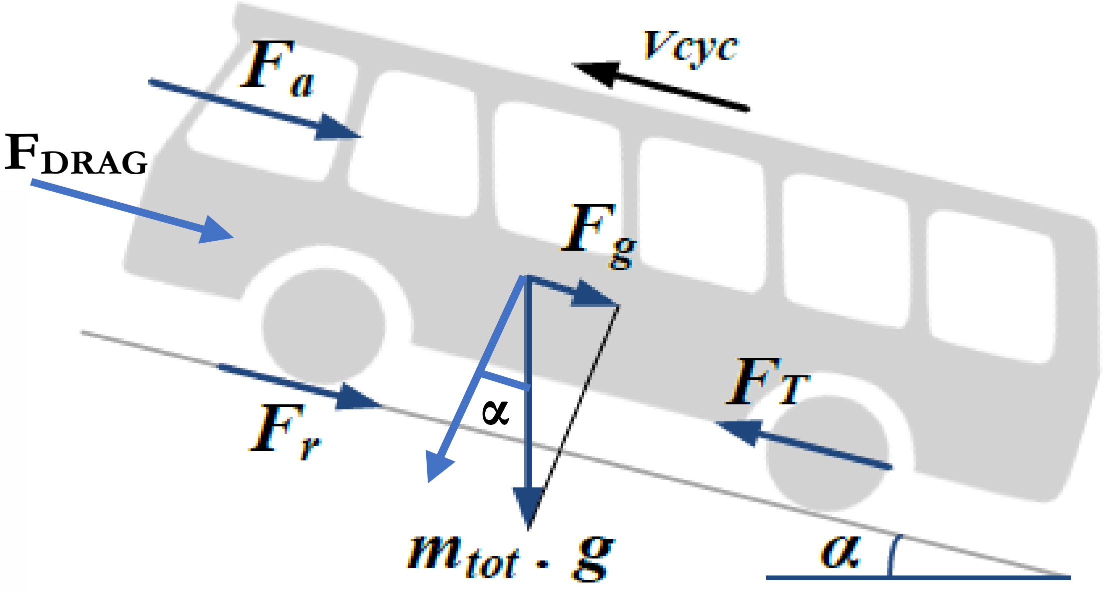
POWERTRAIN DESIGN CRITERIA

➢ Forward-facing model

- Energy flow calculated from torque reference to vehicle kinematics and power demands on the battery.
- Powertrain component constraints respected, e.g., battery current limits, electric motor torque limits.
- Application of control strategy, e.g., vehicle speed reference tracking, cabin setpoint temperature regulation.
- Not as fast as the backward-facing model, but the low-fidelity model is still fast-executing for large fleet simulations.

➢ Backward-facing model

- Energy flow calculated from vehicle kinematics to power demands on the battery.
- Assumes all powertrain components can meet the power demands of the drive cycle.
- Used for rapid sizing of components based on energy requirements of the Use Case scenario.
- Control strategy not used, thus simpler model and faster execution, great for optimizations.



$$F_T = m \cdot g \cdot (F_R \cdot \cos\alpha + \sin\alpha) + \frac{1}{2}\rho \cdot C_D \cdot A \cdot v^2 + m \cdot dv/dt$$

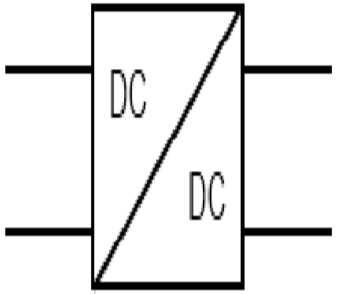
ELECTRIC BUS VIRTUAL MODEL

VIRTUAL POWERTRAIN COMPONENTS

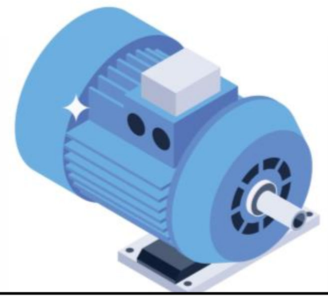
- Quasi-static physics-based empirical models

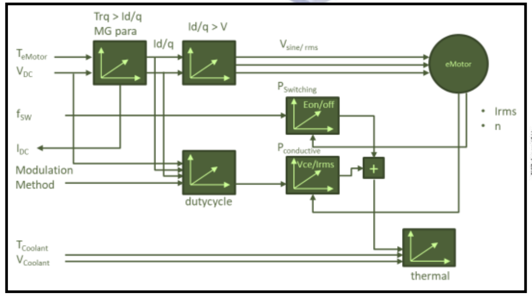
1. Energy flow equations for component
2. Efficiency maps or fixed efficiency value
3. Speed vs torque curve (for EM/Inverter)
4. PF Map (for chargers and transformer)

GEARBOX AND TRANSMISSION

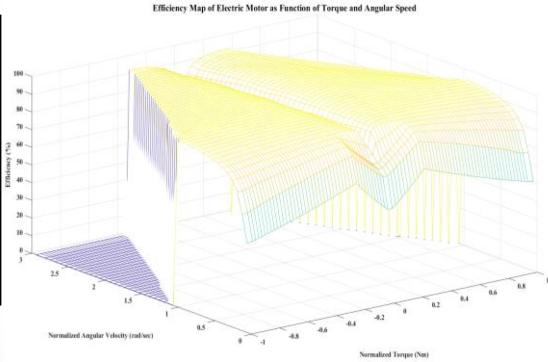


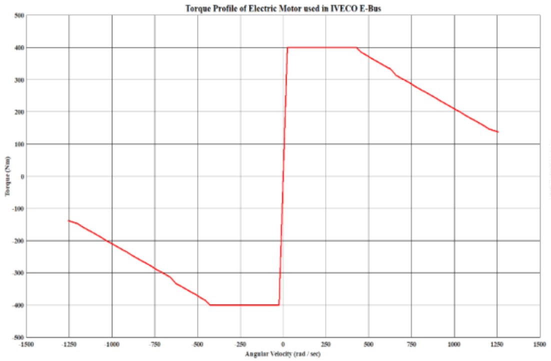
DC-DC CONVERTER

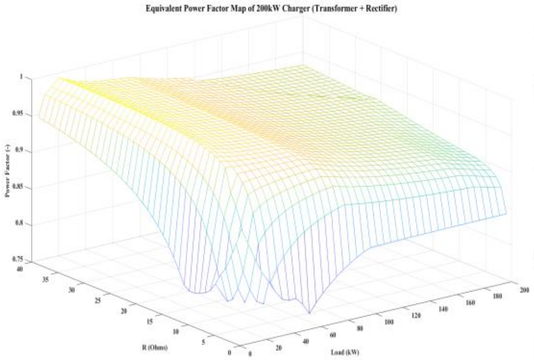


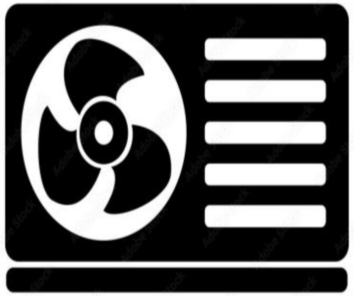


ELECTRIC MOTOR AND INVERTER





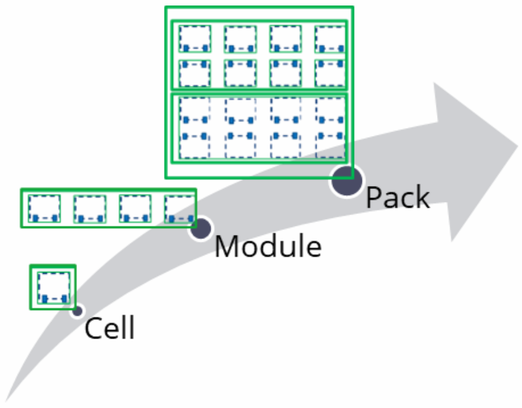




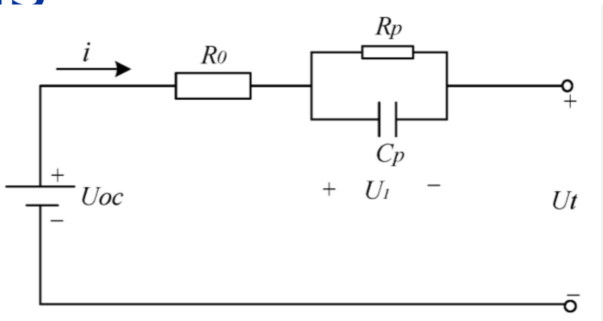
HVAC system

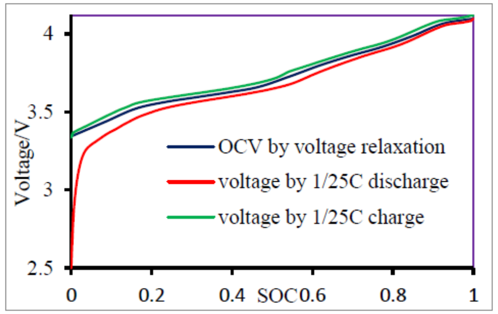
➢Quasi-static physics-based empirical models

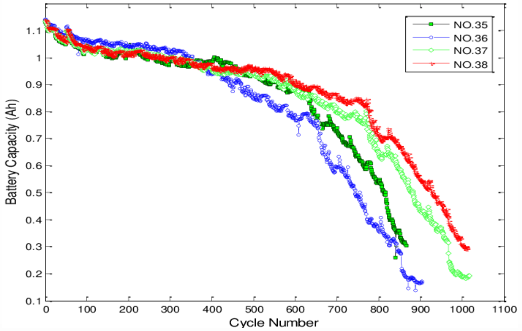
1. 1st order electrical model
2. 1st-order thermal model
3. Maps: Open Circuit Voltage, Relative Capacity Degradation, Series resistance, Polarization resistance, Time constant
4. Lifetime and degradation model

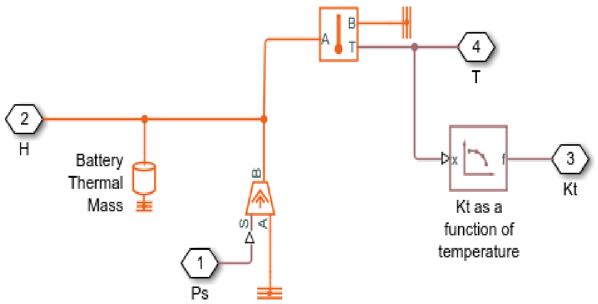


Energy Storage System





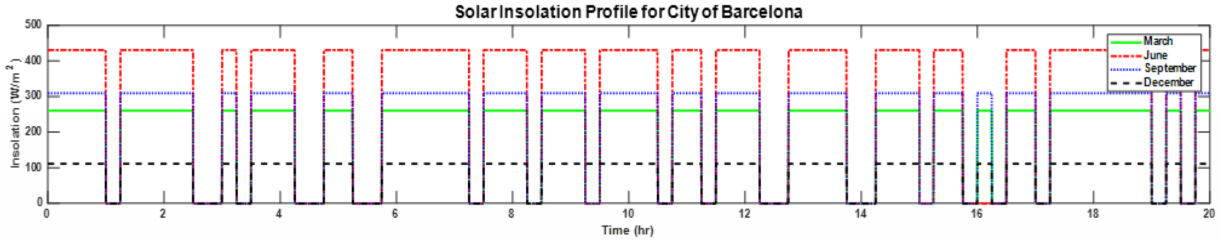


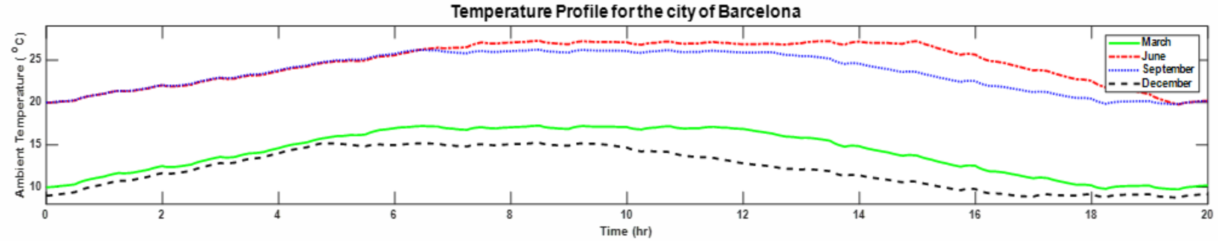


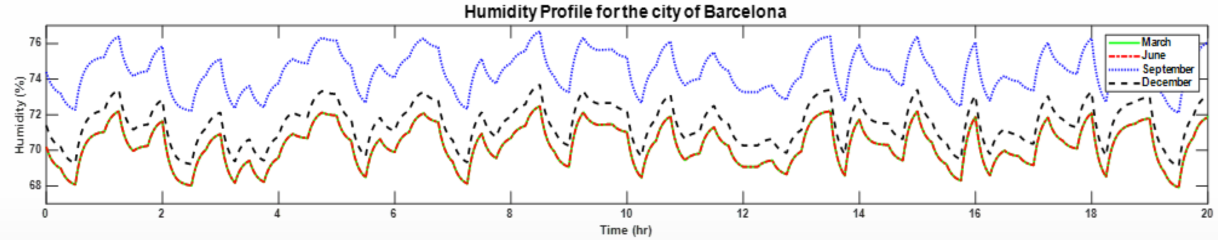
ELECTRIC BUS VIRTUAL MODEL

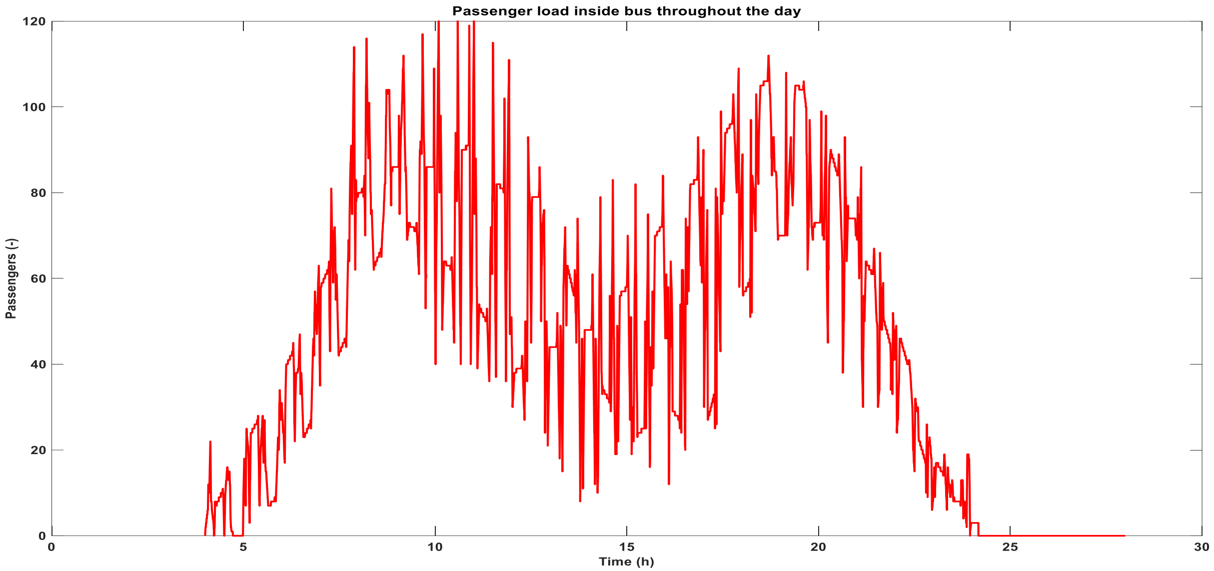
SIMULATION RESULTS

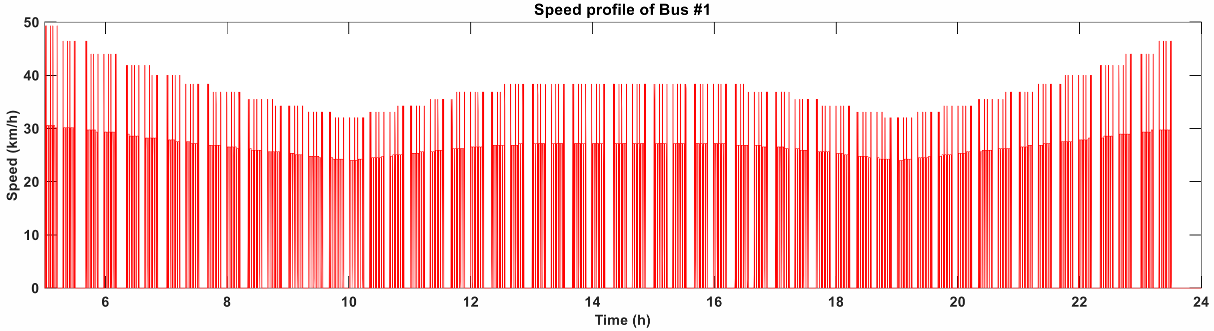
- Simulation Inputs

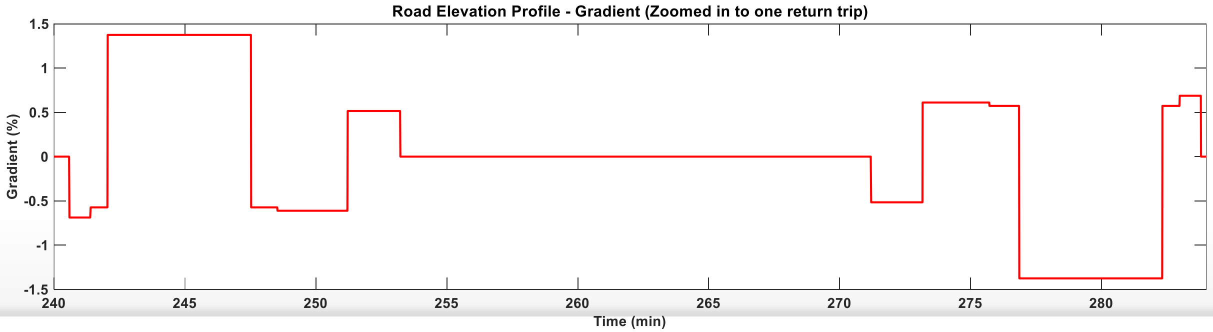








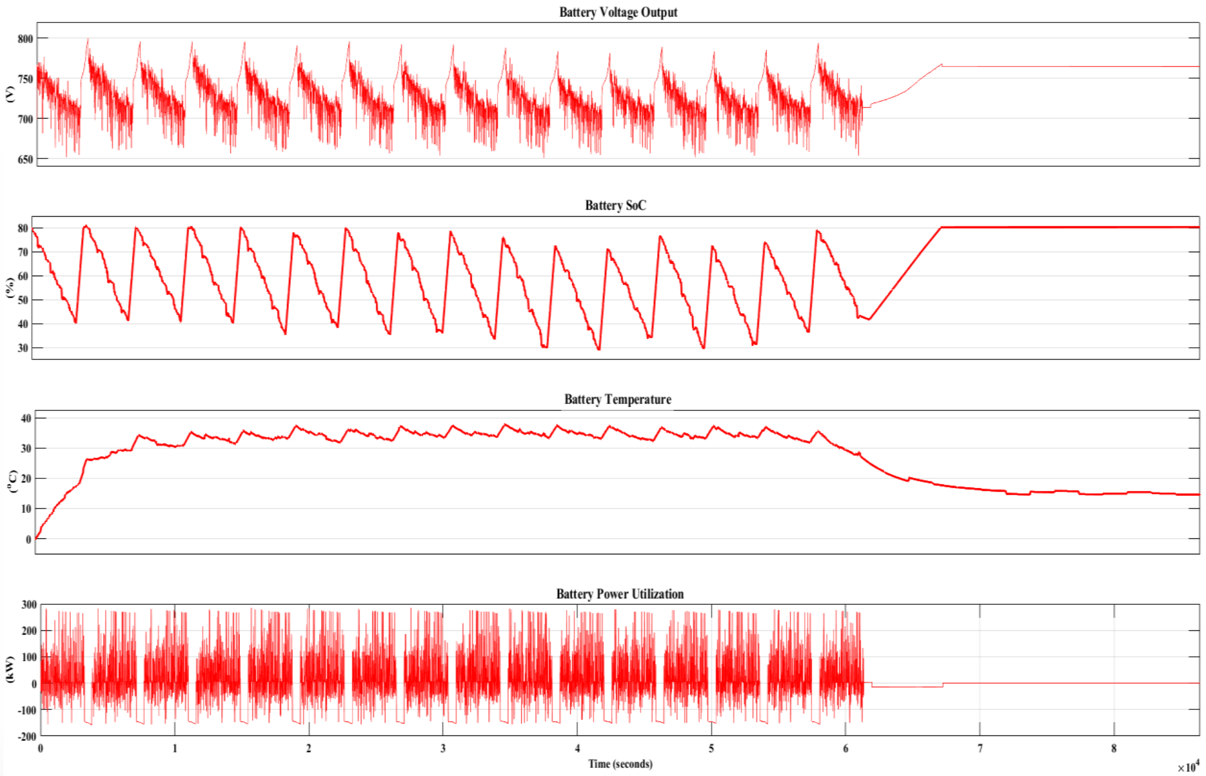


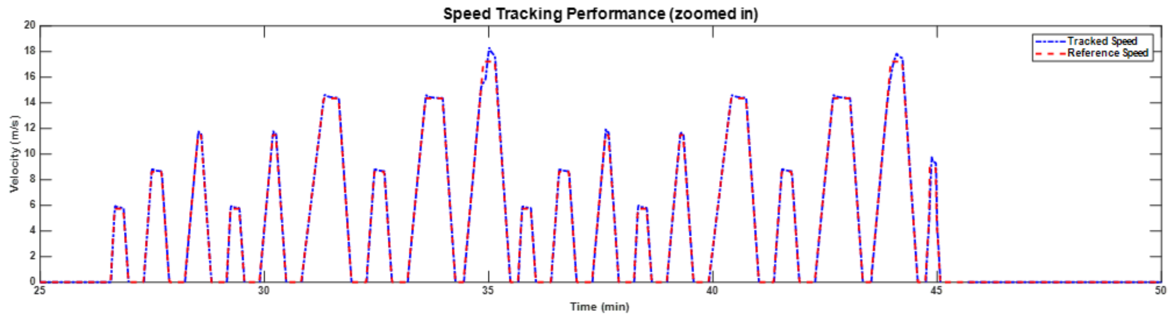


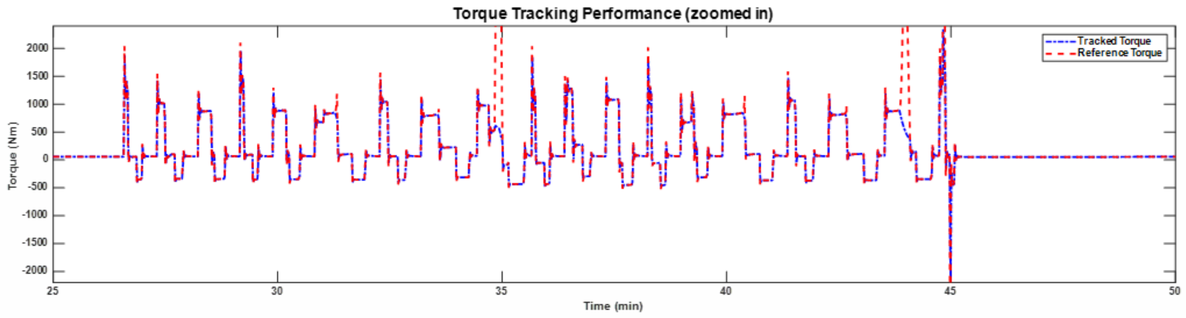
ELECTRIC BUS VIRTUAL MODEL

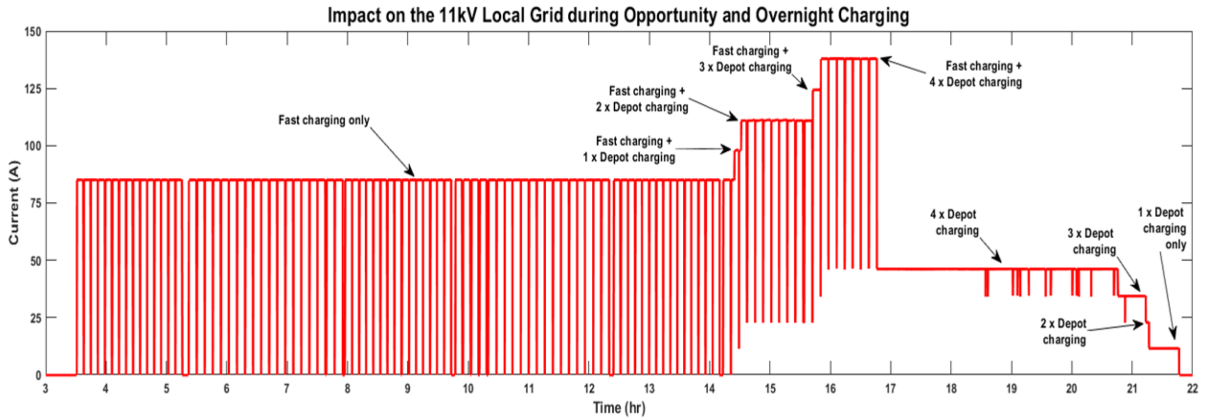
SIMULATION RESULTS

➢Simulation Outputs



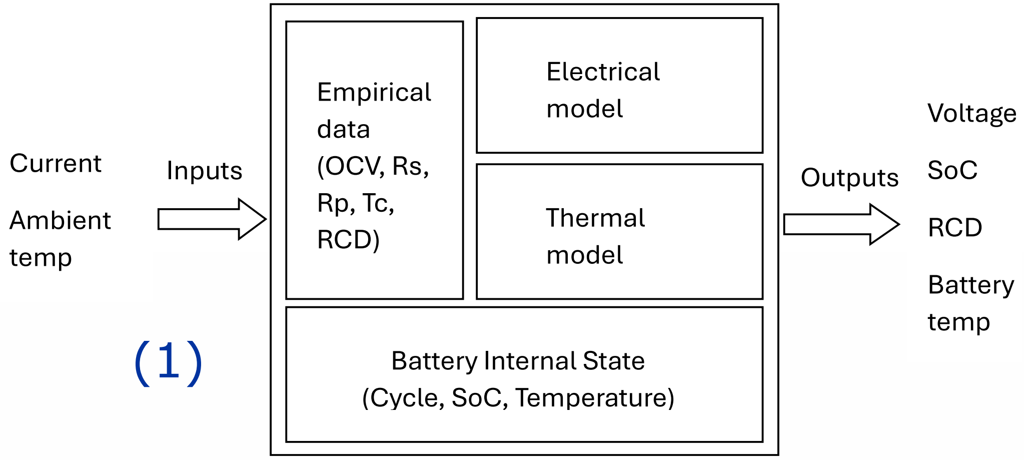


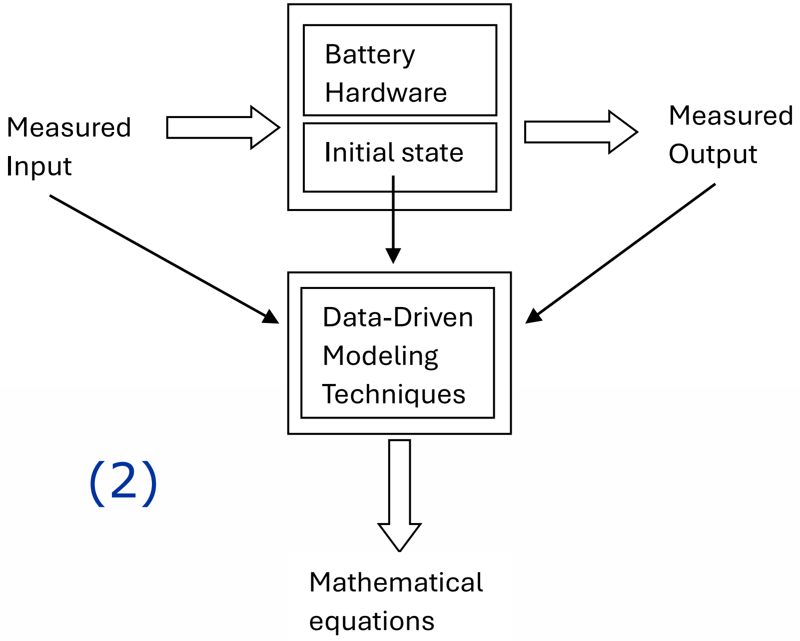


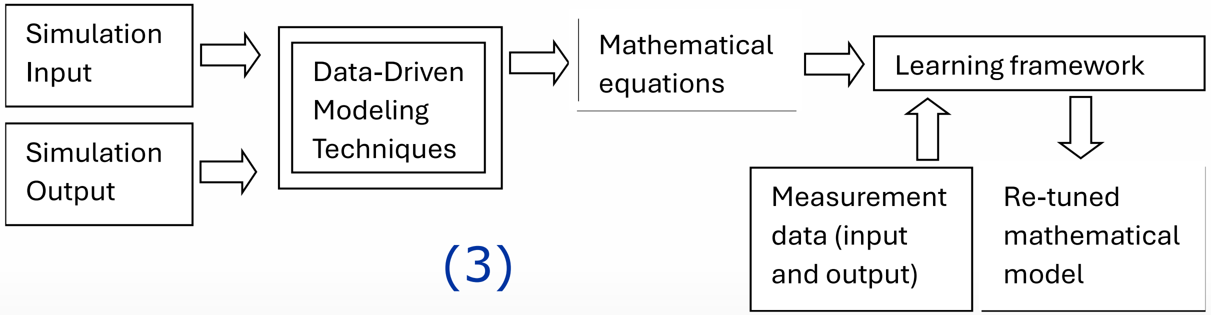


ELECTRIC BUS VIRTUAL MODEL

DATA DRIVEN REPRESENTATION EXAMPLE







1. Start with the quasi-static physics-based model
2. Create initial data-driven model using system identification based on simulation output of virtual battery model
3. Tune and improve data-driven model using machine learning based on measurement data from actual battery hardware

ELECTRIC BUS VIRTUAL MODEL

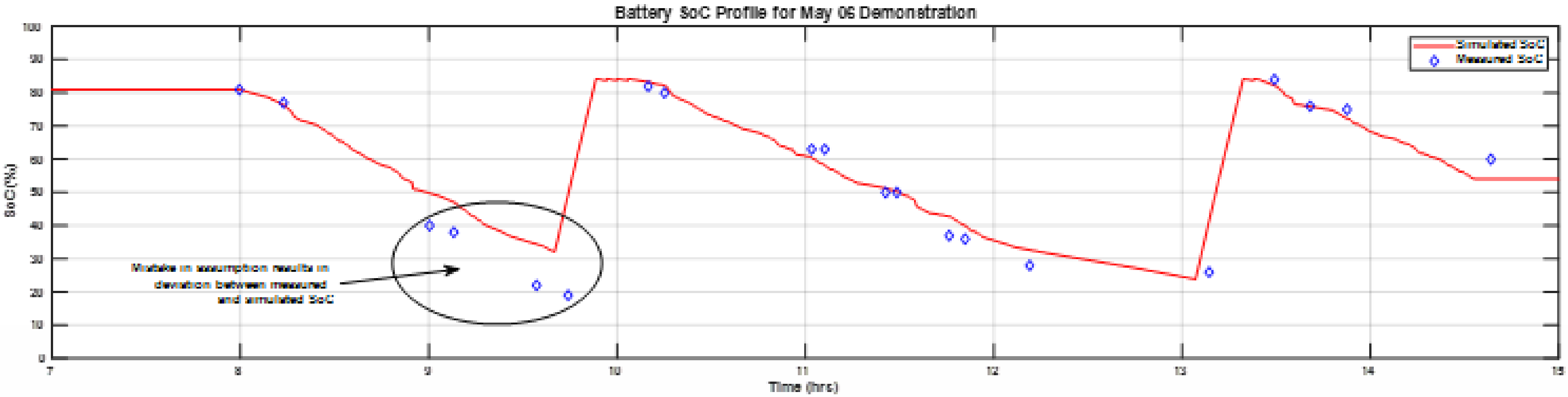
MODEL TUNING RESULTS

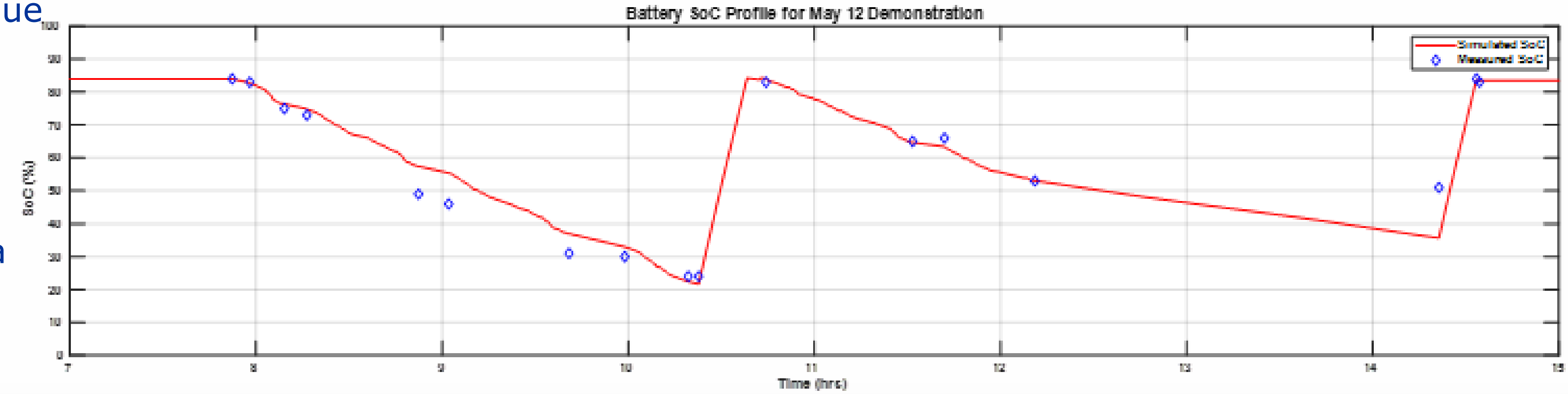
Measurement data represented by discrete diamond points

Simulation output represented by continuous red lines

After tuning of model, there is a high correlation between simulation output and measurement data, with an R^2 value > 0.9

Constraints: minimal dataset
- Limited duration → 8hr only
- Limited measurements → 1 input data (vehicle speed), 1 output data (SoC)
- Lots of assumptions necessary



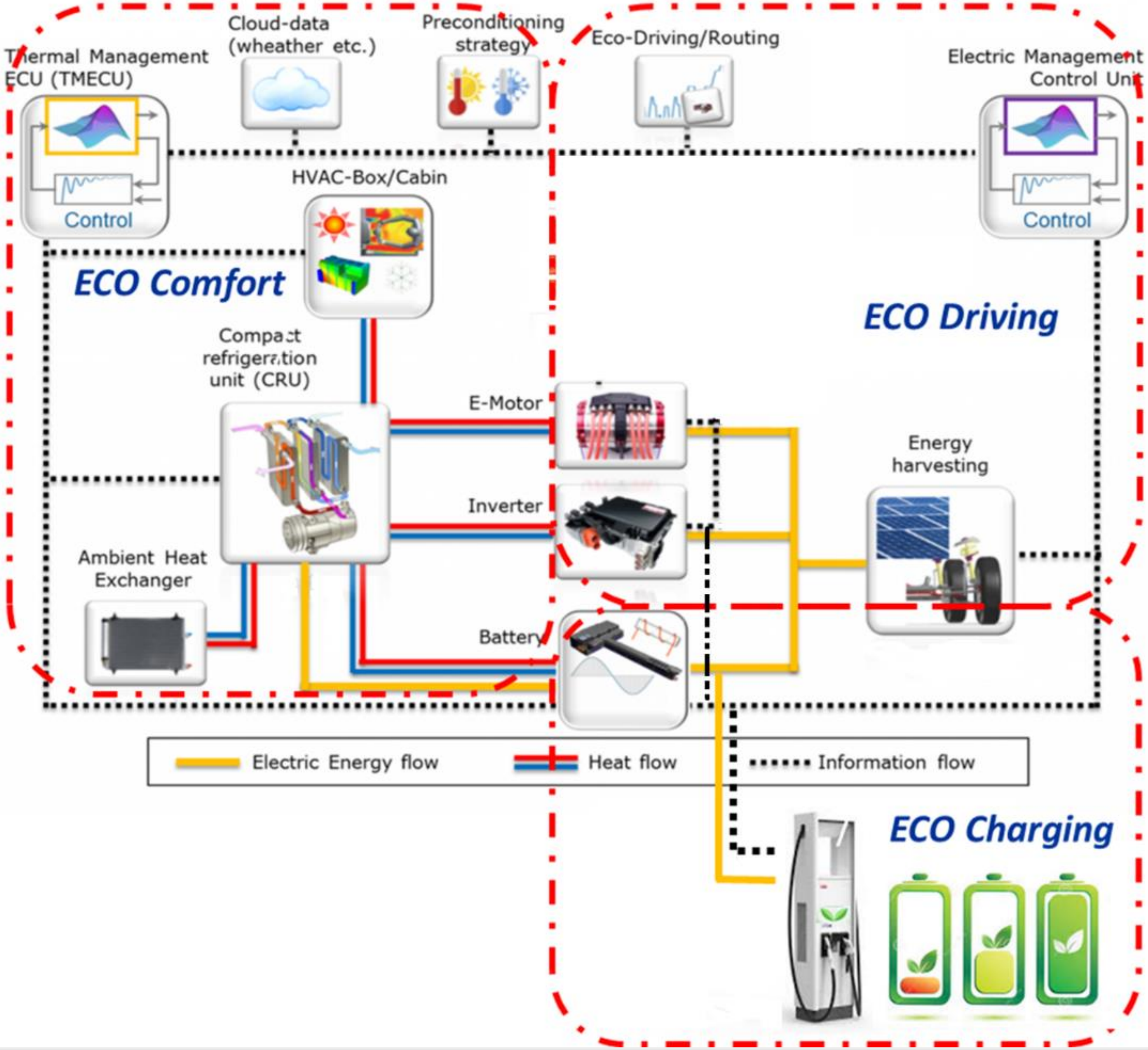


Virtual Models for Controls and Management Strategy

ELECTRIC BUS CONTROL MODEL

ENERGY SAVING STRATEGIES

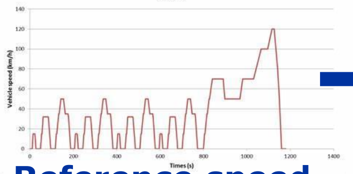
- Energy Management System
  - Controls the traction system: torque reference, braking reference
  - ECO-driving algorithm reduces traction energy requirements
- Thermal Management System
  - Controls the auxiliary system: cabin temperature setpoints, battery cooling and heating setpoints
  - ECO-comfort algorithm reduces auxiliary energy requirements
- Charging Management System
  - Controls the charger: current reference
  - ECO-charging algorithm reduces average and peak grid load and improves battery health and lifetime



ELECTRIC BUS CONTROL MODEL

ENERGY MANAGEMENT

- Driver model
  - Minimize error between vehicle and reference speed
  - PID control

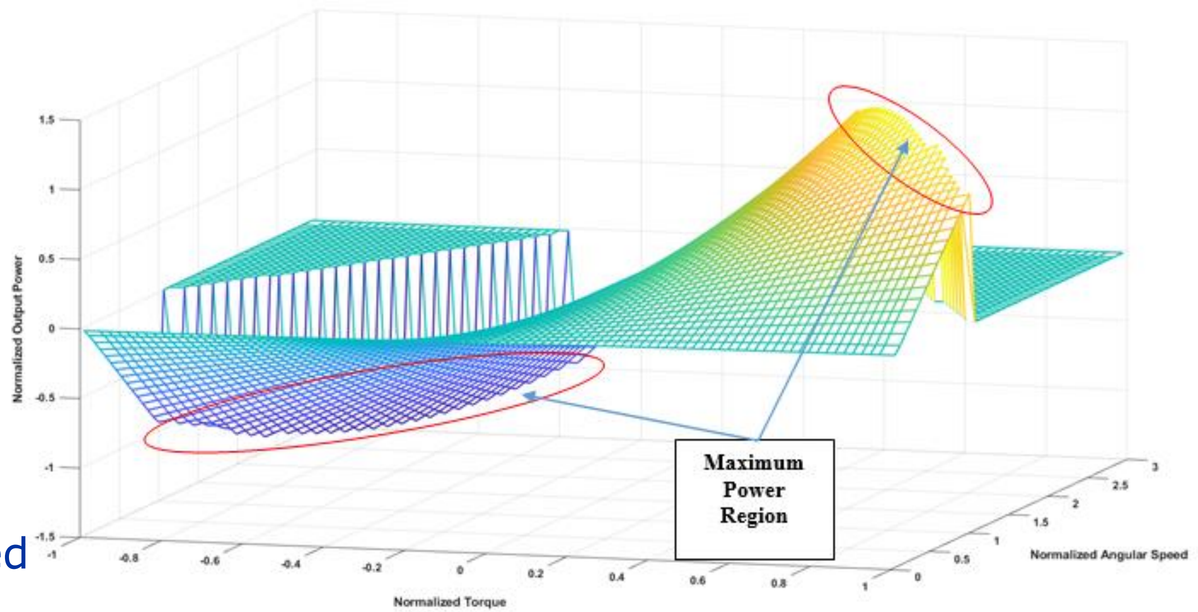


Reference speed

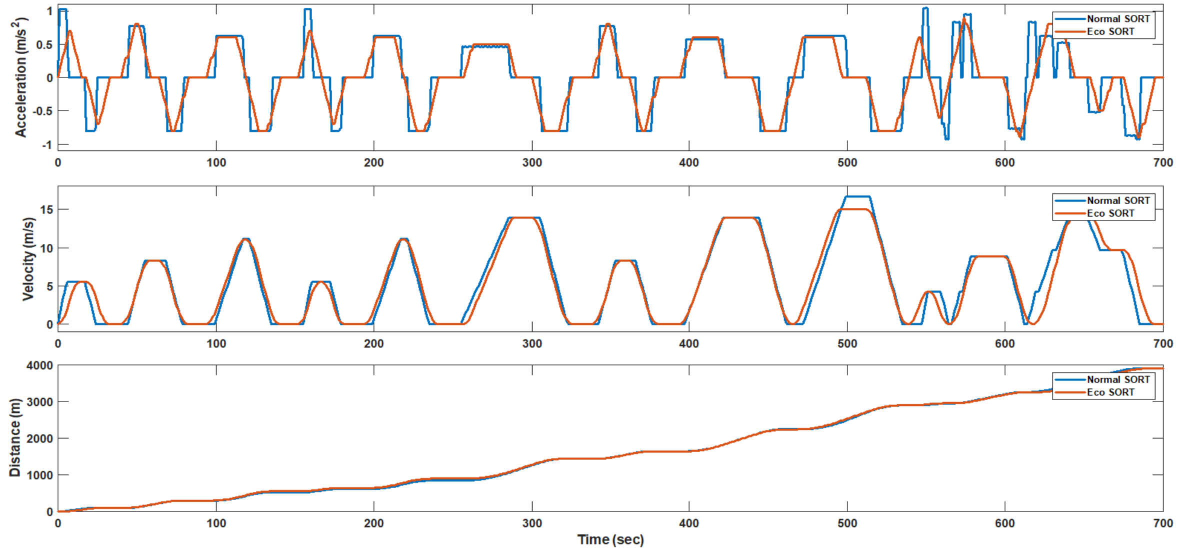
Vehicle speed

Torque reference
Braking reference

ECO DRIVING
1. Modified driving cycle, 2. Optimized torque reference



Torque optimization for maximum efficiency or power

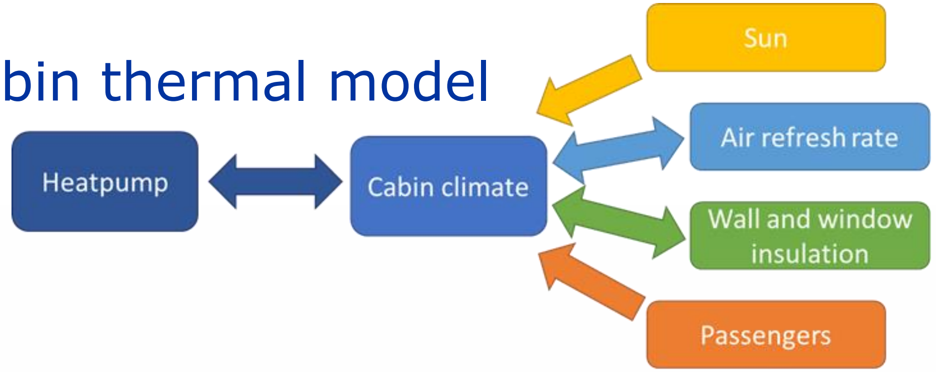


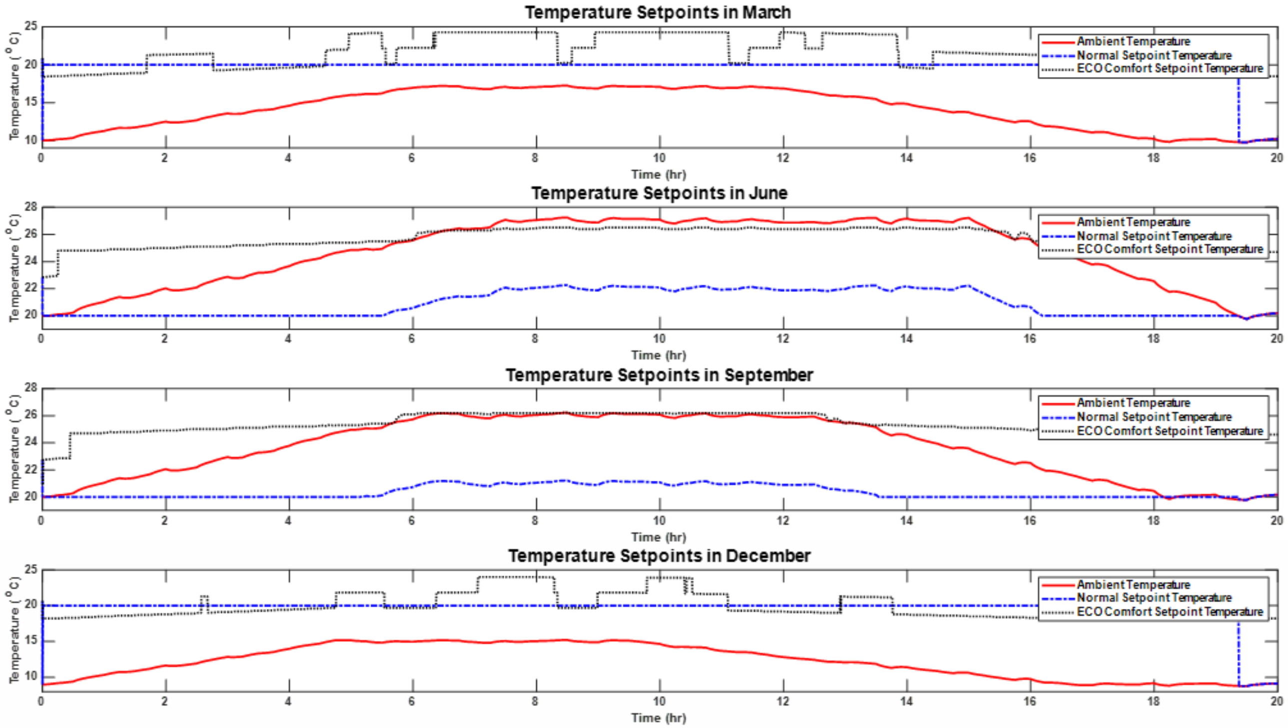
Eco-friendly speed modification

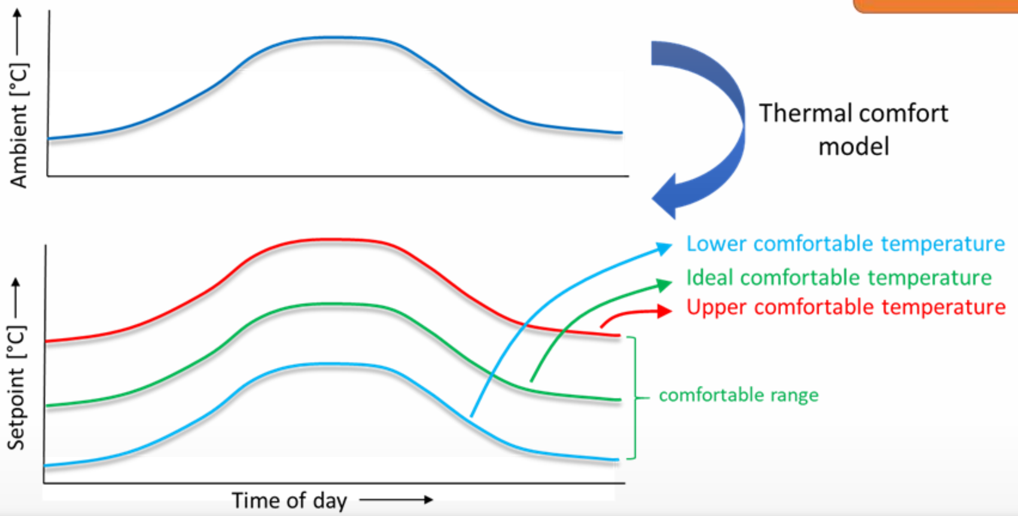
ELECTRIC BUS CONTROL MODEL

THERMAL MANAGEMENT

- Cabin thermal model







1. Dynamic cabin temperature setpoint based on:
   - Setpoint temperature keeps passenger at a slight level of discomfort, but reduces the HVAC power consumption
   - Expect some people in the cabin feel slightly uncomfortable
2. Preconditioning at the depot

ELECTRIC BUS CONTROL MODEL

CHARGING MANAGEMENT

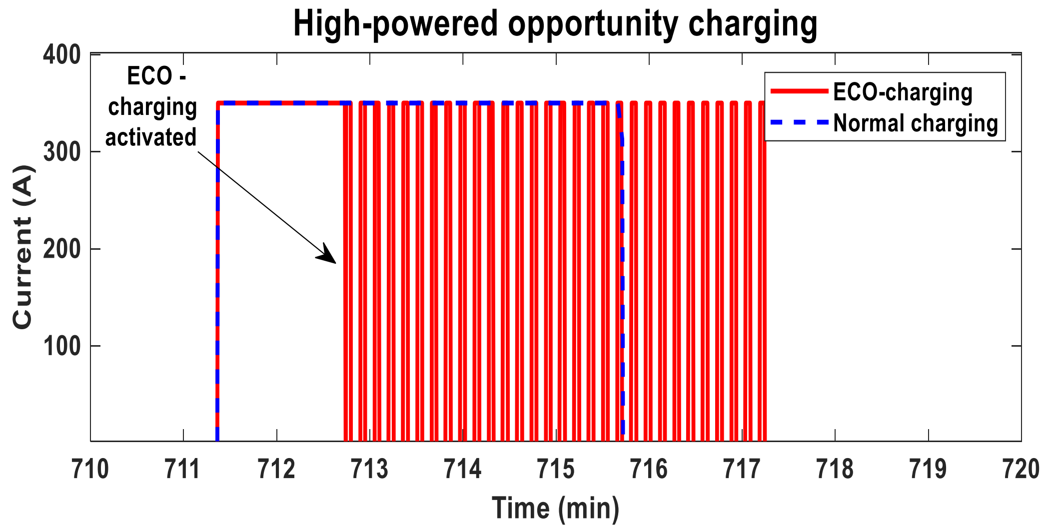
- **Charging infrastructure**
  - High-powered opportunity chargers
  - Lower powered overnight chargers
  - In-motion charger
  - Modular chargers
  - Peak shaving using a battery backup

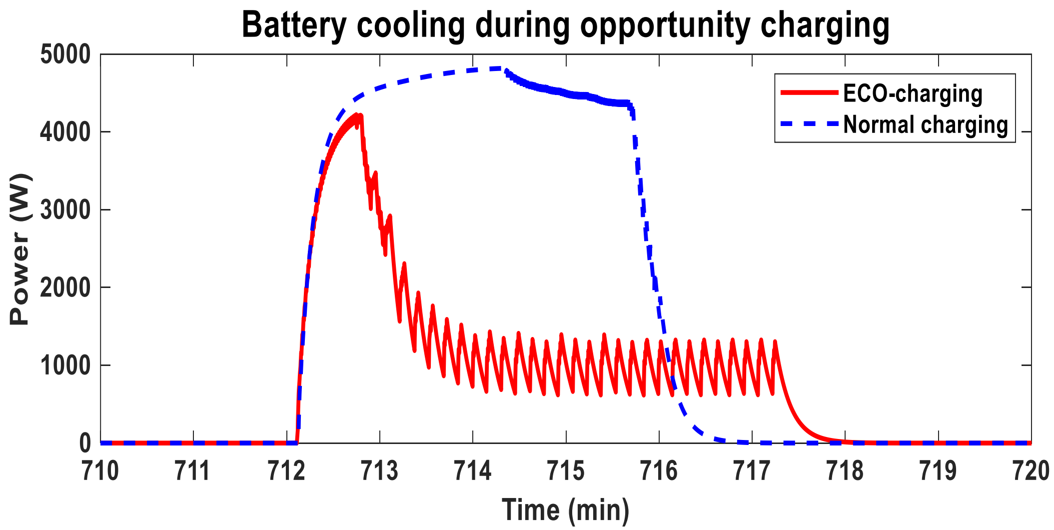
- **Charging strategy**
  - Smallest battery → In-Motion charging
  - Medium-sized battery → Opportunity charging at route end
  - Largest battery → Charging once a day in depot

- **Charge scheduling**
  - Variable charging duration
  - Priority-based charging based on SoC level of the battery

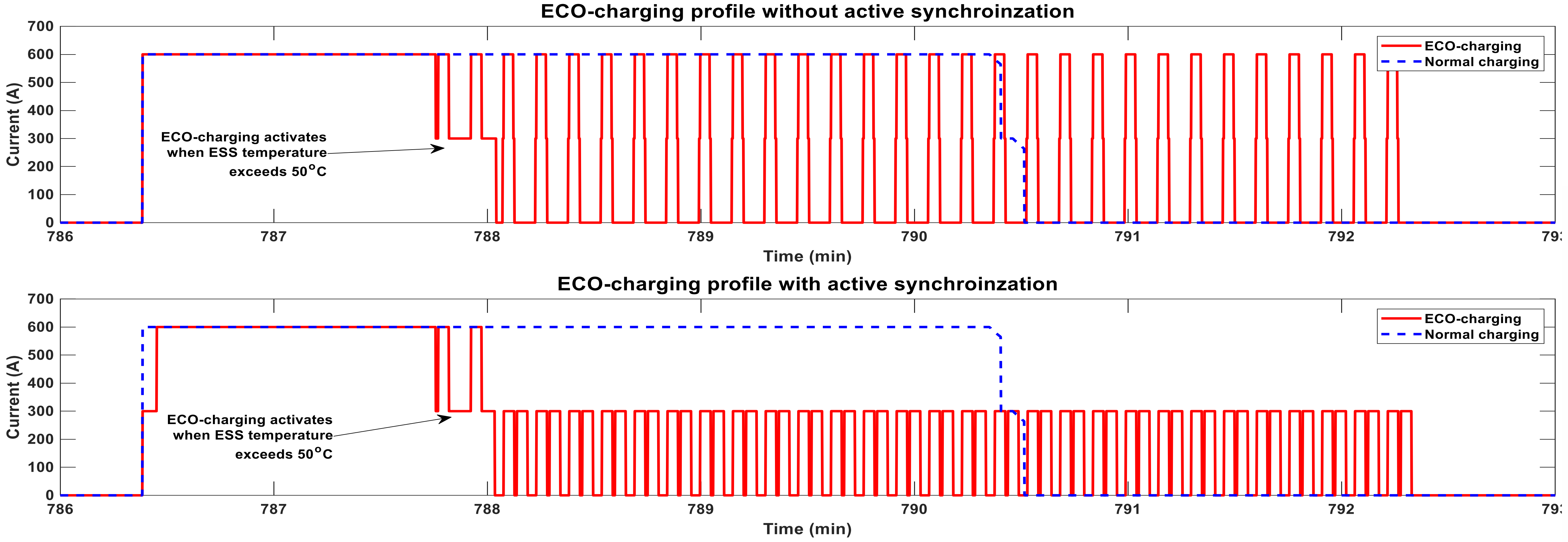
- **ECO-charging**
  - Charging pulses of variable duty cycle, period, and c-rate

ECO-charging

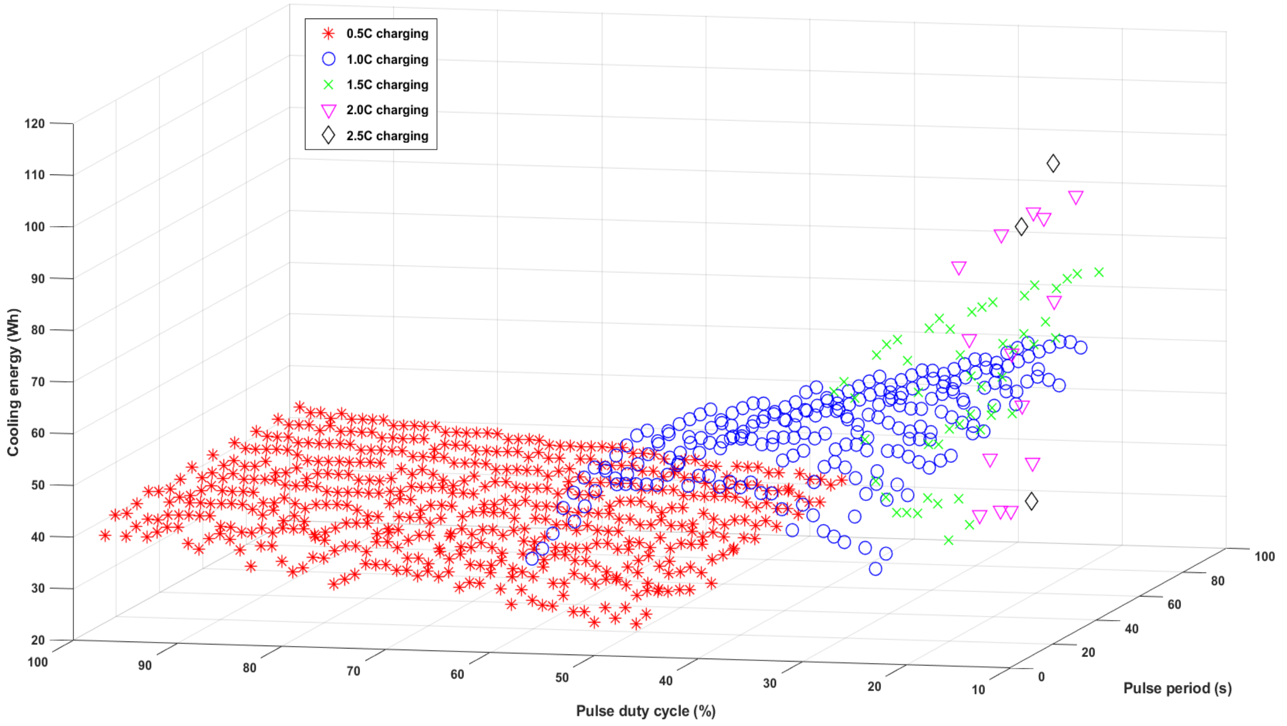


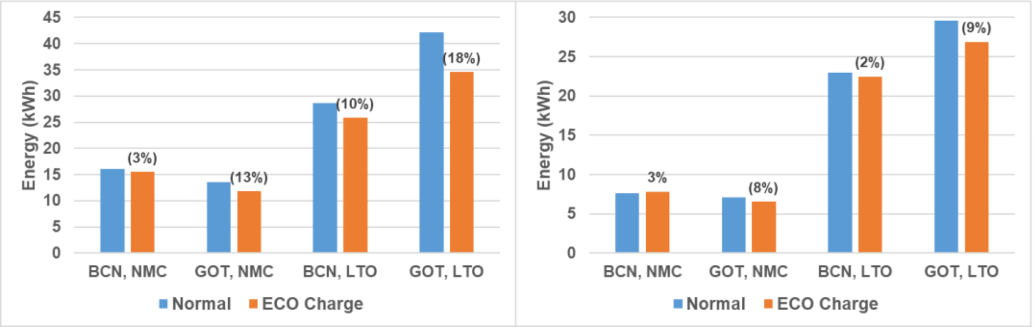


ECO-CHARGING



EFFECT OF CLIMATE ON THE ECO-CHARGING





Summer **Winter**

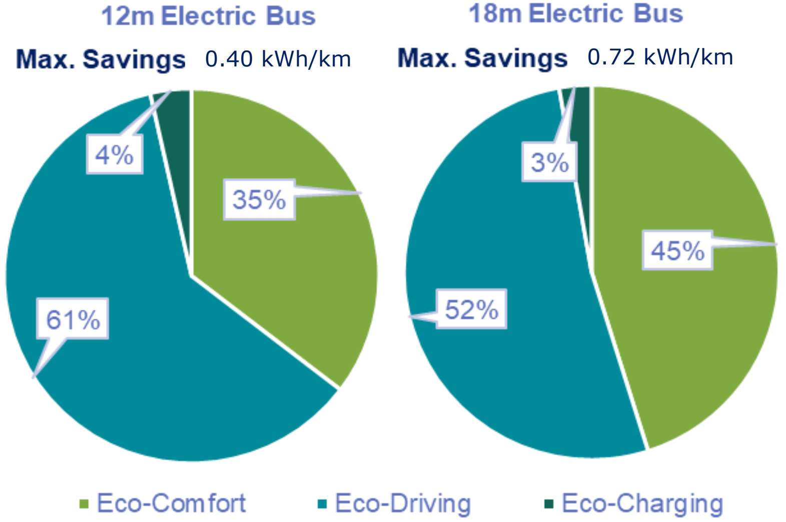
Effect of climate on the ECO-charging effectiveness in reducing the battery cooling energy requirement

ELECTRIC BUS CONTROL MODEL

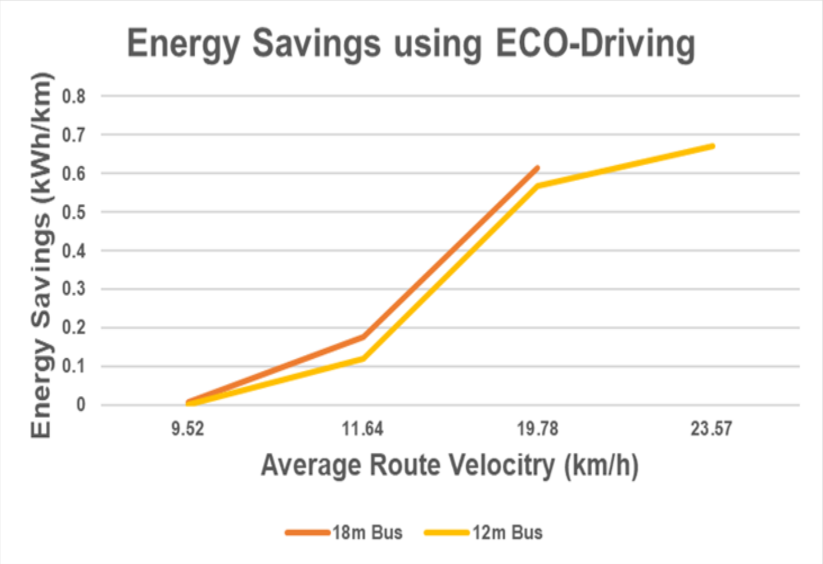
ENERGY SAVING RESULTS

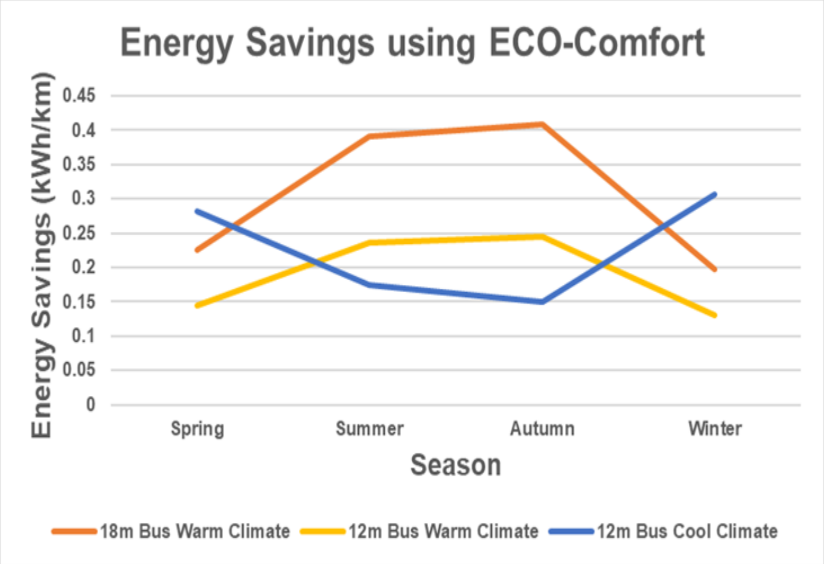
- While ECO-driving and ECO-comfort reduces energy requirements of buses, ECO-charging reduces the impact on the grid

Overall energy savings for both buses: 40% ~ 45%



Energy savings due to ECO-feature

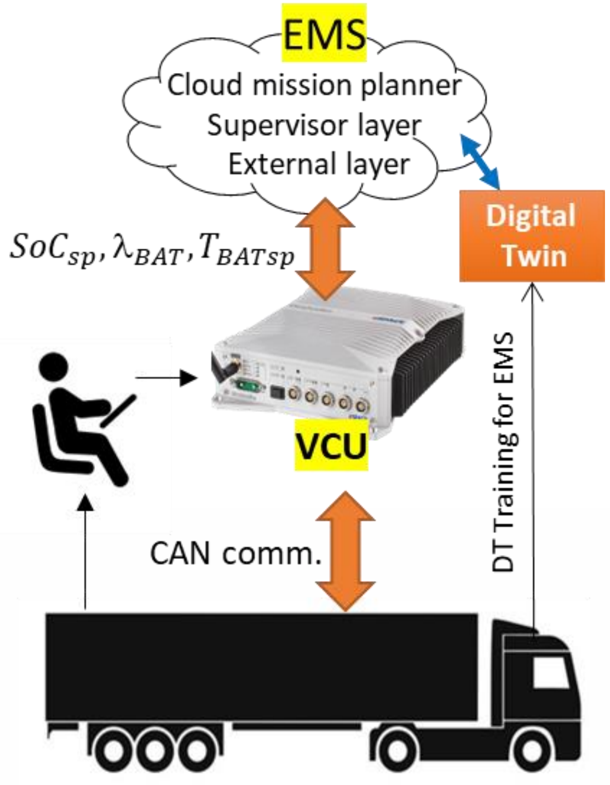


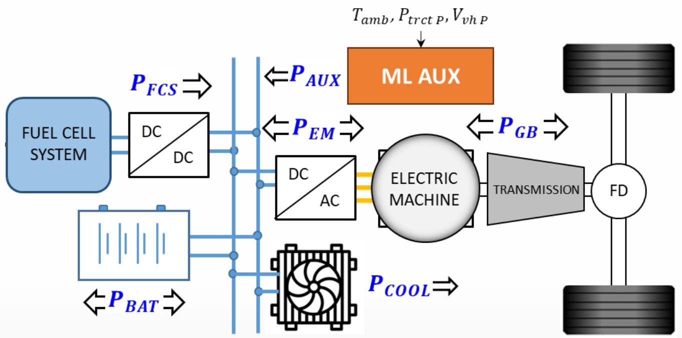


VIRTUAL MODELS FOR PREDICTIVE EMS AND TMS

- Supervisor optimal EMS and TMS tuning (SoC %, T_{batt} ºC), using a-priori driving mission info
  - Minimizing energy consumption and extending FC & battery lifetime
- Data driven backward traction chain and power source models
  - Periodically trained to ageing fuel cell and battery pack ('Training' from vehicle subsystems feedback)
- Machine Learning auxiliary load estimation

  Predicts future cooling and HVAC load depending on:
  - Payload and driving mission
  - Ambient temperature and solar radiation
  - Powertrain SoH





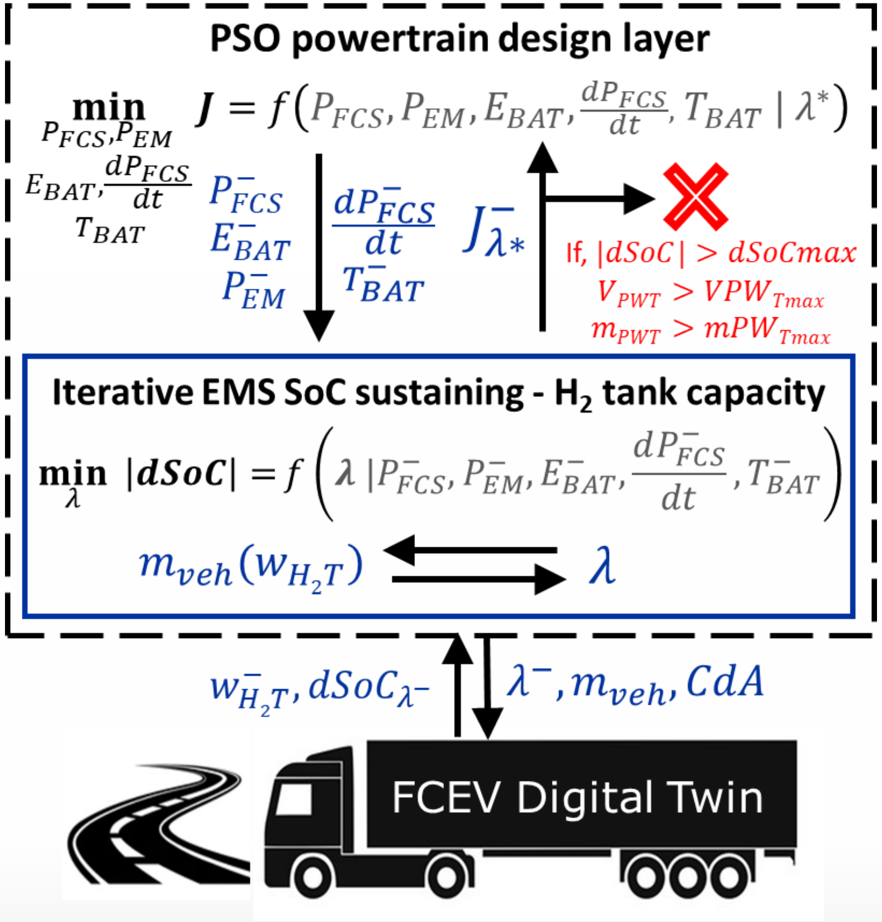
Reduced order digital twin for prediction and EMS tuning

VIRTUAL MODELS FOR POWERTRAIN OPTIMIZATION (FCEV & HEV)

OPTIMAL POWERTRAIN SIZING

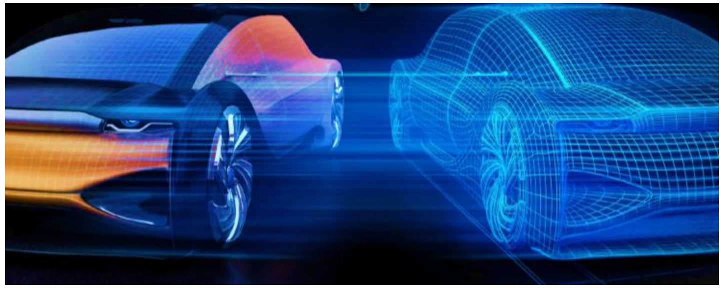
- Iterative nested co-design optimization for HEV and FCEV powertrains
- Scalable data-driven fast acting virtual models represent entire powertrain:-
  - Traction (eDrive)
  - Power sources (FC, battery, ICE)
  - Cooling auxiliary load
- Virtual digital twin models characterized from actual vehicle/subsystem tests

Nested co-design optimization



Virtual Models Parameterization and Calibration

FROM VIRTUAL MODEL TO DATA-DRIVEN DIGITAL TWIN



- ***A digital twin is a real-time virtual replica of a physical asset, unlike traditional models that simulate theoretical behaviour only***
- ***Data-driven digital twin leverages real-time data***

ADVANTAGES

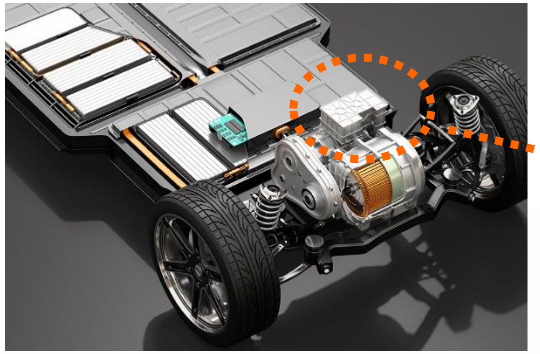
- Improved Accuracy: Reflects actual system behaviour for more precise representation compared to theoretical models
- Dynamic Adaptation: Adjusts in real-time as the system evolves (e.g., wear or changing conditions)
- Data-Driven Decision-Making: Continuous data allows for optimizing performance and strategies
- Cost-Effectiveness: Reduces virtual validation costs or maintenance costs by predicting failures and extending asset lifespan

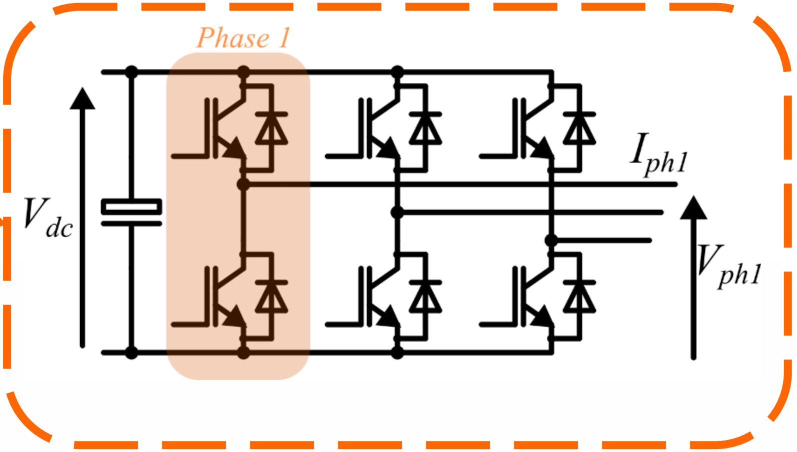
CHALLENGES

- Data Quality & Integration: Accurate, continuous data flow is essential
- Scalability: Managing accuracy and real-time performance becomes harder as system complexity grows
- Computational Requirements: Real-time data processing demands significant computational power, especially in complex systems
- Cybersecurity: Ensuring protection against cyber threats is critical due to real-time connectivity

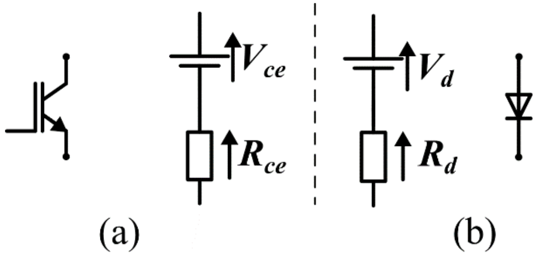
Courtesy: *This research is part of the* ***DT4V SBO project*** *funded and supported by Flanders Make, the strategic research center for the manufacturing industry.*

VIRTUAL MODEL OF A DRIVETRAIN COMPONENT

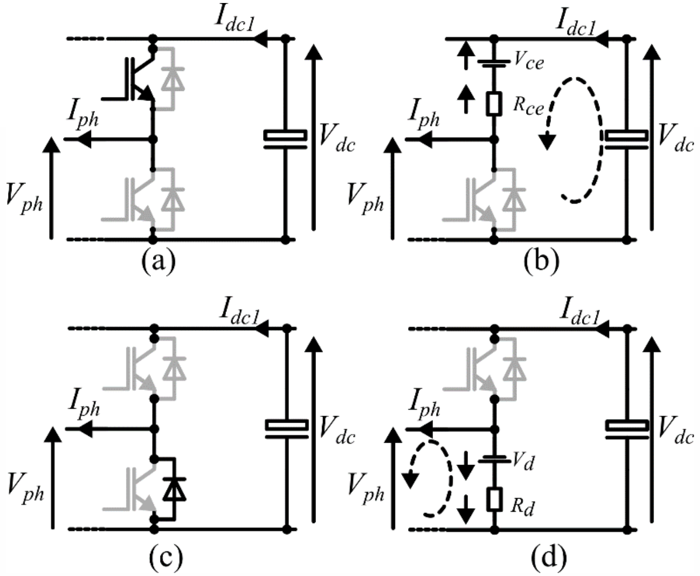




Physical entity → ***Digital entity***



On state equivalent circuit: (a) IGBT, (b) anti-parallel diode



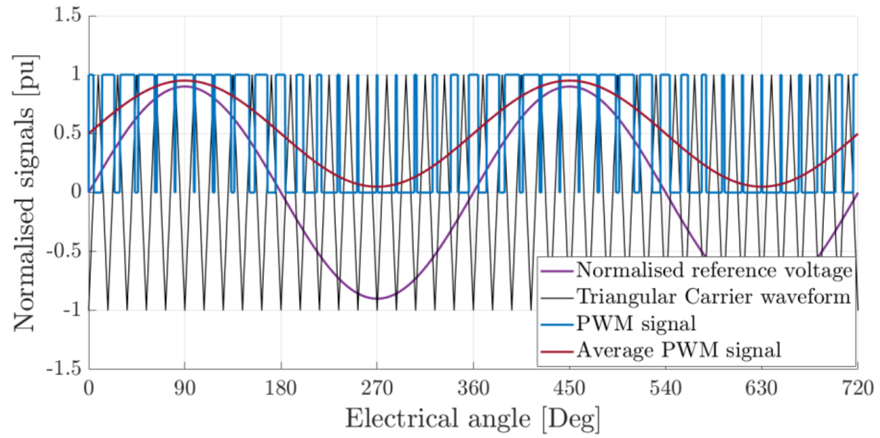
Power converter equivalent circuit (a) upper IGBT conducting (b) upper IGBT conducting equivalent circuit (c) lower IGBT conducting (d) lower IGBT conducting equivalent circuit.

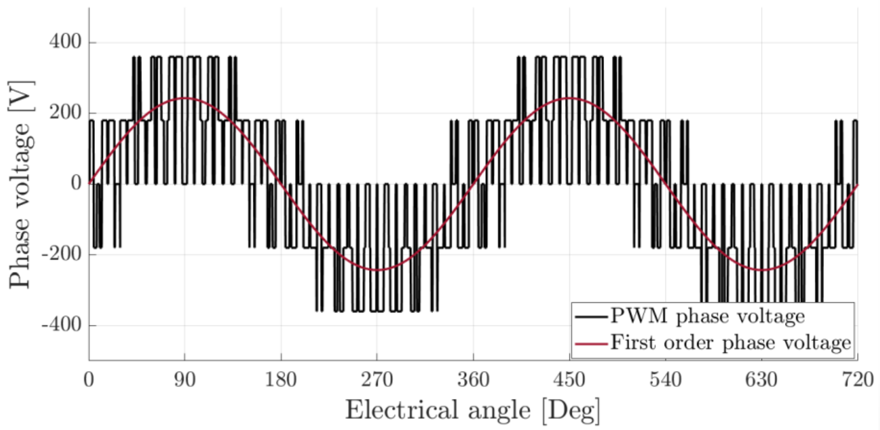
- Why the average model?
  - ***Easier to implement***
  - ***Fast simulation time***

Courtesy: *This research is part of the* ***DT4V SBO project*** *funded and supported by Flanders Make, the strategic research center for the manufacturing industry.*

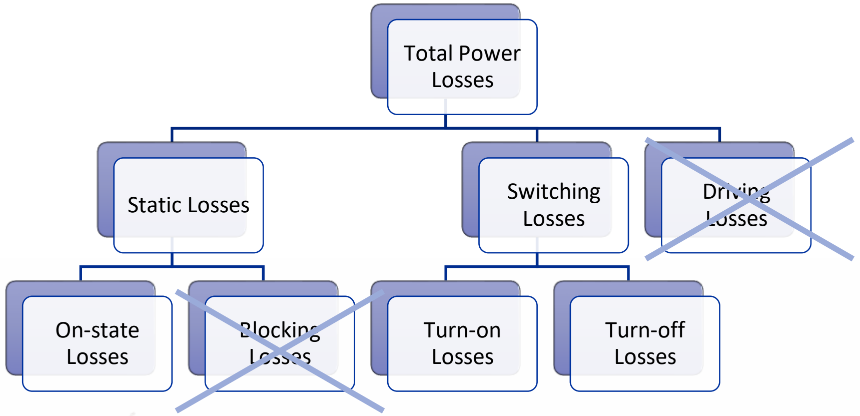
MODELLING APPROACH

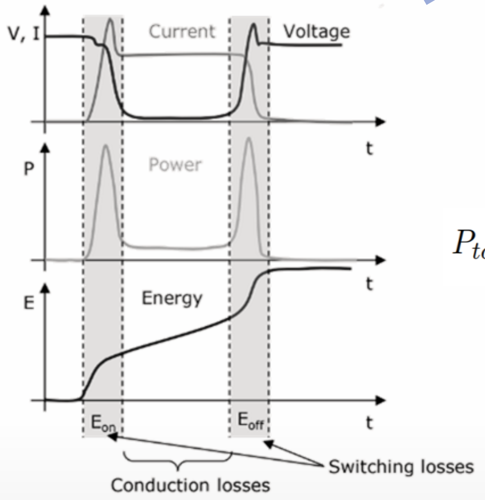
POWER INVERTER CONTROL MODEL: SPWM





POWER INVERTER LOSS MODEL





$$P_{total} = K_1 + K_2 I_{avg} + K_3 I_{rms}^2 + K_4 f_{sw} + R_{ESP} I_{dc,rms}^2$$

Courtesy: *This research is part of the* ***DT4V SBO project*** *funded and supported by Flanders Make, the strategic research center for the manufacturing industry.*

DATA ACQUISITION FOR MODEL PARAMETERIZATION

DATA ACQUISITION

Test setup: 11 kW PMSM with 15kW IM

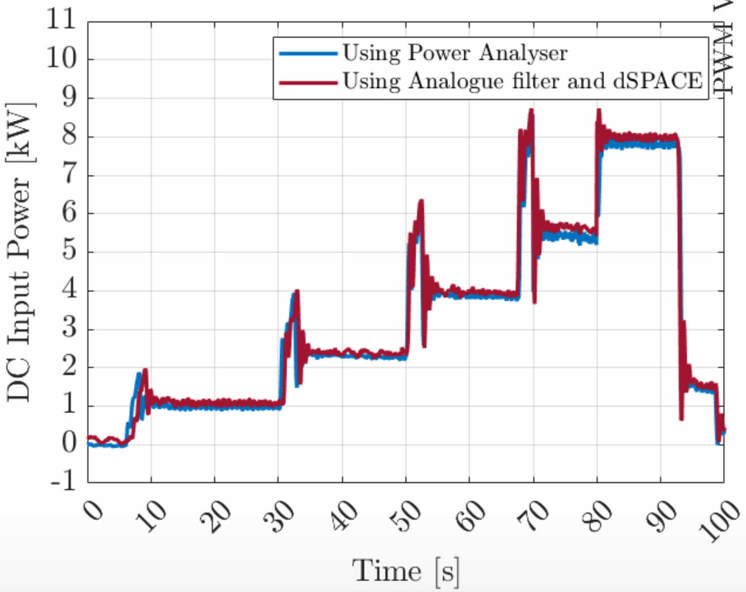
Testing Hardware

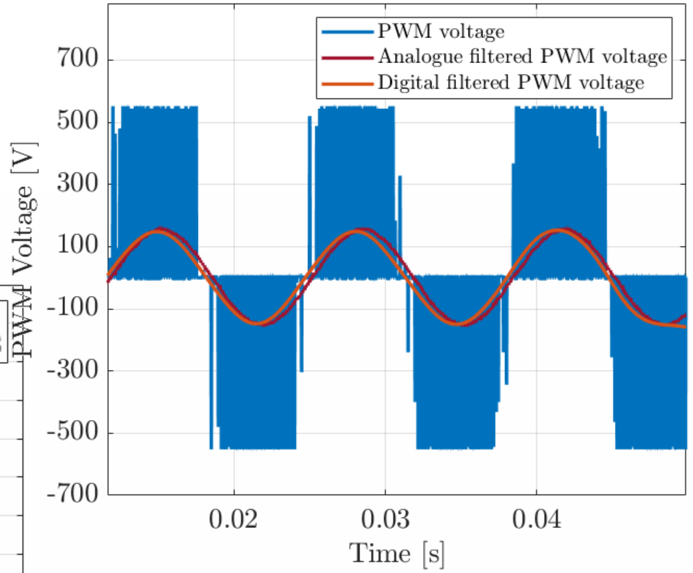
dSPACE MicroLabBox

Analog Filter

COLLECTED DATA CONSISTENCY: VALIDATION USING POWER ANALYSER

Input DC power at different loading





Output phase-to-phase PWM voltage at speed of 1500rpm

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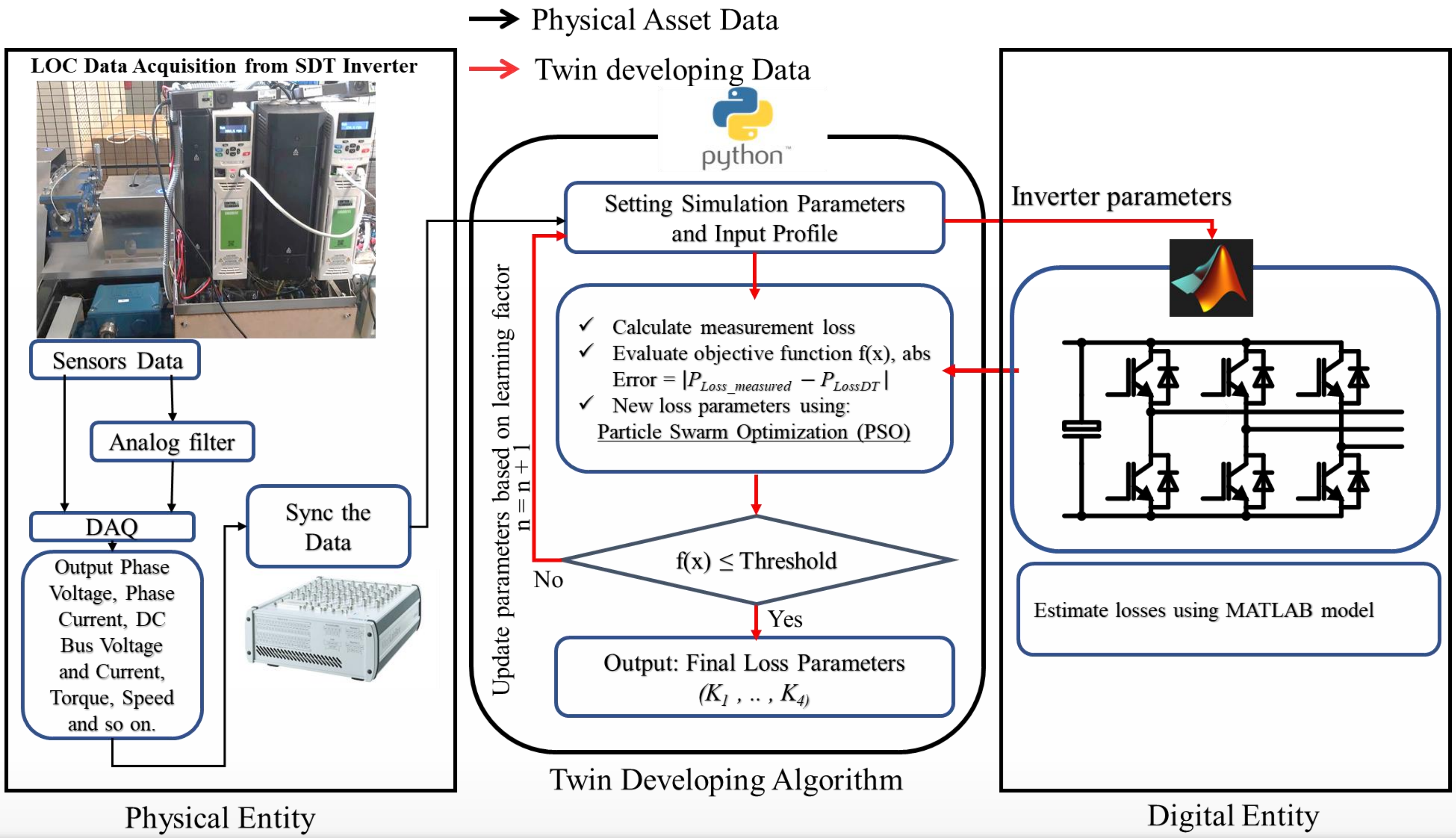
PARAMETRIZATION METHODOLOGY



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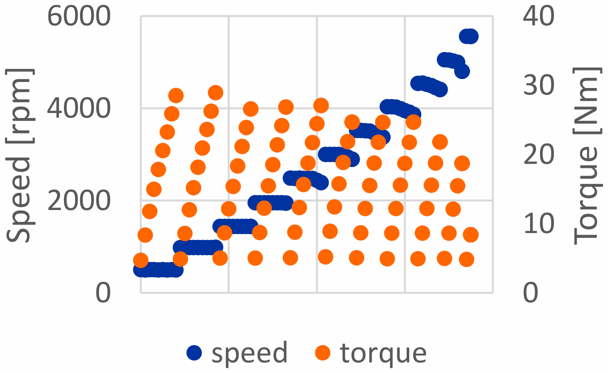
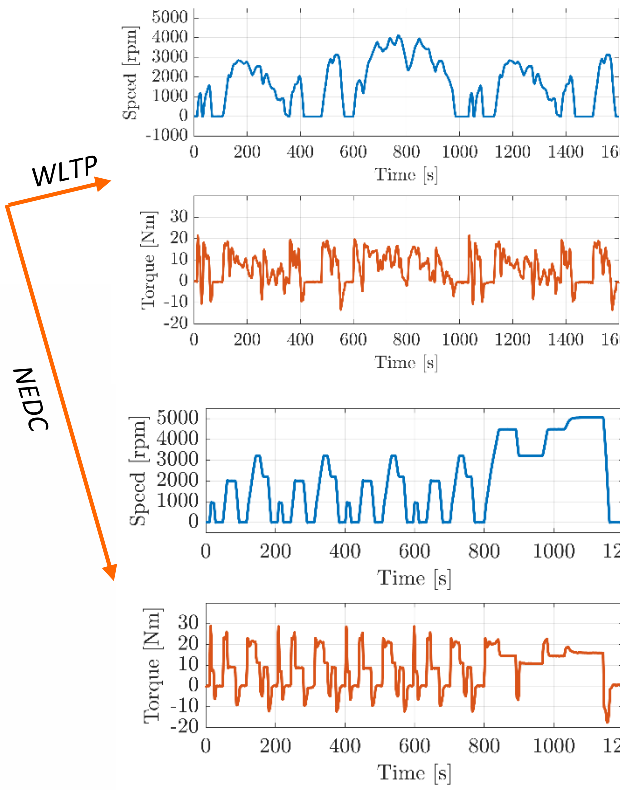
CALIBRATION AND VALIDATION

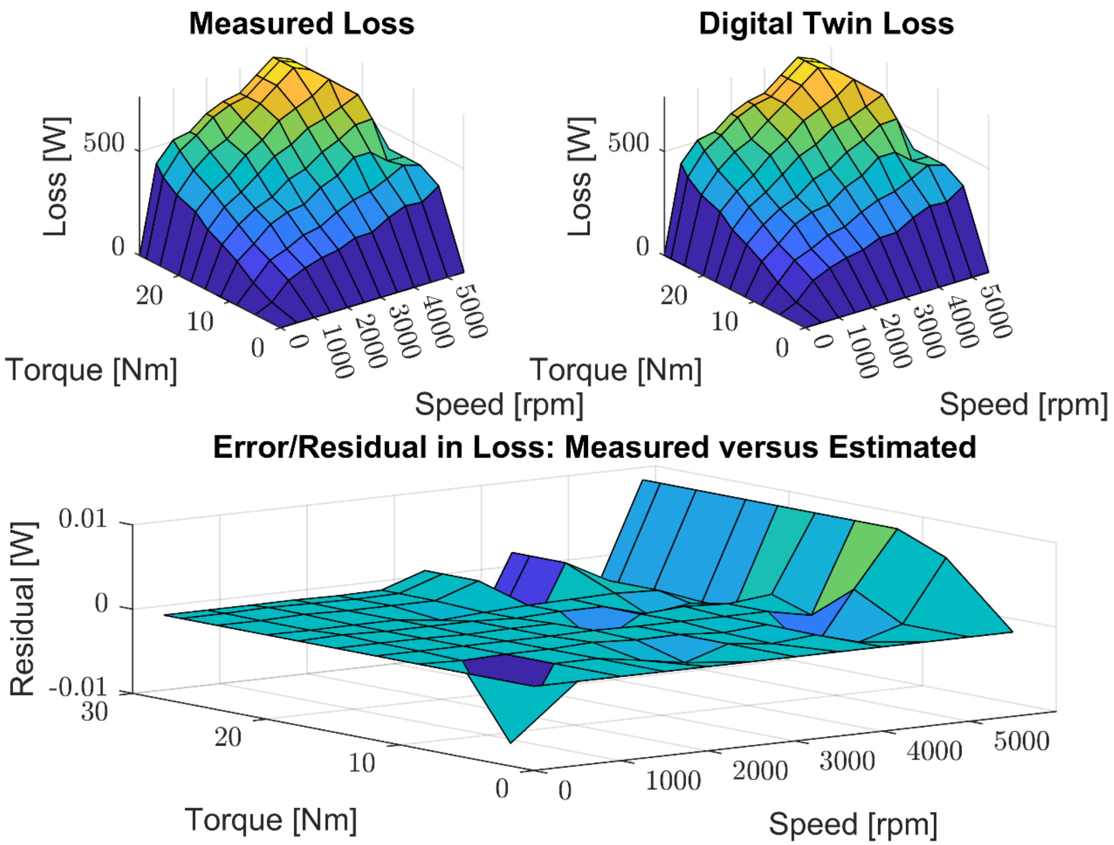
Digital-Twin Data

- Training Data
  - *75 torque/speed points*
- Validation Data



Training torque/speed data test points





Comparison of measured and DT estimated losses

ELECTROMOBILITY RESEARCH CENTRE

EFFICIENT POWER ELECTRONICS, POWERTRAIN & ENERGY SOLUTIONS RESEARCH GROUP

Power Electronics and Motion Control Council PEMC

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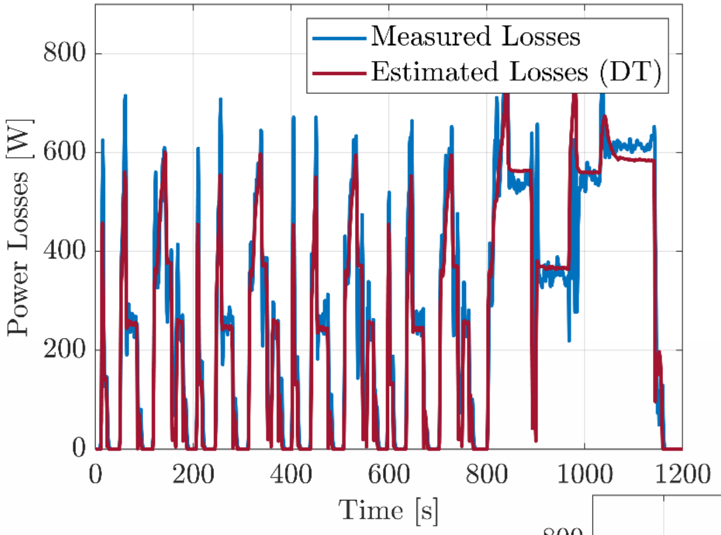
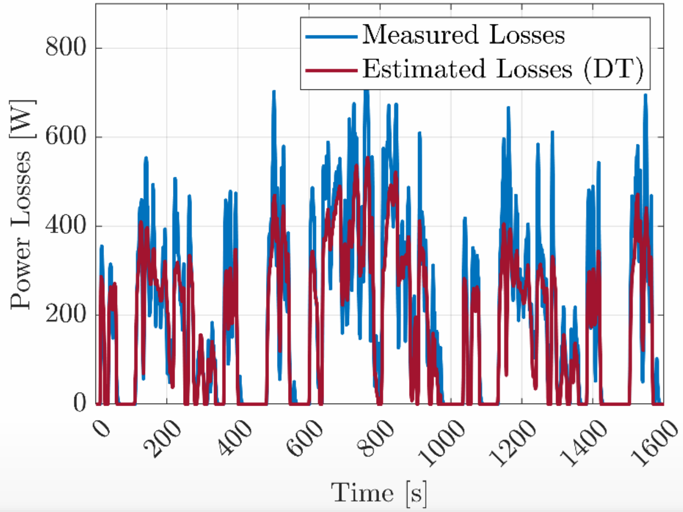
TUNED AND CALIBRATED MODEL FOR DIGITAL WIN



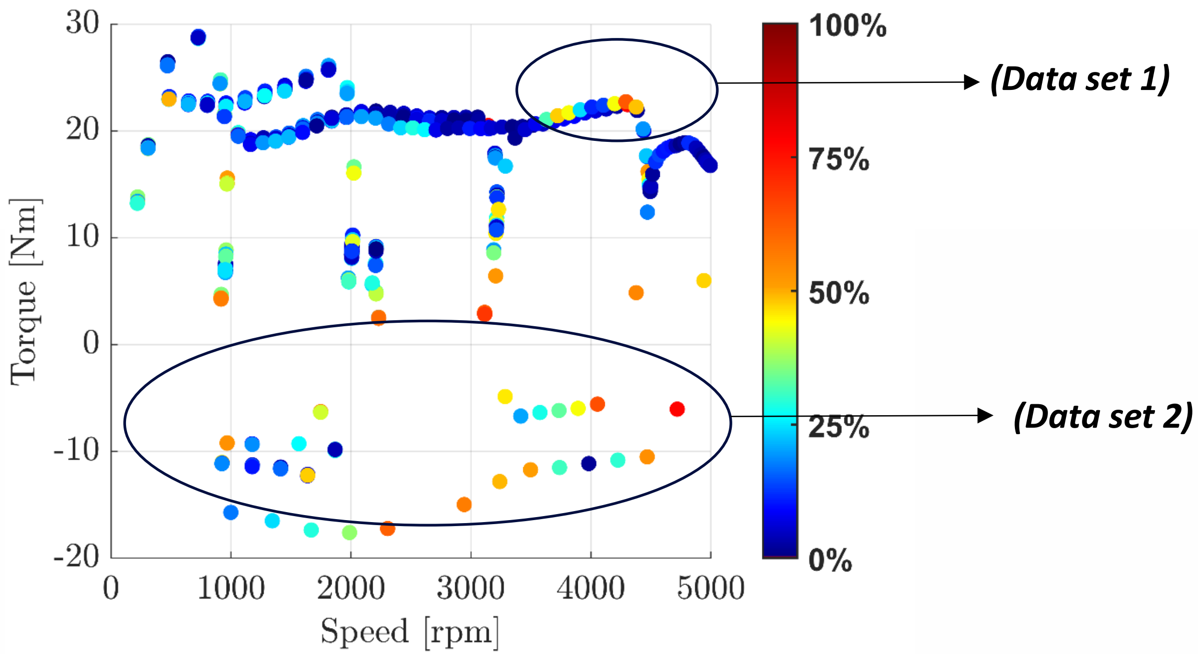
NEDC Driving Cycle

R^2 = 92.4%

WLTP Driving Cycle



Error in percentage versus speed-torque map for NEDC driving cycle



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Virtual Model Transition Towards Digital Twin Concept

ZEFES- ZERO EMISSION, SERVING THE LONG-HAUL FREIGHT ECOSYSTEM

40 partners

- 7 OEM's
- 10 Suppliers
- 8 Shippers & retail
- 9 Research

Project number: 101095856
Duration: 42 months
Start date: 01 January 2023
Total project costs: € 39Mio
Total EC funding: € 23Mio

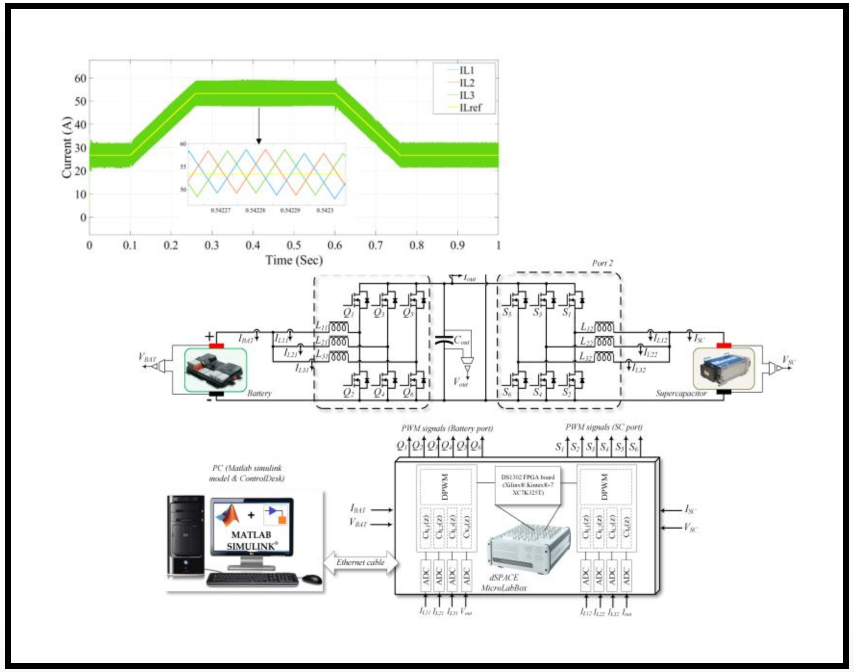
Coordinator: **VUB** (MOBI-EPOWERS RG)

Visit: ZEFES website

FROM VIRTUAL MODEL TO DIGITAL TWIN

Virtual Model

A precise behavioral replica of physical systems using mathematical or hybrid data-driven methods.



Enabling Technologies

Reduced order modelling: Faster Execution

Edge Computing: Computation in real-time

Cloud Computing: Fleet level computation

Internet of Things: Real-Time Data Transfer

Senor Technology: Real-time data collection

AI-ML driven Black box modelling: Unknown behavior prediction

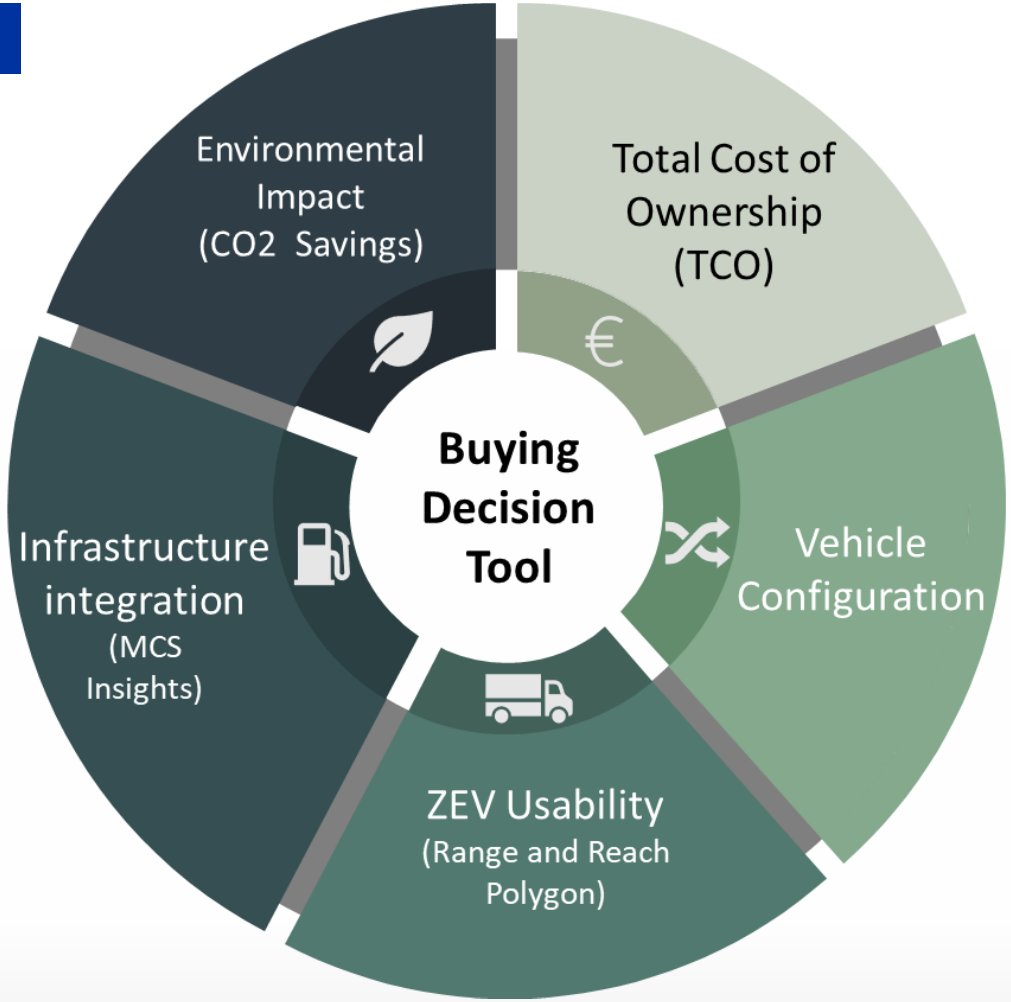
Digital Twin:

A virtual model that uses real-time data to deliver valuable services

VIRTUAL MODELS TRANSITION TOWARDS DIGITAL TWIN CONCEPT

BUYING DECISION TOOL (DIGITAL TWIN SERVICE)

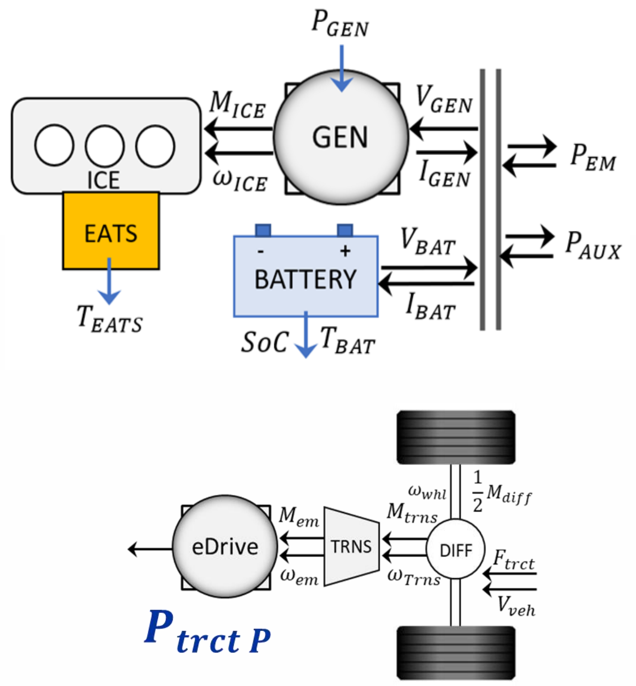
- A tool that can predict if **a chosen vehicle** can complete a selected mission (location-to-location travel) with given battery capacity and initial State of Charge (SoC).
- A right vehicle selection for the right duty
- A complete vehicle DT model with fast SoC calculation is necessary to implement such tool.



VIRTUAL MODELS TRANSITION TOWARDS DIGITAL TWIN: USE CASE

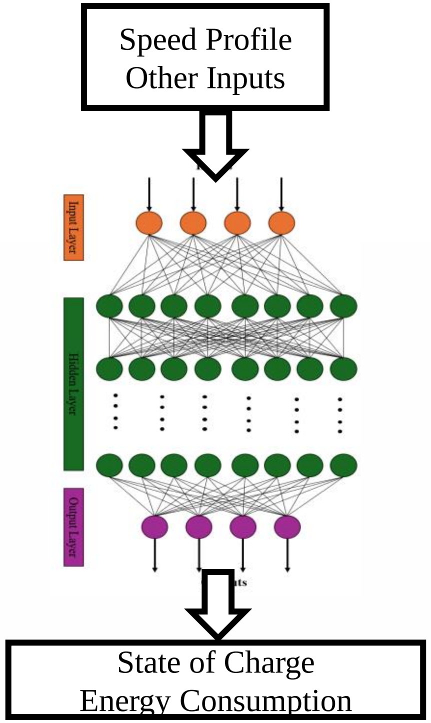
DIGITAL TWIN MODELLING APPROACH

High Computational Requirement
Not Suitable for Online DT Application



Physics-based Vehicle Model

Multi-Physics Model	Data-Driven Model
High Accuracy Instantaneous Outputs Physics-Based Model	Accuracy depends on training data Black Box Model Real-time executable



Deep Learning SoC Estimation Model

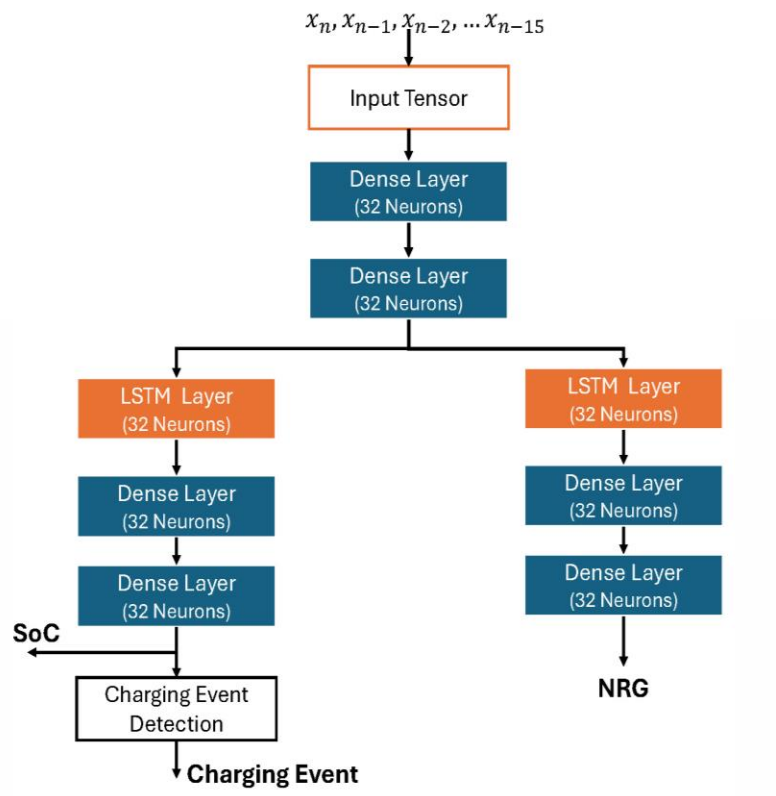
Low computational requirement
Suitable for Online DT Application

DT service model development

DEEP LEARNING CONFIGURATIONS FOR TRAINING

The impact of input availability on prediction accuracy

Target Distance	Battery Capacity	Vehicle Mass	Ambient Temperature	Gradient	Target Speed	R^2 SoC on Testing Data	R^2 NRG of Testing Data
✓	✓					0.664	0.482
✓	✓				✓	0.785	0.700
✓	✓			✓		0.656	0.552
✓	✓			✓	✓	0.814	0.742
✓	✓		✓			0.829	0.909
✓	✓		✓		✓	0.830	0.921
✓	✓		✓	✓		0.901	0.896
✓	✓		✓	✓	✓	0.901	0.918
✓	✓	✓				0.907	0.706
✓	✓	✓			✓	0.879	0.895
✓	✓	✓		✓		0.937	0.878
✓	✓	✓		✓	✓	0.928	0.888
✓	✓	✓	✓			0.923	0.823
✓	✓	✓	✓		✓	0.908	0.938
✓	✓	✓	✓	✓		0.918	0.933
✓	✓	✓	✓	✓	✓	0.952	0.949



Deep Learning Model Configuration

Model configuration and hyper-parameters are optimized by grid search. Advance heuristic optimizations like PSO can be implemented as well.

VIRTUAL MODELS TRANSITION TOWARDS DIGITAL TWIN: USE CASE

ACCURACY OF DIGITAL TWIN MODEL

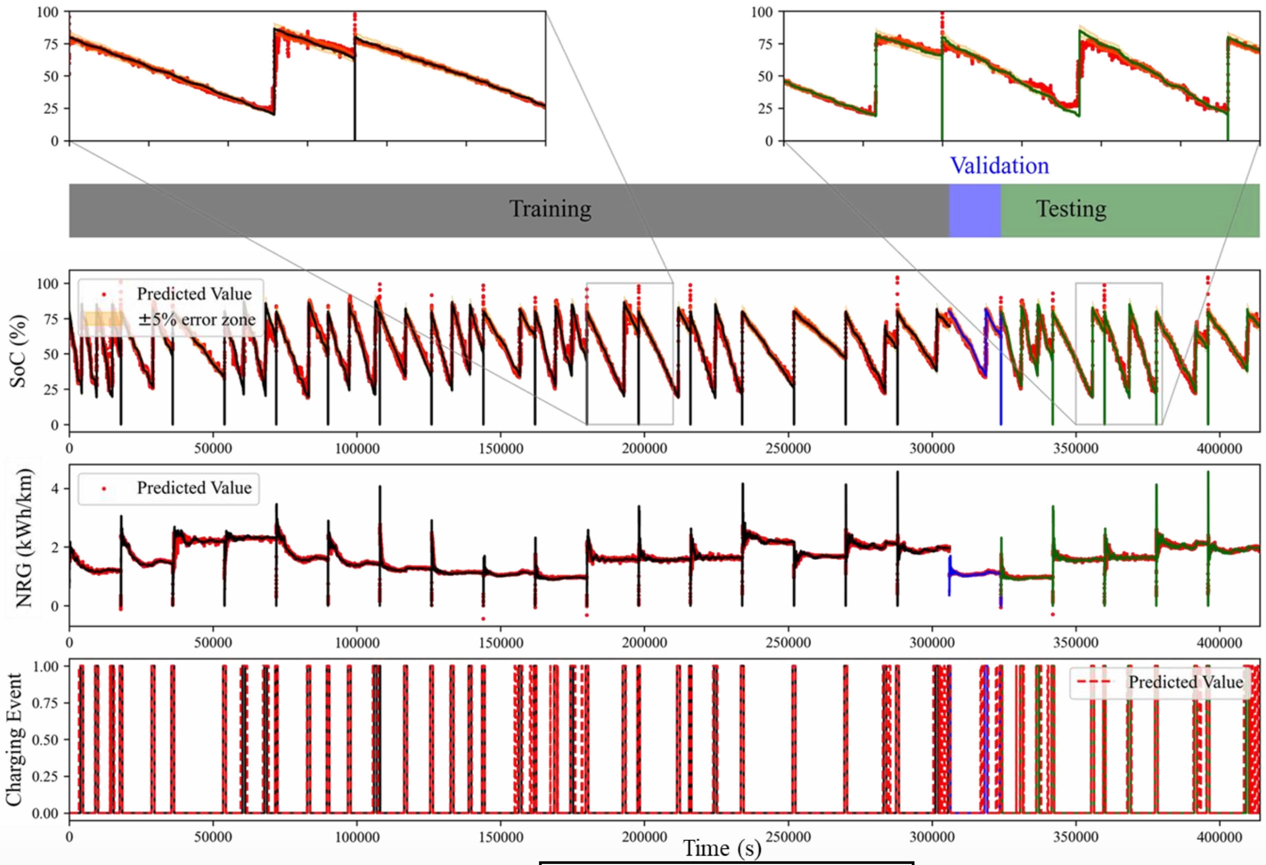
Inputs from mission requirement

Speed Profile
Target Distance
Battery Capacity
Vehicle Mass
Ambient Temperature
Gradient

DT Model Output

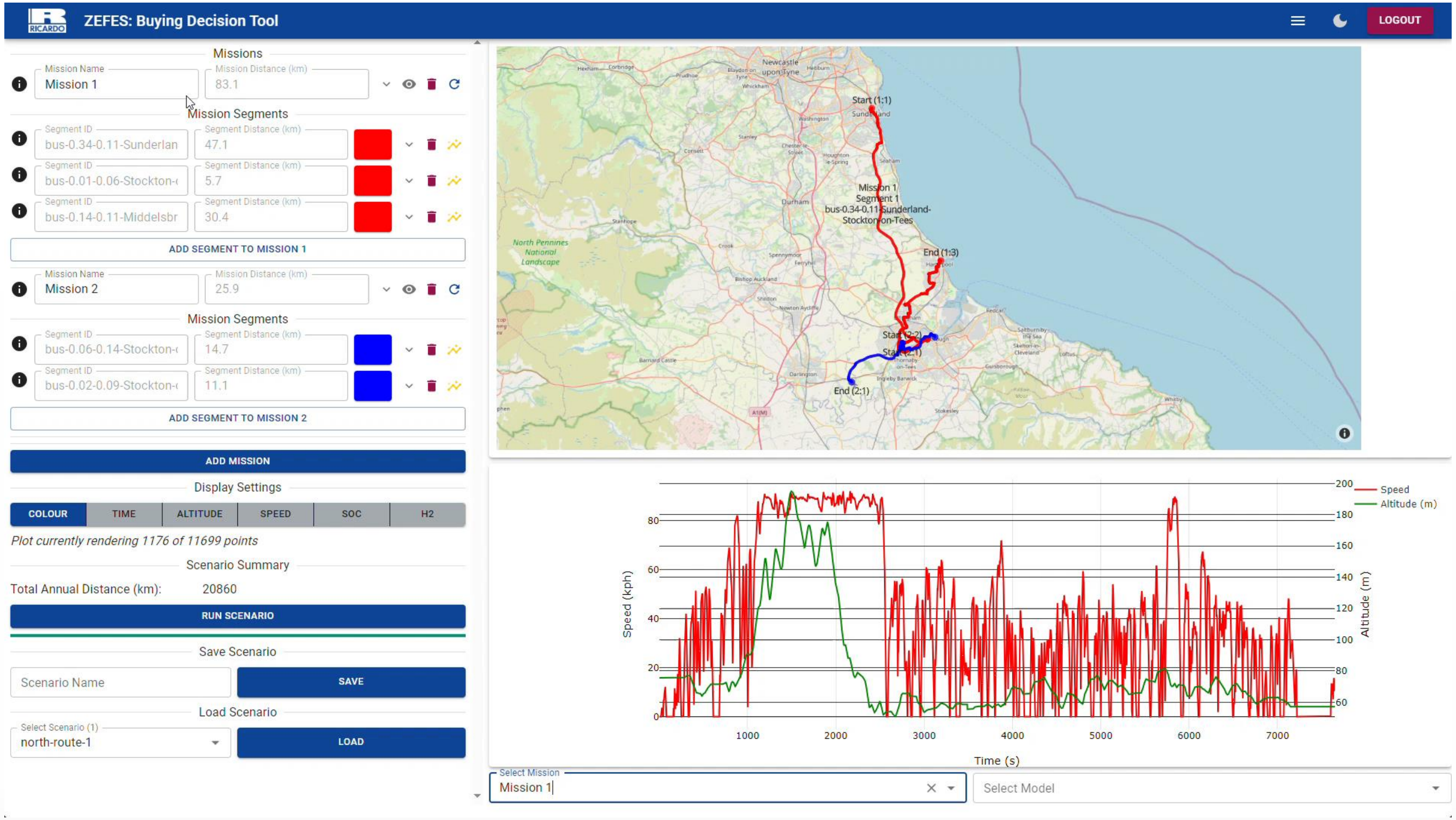
State of Charge
Energy Consumption
Charging Event

5% Error Zone



DT Model Output

FINAL IMPLEMENTATION OF DIGITAL TWIN SERVICE



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ELECTROMOBILITY RESEARCH CENTRE

EFFICIENT POWER ELECTRONICS, POWERTRAIN & ENERGY SOLUTIONS RESEARCH GROUP

Power Electronics and Motion Control Council

Part II: Digital Twin: Lifetime and Safety

HIEFFICIENT

Key Facts

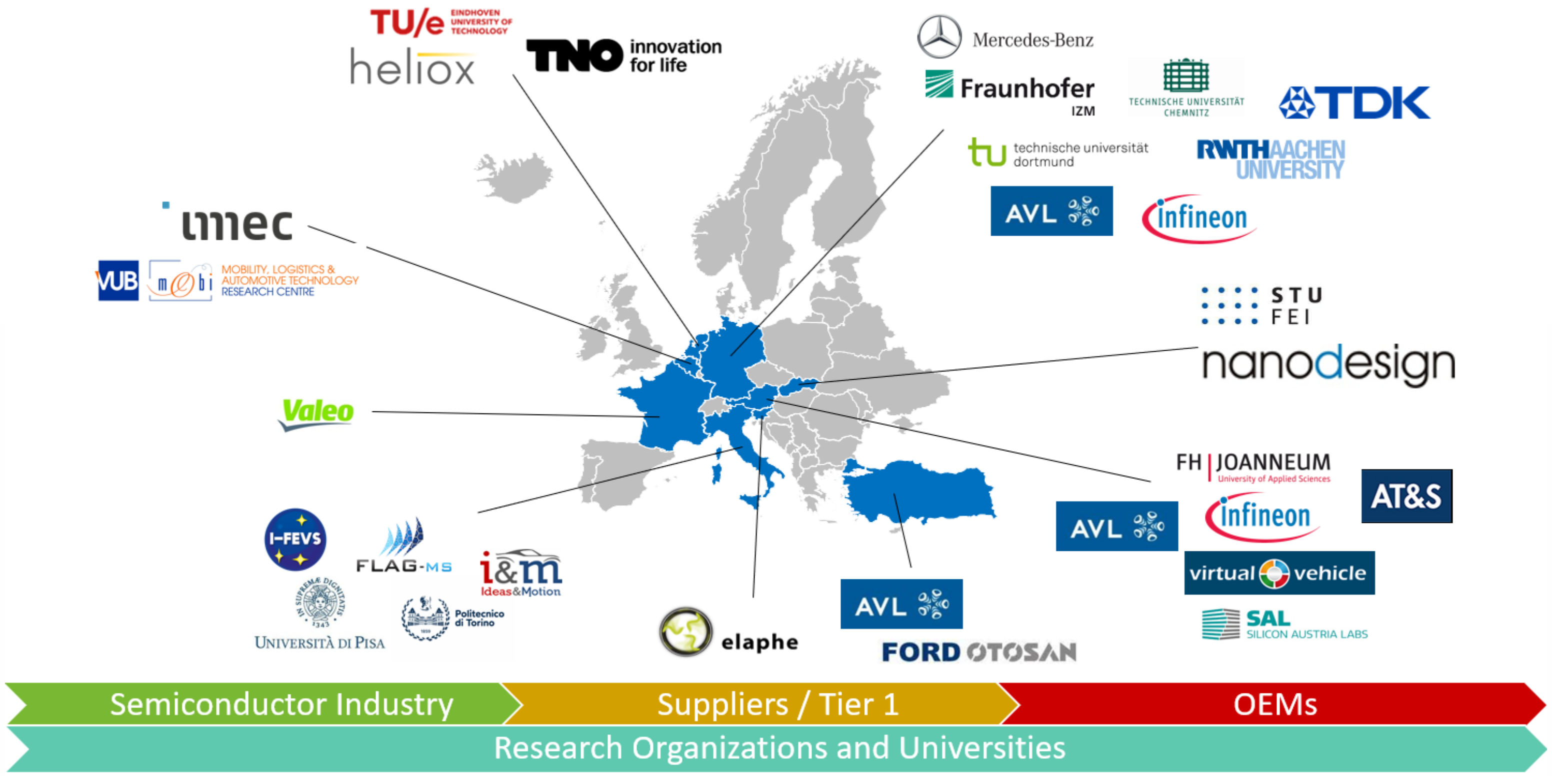
Start: 1st May 2021, 42 Months

Costs: 41.9 Mio €

Funding: 23.8 Mio €

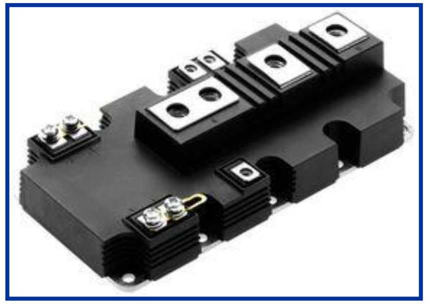
Coordinator: AVL List GmbH

Consortium: 31 Partners



Visit: https://www.hiefficient.eu/

WHY IS RELIABILITY RESEARCH IMPERATIVE?



The explosive consequences of Power Semiconductor Failures (e.g., before and after the failure of a power semiconductor) [5]

Rigorous safety requirements are applied for critical applications (e.g.: EV and wind applications) [5]

Reported PE Lifetime issues

Σ Toyota recalled 400k+ cars in 2014 due to unexplained overheating of semiconductors [1];

Σ Hyundai announced a recall of more than 13,500 vehicles in Australia related to a potential electronic heating issue that could start fires [2];

Σ National Renewable Energy Lab stated setting a 1,127-acre fire at a 250 MW solar power plant, including power electronics components failure [3];

Σ The Beijing-Tianjin high-speed railway in China reported 50% of failures in traction converters [4].

Significances of Poor Lifetime

Σ Revenue loss (e.g., NREL stated an $8-9 million loss in [2])

Σ Customer dissatisfaction

Σ Long delivery delay

Σ Disrupted services

Source:
1. https://www.latimes.com/local/california/la-fi-prius-overheat-inverter-defect-20190414-story.html
2. https://www.bbc.com/news/business-66402202
3. https://www.emainc.net/tag/medium-voltage-vfd-failure
4. J. Liu, st.al., "Reliability evaluating for traction drive system of high-speed electrical multiple units," *2013 IEEE Transportation Electrification Conference and Expo (ITEC)*, Detroit, MI, USA, 2013, pp. 1-6.
5. Google image

AUTOMOTIVE STANDARD LIFETIME REQUIREMENTS

Scenario 1: Standard EVs • Traction Inverter (10000h/15 years) • On-board Charger (11000h/17 years)	**Scenario 2: Vehicle-to-Grid Applications** • Traction Inverter (10000h/15 years) • On-board Charger (22000h/17 years)
Scenario 3: Integrated PE System • Integrated Traction Inverter (20000h/ 15 years)	**Scenario 4: Sharing Vehicles** • Traction Inverter (20000h-50000h) ~(2-5) times
Other PE Systems of EVs Applications • High-Power Charging Stations (20 years) • Power Electronics Wall (20 - 25 years) • On-Road Inductive Charging (20 years)	--------------//--More will be defined--//-----------

Σ From 10000 hours to 50000 hours of operation time

Σ Reducing CO_2 Emissions → Acceptance of EVs, Reliability, Cost

Σ Saving Resources → Material usage, repair, recycling

Σ Novel Use Cases:

- Automated and shared driving
- V2G → lifetime & availability
- Integrated PE systems

WHAT IS A MISSION PROFILE ?

MISSION PROFILE SELECTION FOR RELIABILITY DIGITAL TWIN

What is a Mission profile?

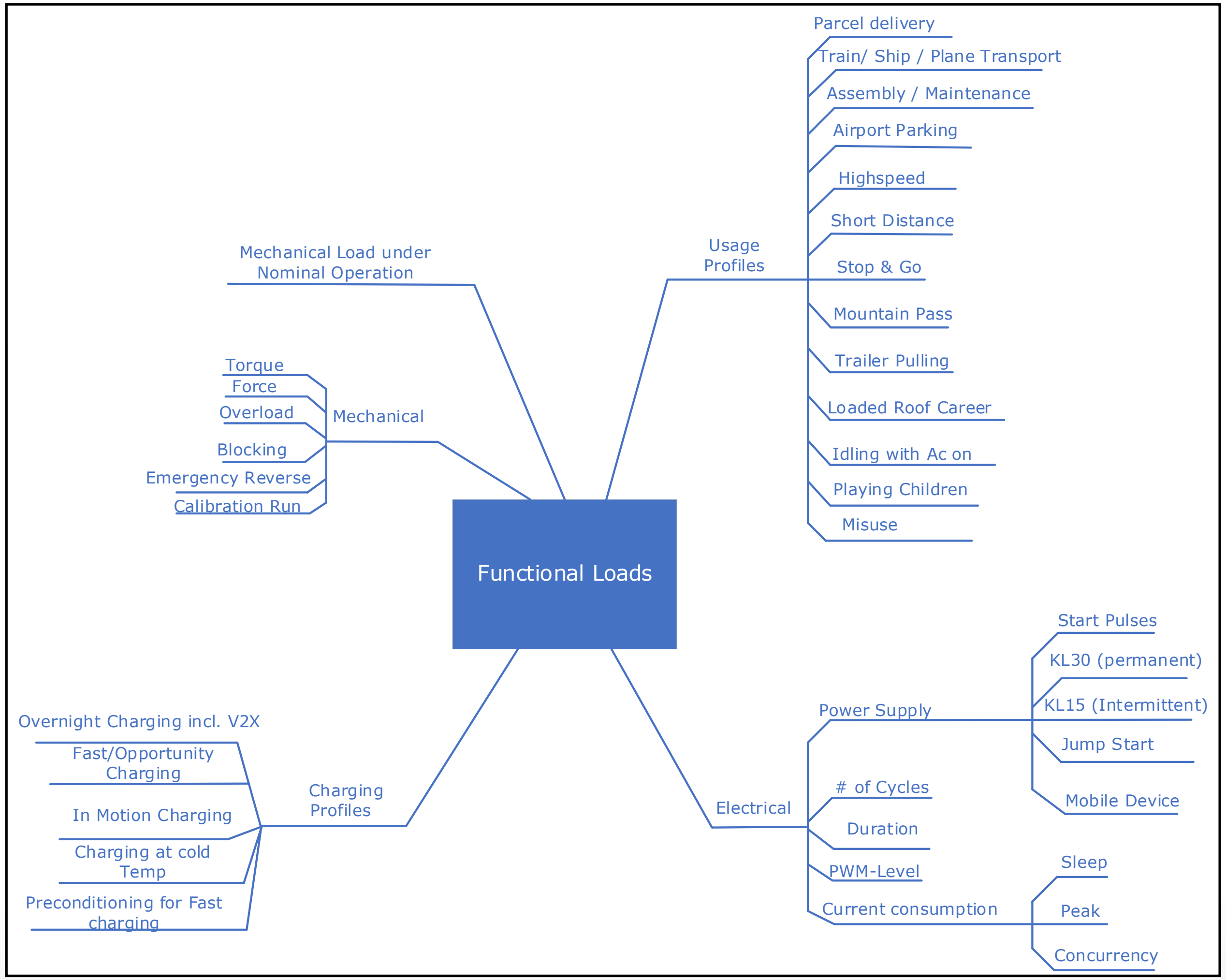
A mission profile is a simplified representation of all relevant static and dynamic load conditions to which a vehicle's electric/electronic components (i.e., a device under test (DUT)) is exposed within its entire lifecycle.

Why are mission profiles essential in the automotive sector?

- A different user profile using the same DUT may result in totally different load profiles and thus, different requirements.
- Therefore, Mission Profile for individual automotive electrical/electronic modules is recommended to be prepared and communicated to the engineers during the early design phase.
- With the proper description of the Mission profile, service and quality target can be integrated into the design phase to achieve „ Zero defects" and robust design

In the Automotive sector, OEMs and Tier1s specify mission profiles for their applications.

FUNCTIONAL LOADS EXAMPLES IN EVS



Source: Handbook for Robustness Validation

EXEMPLARY MISSION PROFILES FOR EVS

Battery Condition *
- ✓ Technology, Int. SoC

Payload Info *
- ✓ No of passengers, Max Weight of luggage

Environmental condition!
- ✓ Seasonal temperature, Wind speed

Usage Scenarios *
- ✓ Start point and end point
- ✓ Parcel delivery service
- ✓ Commercial traveler
- ✓ Short city trip
- ✓ Short-range commuter
- ✓ Long-range commuter

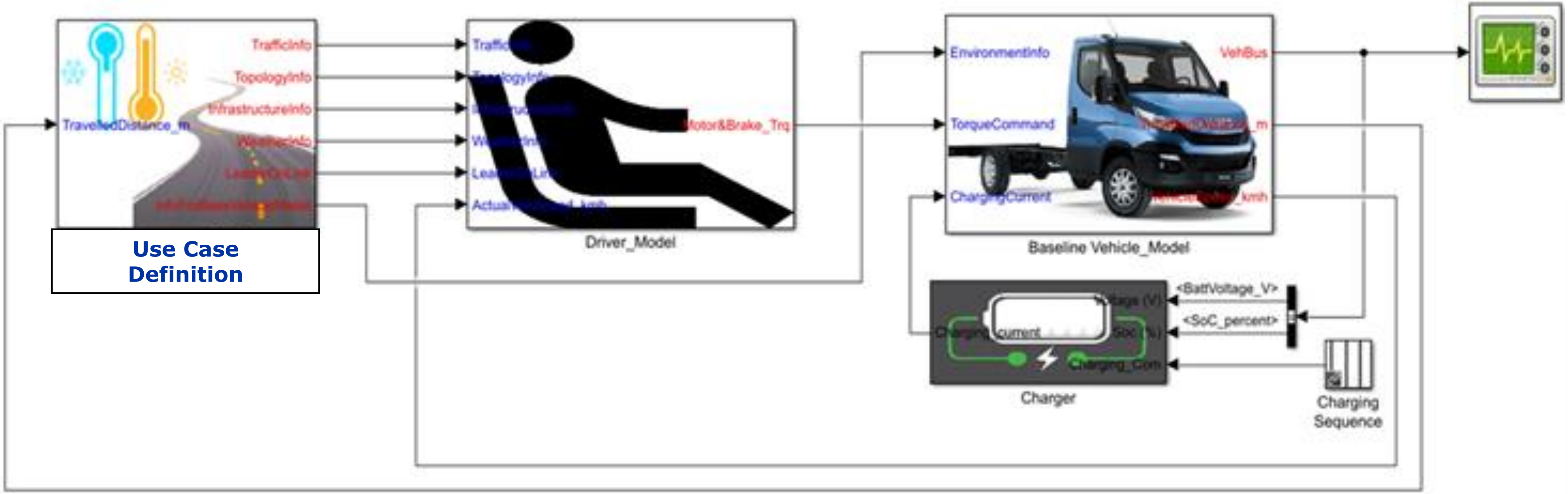
Charging Scenarios *
- ✓ Fast, semi-fast, slow
- ✓ Driving after fast charging
- ✓ Pre-conditioned or not?

Road characteristics!
- ✓ Traffic, Road slope, Vehicle grading

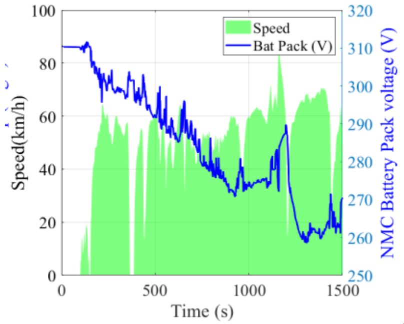
* Functional Load
! Environmental Load

Source: PhD Thesis of Sajib Chakraborty 2022

UTILIZATION FOR DIGITAL TWIN FOR MISSION PROFILE TRANSLATION

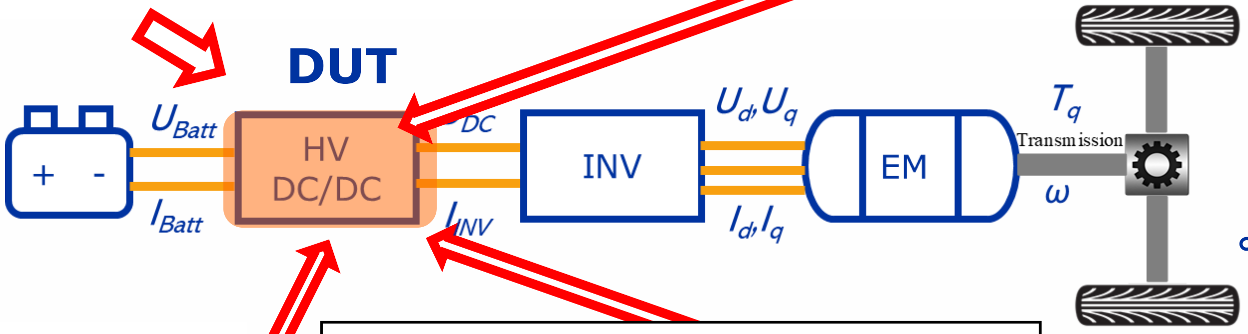


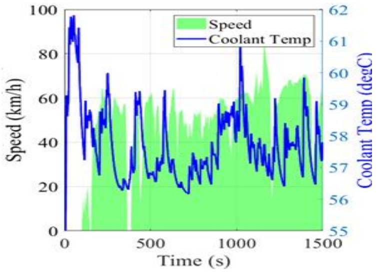
DEVICE–LEVEL LOADING FOR ‘DEVICE UNDER TEST CONVERTER’



Battery Voltage

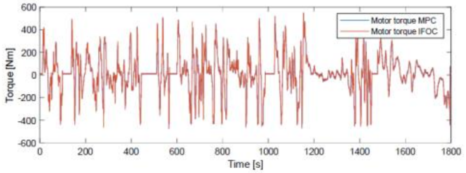
✓ Technology
(i.e., NMC, LFP, LTO)





Coolant Profile

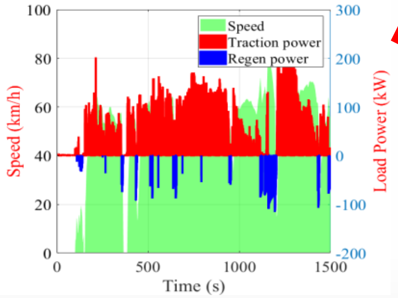
✓ Type of cooling
(i.e., Liquid, Forced air)



All have impacts on thermal cycling and reliability !!!

Control strategy

✓ Type of control
(i.e., DFC, IFOC, MPC)



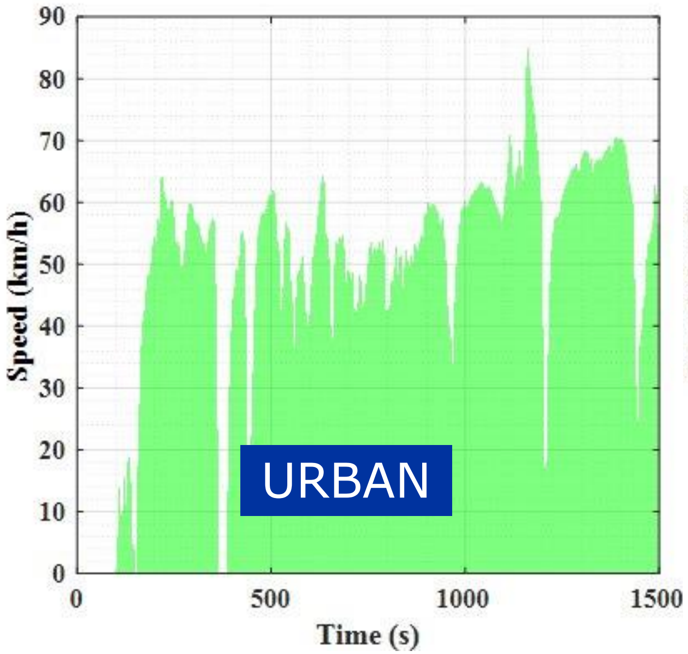
Load Profile

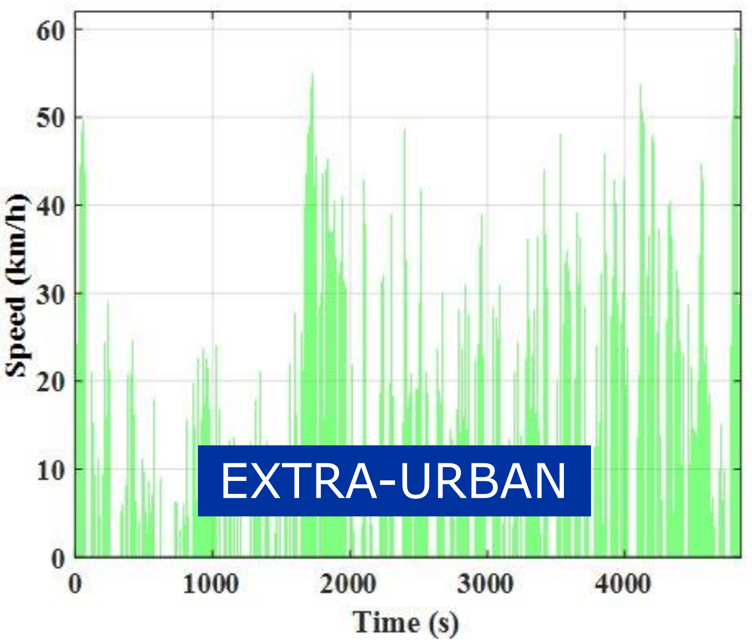
✓ EV cycle
(i.e., NEDC, WLTC, Urban..)

EXEMPLARY EV MISSION PROFILE FROM EU PROJECT

OEM DATA

Use Case Scenario	Description of Use Case	Resulting velocity profile
(A1) Special goods deliver inside the Turin City → Standard ambient condition of 25⁰C	Parcel service with multiple stops for (un-) loading: delivery in urban areas	Distance: 20.4 km Duration: 4845 s Average Speed: 4.24 m/s
(B1) Parcel service inter-city daily job (highway driving) → Standard ambient condition of 25⁰C	Parcel service without any intermediate stops for (un-) loading: delivery outside the city	Distance: 20.3 km Duration: 1500 s Average speed: 13.55 m/s





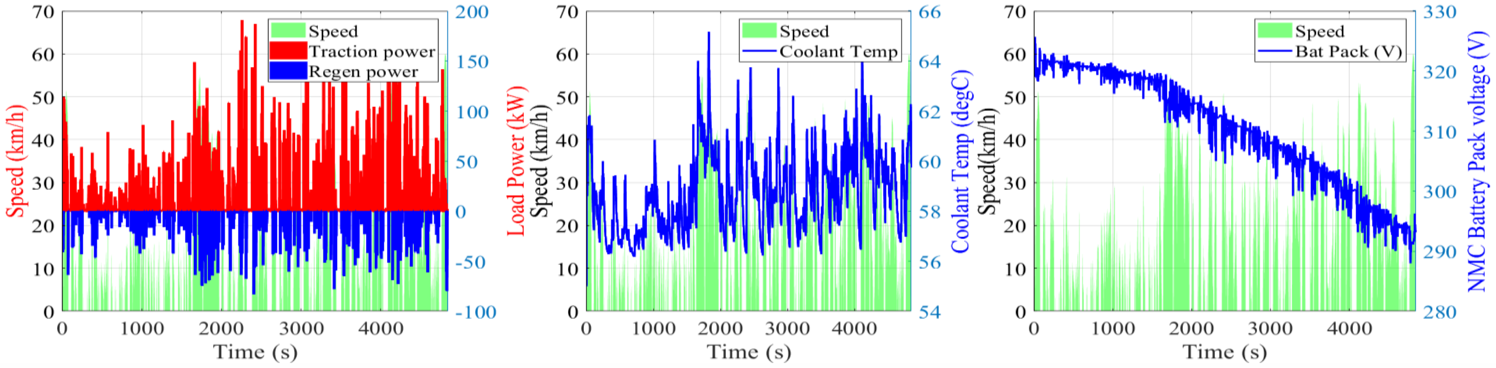
Key Observations:

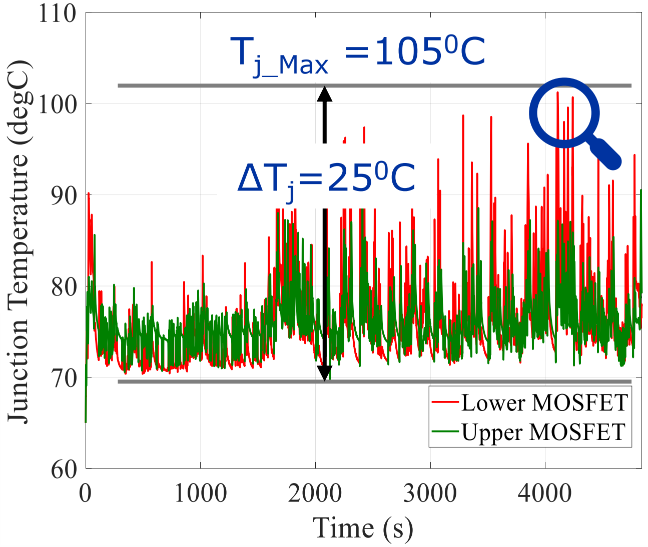
- Almost the same distance traveled
- The stressors will be different
- Equal lifetime requirements can't be applied for both UCs

Courtesy of https://www.hifi-elements.eu

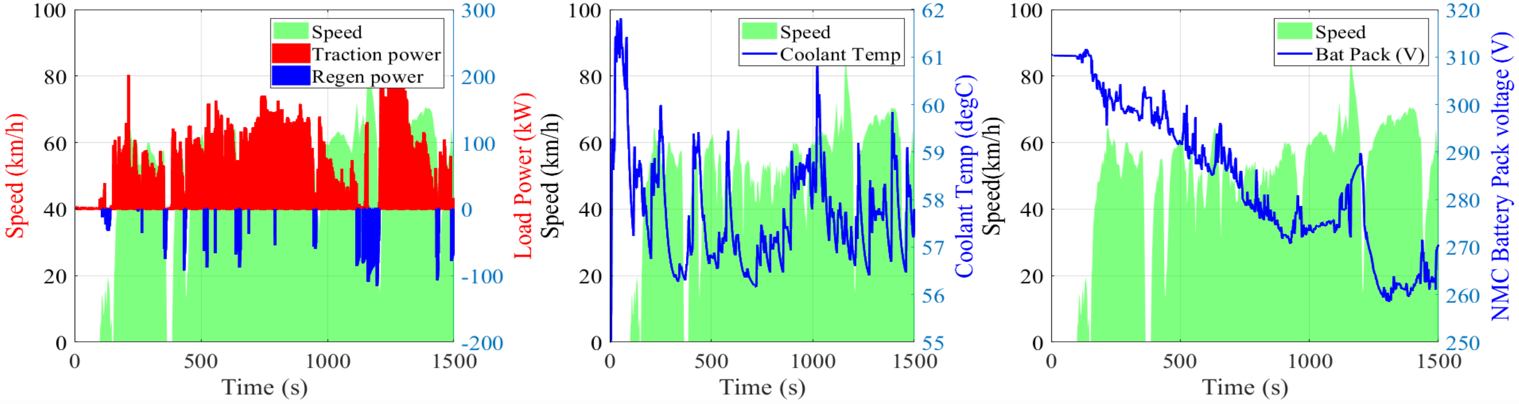
HIFI-ELEMENTS

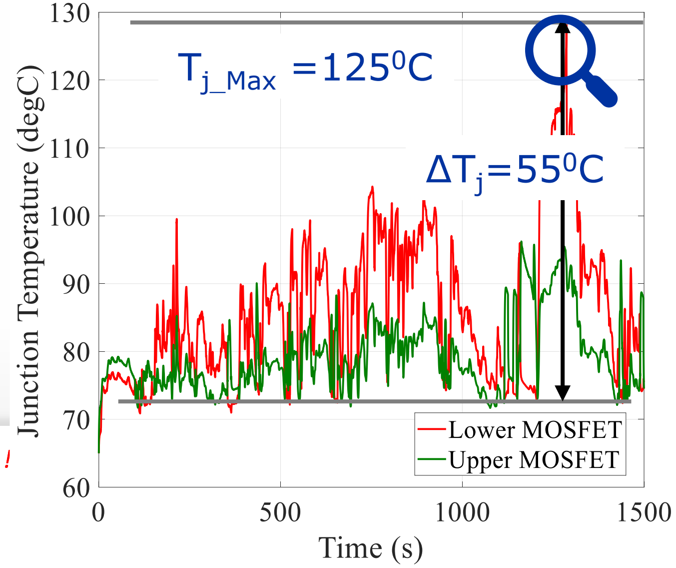
MISSION PROFILE IMPACT ON THERMAL STRESS





(A1) Extra-Urban Cycle (Van for Parcel delivery)
Distance: 20.6 km; Duration: 4845 s; Average Speed: 4.24 m/s





(B1) Urban Cycle (Use Case: Van for intra-city duty)
Distance: 20.3 km, Duration: 1500 s; Average speed: 13.55 m/s

mission.

ELECTROMOBILITY RESEARCH CENTRE

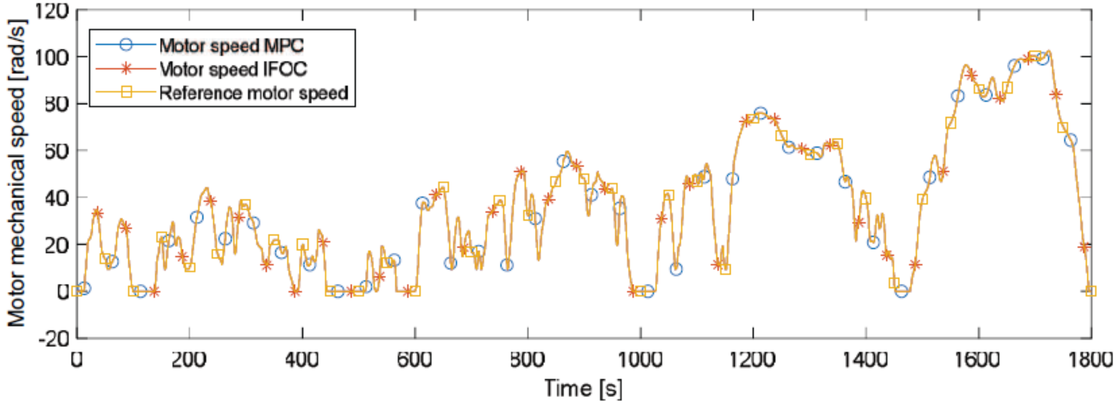
EFFICIENT POWER ELECTRONICS, POWERTRAIN & ENERGY SOLUTIONS RESEARCH GROUP

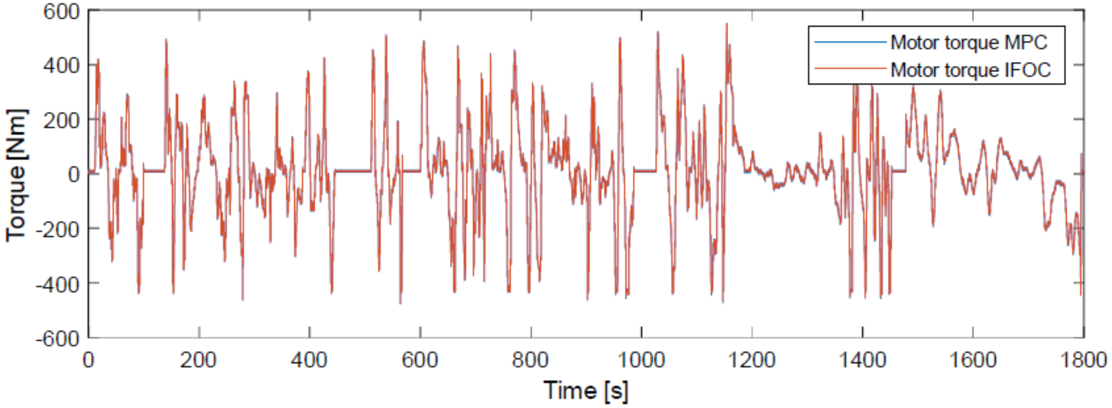
Power Electronics and Motion Control Council

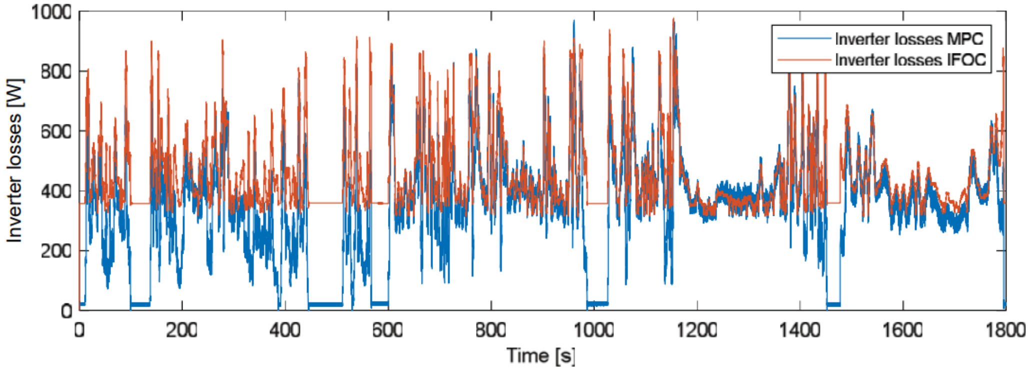
PEMC

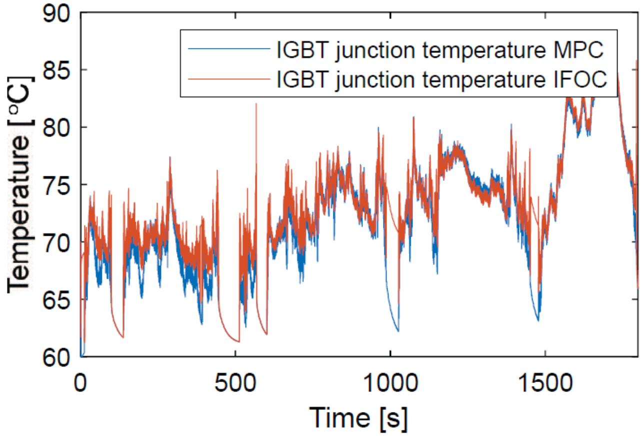
LOW-LEVEL CONTROL IMPACT ON THERMAL STRESS

Use Cases Description:
- A2: 1 WLTP cycle drive using MPC-based PWM control for traction inverter
- B2: 1 WLTP cycle drive using IFOC-based PWM control for traction inverter







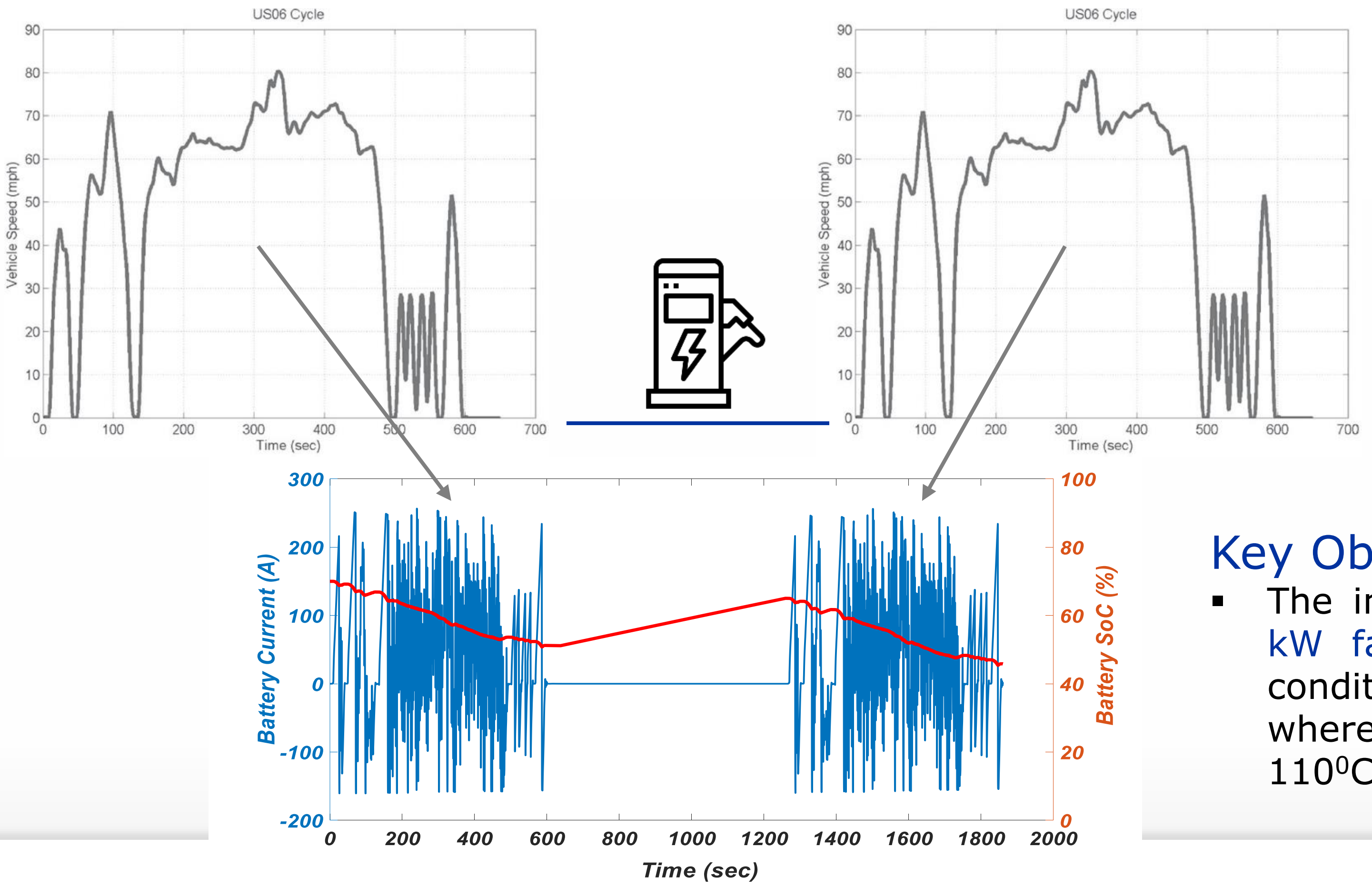


Key Observation:
- Same coolant profile and battery profile were used, while the MPC resulted in a 1.77% lower IGBT temperature

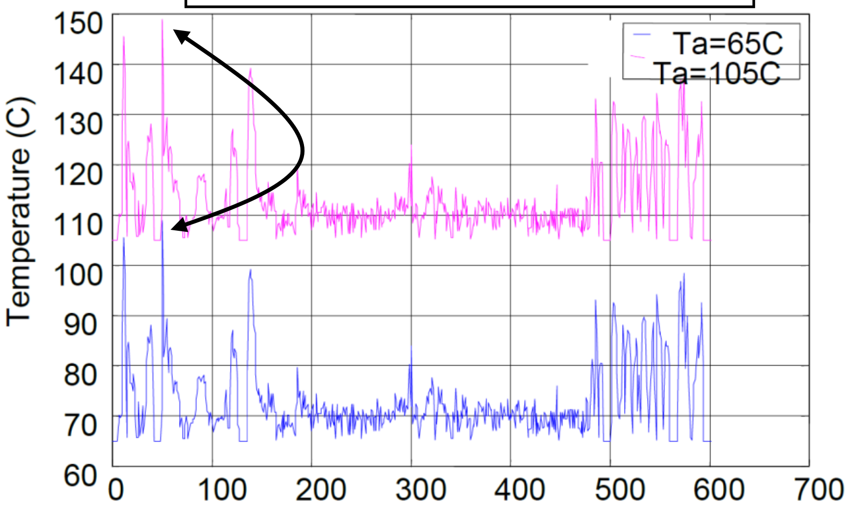
CHARGING IMPACT ON THERMAL STRESS

Use Cases Description:

- 1 US06 cycle drive + 11 min charge with 75 kW (with thermal conditioning) + 1 US06 cycle drive
- 1 US06 cycle drive + 11 min charge with 75 kW (without thermal conditioning) + 1 US06 cycle drive



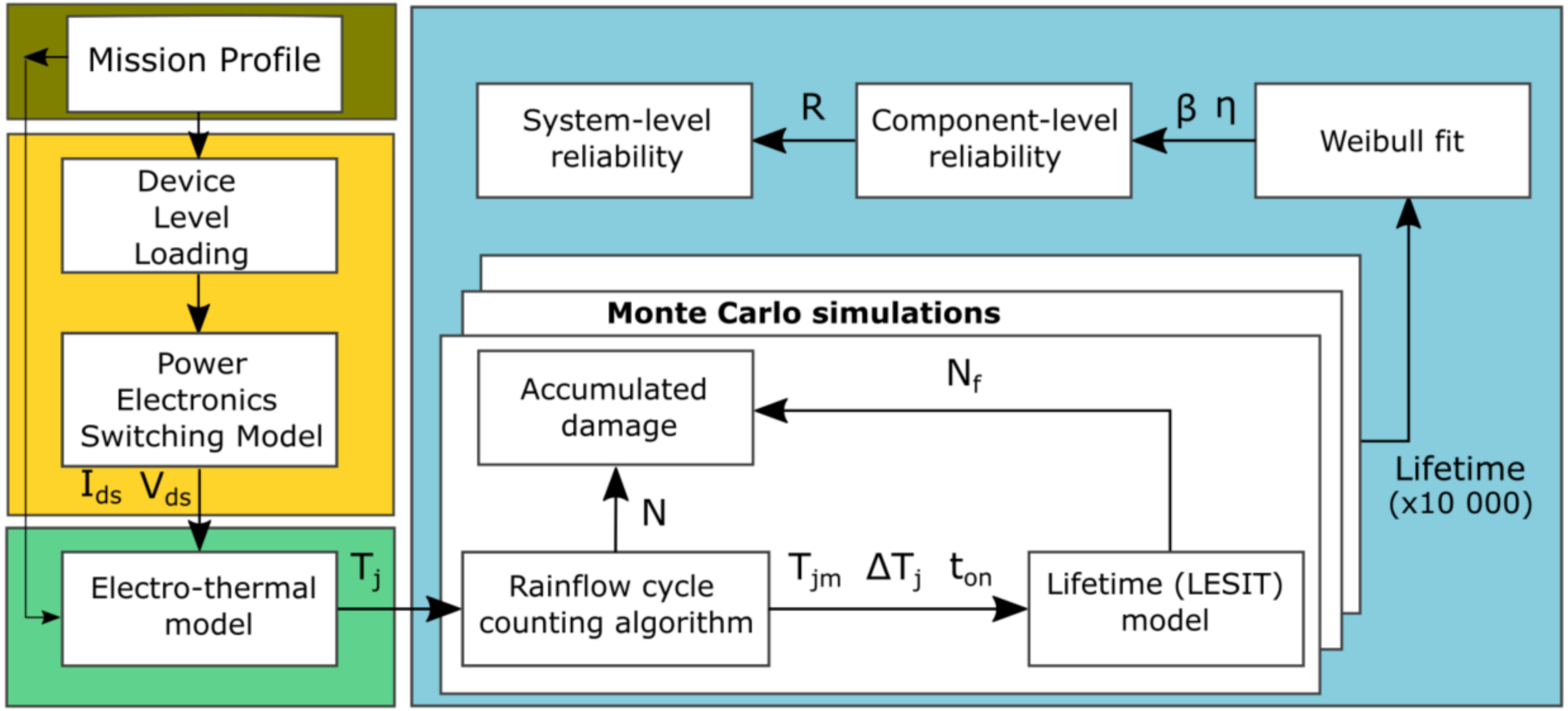
Thermal Cycle after Charging



Key Observation:

- The initial coolant temperature reach 105^{0}C after 75 kW fast Charging for 11 minutes without thermal conditioning, and maximum T_j goes beyond 145^{0}C; whereas smart thermal management keeps it below 110^{0}C

RELIABILITY ASSESSMENT USING DIGITAL TWIN

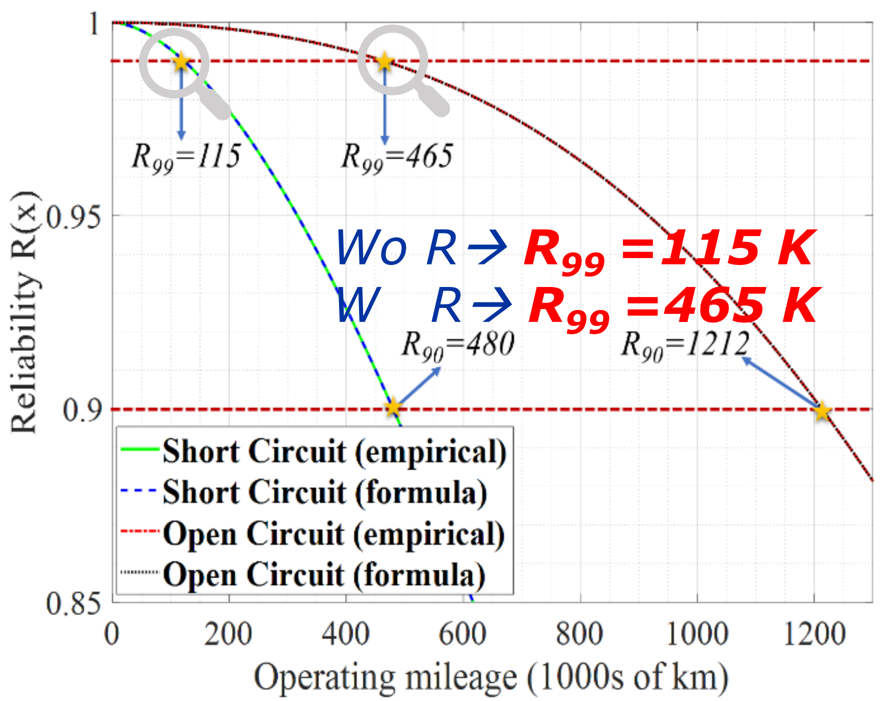


***MREL**: connected Mission Profile oriented RELiability assessment tool*

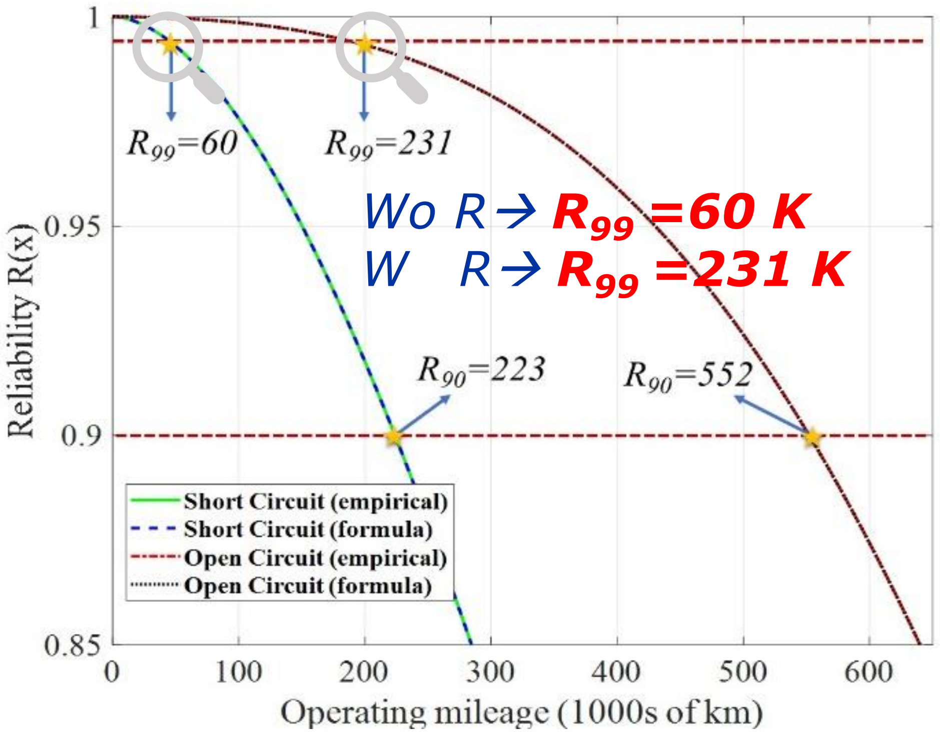
Details in: S. Chakraborty et al., IEEE Journal of Emerging and Selected Topics in Power Electronics, vol. 10, no. 5, pp. 5142-5167, Oct. 2022

RESULT AND ANALYSIS

EXTRA-URBAN



URBAN

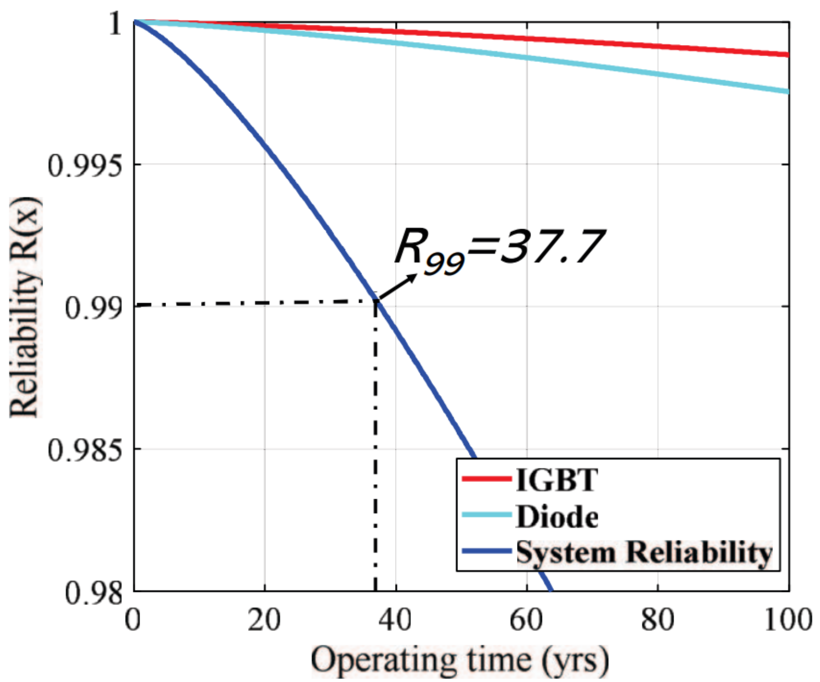


Analysis: The same DUT is ***~2 Times*** more reliable if the EV is subjected to an Extra-urban profile compared to the urban throughout its lifecycle;

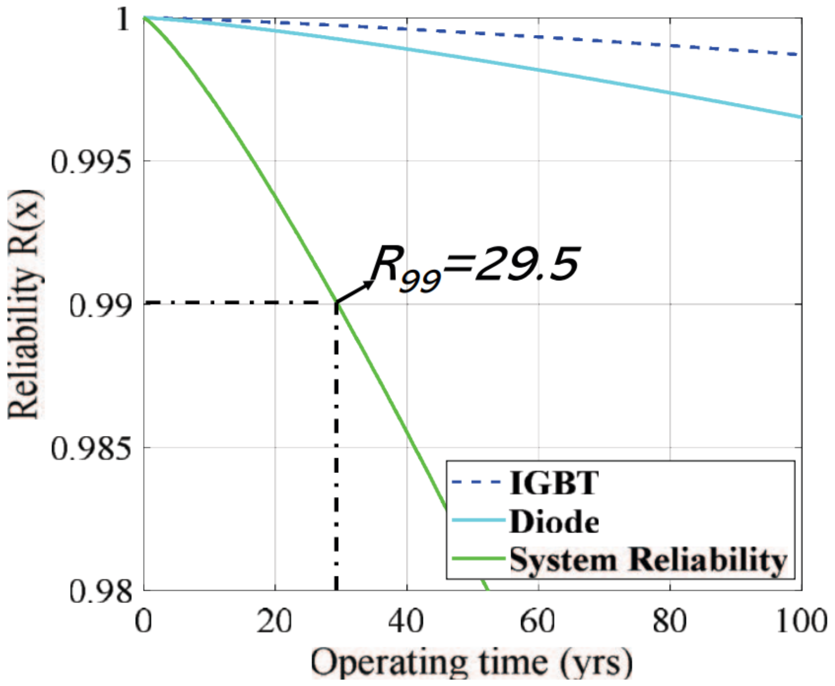
Details in: S. Chakraborty et al., IEEE Journal of Emerging and Selected Topics in Power Electronics, vol. 10, no. 5, pp. 5142-5157, Oct. 2022

RESULT AND ANALYSIS

IFOC-BASED CONTROLLER



MPC-BASED CONTROLLER

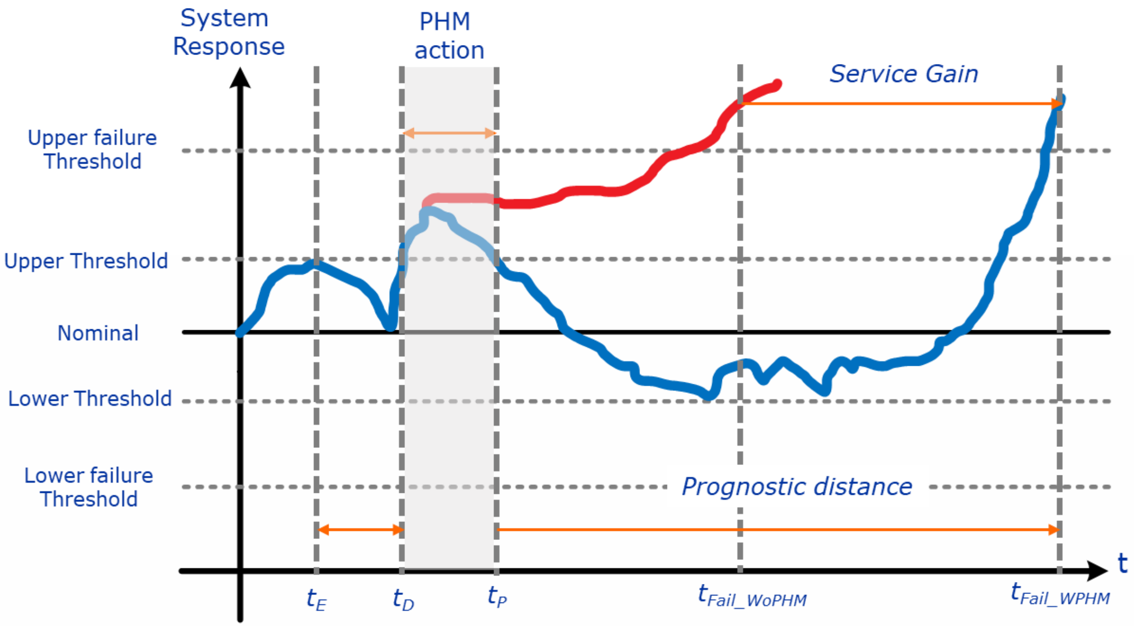


Analysis: the IFOC resulted in a **21%** longer lifetime, due to the lower temperature swings in the MPC inverter devices, even though its average junction temperature is higher for same mission profile.

Details in: A. Zhaksylyk, et. Al., *2021 Sixteenth International Conference on Ecological Vehicles and Renewable Energies (EVER)*, Monte-Carlo, Monaco, 2021, pp. 1-6, doi: 10.1109/EVER52347.2021.9456616.

PHM ACTIVATION APPROACH AND RELATED TESTS

ONLINE DIGITAL TWIN



t_E → First-time exhibit an off-nominal behavior
t_D → Time PHM detects an off-nominal behavior
t_P → Time PHM complete predictive action
$t_{FailWoPHM}$ → Actual Time System fails without PHM
$t_{FailWPHM}$ → Actual Time System fails with PHM

On Device level:

- AEC-Q100, AEC-Q101 (Devices, Power Devices)
- AQG 324 (Modules)

On Component (ECU) level:

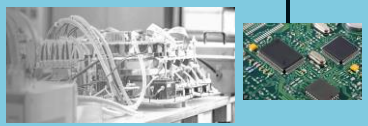
- Stress tests based on IEC norms (HTOL test, vibration, corrosion, …)
- Mission critical test for the life expectancy of the car

Source: IEEE Std 1856™-2017

CONDITION MONITORING FOR PHM

Non-Invasive
- *Use of Global signals*
- *Hybrid (Physics/Data-driven) models*

Inputs

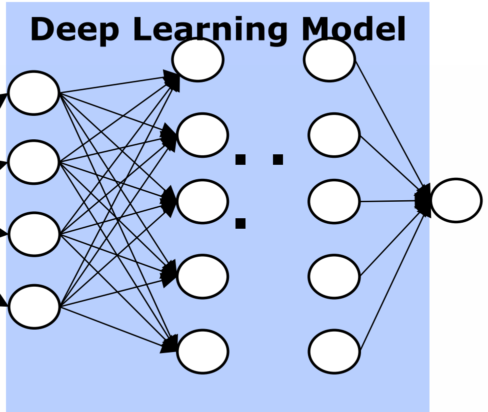


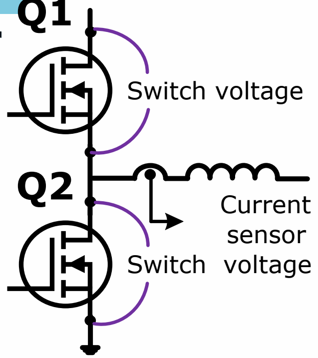
Power Converter

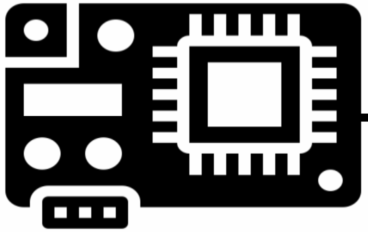
Outputs

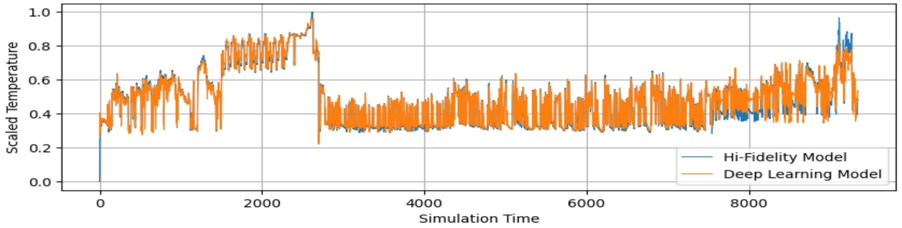
Invasive Circuits/Sensors
- *Integrated into Power Converter Hardware*

Triggering

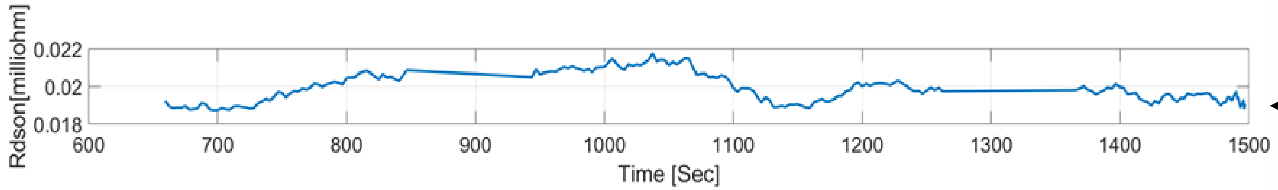






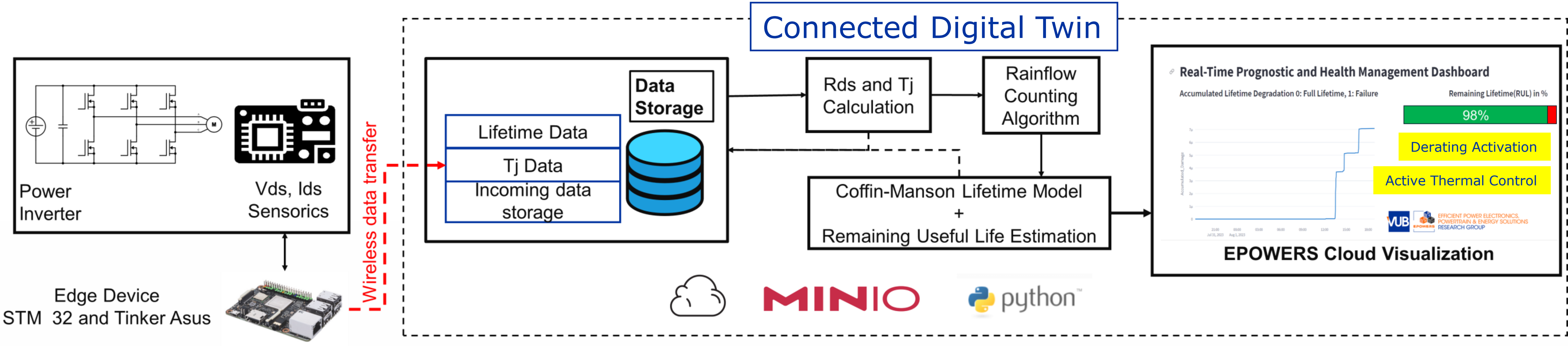


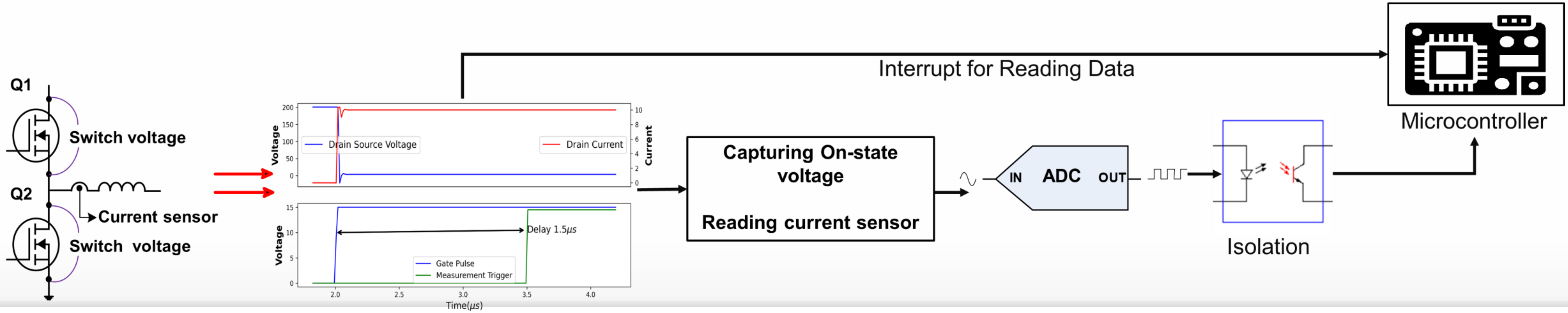
Simulation and Real-time Estimations



Measurement Results

FULL-SCALE EXAMPLE OF A PHM IMPLEMENTATION AT COMPONENT-LEVEL





SUMMARY

- User-centric design and connected digital twins in the cloud offer significant opportunities to improve both the operation and safety of EVs
- Capability to anticipate unexpected failures to prevent downtime
- Make EVs more energy-efficient, comfortable, safe and affordable

REMARKS

Which method is mandatory for Reliability and safety-related design?

✓ Mission-profile-oriented design

Which method is better for the C&HM?

✓ Depends on the access to DUT

What are the constraints for Reliability and PHM implementation?

✓ The access point, historical data availability, lifetime model parameters, maturity of the DUT, time availability for the test, and OEM preference

Conclusions and Future Outlooks

SUMMARY

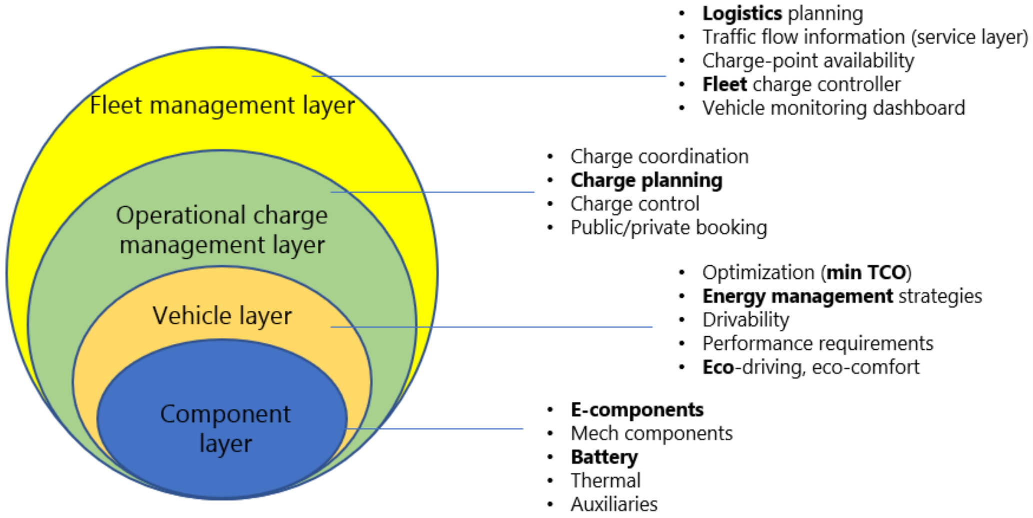
DIGITAL TWINS AT DIFFERENT LAYER

- **Component Layer:** ***Multi-X simulations*** are used to model the interactions of e-components, mechanical parts, batteries, and auxiliary systems at various scales and fidelities.

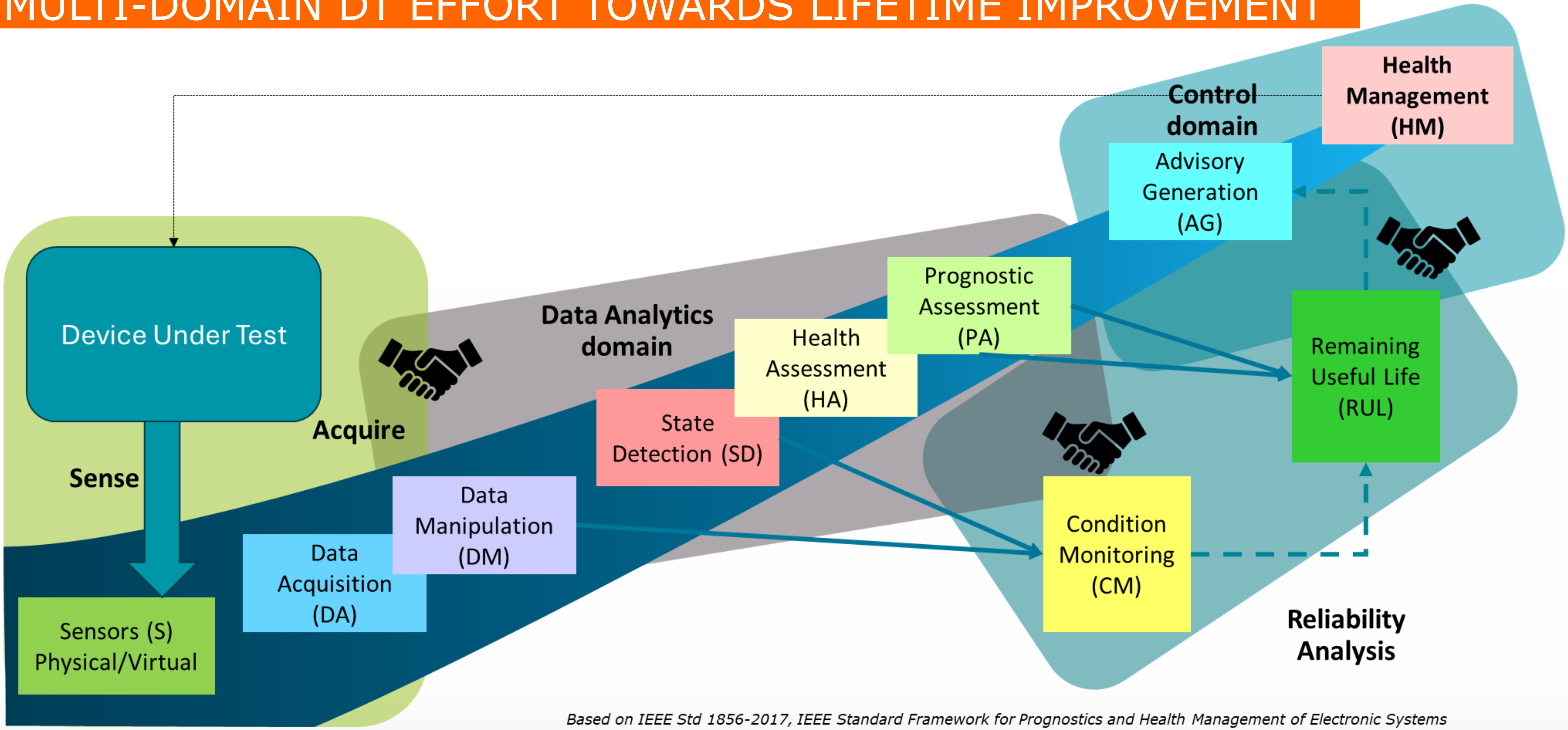
- **Vehicle Layer:** The vehicle layer utilizes ***an analytical framework*** for multi-objective design exploration and optimization, focusing on energy management, drivability, and minimizing total cost of ownership (TCO).

- **Operational Charge Management Layer:** ***Resource-efficient modeling*** methods are employed to coordinate, plan, and control charging processes.

- **Fleet Management Layer:** ***Data-driven, fast, and accurate*** models are used to optimize logistics, traffic flow, charge-point availability, and fleet-wide charging, supported by real-time monitoring dashboards.



MULTI-DOMAIN DT EFFORT TOWARDS LIFETIME IMPROVEMENT



Based on IEEE Std 1856-2017, IEEE Standard Framework for Prognostics and Health Management of Electronic Systems

LINKED PROJECT

For more details visit: https://ebrt2030.eu/

For more details visit: https://zefes.eu/

For more details visit: https://www.hiefficient.eu/

For more details visit: https://www.hifi-elements.eu

*This Tutorial result is part of the **DT4V SBO project** funded and supported by Flanders Make, the strategic research center for the manufacturing industry.*

INTERESTING PUBLICATIONS FROM MOBI

PART I

1. Hasan, M.M.; et.al., "Parameter Optimization and Tuning Methodology for a Scalable E-Bus Fleet Simulation Framework: Verification Using Real-World Data from Case Studies," *Appl. Sci.* 2023, *13*, 940.
2. Bhoi, S. K., et.al., "Intelligent data-driven condition monitoring of power electronics systems using smart edge–cloud framework," Jul 2024, In Internet of Things; Engineering Cyber Physical Human Systems. 26, 101158, 17 p., 101158.
3. Bhoi, S. K., et. Al., "A Data-Driven Thermal Digital Twin of a 3-Phase Inverter Using Hi-Fidelity Multi-Physics Modelling," 2 Oct 2023, *2023 25th European Conference on Power Electronics and Applications (EPE'23 ECCE Europe).* Aalborg, Denmark: IEEE Explore, p. 1-8.
4. Frikha, M. A., et. Al., "Concept Validation of Digital Twin-Based Power Losses Estimation Method for Traction Inverter Applications," 2 Oct 2023, *2023 25th European Conference on Power Electronics and Applications (EPE'23 ECCE Europe).*
5. Tran, D., et.al., "Advanced Digital Twin Framework for Electric Truck," *2023 IEEE Vehicle Power and Propulsion Conference, VPPC 2023 - Proceedings.* Institute of Electrical and Electronics Engineers Inc., 6 p.
6. Pardhi, S., "Optimal Powertrain Sizing of Hydrogen Fuel Cell Electric Coach for Lifetime Carbon Footprint, Total Costs and Fuel Consumption Minimization," *2023 IEEE Vehicle Power and Propulsion Conference, VPPC 2023 - Proceedings.* Institute of Electrical and Electronics Engineers Inc., 6 p.
7. Pardhi, S., et.al., "A Review of Fuel Cell Powertrains for Long-Haul Heavy-Duty Vehicles: Technology, Hydrogen, Energy and Thermal Management Solutions," 16 Dec 2022, In: Energies. 15, 24, p. 1-56 56 p., 9557.

INTERESTING PUBLICATIONS FROM MOBI

PART II

1. S. Chakraborty *et al.*, "X-in-the-Loop Validation of Deep Learning-Based Virtual Sensing for Lifetime Estimation of Automotive Power Electronics Converters," in IEEE Journal of Emerging and Selected Topics in Power Electronics, doi: 10.1109/JESTPE.2024.3391930.
2. S. Chakraborty *et al.*, "Real-Life Mission Profile-Oriented Lifetime Estimation of a SiC Interleaved Bidirectional HV DC/DC Converter for Electric Vehicle Drivetrains," in *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 10, no. 5, pp. 5142-5167, Oct. 2022, doi: 10.1109/JESTPE.2021.3083198.
3. F. Hosseinabadi, et. al, "A Comprehensive Overview of Reliability Assessment Strategies and Testing of Power Electronics Converters," in IEEE Open Journal of Power Electronics, doi: 10.1109/OJPEL.2024.3379294.
4. S. K. Bhoi, et. al, "Intelligent data-driven condition monitoring of power electronics systems using smart edge–cloud framework," Internet of Things, Volume 26, 2024.
5. S. K. Bhoi et al., "A Data-Driven Thermal Digital Twin of a 3-Phase Inverter Using Hi-Fidelity Multi-Physics Modelling," 2023 25th European Conference on Power Electronics and Applications (EPE'23 ECCE Europe), Aalborg, Denmark, 2023, pp. 1-8, doi: 10.23919/EPE23ECCEEurope58414.2023.10264373.
6. Verbrugge, B.; et al., "Reliability Assessment of SiC-Based Depot Charging Infrastructure with Smart and Bidirectional (V2X) Charging Strategies for Electric Buses". Energies 2023, 16, 153. https://doi.org/10.3390/en16010153
7. F. Hosseinabadi, et. al, "Active Thermal Control of a DC-DC Converter Using Dynamic Gate-drive for Reliability Improvement," 2023 25th European Conference on Power Electronics and Applications (EPE'23 ECCE Europe), Aalborg, Denmark, 2023, pp. 1-8, doi: 10.23919/EPE23ECCEEurope58414.2023.10264268.
8. A. Zhaksylyk, et.al., "Effects of modularity on the performance and reliability of SiC MOSFET-based active front-end rectifiers in EV charging application," IECON 2022 – 48th Annual Conference of the IEEE Industrial Electronics Society, Brussels, Belgium, 2022, pp. 1-7, doi: 10.1109/IECON49645.2022.9968778.
9. S. Chakraborty et al., "Scalable Modeling Approach and Robust Hardware-in-the-Loop Testing of an Optimized Interleaved Bidirectional HV DC/DC Converter for Electric Vehicle Drivetrains," in IEEE Access, vol. 8, pp. 115515-115536, 2020, doi: 10.1109/ACCESS.2020.3004238.

SUPPORT TEAM

Many thanks to our support team:

Ashleigh HRUZ

Gamze EGIN MARTIN

Mohamed Amine FRIKHA

Mohamed Mahedi HASAN

Sachin Kumar BHOI

Saeed KAZEMIAN

Shantanu PARDHI

Pegah Rahmani

Thanks for your attention !!

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VUB VRIJE UNIVERSITEIT BRUSSEL

Power Electronics and Motion Control Council PEMC

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