APPLYING MODULAR ENERGY MANAGEMENT STRATEGY TO HEV POWERTRAIN DESIGN & CONTROL

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EVS35
OSL2022

WHY HYBRID?

Hybridization benefits	engine downsizing and operating point shifting
	elimination of idling and clutching losses
	energy recuperation
	additional control freedom

additional control freedom → How to exploit this benefit?

MANY CONTROL POSSIBILITIES ARE AVAILABLE

Heuristic Control (rule-based)	simple and robust
	easily implementable
	does not provide optimal solution

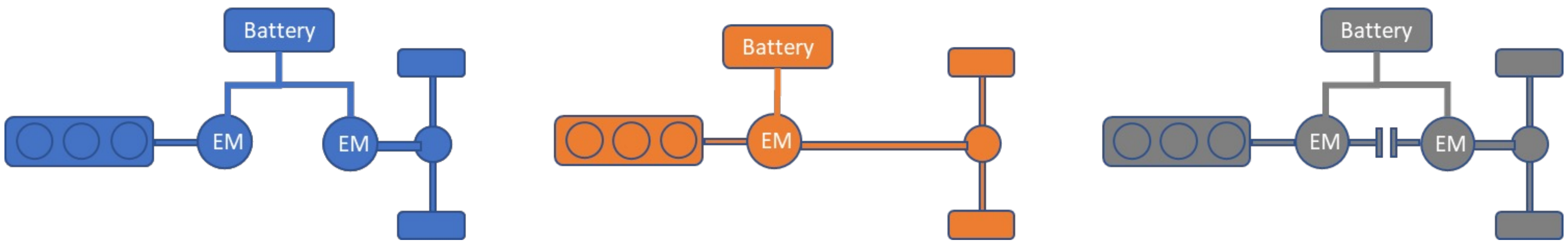
Optimal Control	complex to derive
	computationally expensive
	provides optimal solution

Trade-off solution? → Modular Energy Management Strategy (MEMS) by TNO [1]

[1] Romijn, T. C. J., Pham, T. H., & Wilkins, S. (2019). Modular ECMS Framework for Hybrid Vehicles. *IFAC-PapersOnLine*, *52*(5), 128–133. https://doi.org/10.1016/j.ifacol.2019.09.021

WHY MODULAR?

- The energy management strategy is different for every vehicle topology/configuration



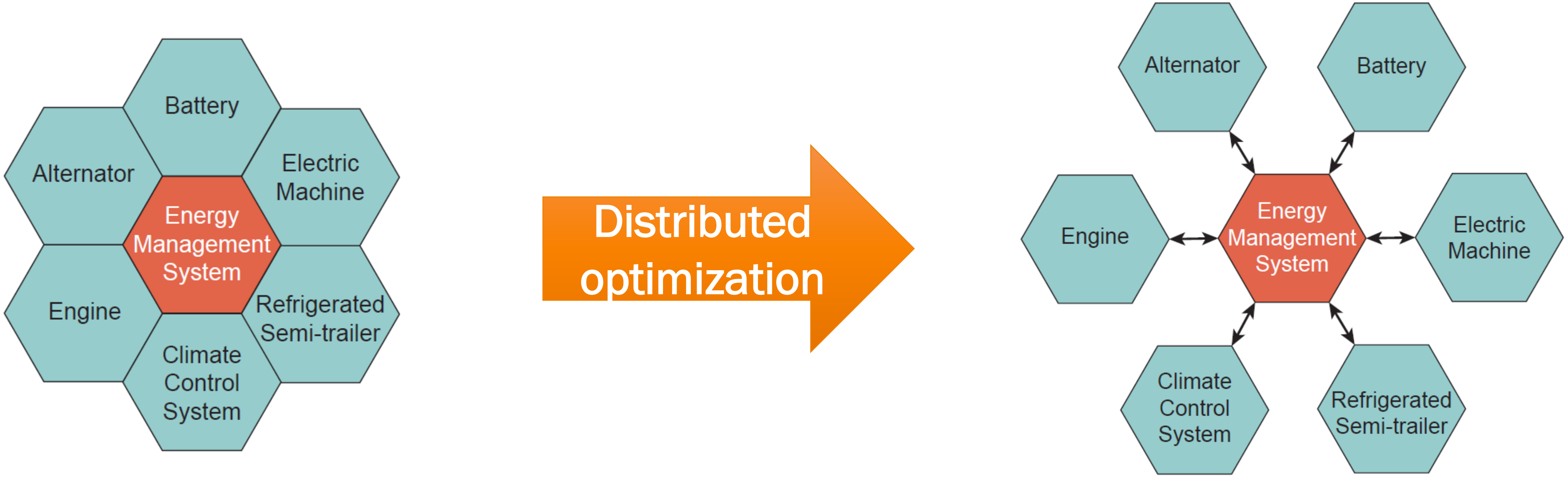
- For maximum performance, recent developments also included **control of auxiliaries**
- EMS development is **complex** and **labour-intensive**
- Modularity allows **distributed development**
  - Engine -> Emissions, thermal management
  - Battery -> Aging, thermal management
- Enables **automatic generation** of the control block and its settings

MODULAR ENERGY MANAGEMENT STRATEGY (MEMS)

Modular Energy Management Strategy (MEMS) by TNO to achieve **maximum performance** (fuel/energy consumption, battery life, emissions)

- Based on applying decomposition to the ECMS optimal control problem
- Minimizing power losses instead of fuel consumption
- Scalable to any powertrain configuration

$$\textbf{min} \ \dot{m}_f(y_{ice}) - \lambda \dot{E}_s \Leftrightarrow \textbf{min} \sum_{m \in M} u_m - y_m - \lambda \dot{E}_s$$

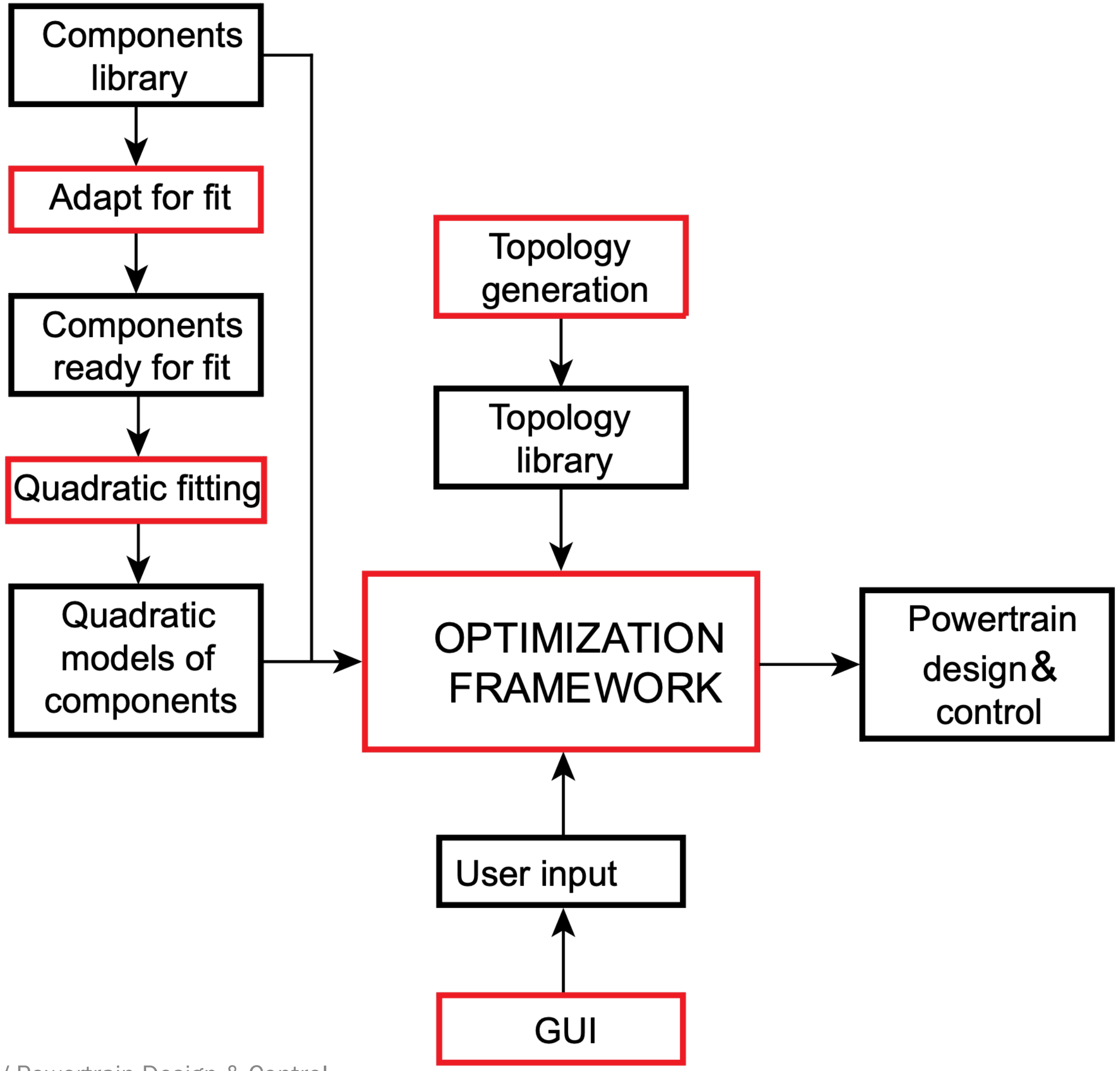


PROBLEM STATEMENT

- Hybrid electric vehicles (HEVs) have many potential different topologies / configurations
  - Many new technologies to combine power sources (e.g. engine, motor, battery, transmissions)
  - Therefore, the design process posses challenges in terms of the cost of development, choice of technologies, optimisation

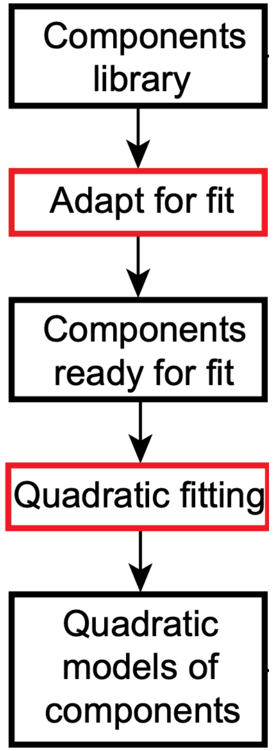
- Automating the design process: development of a tool which can advise on the plant and control design (Co-Design) based on optimal control
  - the objective of this project is to develop such a tool, incorporating TNO's Modular Energy Management Strategy
  - this goal of the tool is to recommend a topology, component sizing and derive the corresponding energy management strategy

DEVELOPMENT OF TOPDSIGN
SYSTEM OVERVIEW



DEVELOPMENT OF TOPDSIGN

TOPOLOGY AND COMPONENT LIBRARY



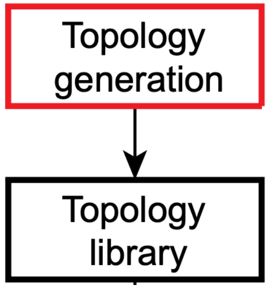
COMPONENT LIBRARY

- Power sourses prepresented with efficiency maps
- Battery represented as cells connected in series and parallel
- Quadratic fitting to obtain quasiconvex models (required for MEMS)

$$q_m(\omega_m)u_m^2 + f_m(\omega_m)u_m + e_m(\omega_m) + y_m = 0$$

TOPOLOGY LIBRARY

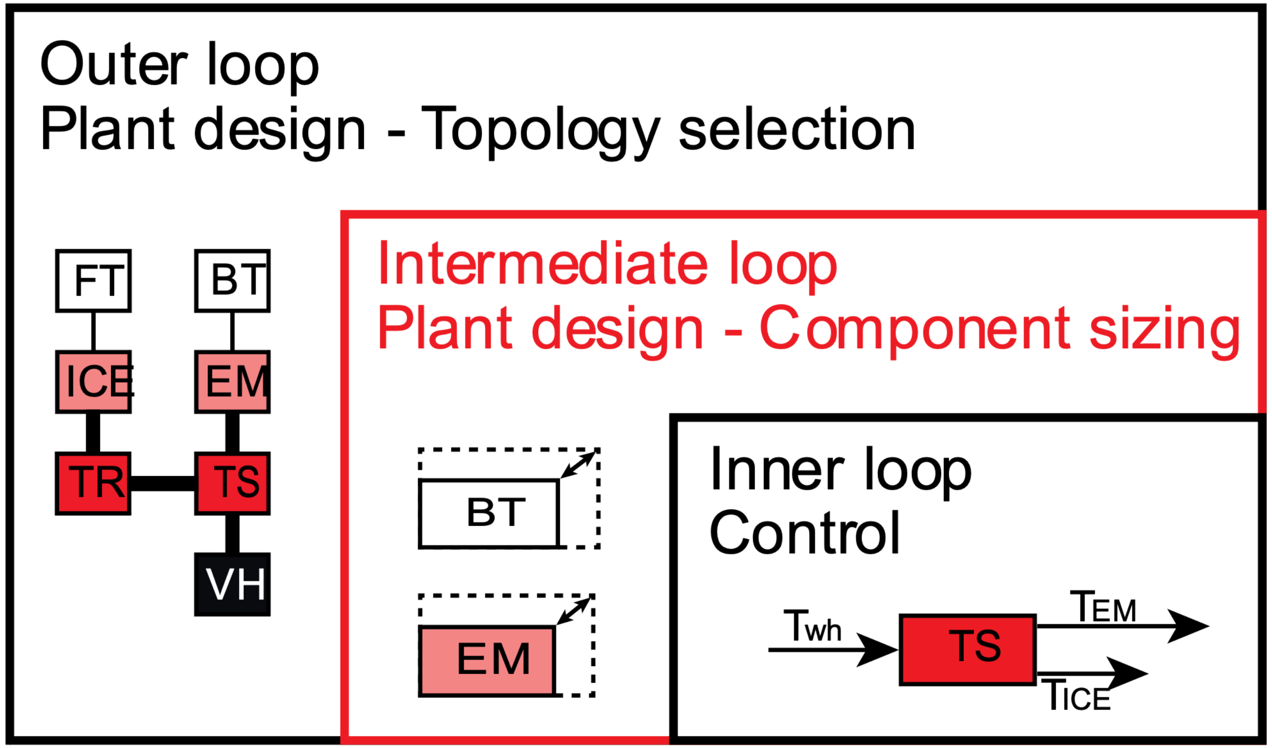
- Series & Parallel (P2, P3) hybrid topologies
- User can include up to 4 electric machines



DEVELOPMENT OF TOPDSIGN

OPTIMIZATION FRAMEWORK

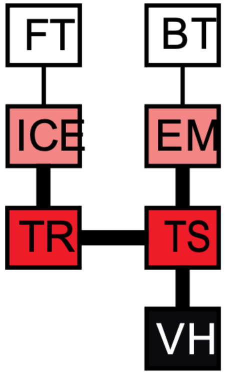
OPTIMIZATION FRAMEWORK



More info: Silvas, E., Hofman, T., Murgovski, N., Etman, P. F. P., & Steinbuch, M. (2017). Review of optimization strategies for system-level design in hybrid electric vehicles. *IEEE Transactions on Vehicular Technology*, *66*(1), 57. https://doi.org/10.1109/TVT.2016.2547897

DEVELOPMENT OF TOPDSIGN

Outer loop
Plant design - Topology selection

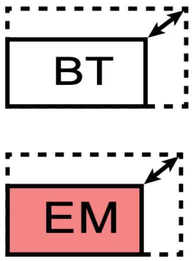


THE TASK OF THE OUTER LOOP IS TO CREATE THE PLANT DESIGN IN TERMS OF A TOPOLOGY.

- The limited amount of topologies omits the need for a sophisticated optimization algorithm
- Implemented with via loop with parallel execution

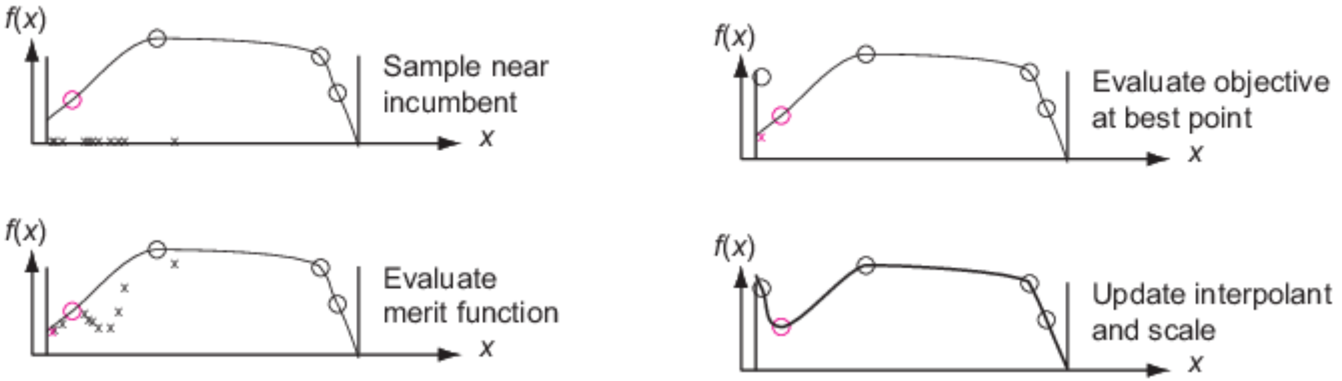
DEVELOPMENT OF TOPDSIGN

Intermediate loop
Plant design - Component sizing

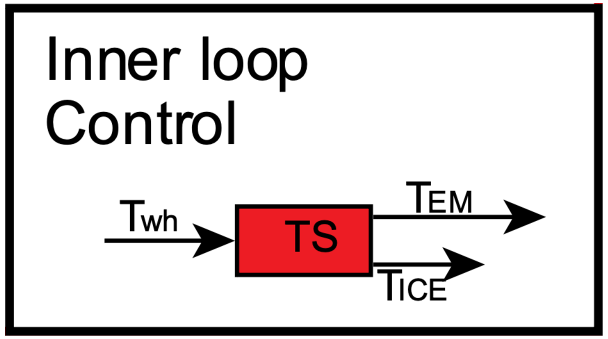


THE TASK OF THE INTERMEDIATE LOOP IS TO CREATE THE PLANT DESIGN IN TERMS OF COMPONENT SIZING.

- Enourmous design space → introduce Surrogate optimization algorthm in MATLAB
- Does guarantee locally optimal solution
- Component sizes are picked and then matched to actual components and scale



DEVELOPMENT OF TOPDSIGN

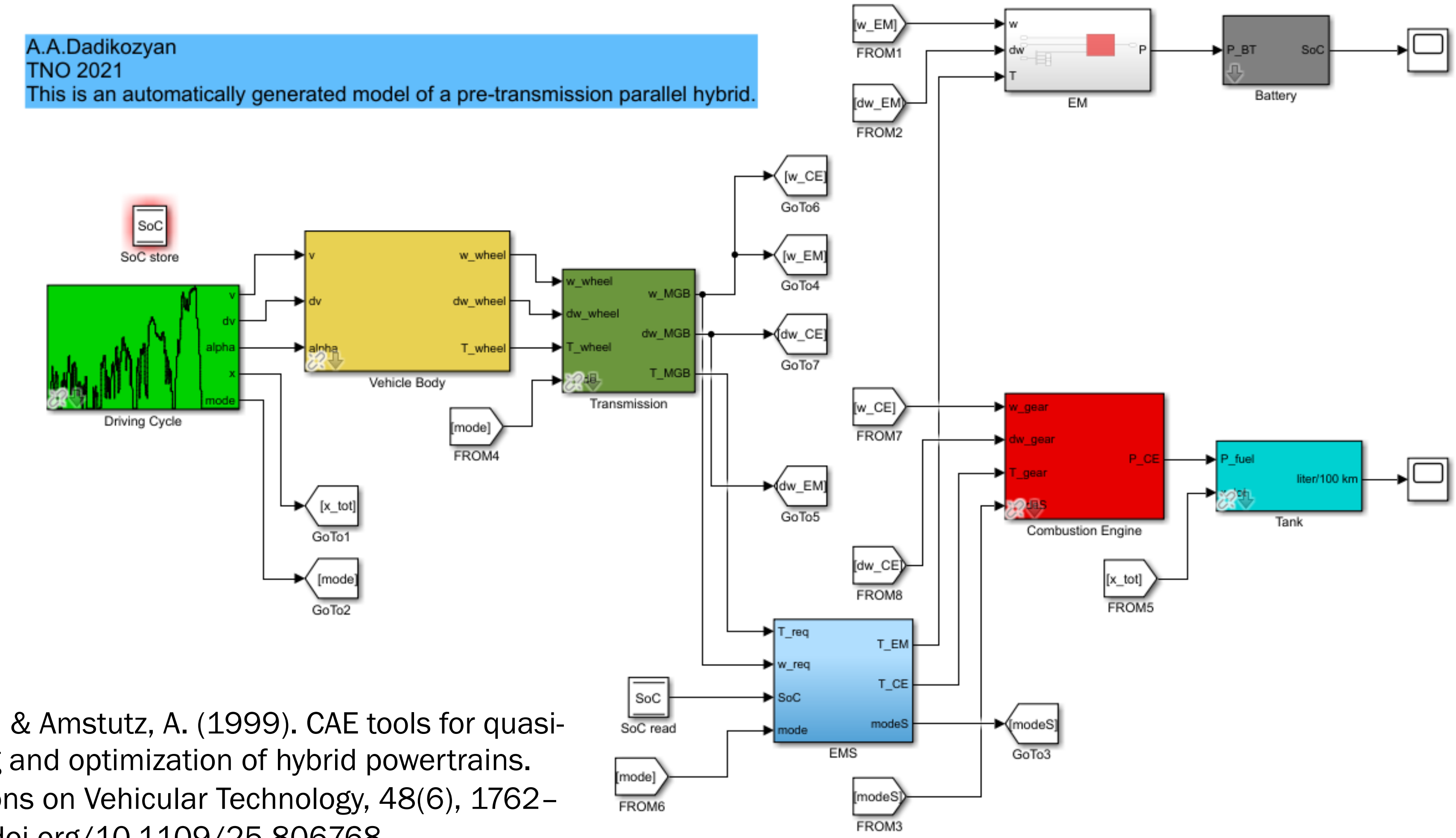


THREE CONTROL ASPECTS ARE DERIVED IN THE INNER LOOP

Torque split	For parallel and series (with 2 or more motors) topologies
	Couple transmission shaft speed with movers speed
Generator-engine on/off	Mixed-integer problem
	Only in series hybrids
	Predetermine optimal operation point and let MEMS decide when to turn on/off
Gear shift	Mixed-integer problem
	Used in all topologies
	Compare efficiency for each gear and determine optimal gear (also for regenerative braking)

DEVELOPMENT OF TOPDSIGN

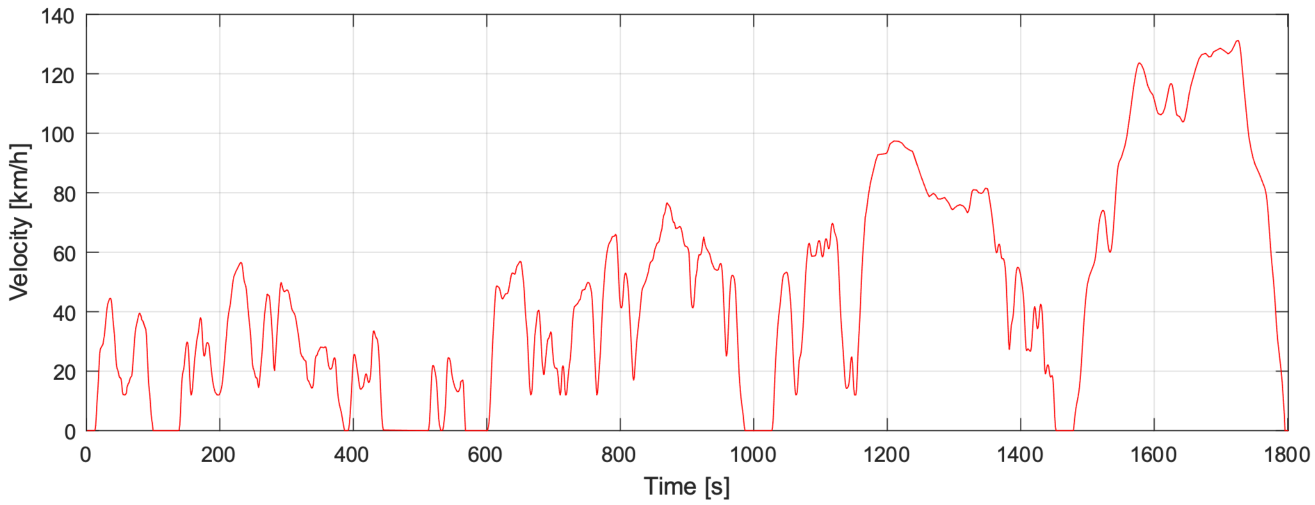
CLOSED-LOOP AUTOMATIC TESTING WITH QSS TOOLBOX FROM ETH [2] ADAPTED BY TU/E



[2] Guzzella, L., & Amstutz, A. (1999). CAE tools for quasi-static modeling and optimization of hybrid powertrains. IEEE Transactions on Vehicular Technology, 48(6), 1762–1769. https://doi.org/10.1109/25.806768

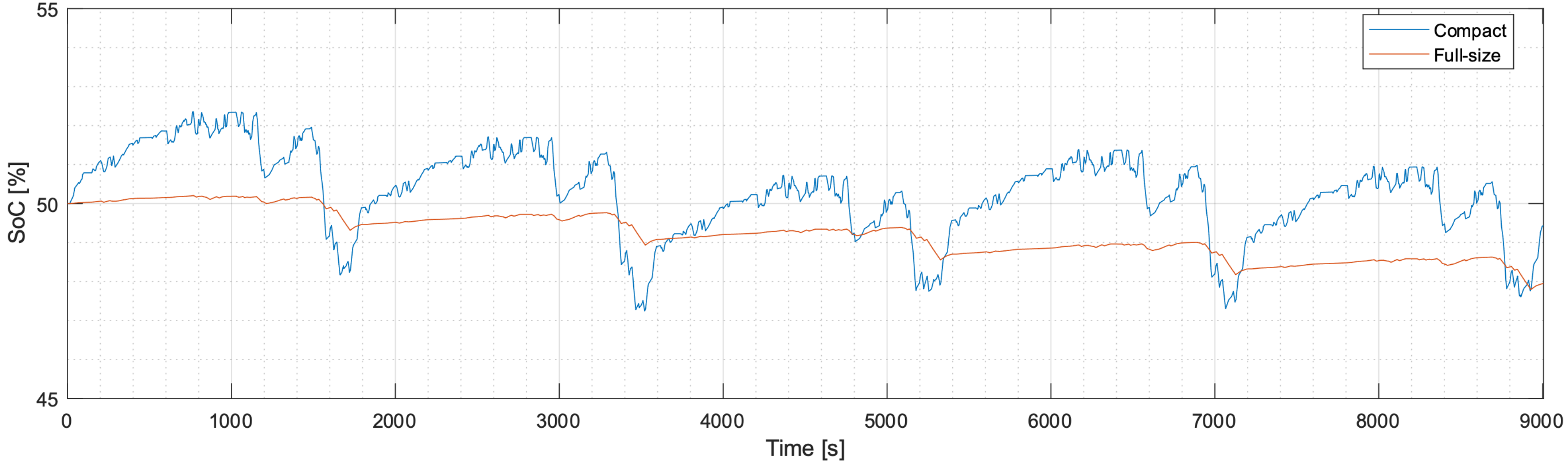
USE CASE
COMPACT & SEDAN VEHICLE OPTIMIZATION

- Minimization of fuel consumption for 2 passenger vehicles
  - Sedan and compact vehicles
- Charge-sustaining behavior ensured by a PI controller
- Optimized over 5 repetitions of the WLTP Class 3 driving cycle
  - 2,5 h total driving time
  - 116 km total driving distance



USE CASE

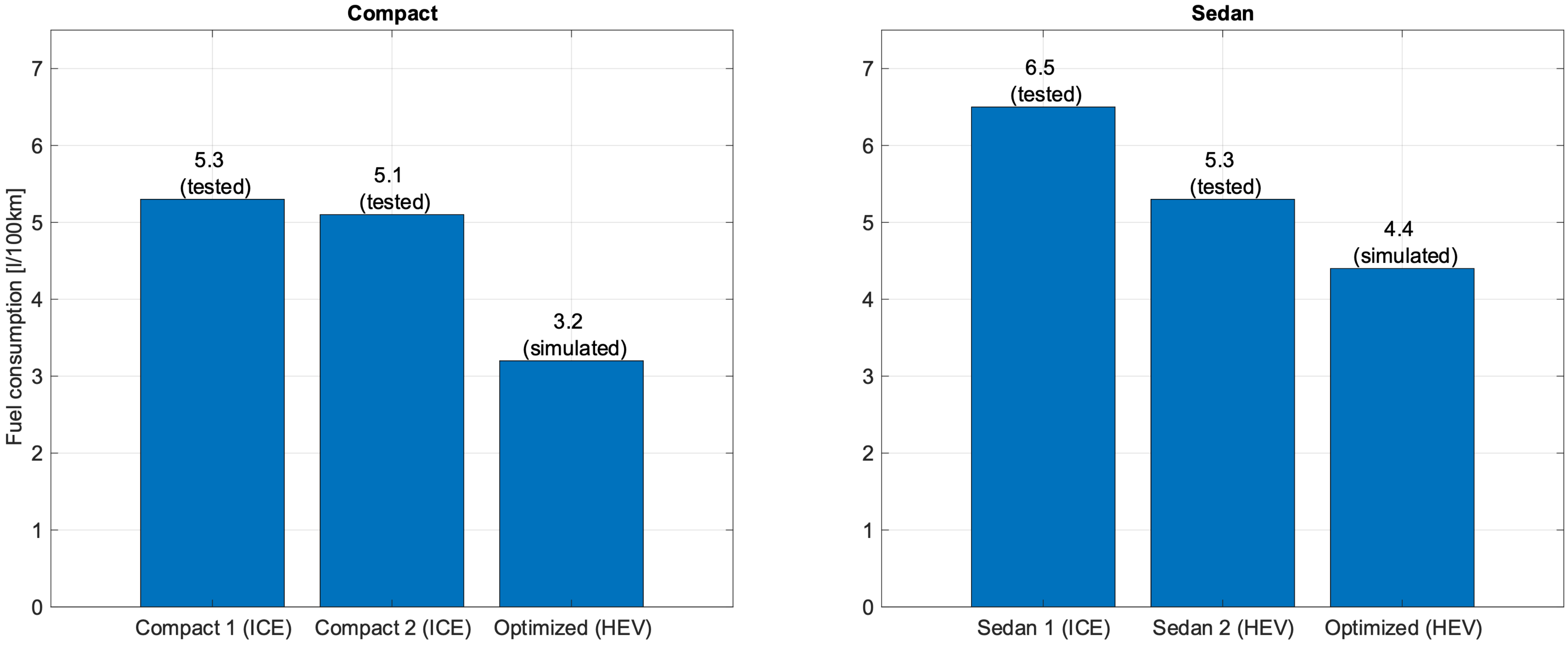
COMPACT & SEDAN VEHICLE OPTIMIZATION



	Compact (P2)	Sedan (P3)
Combustion engine size [kW]	35	81,2
Electrical motor size [kW]	35	34,6
Battery size [kWh]	6,3	12,3
Fuel consumption [l/100km]	3,19*	4,37*
Vehicle mass [kg]	1024	1747

* without auxiliary systems

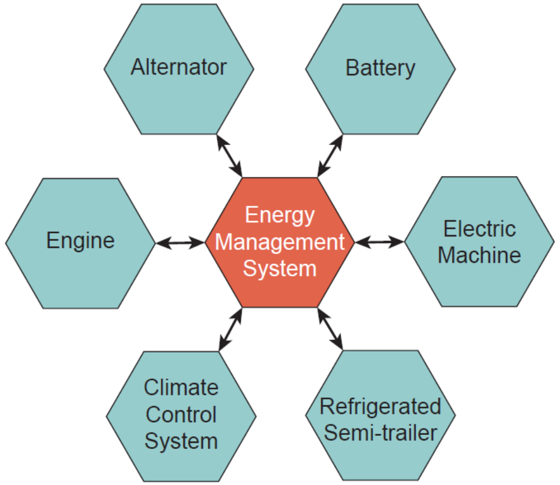
COMPARISON WITH ICE VEHICLES



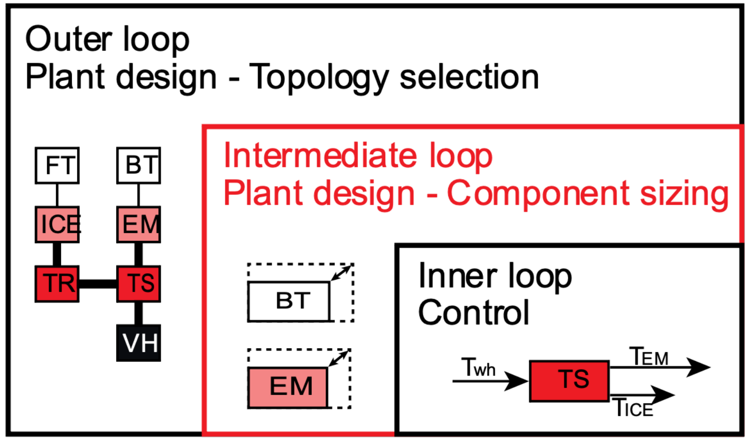
* without auxiliary systems

SUMMARY

- Modular Energy Management Strategy (MEMS)
  - **Enables optimal control methods** to be used to maximize powertrain performance
  - **Manages the complexity** of vehicle energy management through decomposition
  - **Automated control generation means reduced calibration effort within co-design**



- TOPDSIGN tool
  - Co-design method for HEV powertrains through **nested optimization framework**
  - **Automated plant generation** for closed-loop testing in Simulink
  - **Reduces development time and costs** for HEV powertrains design



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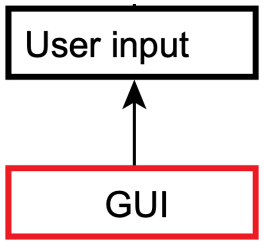
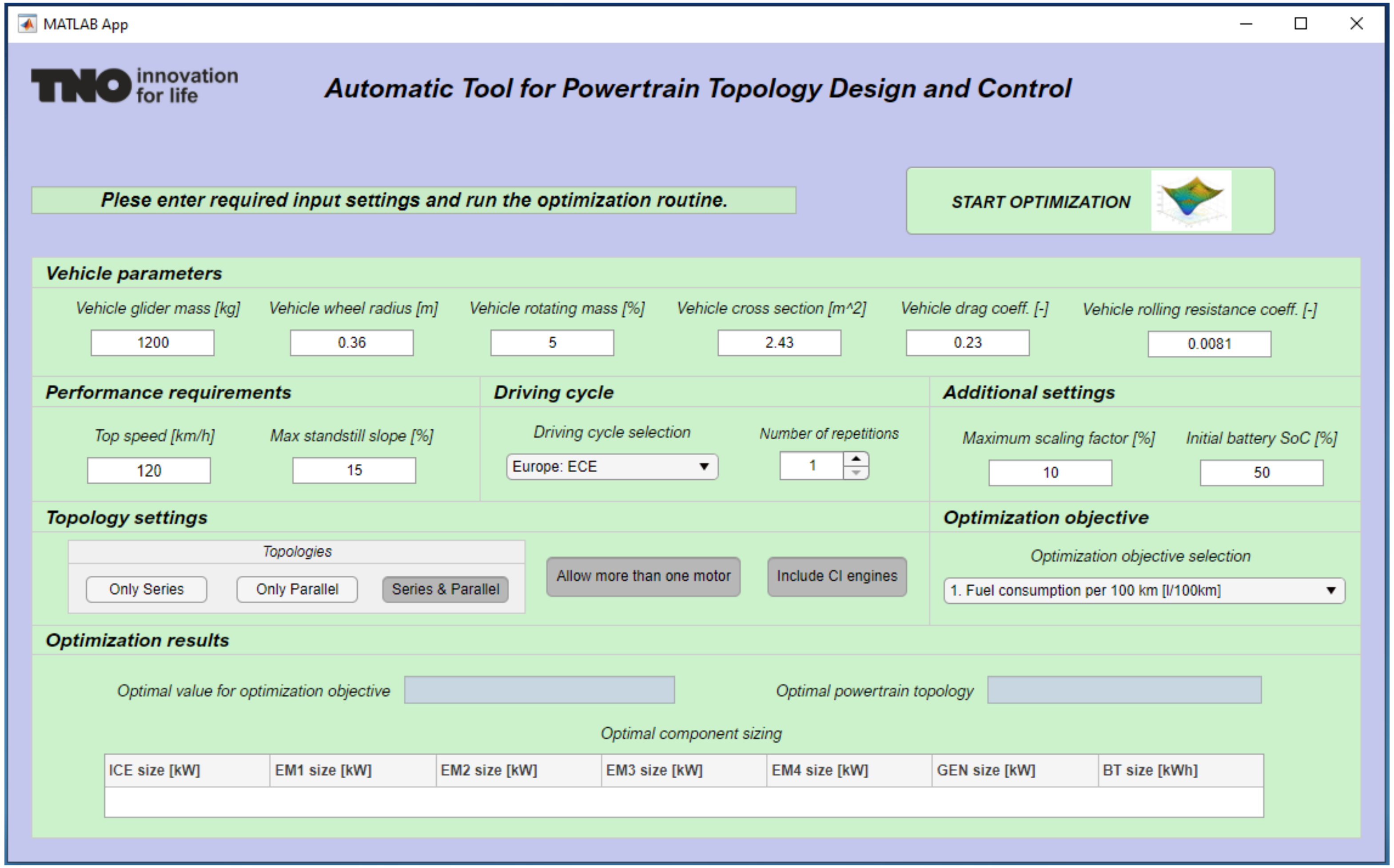
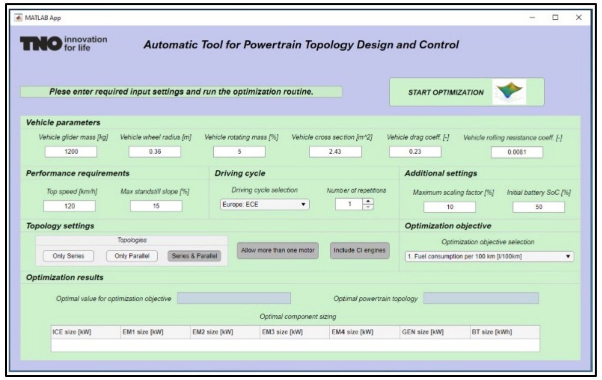
EXTRA SLIDES

DEVELOPMENT OF TOPDSIGN
USER INPUT AND GUI

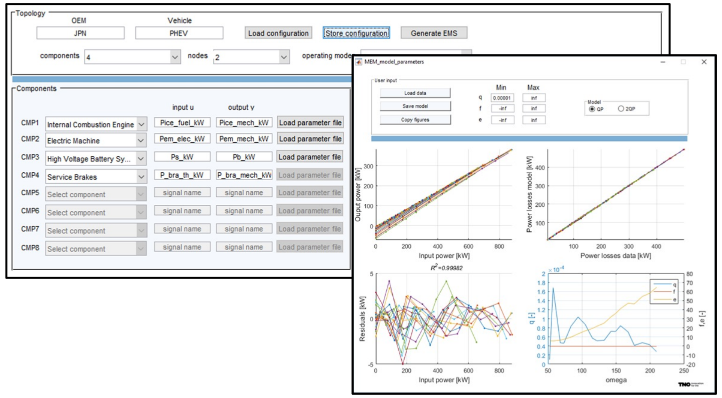




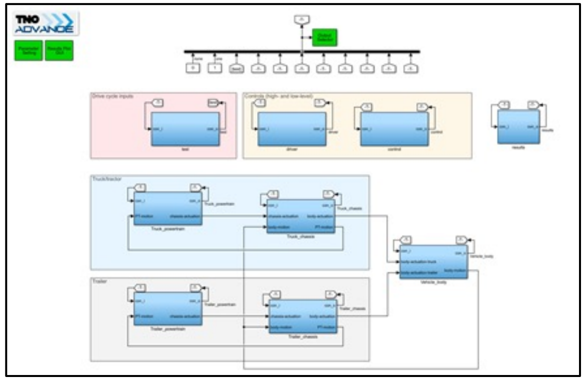
DEDICATED END-USER CUSTOMIZED TOOLCHAIN



Topology optimization and design tool



Convex control model calibration & supervisory optimal control algorithm generation tool



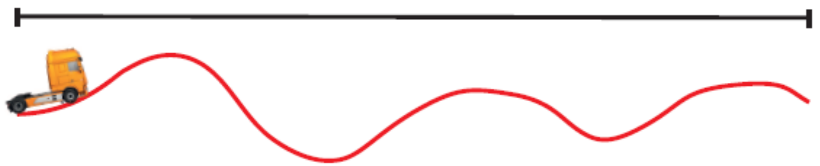
Flexible plant powertrain model library & data analytics environment

Accompanied with TNO knowledge transfer workshops

OFFLINE AND ONLINE ENERGY MANAGEMENT

Offline

- Power demand is known
- Complete drive cycle



- Optimal fuel consumption
- Analysis

- Reduced computation time: 3h to 150s
- Fuel reduction: 1.42 % (€520/year)

Online

- Power demand is predicted
- Receding horizon

- (Close to) optimal fuel consumption
- Implementation

- Real-time execution: 150ms/1s
- Fuel reduction: 1.3 % (€480/year)

Important to also focus on integrating auxiliaries into the energy management problem.

ENERGY MANAGEMENT IN HYBRID VEHICLES

An energy management strategy is required to **control** the **powerflows** from each component while optimizing the **powertrain efficiency** within the **powertrain constraints**

Objective
- minimizing fuel consumption $\min_{u} \int_{t_0}^{t_f} \dot{m}_{fuel}(u)dt$

Control input constraints
- Engine power
- Electric machine power
- Battery power

$u \in \mathcal{U}$

State constraints
- Battery SoC $x \in \mathcal{X}, \quad x(t_0) = x_0, \quad x(t_f) \in \mathcal{S}$

Dynamic constraints
- Battery SoC $\dot{x} = f(u, x)$

Optional constraints
- Engine emissions
- Battery aging

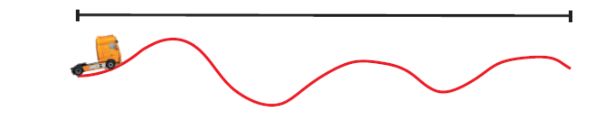
ENERGY MANAGEMENT STRATEGIES

EMS

$$\min_{u} \int_0^T \dot{m}_{fuel}(u)dt \quad s.t.\ \ u \in \mathcal{U}, x \in \mathcal{X}, \dot{x} = f(u,x)$$

Offline control strategies

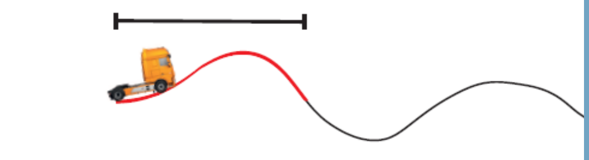
- Power demand over **entire route** known



Online control strategies

- **Instantenous power demand** known

Optionally, future power demand predicted



Dynamic Programming	Convex optimization	Pontryagin's Minimum Principe	Rule-based	Neural Networks	Pontryagin's Minimum Principle	Equivalent Consumption Minimization Strategy	Stochastic Dynamic Programming	Model Predictive Control

EQUIVALENT COST MINIMISATION STRATEGY (ECMS)

The objective in ECMS is **minimizing** the sum of the **fuel consumption** and an **equivalent fuel consumption** for the energy used from the battery

$$\text{minimize} \quad \underbrace{\overbrace{\dot{m}_f}^{\text{Fuel consumption}}(y_{ice}(t))}_{\text{Engine power}} \; - \; \underbrace{\overbrace{\lambda(t)}^{\text{Eq. cost factor}}\dot{E}_s(t)}_{\text{Battery energy consumption}}$$

Taking into account

- Power limitations of each component (e.g. maximum engine power)
- Energy limitations of the battery
- Power required for driving the vehicle P_r
- Power consumed by auxiliaries

Paganelli, G., Ercole, G., Brahma, A., Guezennec, Y., and Rizzoni, G., 2001, "General Supervisory Control Policy for the Energy Optimization of Charge-Sustaining Hybrid Electric Vehicles," JSAE Rev., **22**(4), pp. 511–518.

PONTRYAGIN'S MINIMUM PRINCIPLE

Serrao, L., Onori, S., and Rizzoni, G. (2009). ECMS as a Realization of Pontryagin's Minimum Principle for HEV Control. In Proc of American Control Conf.

- ECMS as a realization of Pontryagin's Minimum Principle

$$\min_u \int_0^T F(x,u)dt = \min_u \int_0^T \dot{m}_{fuel}(u)dt \qquad \dot{x} = f(u,x) = \dot{E}_{hvb}$$

$$Hamiltonian = F - p^T f(u,x) \quad \Rightarrow \quad \dot{m}_{fuel}(u) - p^T \dot{E}_{hvb}$$

ECMS $p = \lambda$

- Optimality conditions

$$\frac{\partial H}{\partial x} = \dot{p}^* \qquad \frac{\partial H}{\partial p} = -\dot{x}^* \qquad \frac{\partial H}{\partial u} = 0$$

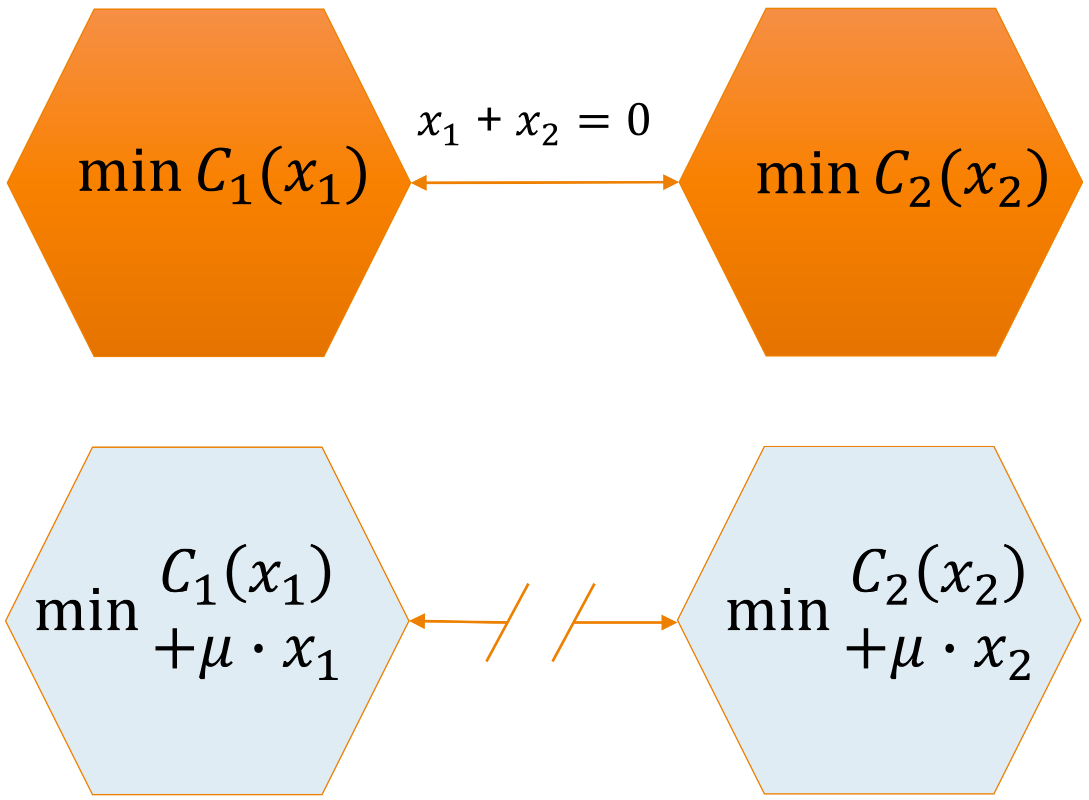
ECMS satisfies optimality conditions if the Hamiltonion is independent of the state x (SoC)

THE DUAL DECOMPOSITION METHOD

- Minimum of $C_1(x_1) + C_2(x_2)$

- Dual decomposition theory
  - Introduce **dual variable** μ
  - minimize $C_1(x_1) + C_2(x_2) + \boldsymbol{\mu}\,(\boldsymbol{x_1} + \boldsymbol{x_2})$
  - Iteratively find the **equilibrium** dual variable
  - **Global minimum** is attained at equilibrium

- Dual decomposition allows to **decouple networks** of optimization problems



$\min C_2(x_2)$

SECOND-ORDER CONDITION FOR CONVEXITY

For the convexity of ***f*** it is necessary and sufficient that $\nabla^2 f(x) \succeq 0$ for all x

Definition (Second-order Condition for Convexity)

A twice-differentiable function $f : \mathrm{dom}(f) \to \mathbb{R}$ with a convex domain is convex if and only if

$$\nabla^2 f(x) \succeq 0,$$

where the Hessian is defined as

$$\nabla f(x)_{ij} = \frac{\partial^2 f(x)}{\partial x_i \partial x_j}.$$

If $\nabla^2 f(x) \succ 0$, then the function is **strictly** convex.