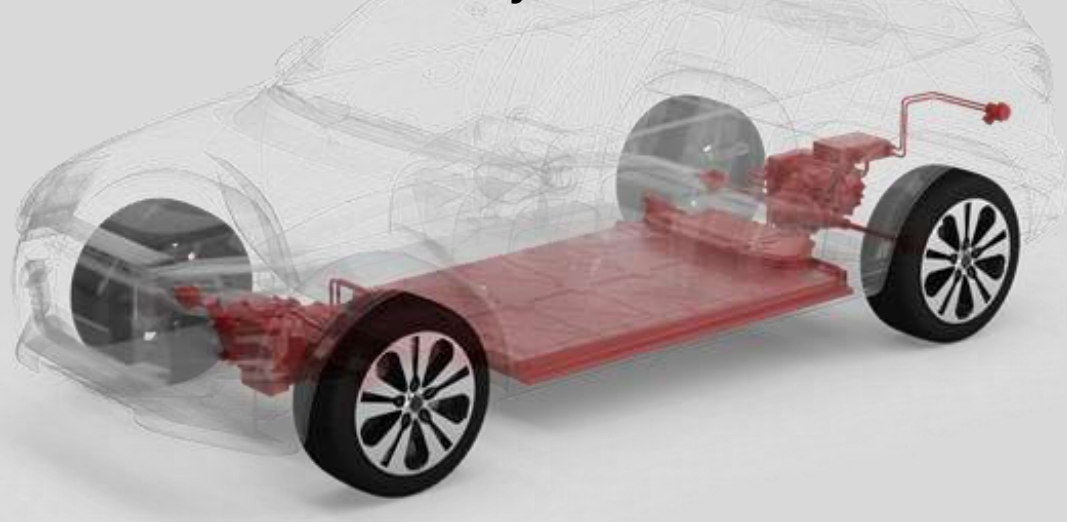
Prepared for

Automotive World

OPTIMIZATION OF MULTI-MOTOR ELECTRIC DRIVE SYSTEMS

What is the optimum combination in terms of efficiency and cost?



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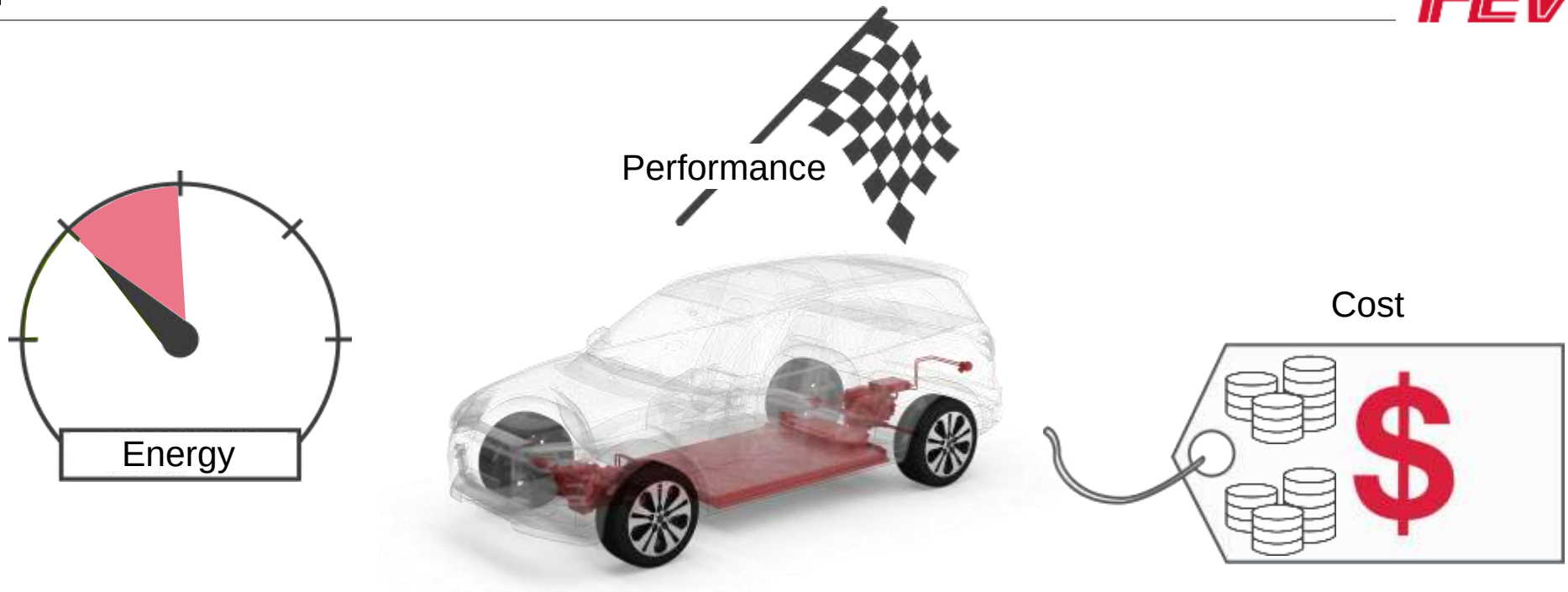
FEV

Agenda

- Introduction
- Longitudinal Dynamics Simulation
- Simulation Results
- Cost Analysis
- Summary and Recommendations

Optimization of Multi-Motor Electric Drives
Hypothesis: Multi EDU statements



Multi EDU Electric Vehicle

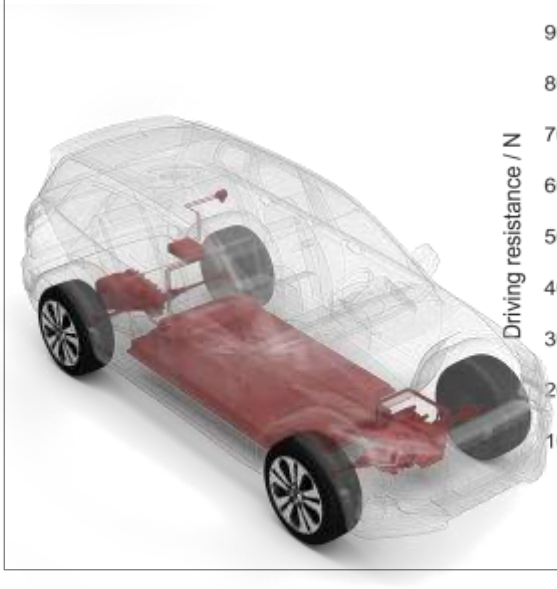
Hypothesis:

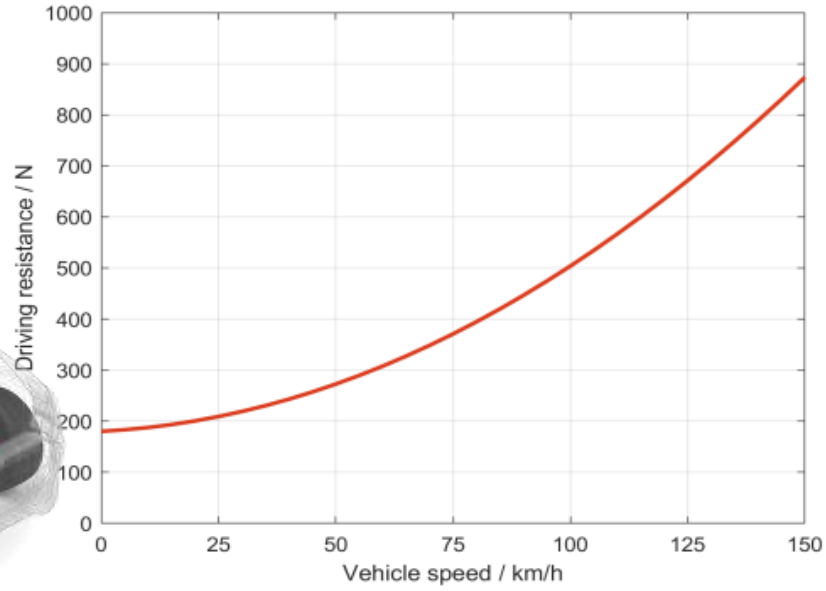
1. Multi-EDU solutions offer increased drivability by AWD, but at the cost of energy efficiency
2. Multi EDU solutions nearly double the cost for the electric drivetrain, since two units are installed in the vehicle

Optimization of Multi-Motor Electric Drives
Introduction: Base vehicle for study

BASE VEHICLE SPECIFICATION

		Specifications
Vehicle Weight	kg	2150
Coast Down Parameter F0	N	180
Coast Down Parameter F1	N/(km/h)	0.4635
Coast Down Parameter F2	N/(km/h)²	0.0278



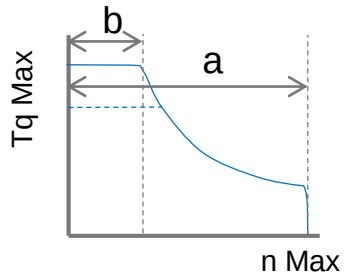


Description

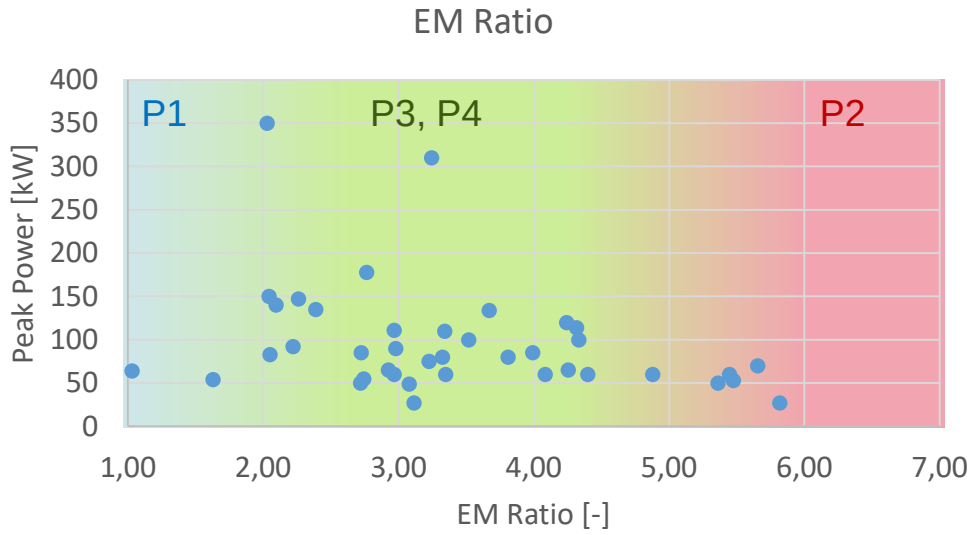
- D-Class Passenger Car
- Peak power 230 kW
- Combined axle Torque 5000 Nm
- Top Speed 200 km/h
- Max axle speed 1600 rpm
- LV Electric load 200 W in all variants
- Variation of power split rear-front 100..0 to 50..50
- Vehicle weight kept constant
- Battery 90 kWh

Optimization of Multi-Motor Electric Drives
Introduction: How many gear ratios are needed?

E-MOTOR DATABASE



E-Motor ratio = a/b

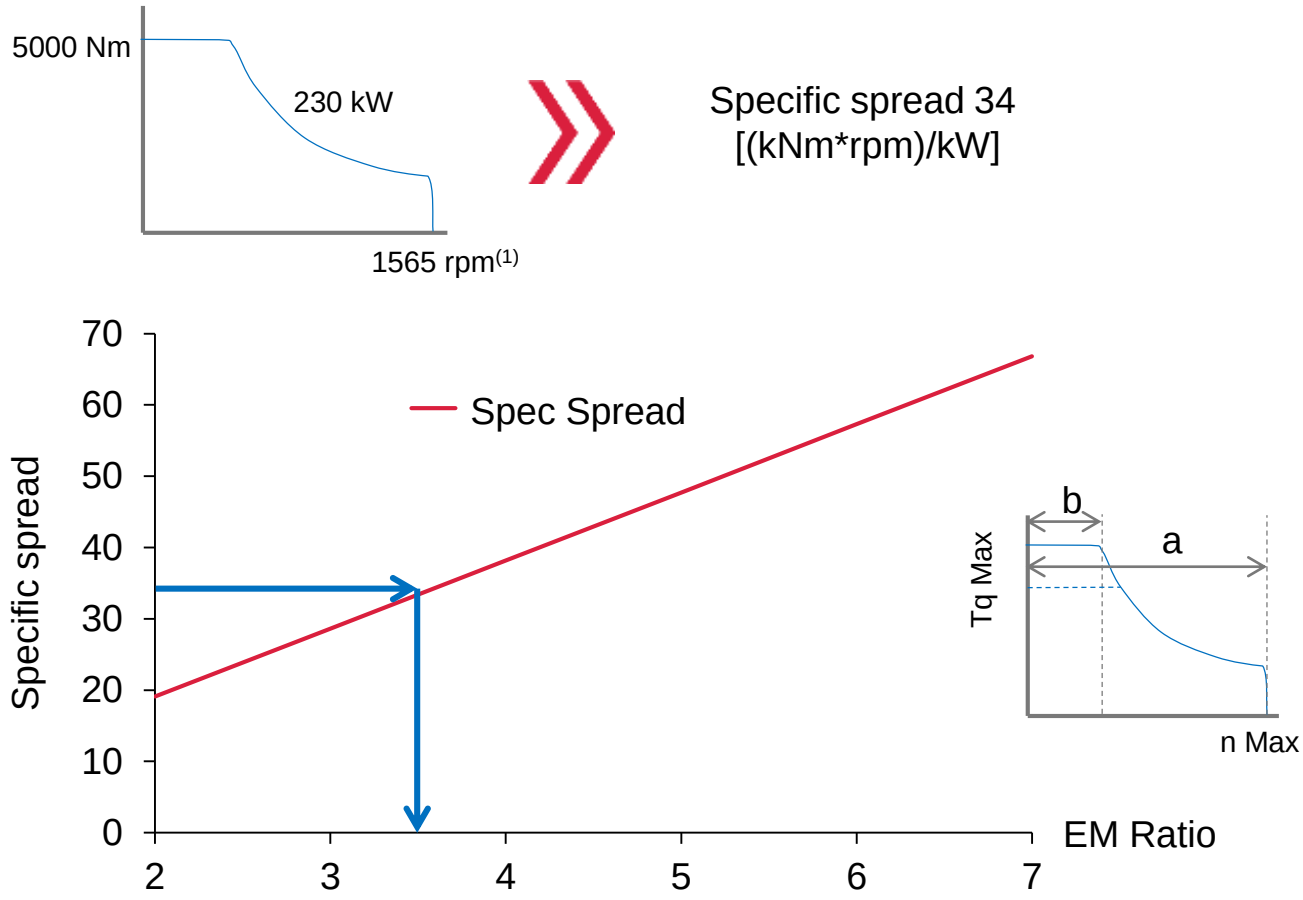


Description
■ E-Motors can be built with different power to torque levels, defined as the E-Motor ratio
■ The absolute performance linearly scales the E-Motor
■ The absolute speed level is irrelevant here, as it only defines the total ratio required
■ FEV gathered a database with >250 traction motors and their key data
■ Electric machines with a spread of 2,5 ..4 are most widely used as traction motors, as they show a good cost to benefit ratio

Source: FEV

Optimization of Multi-Motor Electric Drives
Introduction: How many gear ratios are needed?

BASE VEHICLE SPECIFICATION



Description

- Spread demand 1565 (1) rpm x 5000 Nm = 7.828.191 [Nm*rpm]
- Specific spread 7.828/230= 34.04 [(kNm*rpm)/kW]
- An EM Ratio of ~ 3,5 is sufficient to meet the vehicle requirements
- A 1-speed solution is best choice for this application

1) Wheel speed @ 200 km/h, using 245/45R18 wheels

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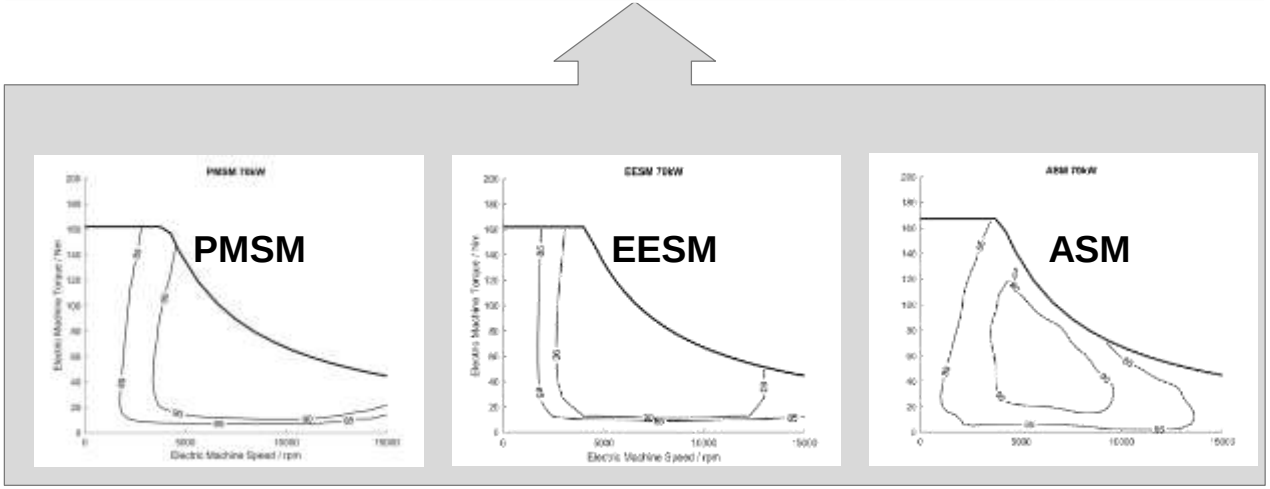
Optimization of Multi-Motor Electric Drives
Simulation: Definition of EDU family

EDU FAMILY OVERVIEW

Item	EDU 1	EDU 2	EDU 3	EDU 4
Peak power [kW]	70	115	160	230
Rotor diameter [mm]	165		200	
Max speed [rpm]	15.000		12.500	
Ratio [-]	9,38		7,81	
Output Torque [Nm]	1522	2500	3478	5000



Description

- Power range is too wide to be handled by active length only
- Family 1 (EDU 1&2):
  - Air gap diameter 165 mm
  - Rated speed 15.000 rpm

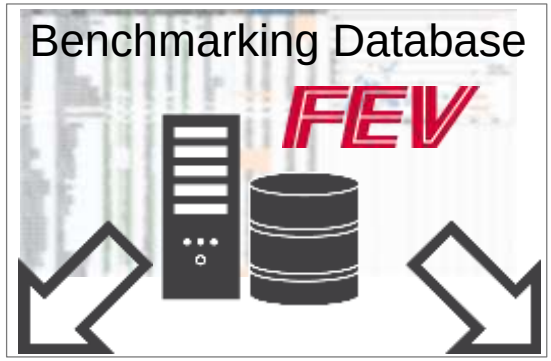
  → Ratio 9,38 (*)
- Family 2 (EDU 3&4):
  - Air gap diameter 200 mm
  - Rated speed 12.500 rpm

  → Ratio 7,81 (*)
- DC voltage 350 V constant
- Three E-Motor types
  - PMSM
  - EESM
  - ASM

  Stator/ Rotor dimensions identical

(*) Maximum air gap speed was kept constant at 130 m/s for all variants

Optimization of Multi-Motor Electric Drives
Simulation: Input data and scaling

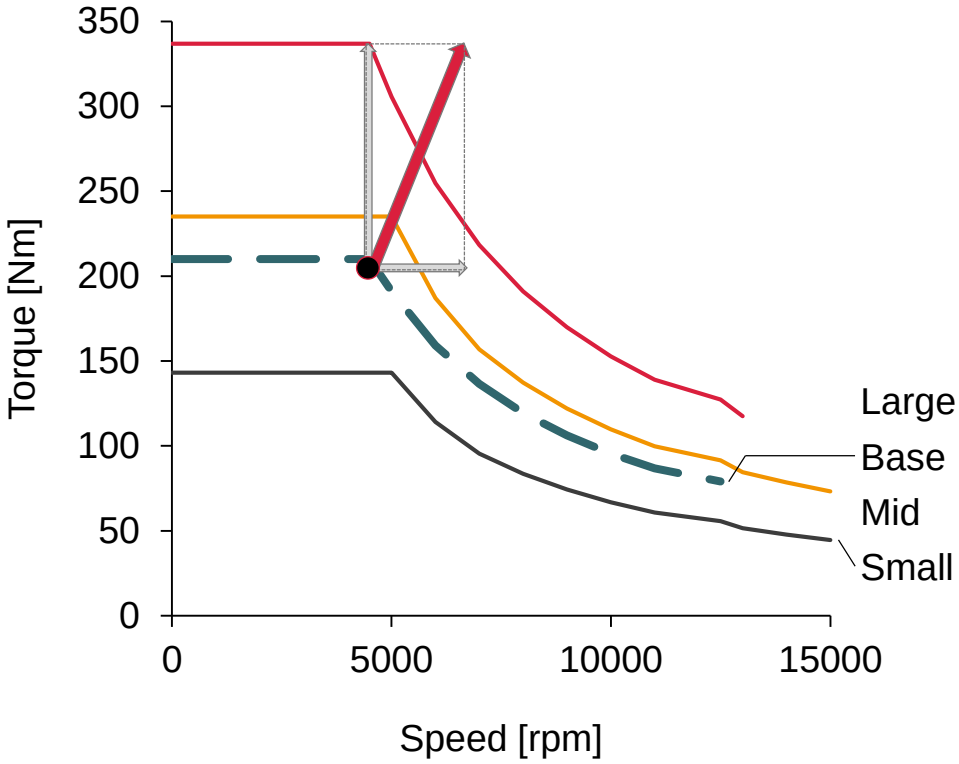


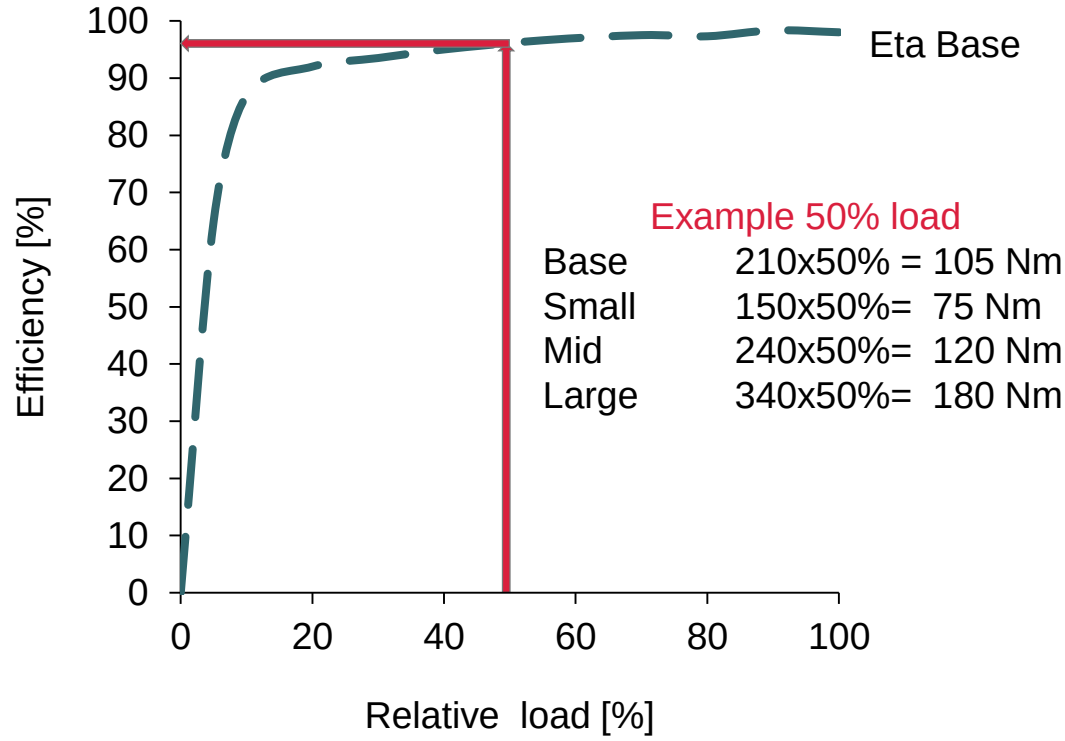
E-Motor Scaling

- Constant EM ratio torque/power
- Adaptation of power (vertical) and speed (horizontal)

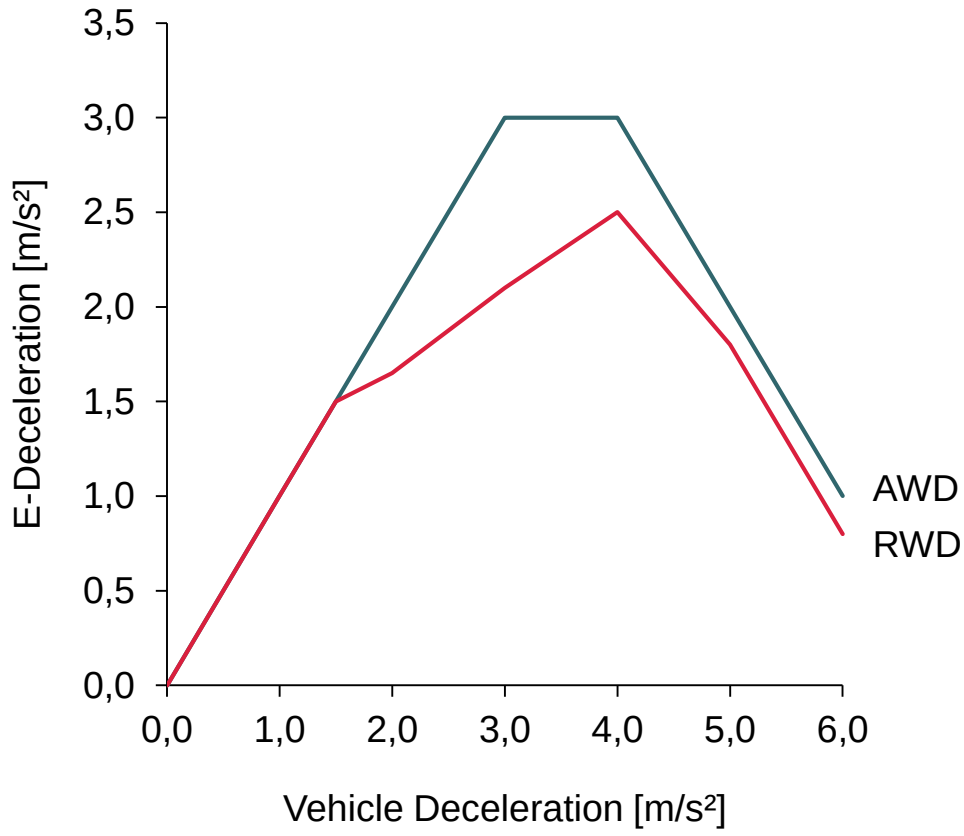
Reducer Scaling

- Two ratio variants, generated by database from actual hardware
- Efficiency stays the same for relative load





Optimization of Multi-Motor Electric Drives
Simulation: Settings regenerative braking RWD and AWD



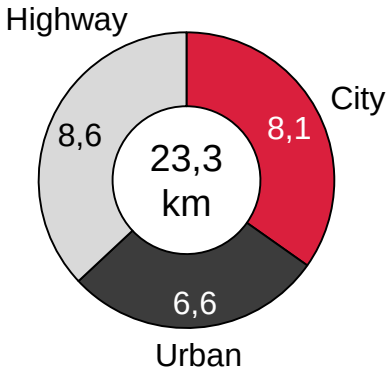
Recuperation strategy

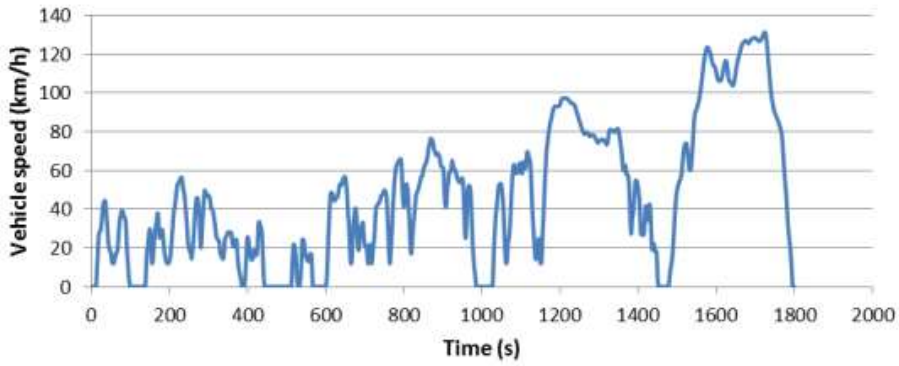
- Assuming brake by wire system
- For AWD full recuperation up to 3 m/s² deceleration
- For RWD full recuperation up to 1,5 m/s² deceleration
- No thermal constraints

Optimization of Multi-Motor Electric Drives
Simulation: Driving cycles

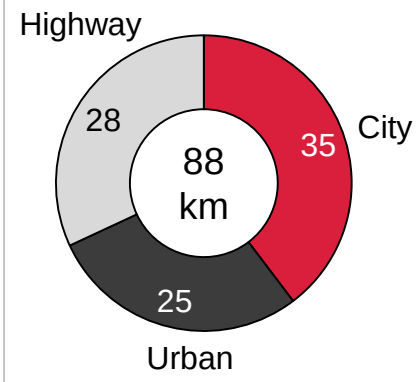
DEFINITION OF DRIVING CYCLES USED

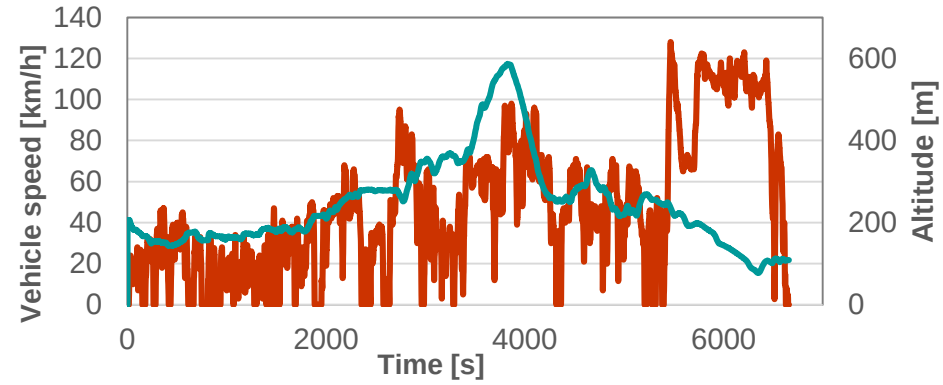
WLTC (Class 3)





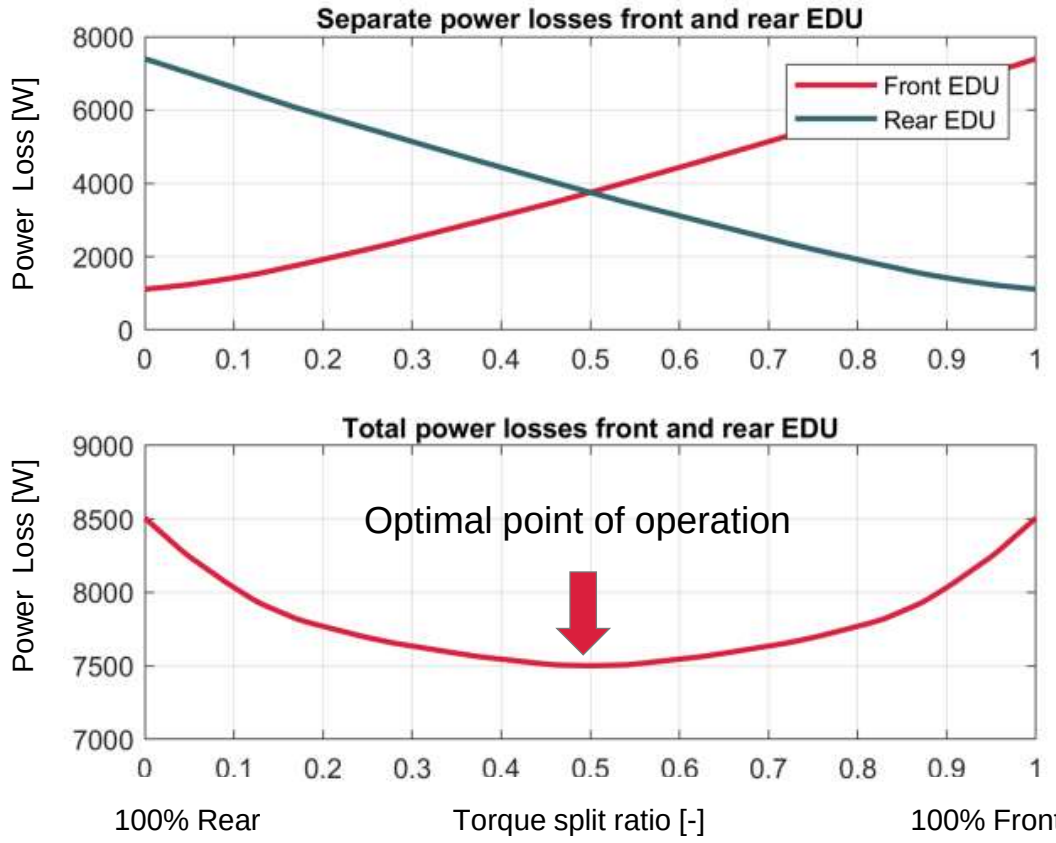
FEV RDE Cycle “Eifelrunde”





Optimization of Multi-Motor Electric Drives
Simulation: Operating strategy

OPTIMAL TORQUE SPLIT IS DETERMINED BY POWER LOSSES MINIMIZATION OF THE SYSTEM



Example torque split ratio for 50% / 50% PMSM application

Source: FEV

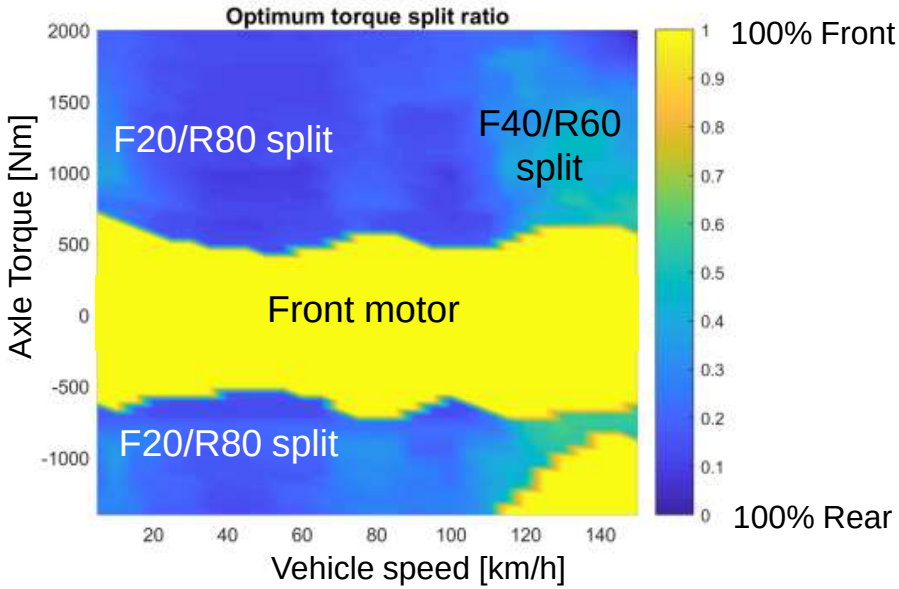
Method

- For each operating point, the separate power losses for the front and rear EDU (Inv. + EM + TRM) are calculated for each operating point (axle speed /torque)
- By adding the front and rear power losses, the total power losses are obtained
- By searching for the minimum power losses, the optimum torque split ratio for each point of operation can be obtained
- This results in a unique power split map for each combination

Optimization of Multi-Motor Electric Drives
Simulation: Operating strategy - Example power split maps

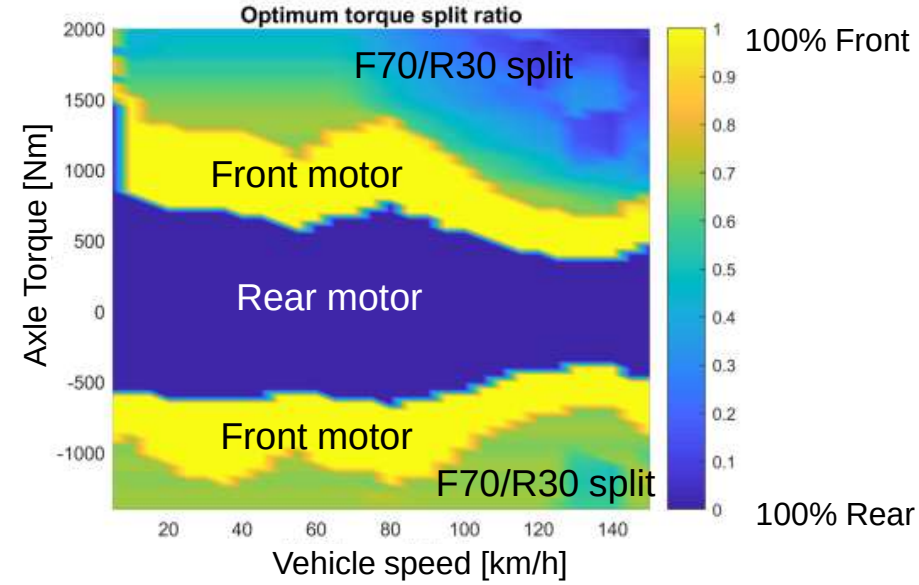
System power 230kW / combined axle Torque 5000 Nm

70 kW PMSM Front
160 kW EESM Rear



- Optimum torque split:
  - Low loads PMSM: electric motor
  - Medium and high loads: various split ratios

160 kW EESM Front
70 kW EESM Rear



- Optimum torque split:
  - Low loads: small (rear) motor
  - Medium loads: large (front) motor
  - High loads: load distribution
    - ≈ 70% Front
    - ≈ 30% Rear

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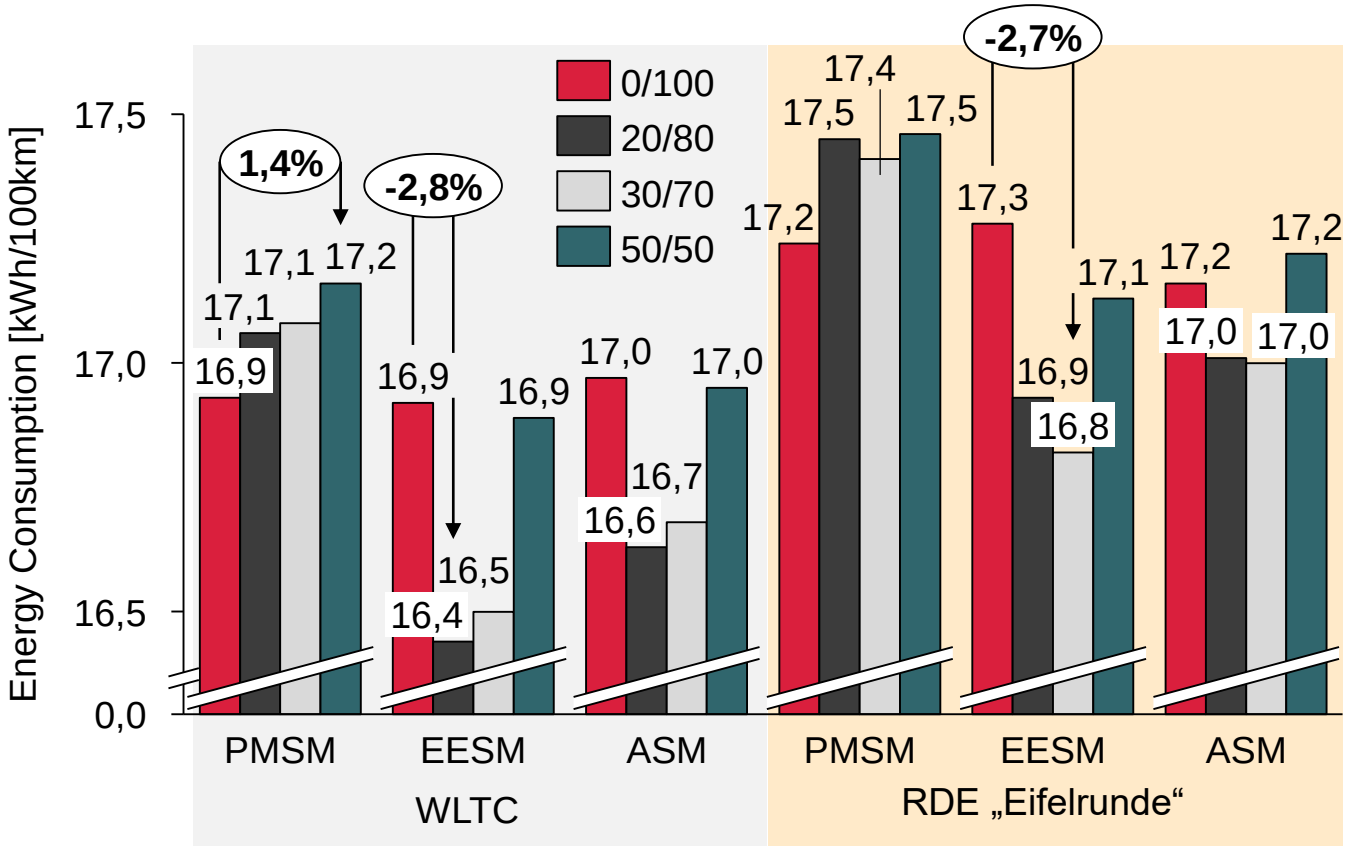
Optimization of Multi-Motor Electric Drives
Simulation Results: Energy consumption in WLTC and FEV “Eifelrunde”

SINGLE EM TYPES



Source: FEV

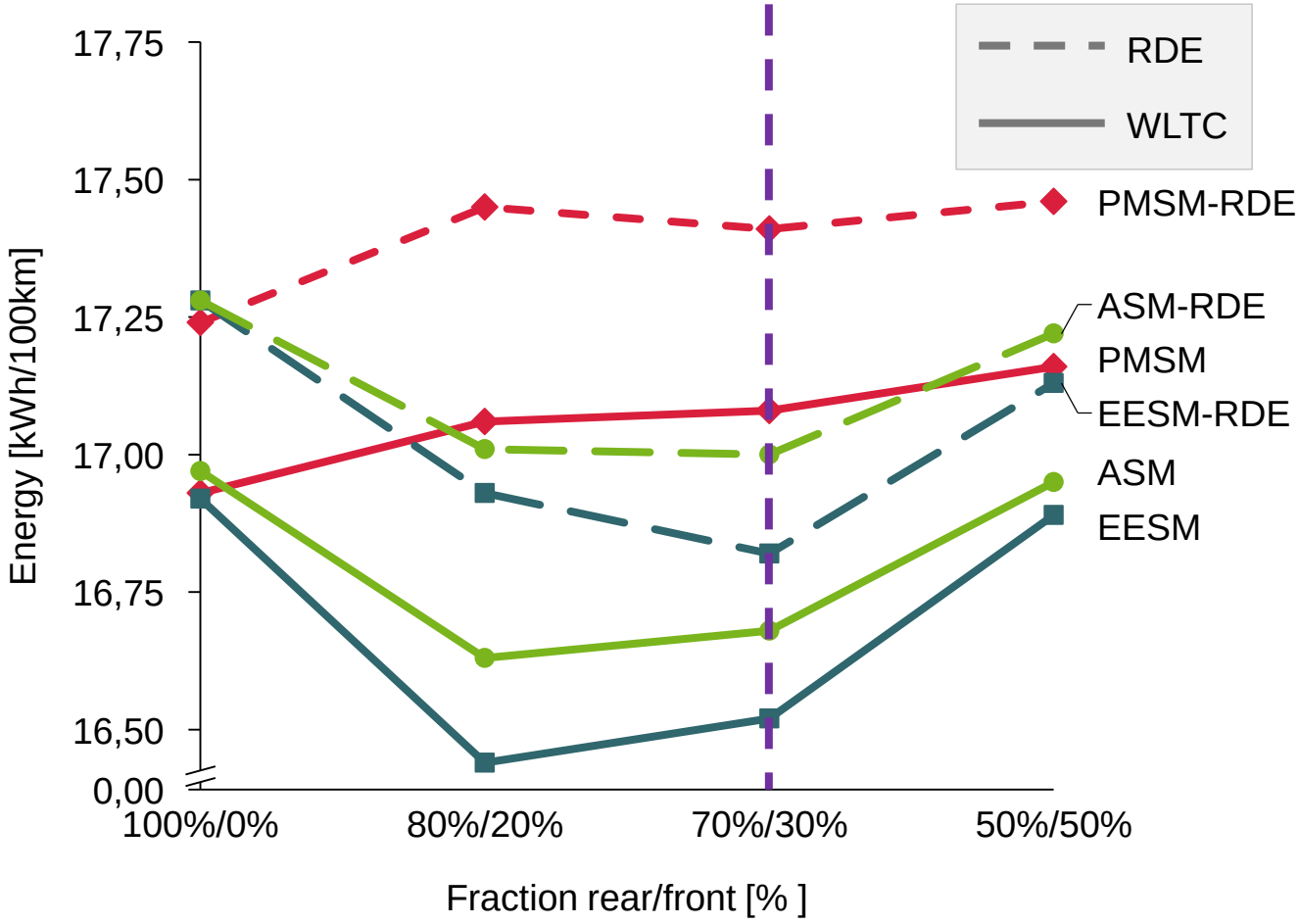
Description

Assuming a single EDU PMSM vehicle as a baseline:

- Dual Motor PMSM is the worst combination, resulting in additional energy consumption of around 1.4 %
- For single EDU applications, the energy consumption is nearly identical, despite significant differences in efficiency maps
- Using E-Motors without permanent magnets, an energy efficiency increase of up to ~3% can be achieved by multi EDU applications in both test cycles

Optimization of Multi-Motor Electric Drives
Optimal power distribution

OPTIMAL POWER SPLIT RATIO



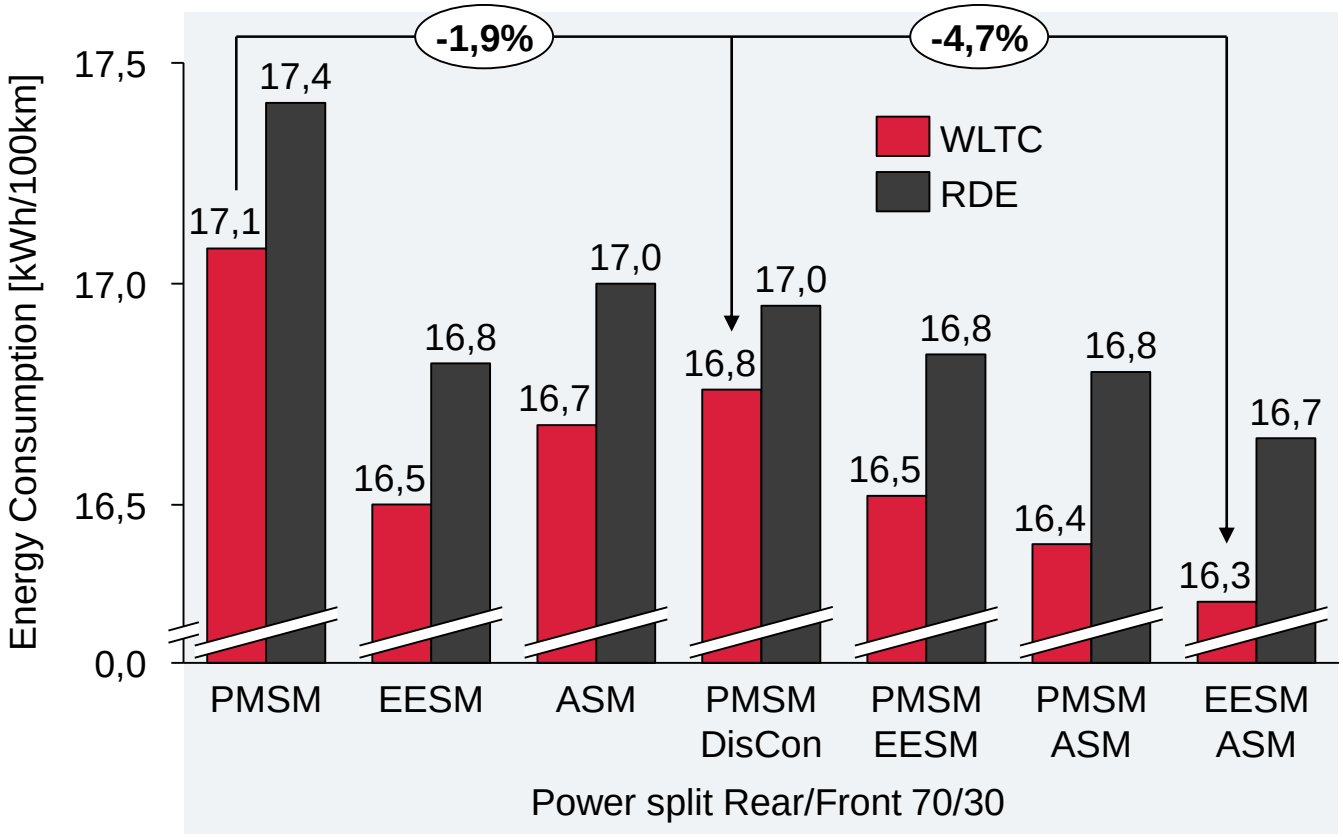
Analysis

- PMSM shows increased energy consumption when using multi EDUs, other machine types show a reduction
- Optimum power split range both for WLTC and RDE is in the range of 70% to 80% on rear axle
- For this study focus was on 70%/30% power split rear to front
  - Optimum for energy consumption, both in RDE and WLTC
  - Optimum for performance and traction, especially in case of non-ideal road conditions (not shown)

Note: PMSM without disconnect feature

Optimization of Multi-Motor Electric Drives
Simulation Results: Single and mixed EM types in 30/70 power distribution

70/30 POWER SPLIT, COMBINED EM



Analysis

- Equipping the large EDU in a dual PMSM configuration with disconnect saves ~2% energy
- Combining different motor types in a smart way can increase energy efficiency even further, w/o the need for disconnect
- Compared to one PMSM only, a vehicle with a combination of EESM and large ASM can save energy up to > 4%, both in WLTC and RDE
- Best combination for lowest energy consumption is a small EESM or PMSM with a large ASM

Source: FEV

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Optimization of Multi-Motor Electric Drives
Cost Analysis: Bill-of-materials (BOM) based approach

BASE ASSUMPTIONS

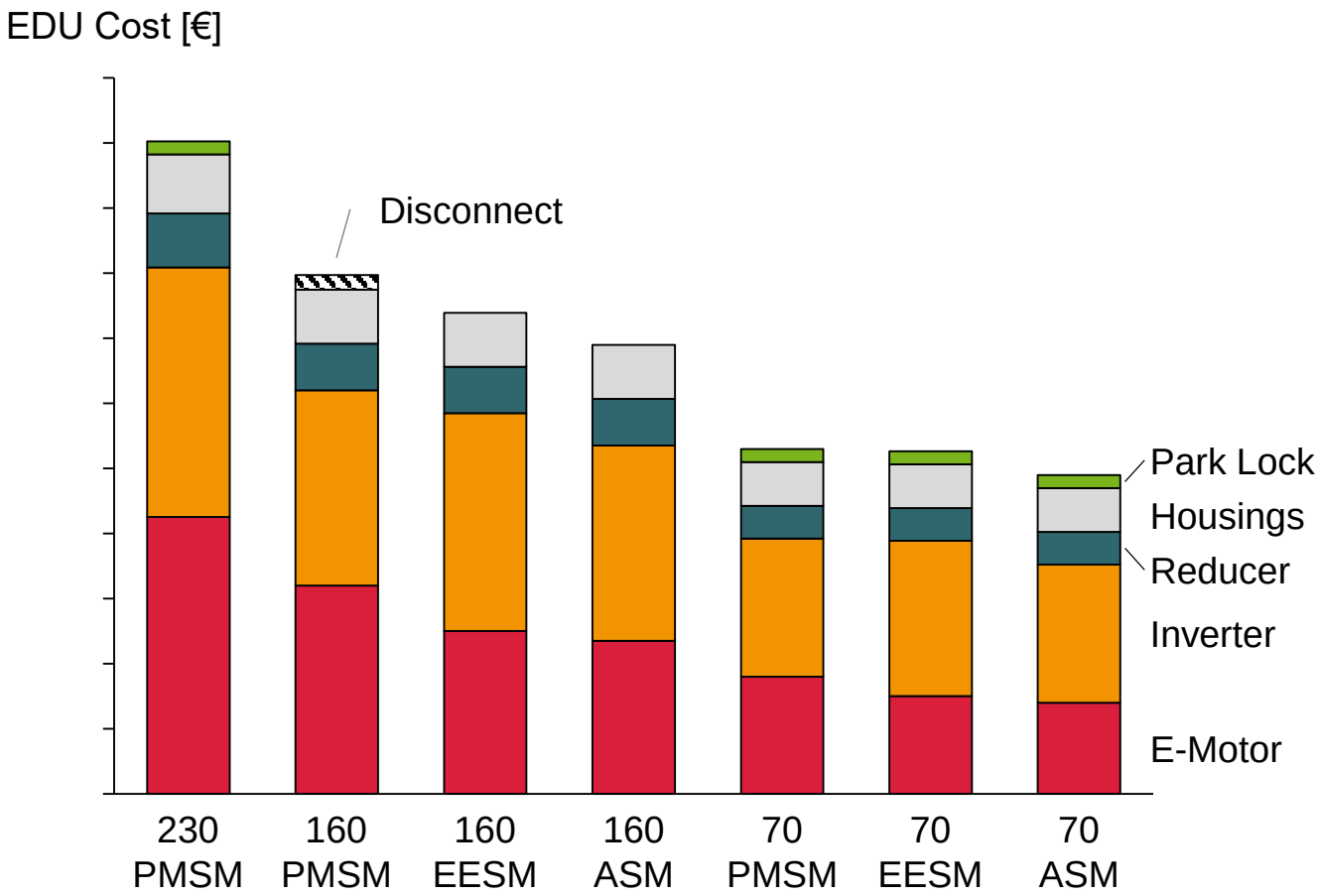
- ❑ Production scenario 250.000 units/year
- ❑ Same overhead cost in % for all EDU´s
- ❑ One system housing (3 in 1 unit) for all variants
- ❑ In case of multi EDU, only one (front) is equipped with a park lock
- ❑ Stator dimensions identical for all machine types (ASM has a lower power density, but compensates by higher overload capacity)
- ❑ 650V Class IGBT inverter and, if necessary, an additional DC/DC converter for EESM rotor excitation current
- ❑ For PMSM magnets in typical mid class range

Group	Item	Qty./ assembly gro	Qty./ emotor	Cost/ item	Cost/ assembly group	Cost/ emotor
Housing	Front cover	1	1			
Housing	Bolt M6x25	7	7			
Housing	Housing	1	1			
Housing	Seal ring	1	1			
Housing	Back cover	1	1			
Stator	Stator assembly	1	1			
Stator	Lamination sheets	1	1			
Stator	Isolated copper wire 0.55mm	1	1			
Stator	PE cord 2mm	1	1			
Stator	Electrical resin	1	1			
Stator	Isolation paper	1	1			
Stator	Temperature sensors incl. cable & plug	2	2			
Stator	Crimp connectors	4	4			
Stator	Crimp connecting terminals	3	3			
Stator	Isolation tube (thin)	24	24			
Stator	Isolation tube (thick)	7	7			
Stator	Tape	1	1			
Rotor	Rotor assembly	1	1			
Rotor	Shaft	1	1			
	Lamination sheets	1	1			
		48	48			

BOM based cost evaluation (Example E-Motor)

Optimization of Multi-Motor Electric Drives
Cost Analysis: BOM based approach

EDU COST BREAKDOWN



Basis 250k units/year, off axis 1 speed solution, one park lock in vehicle, PMSM optionally with disconnect

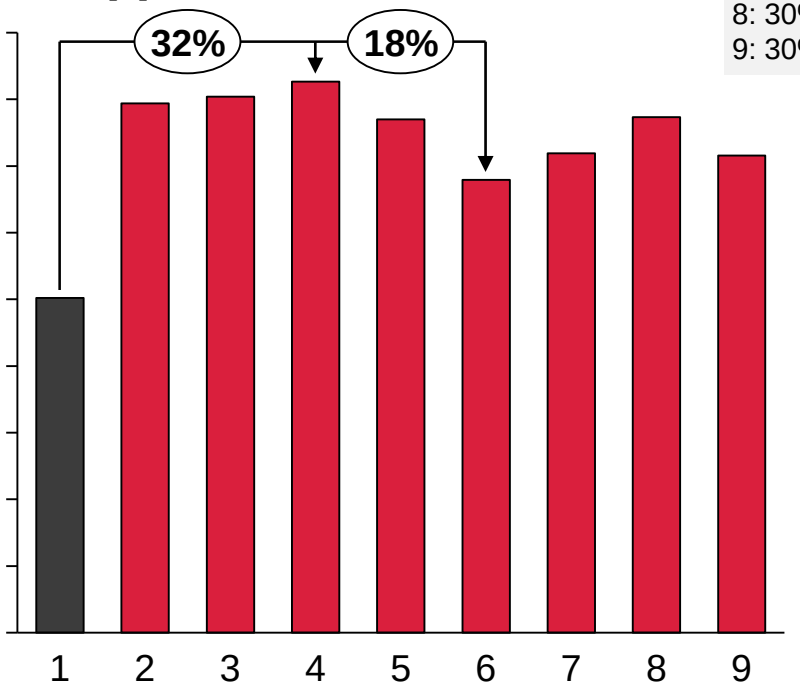
Analysis

- Main cost driver in EDUs are E-Motor and Inverter
- ASM motor is significantly cheaper than PMSM
- 160 kW systems without park lock (already installed in small EDU)
- PMSM 160 kW optionally with disconnect

Optimization of Multi-Motor Electric Drives
Cost Analysis: BOM based approach

EDU SYSTEM COST

System Cost [€]



1: Baseline: RWD PMSM
2: 50% PMSM / 50% PMSM
3: 30% PMSM / 70% PMSM
4: 30% PMSM / 70% PMSM-Discon
5: 30% EESM / 70% EESM
6: 30% ASM / 70% ASM
7: 30% PMSM / 70% ASM
8: 30% PMSM / 70% EESM
9: 30% EESM / 70% ASM

Analysis

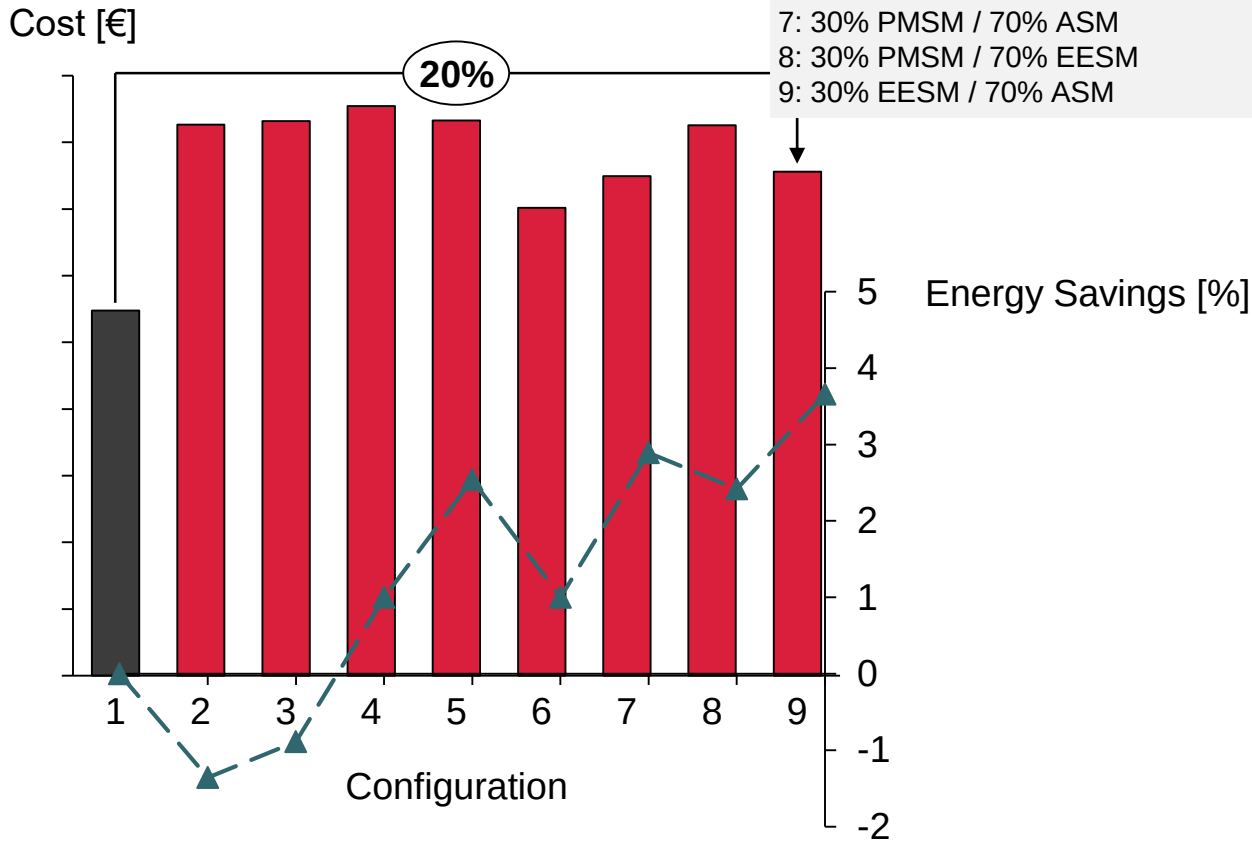
- Additional cost multi motor solution 18..32% compared to single EDU PMSM

Basis 250k units/year, off axis 1 speed solution, one park lock in vehicle, PMSM optionally with disconnect

Optimization of Multi-Motor Electric Drives
Cost Analysis: BOM based approach

EDU SYSTEM COST

1: Baseline: RWD PMSM
2: 50% PMSM / 50% PMSM
3: 30% PMSM / 70% PMSM
4: 30% PMSM / 70% PMSM-Discon
5: 30% EESM / 70% EESM
6: 30% ASM / 70% ASM
7: 30% PMSM / 70% ASM
8: 30% PMSM / 70% EESM
9: 30% EESM / 70% ASM



Analysis

- Additional cost multi motor solution 18..32% compared to single EDU PMSM
- Highest energy savings are not with the most expensive solution!
- Cheapest solution #6 shows ~ 1% energy savings (ASM/ASM)
- Interesting solutions are also #7 and #9

Basis 250k units/year, off axis 1 speed solution, one park lock in vehicle, PMSM optionally with disconnect

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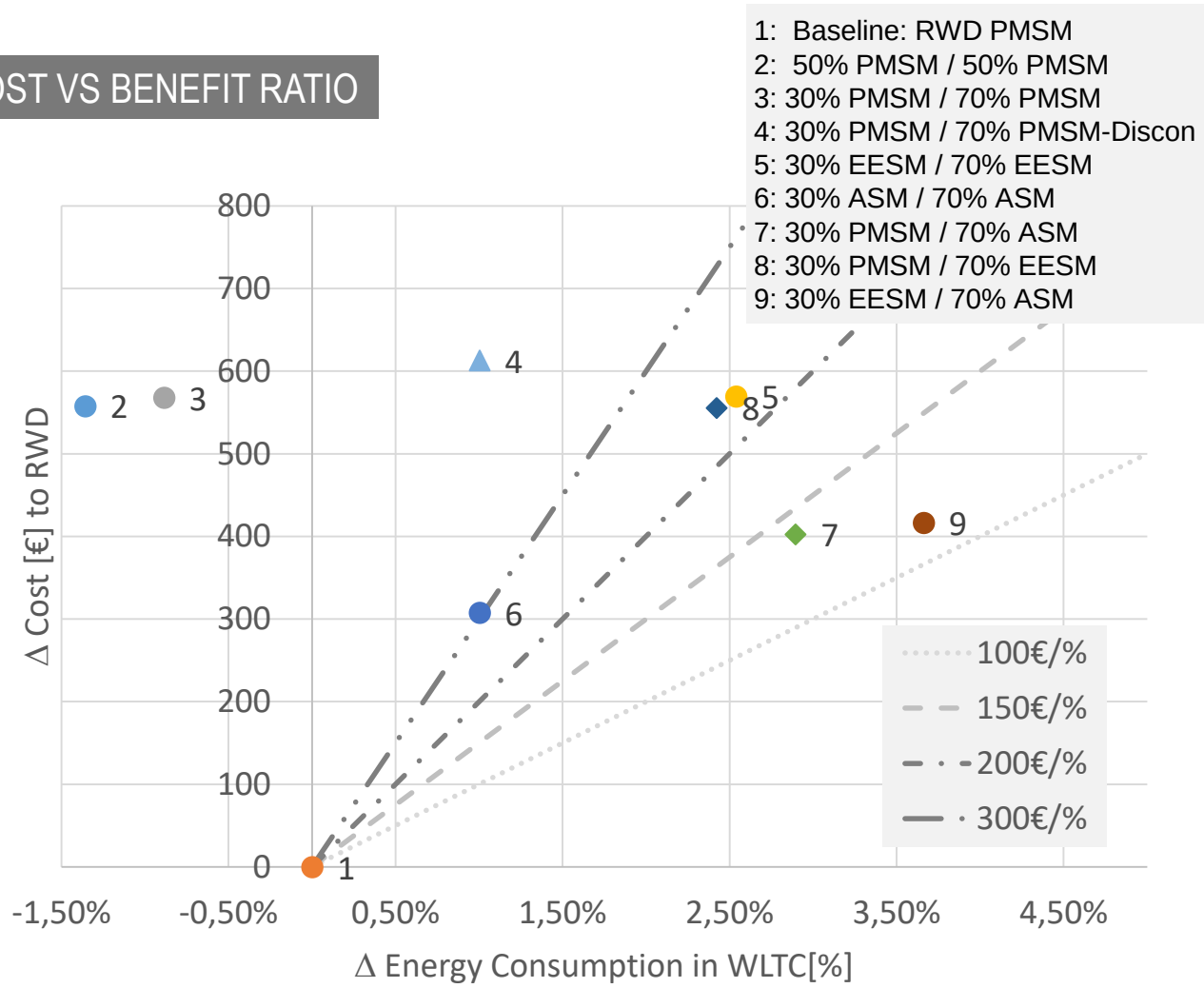
Application of multi EDUs can save up to 4% energy consumption at an additional cost of approx. 500 Euro

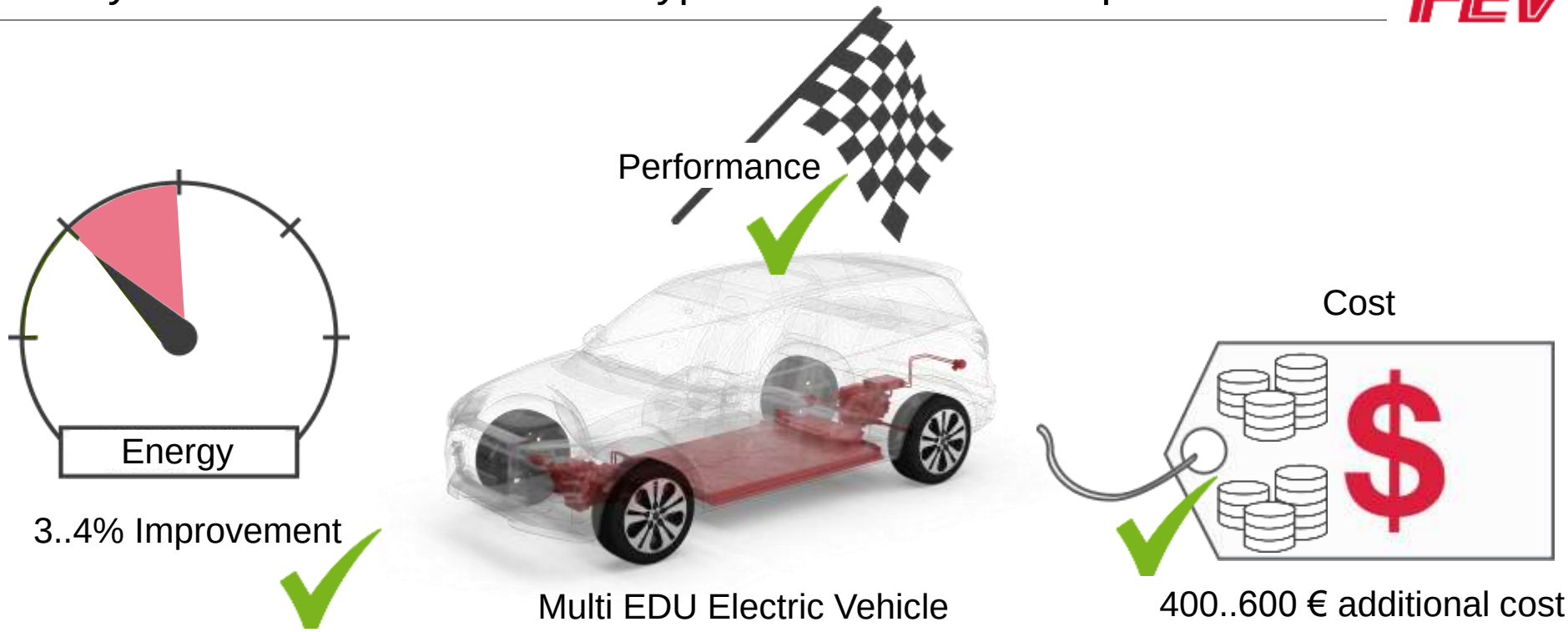
COST VS BENEFIT RATIO



- Multi PMSM machines (without disconnect) lead to higher cost AND higher energy consumption
- Good solutions (#7,#9) can save up to 4% energy with a cost rate of approx. 150..200 €/%

Remarks: 1)Cost study on EDU Level. Any vehicle sided additional effort for 4WD is not included (e.g. drive shafts, HV connectors,..) 2. Use cade dependent EDU optimization (e.g. winding variation) is not foreseen in this study

Optimization of Multi-Motor Electric Drives
Summary and Recommendations: Hypothesis must be adapted!



Hypothesis needs to be modified:

1. Multi-EDU solutions in AWD vehicle applications offer improved drivability, and save up to 4% energy consumption at the same time
2. Multi EDU solutions lead to additional costs around 500€, thus giving a cost to performance ratio of ~ 150€/% plus AWD capability

Thanks for your attention!

MSc.
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