FEV

Evaluation Methodologies for EDU Fluids Development

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Prepared for:

API

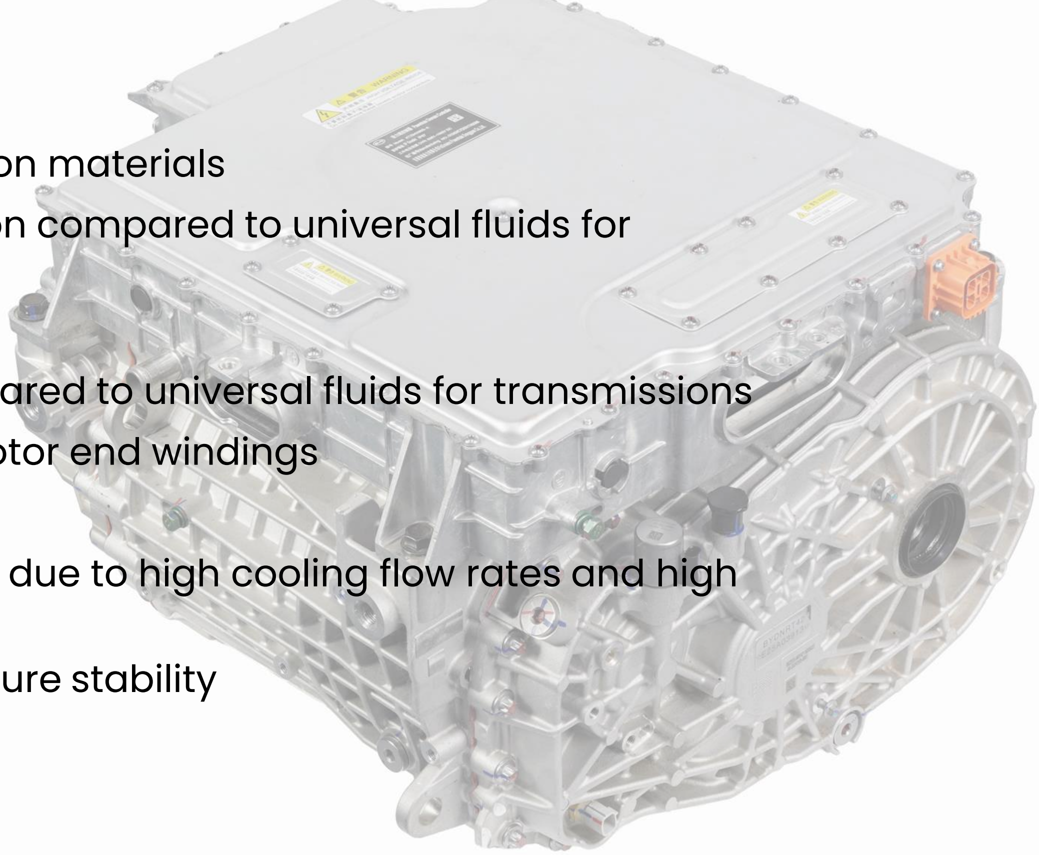
Presentation

AGENDA

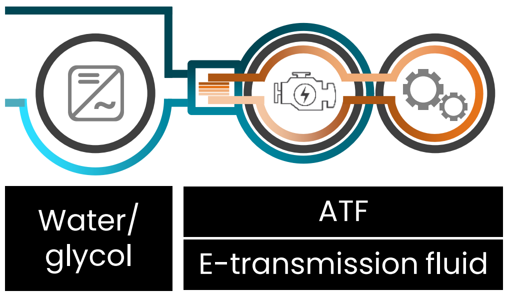
E-fluid development will continue to be important as many attributes will need to be satisfied in integrated systems

E-FLUID REQUIREMENTS SUMMARY

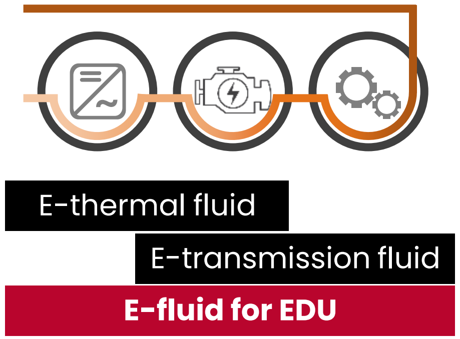
- Low viscosity
- Less friction modifiers - no synchronizer or clutch friction – less friction control
  - Specific for single-speed EDU
- Material compatibility
  - Contact with copper, insulation materials
- High copper corrosion protection compared to universal fluids for transmissions
- High specific heat capacity
- Superior thermal stability compared to universal fluids for transmissions
  - High local temperature at motor end windings
- Low conductivity
- High foam and aeration control due to high cooling flow rates and high reduction gear speeds
- Anti-oxidants for high temperature stability



Hybrid cooling



Oil cooling



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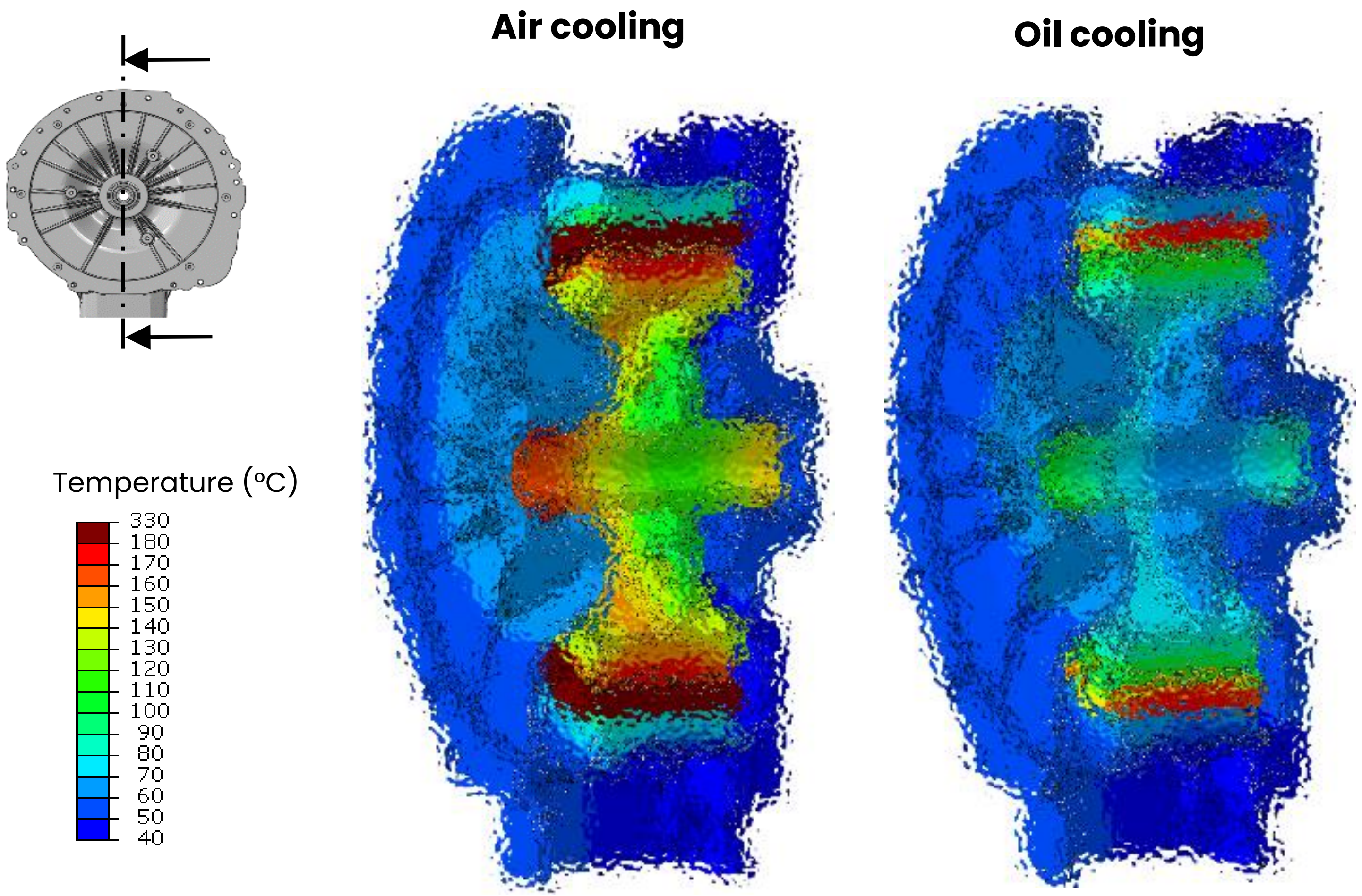
Thermal simulation allow for optimizing cooling architecture and avoiding hot-spots in the EDU design

MAX SPEED, MAX CONTINUOUS TORQUE (COMPARISON OIL/AIR COOLING)

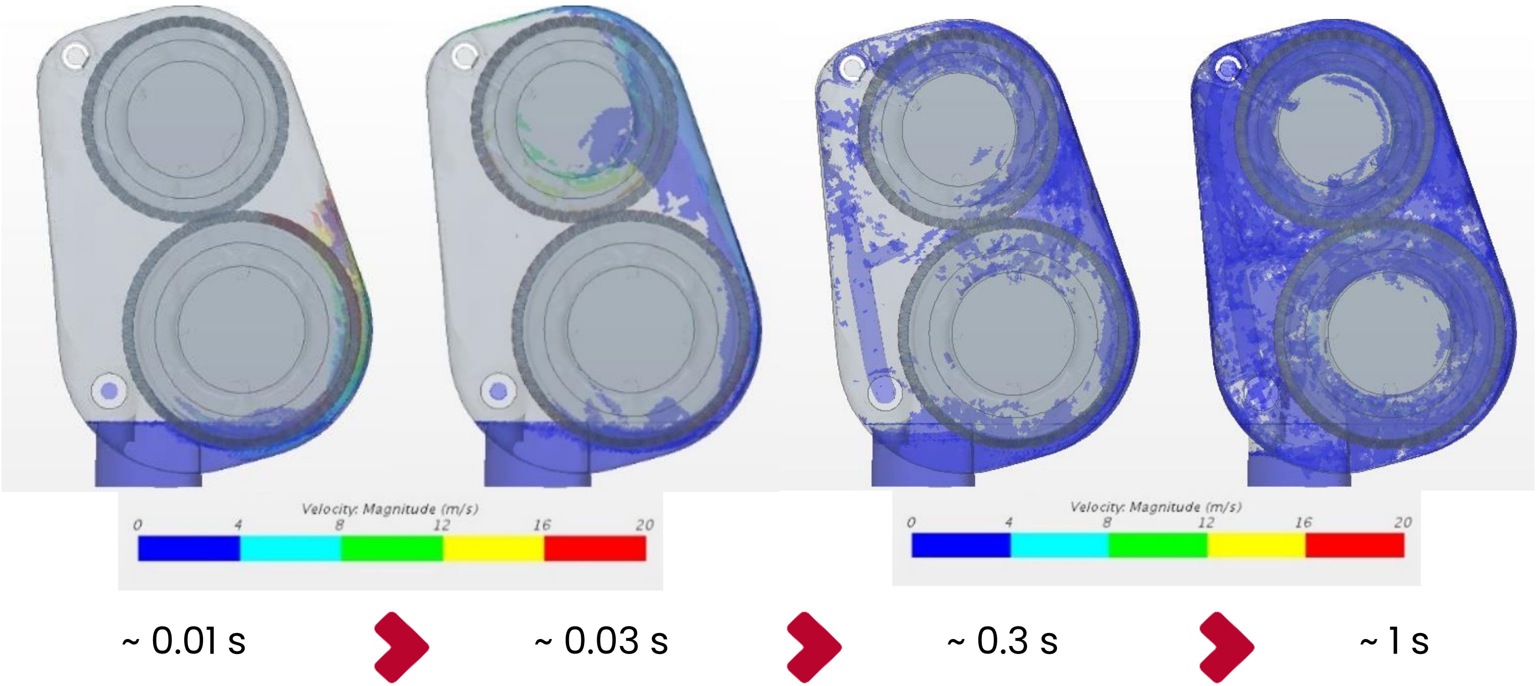


Study of thermal behavior

- Air cooling of given examples reveals hot spots exceeding 180°C
  - Motor will overheat and be damaged during operation at this temperature
- Change to oil cooling allows motor to be operated at its max. continuous torque while staying below its temperature limit

Advanced 3D CFD simulations can be utilized to visualize the oil flow in a transmission and calculate oil velocities

FLOW ANALYSIS EXAMPLE AFTER START LAUNCH OF A SINGLE SPEED GEAR TRAIN



Study of oil flow behavior

- Model details:
  - Width of input gear: 55 mm
  - Oil volume: 360 ml
  - Oil temperature: 40 °C
  - Volume flow: 6 l/min
  - Input speed: 2250 rpm
- Model output:
  - Oil velocities to determine churning/windage influence

AGENDA

Fundamentals and boundaries of testing

OVERVIEW

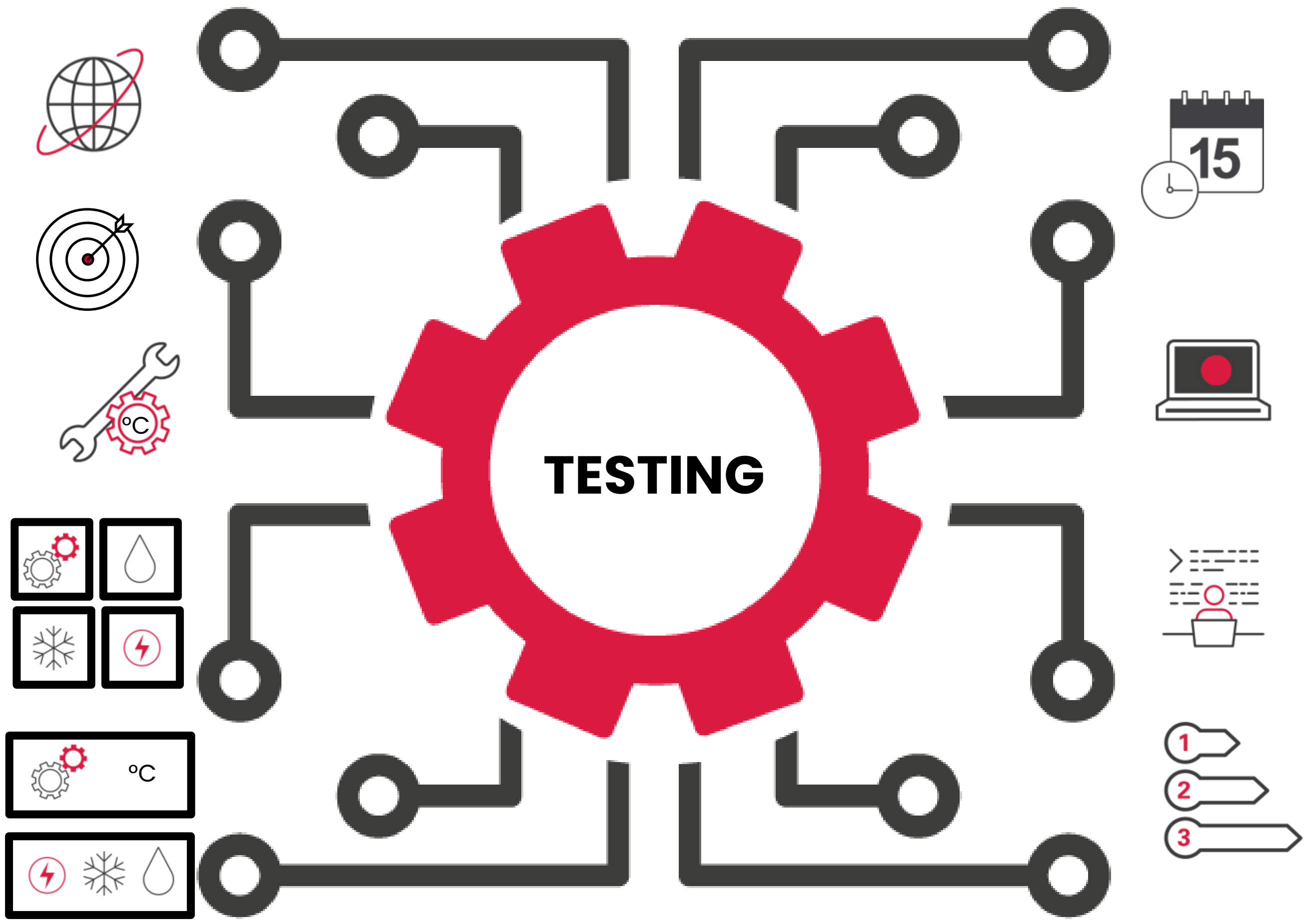
Simulate real-life conditions

Repeatable and reproducible

Allow control on testing parameters

Specialized for specific testing tasks

Focus on single or multiple influences



Allow accelerated testing

Ensure and realize data logging

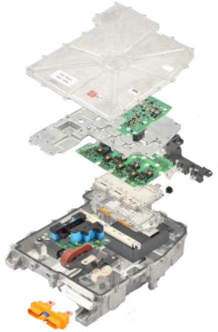
Monitor key parameters and limits

Handle different UUT and test levels

Electric drive units are integrated systems and fluid specific evaluations can be conducted at sub-system and EDU-system levels

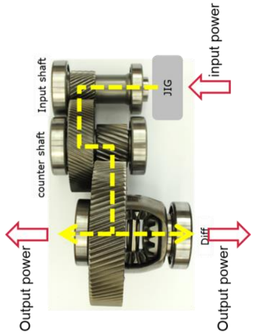
MOTOR

- Motor efficiency
- Motor thermal stress testing
- Focus on:
  - Motor cooling
  - Oil distribution
  - Thermal stress
  - Motor durability
  - Thermal motor model validation



POWER ELECTRONICS

- Thermal testing
- Inverter performance
  - Power electronics are currently less relevant for stand-alone fluid testing



GEARBOX

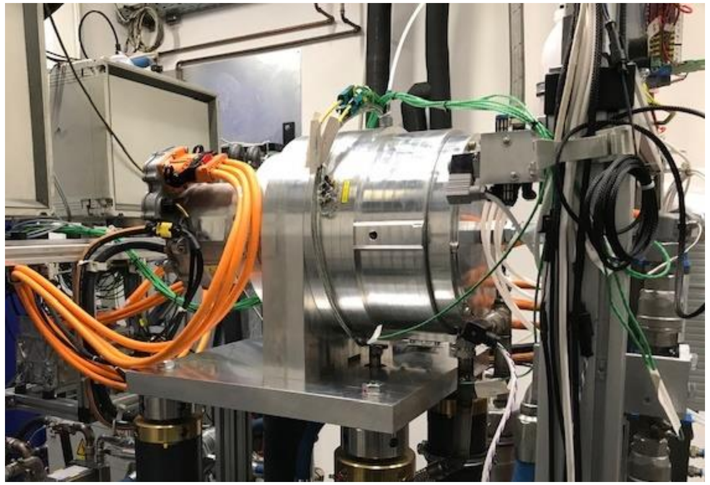
- Gear efficiency
- Gear spin loss
- Effect of lubrication to gear train
- Focus on:
  - Mechanical torque path
  - Parasitic losses
  - Gear protection

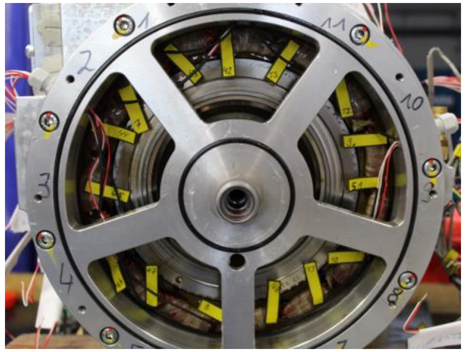
EDU SYSTEM

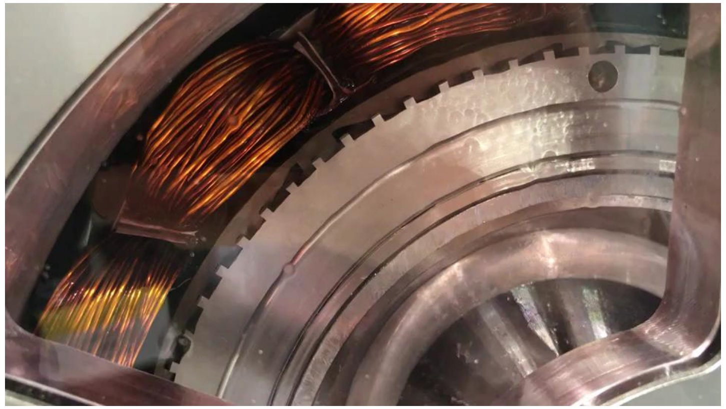
- EDU efficiency
- EDU spin loss
- Oil aeration
- Thermal testing
- Focus on:
  - Interaction of EDU components
  - System behavior
  - System durability
  - Oil distribution
  - Etc.

One key aspect for electric motor testing is system cooling evaluations

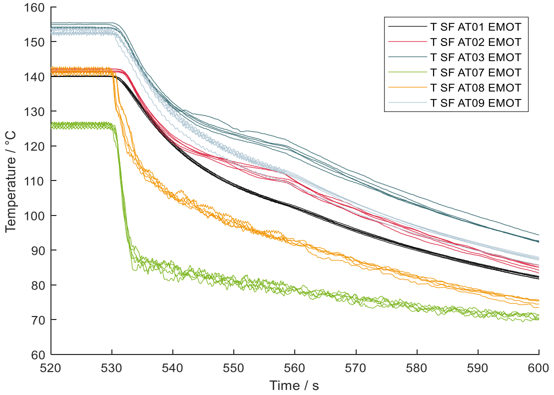
DEVELOPMENT OPTIMIZATION OF OPTIMIZATION OF OIL COOLING SYSTEM



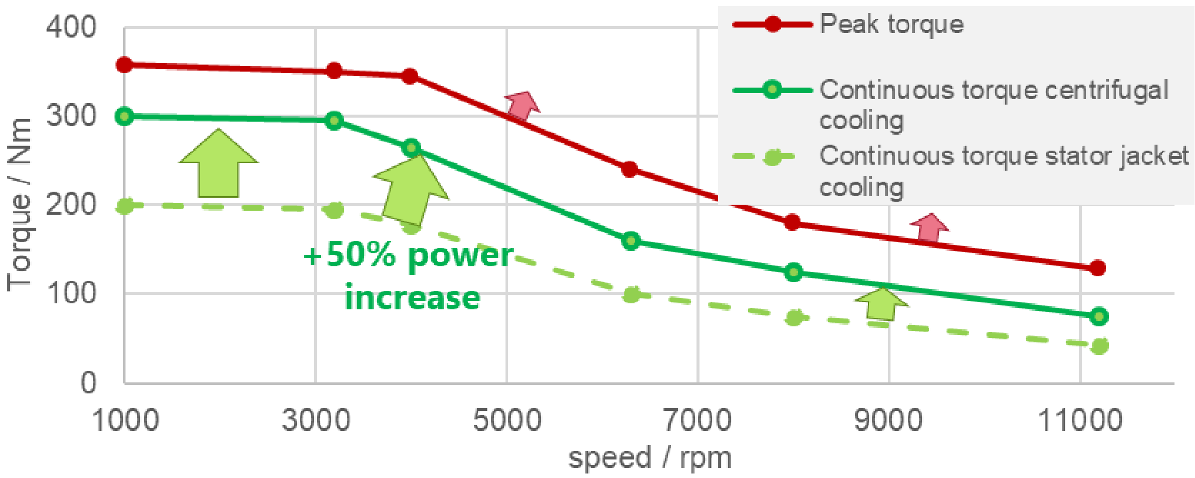




Reproducibility

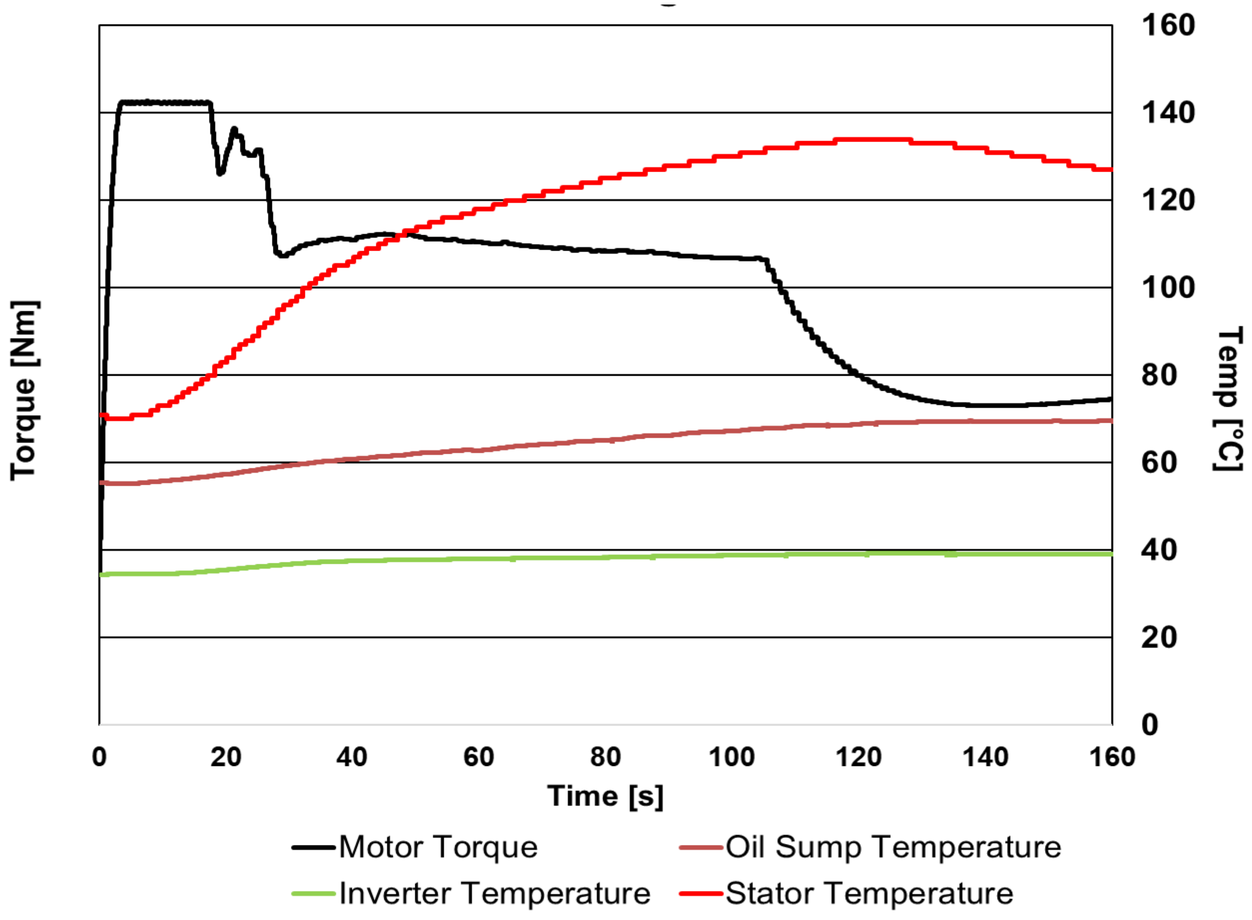


Motor characteristic



Motor thermal testing shows the influence of motor temperature on derating

CONTINUOUS TORQUE TESTING, 4500 RPM

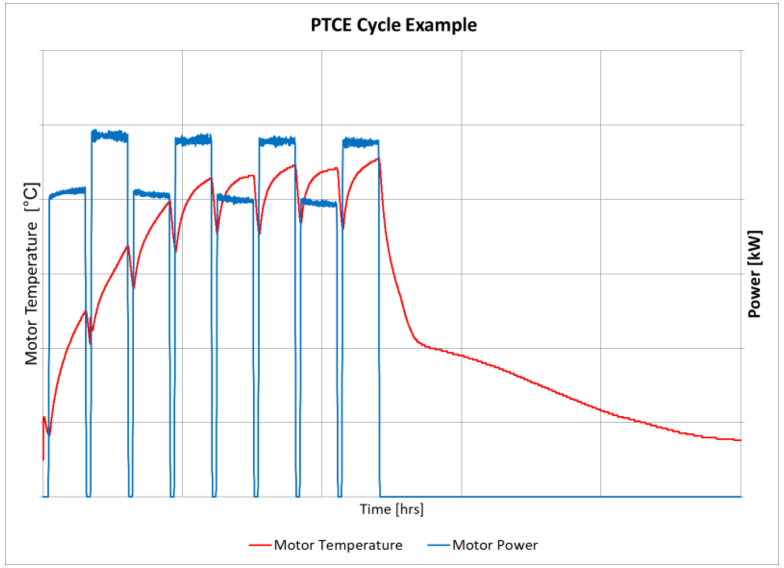


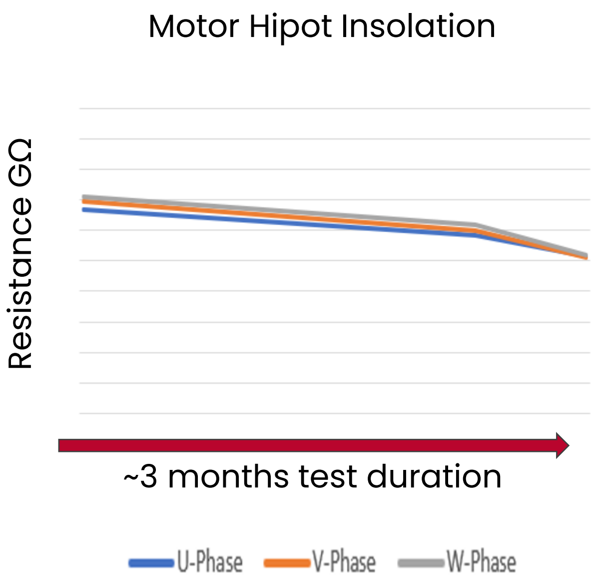
- Motor de-rates after short duration of running peak torque
- Stator temperature raises rapidly during peak torque operation
- Further de-rate necessary to avoid stator temperature reach above 135°C
- Efficient motor cooling can further increase operation at high power
- Testing can be done as motor test, or as system test in EDU environment

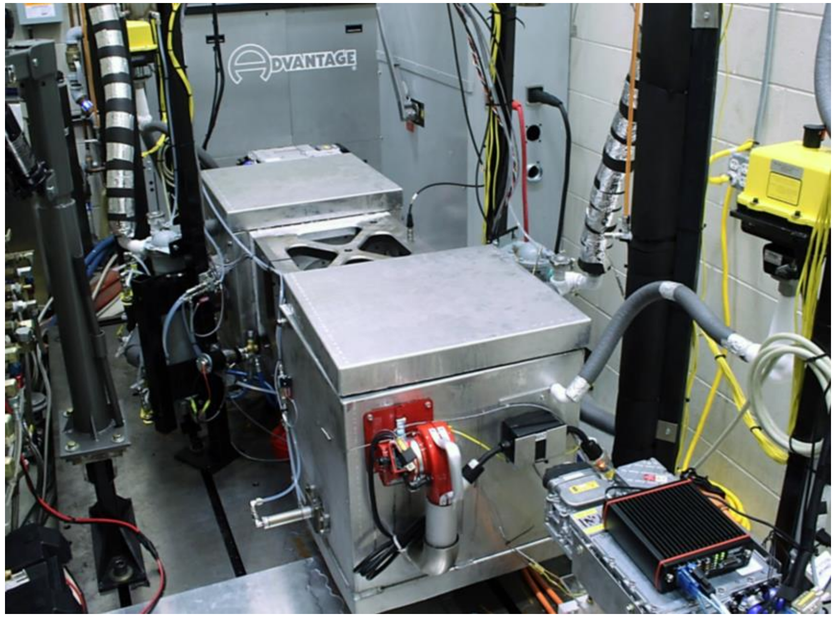
Back-to-back e-machine testing can be used to assess the influence of thermal cycling

POWERED THERMAL CYCLING ENDURANCE (PTCE)

- Assess the durability of the test unit under severe thermal cycling
- The test unit is repeatedly cooled to minimum operating temperature and ran through set drive cycles until maximum operating temperature is reached
  - Typical motor test temps. between -40°C and ≥180°C



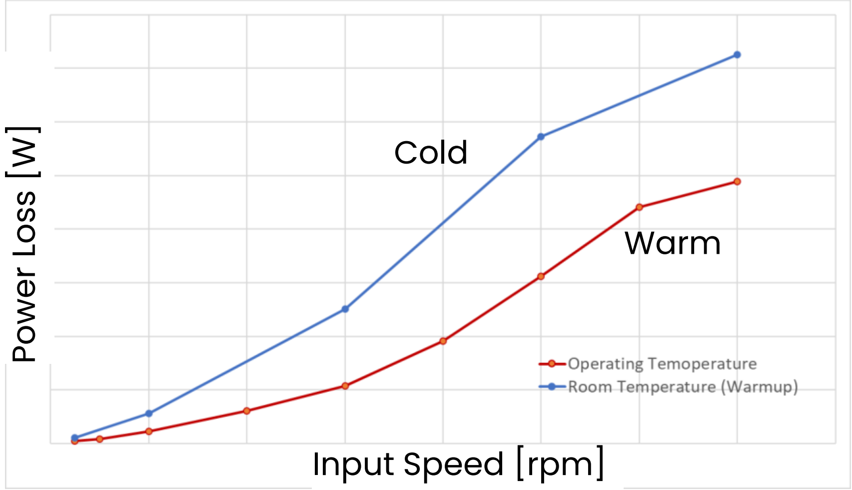


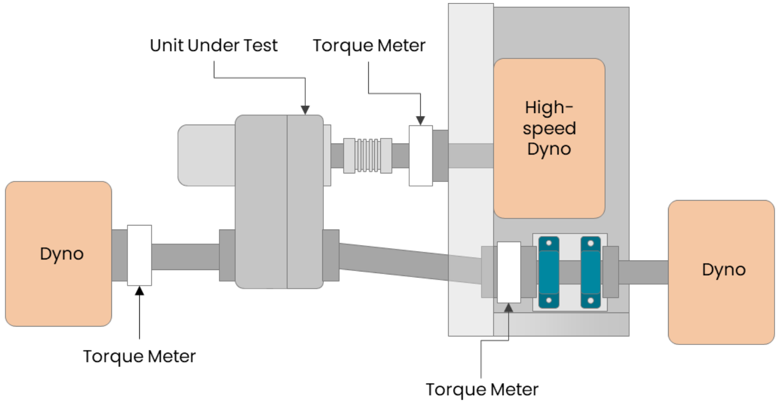


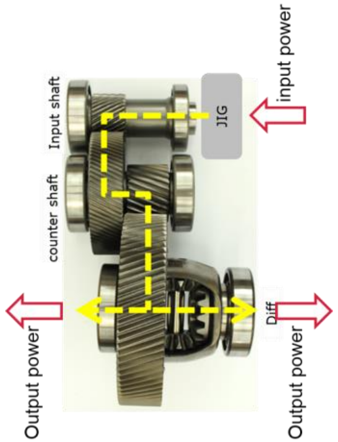
Gearbox testing can be used to understand spin losses and loaded efficiency under controlled test conditions

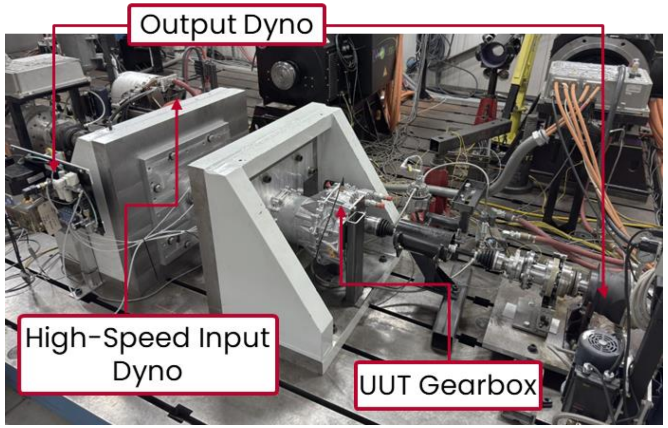
TEST SETUP AND CHALLENGES WITH EDU GEAR REDUCER TESTING

- Challenging mechanical setup due to the high input speed
  - Alignment and run-out of shaft system and inline torque meter
  - Shaft balancing
- Close axis offset between motor axis and EDU output axis leads often to challenging positioning of dynos for testing
- Re-routing of oil circuits for EDU's with wet motor









AGENDA

INTRODUCTION

SIMULATION METHODS FOR EDU COMPONENT AND SYSTEM THERMAL DEVELOPMENT

EDU SUB-COMPONENT TESTING METHODS

EDU-SYSTEM EVALUATION TESTING METHODS

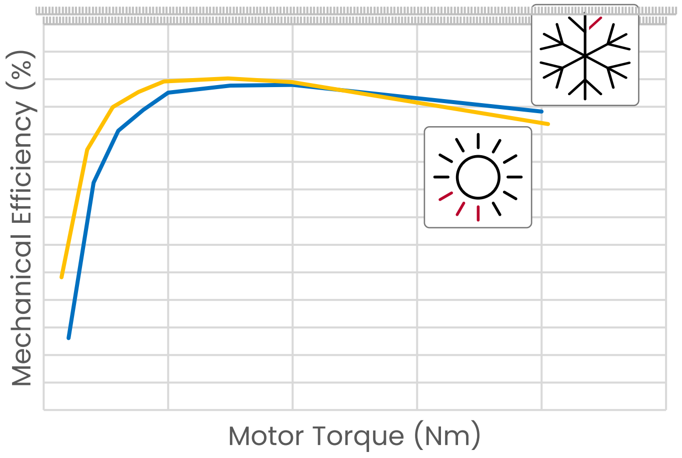
EDU SYSTEM EFFICIENCY AND ITS INFLUENCE ON DRIVE RANGE

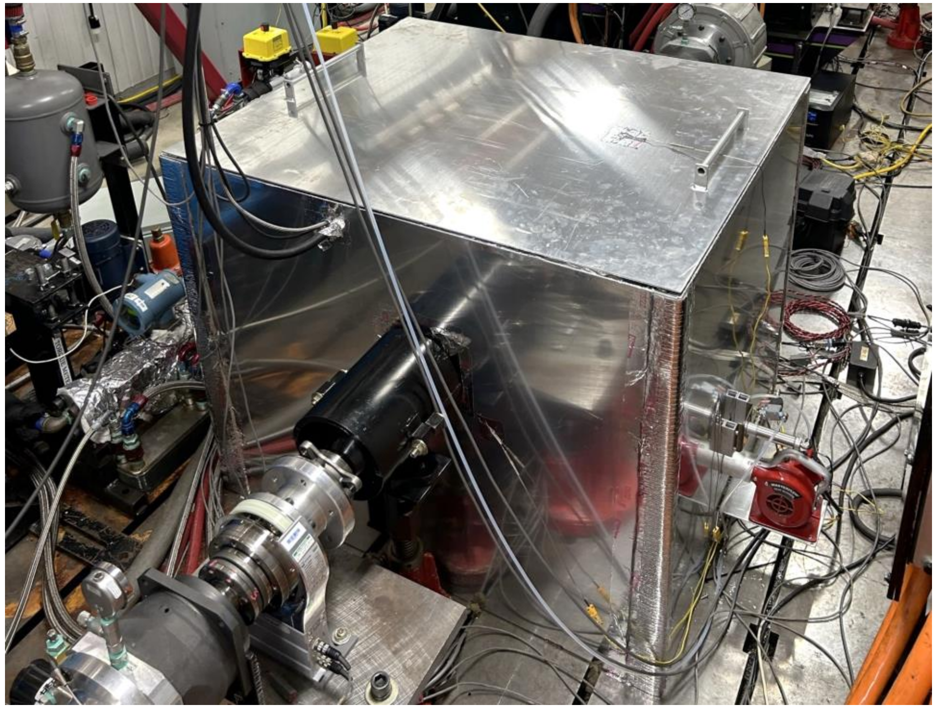
SUMMARY

System level EDU testing can be used to understand spin losses and loaded efficiency under controlled test conditions

TEST SETUP AND EXAMPLES

- Entire EDU system operated at a test bench under controlled conditions
- Thermal enclosure used for any thermal testing or extreme temperature testing
- Examples include:
  - System durability and endurance
  - High temperature operating endurance (HTOE)
  - System efficiency testing
  - Fluid screening for E-fluid development





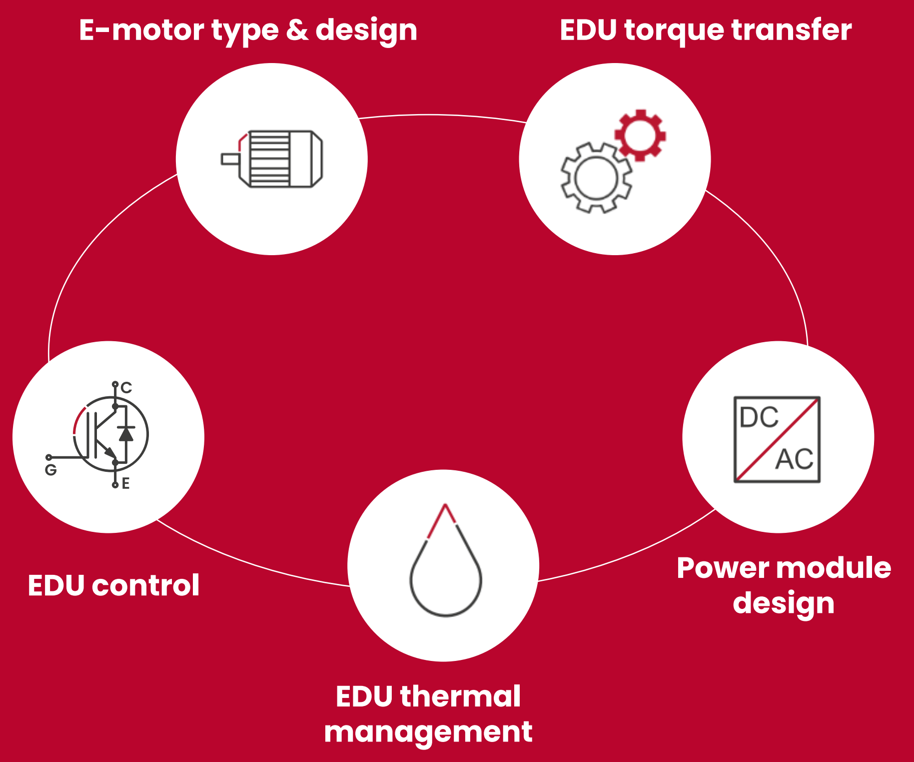
There are several factors influencing the EDU efficiency; to mitigate them, the first step is to recognize the key controllable variables

FACTORS IMPACTING EDU ENERGY CONSUMPTION

Main factors having an impact on EDU energy consumption

General losses	Mechanical / gear losses	Busbars / wires losses	Temperature influence
E-motor specific	Hysteresis losses	Copper losses	Mechanical / stray losses
Inverter specific	Conductive losses	Switching losses	DC Link losses

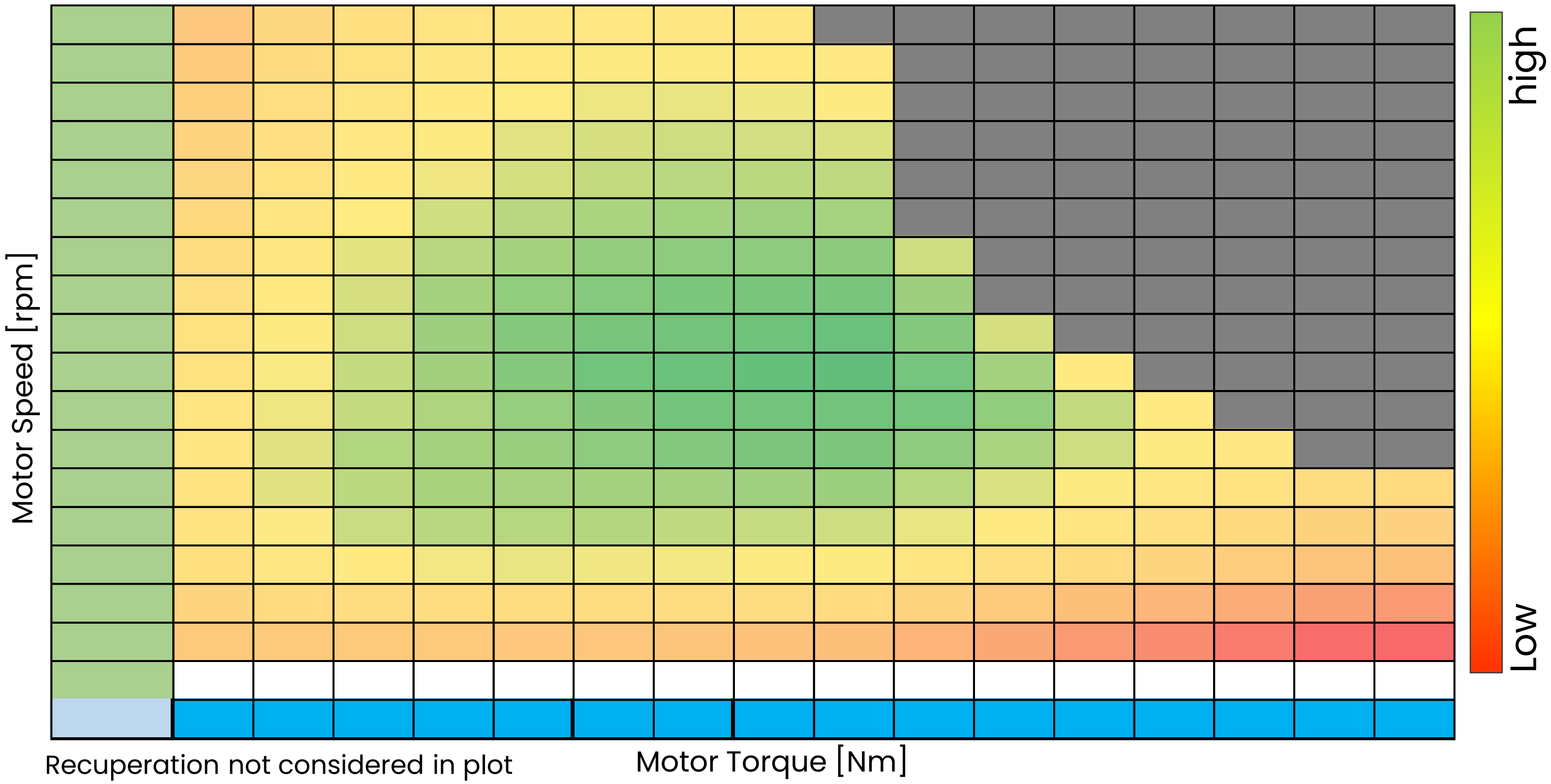
Controllable variables allowing to increase EDU efficiency



System level EDU efficiency map under entire speed and loads

LOADED EFFICIENCY MAP, NORMAL OPERATING TEMPERATURE

Baseline Fluid EDU Efficiency – full map



- Plot reveals typical EDU efficiency characteristic
  - Motor defines best efficiency at mid speed- and torque range
  - Motor losses increase in high speed- and torque areas
  - Gearbox losses increase at high speed
  - High speed and torque points are usually not relevant for drive cycle efficiency

System level EDU efficiency testing can be used to compare the performance of different fluids under vehicle-relevant speeds and loads

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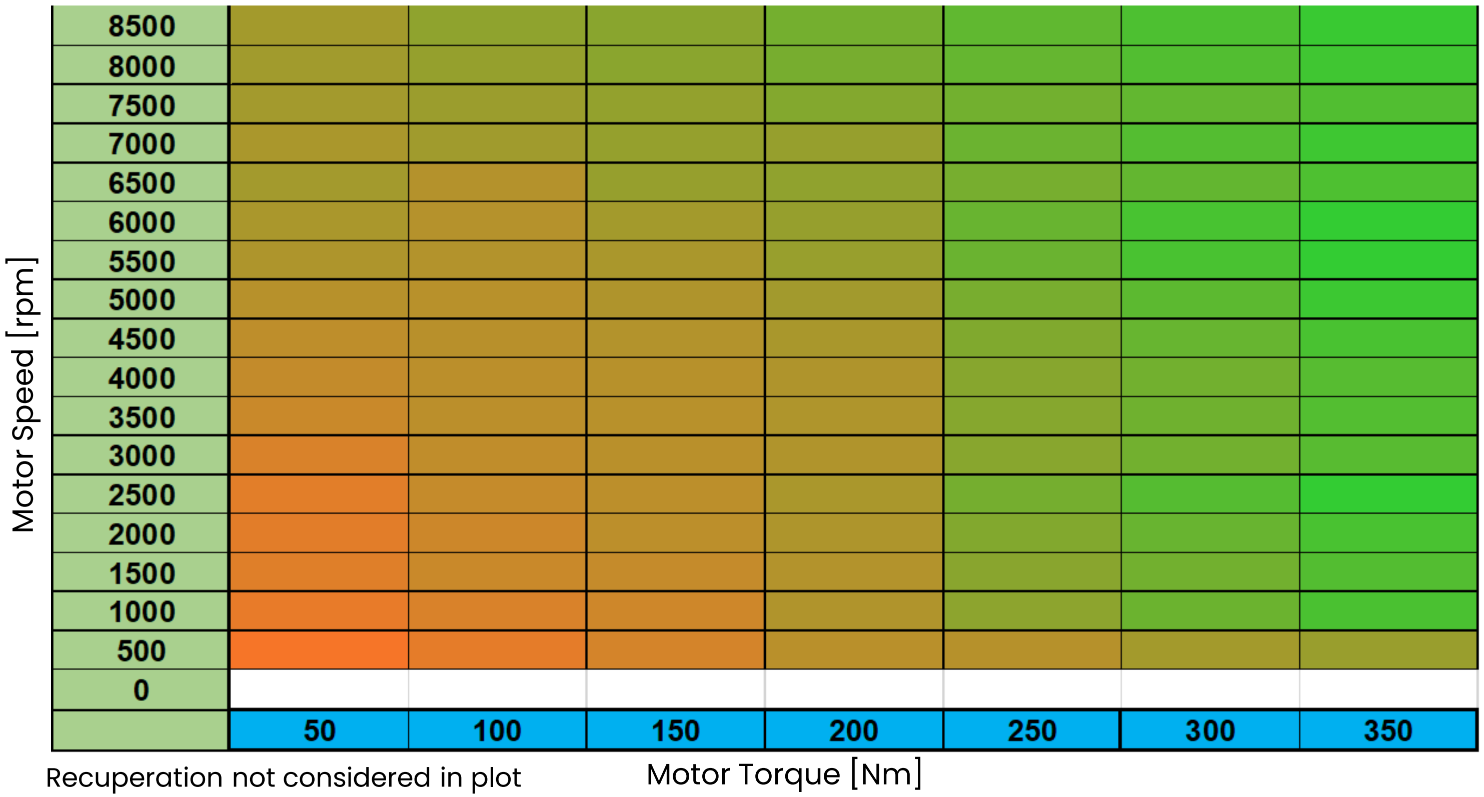
LOADED EFFICIENCY MAP, NORMAL OPERATING TEMPERATURE

Baseline Fluid – (minus) ULV Fluid efficiency map



- For efficiency impact in vehicle, boundary conditions of drive cycles must be understood
  - Speed and load
  - Operating temperature

X UDDS ● HWFT

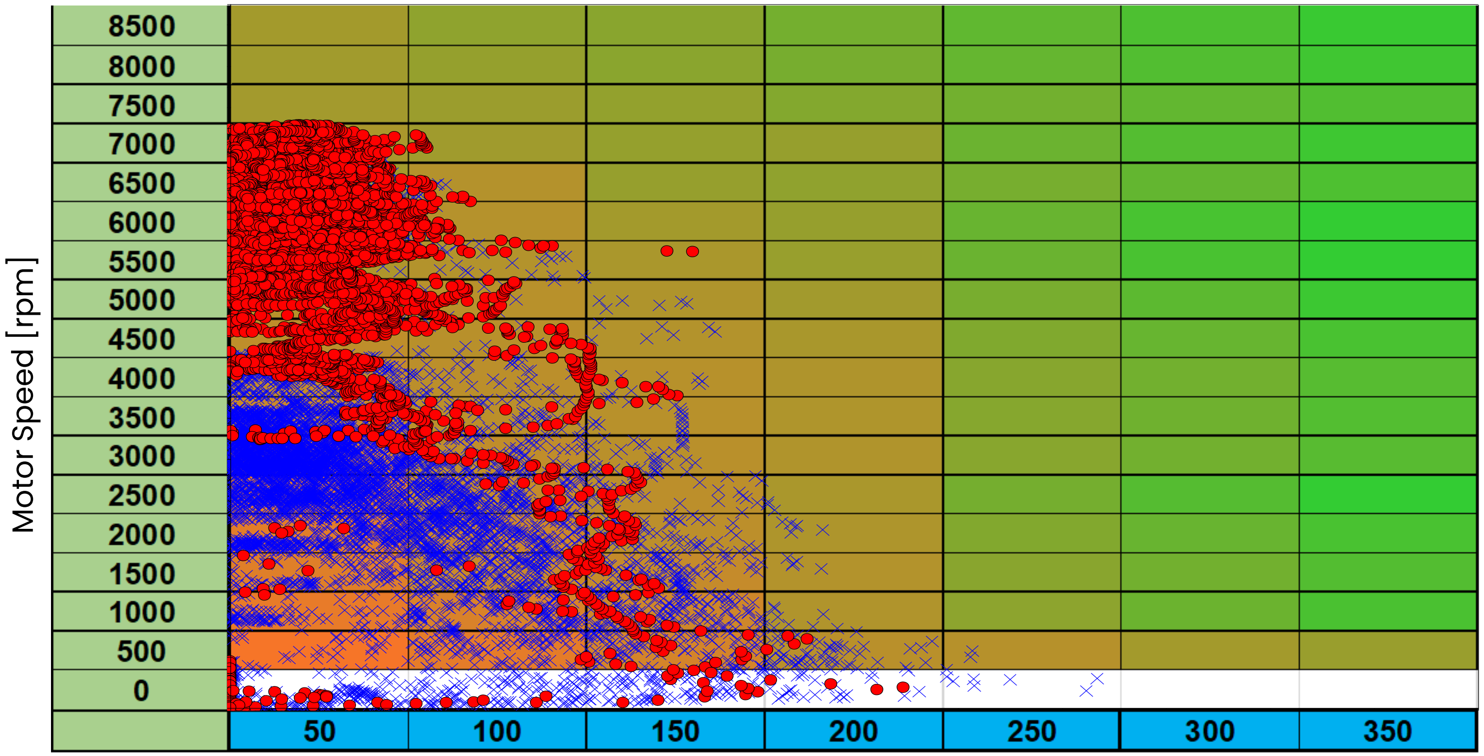
Higher efficiency with BL fluid

Higher efficiency with ULV fluid

System level EDU efficiency testing can be used to compare the performance of different fluids under vehicle-relevant speeds and loads

LOADED EFFICIENCY MAP, NORMAL OPERATING TEMPERATURE

Baseline Fluid – (minus) ULV Fluid efficiency map



Recuperation not considered in plot

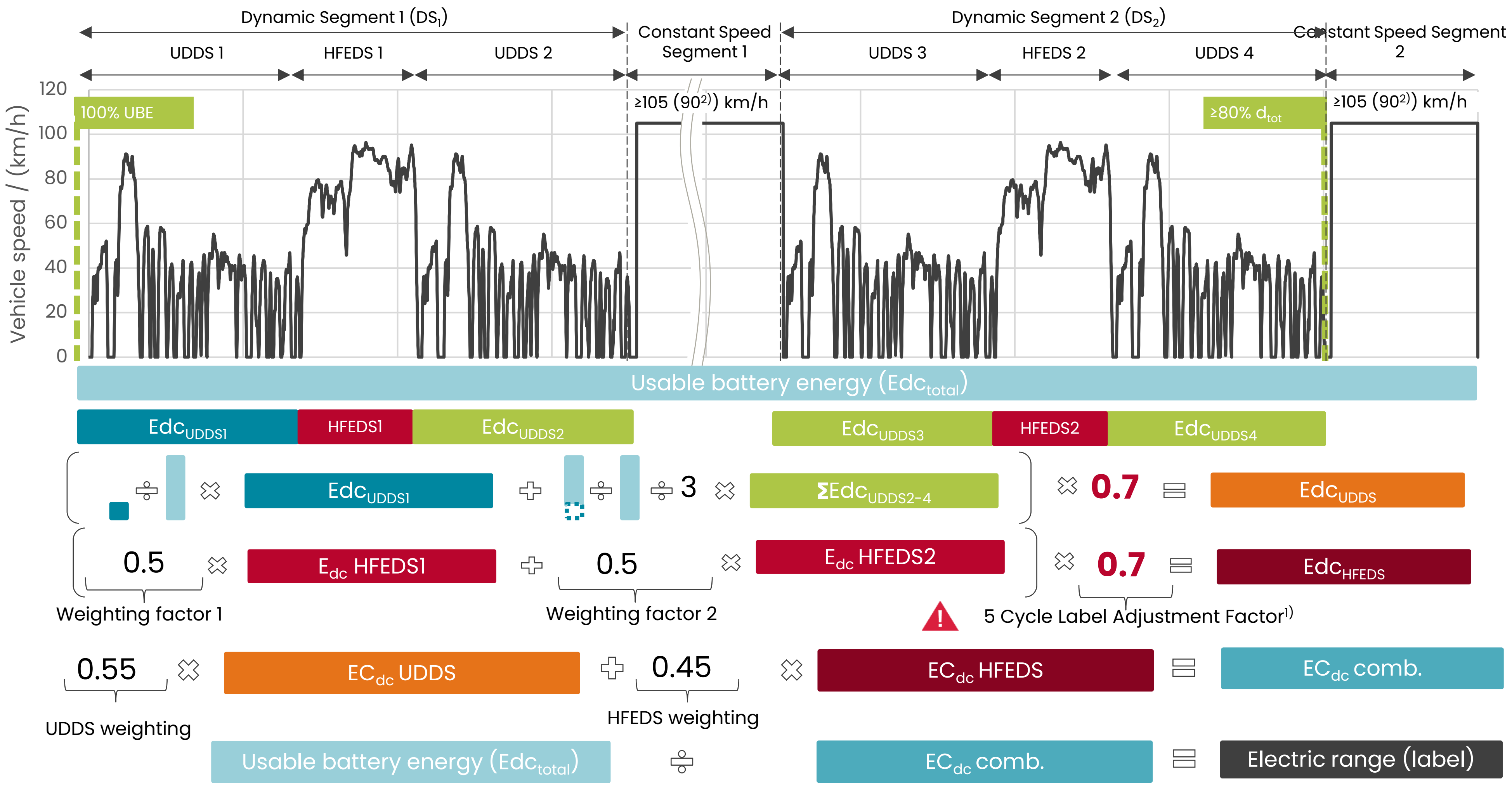
- For efficiency impact in vehicle, boundary conditions of drive cycles must be understood
  - Speed and load
  - Operating temperature

X UDDS ● HWFT

Higher efficiency with BL fluid (green)

Higher efficiency with ULV fluid (red)

Multi-Cycle procedure and weighting factors to determine label values



UBE=Usable Battery Energy (over complete MCT), E = Energy measured at battery clamps, EC = Energy Consumption, DC = Direct Current (w/o charging losses), d = distance, PER = Pure Electric Range, SOC = State of Charge

1) Energy Consumption and Range of Multi Cycle Procedure have to be adjusted for equivalent 5 Cycle fuel economy label results. Either standard factor of 0.7 or individual factor from 5-cycle testing can be applied

2) SAE J1634-2012 allows 90km/h (55 mi/h) and is still allowed according to §40 CFR 600.011 C2

Source: SAE J1634:2012/2017, 40 CFR parts 86,600

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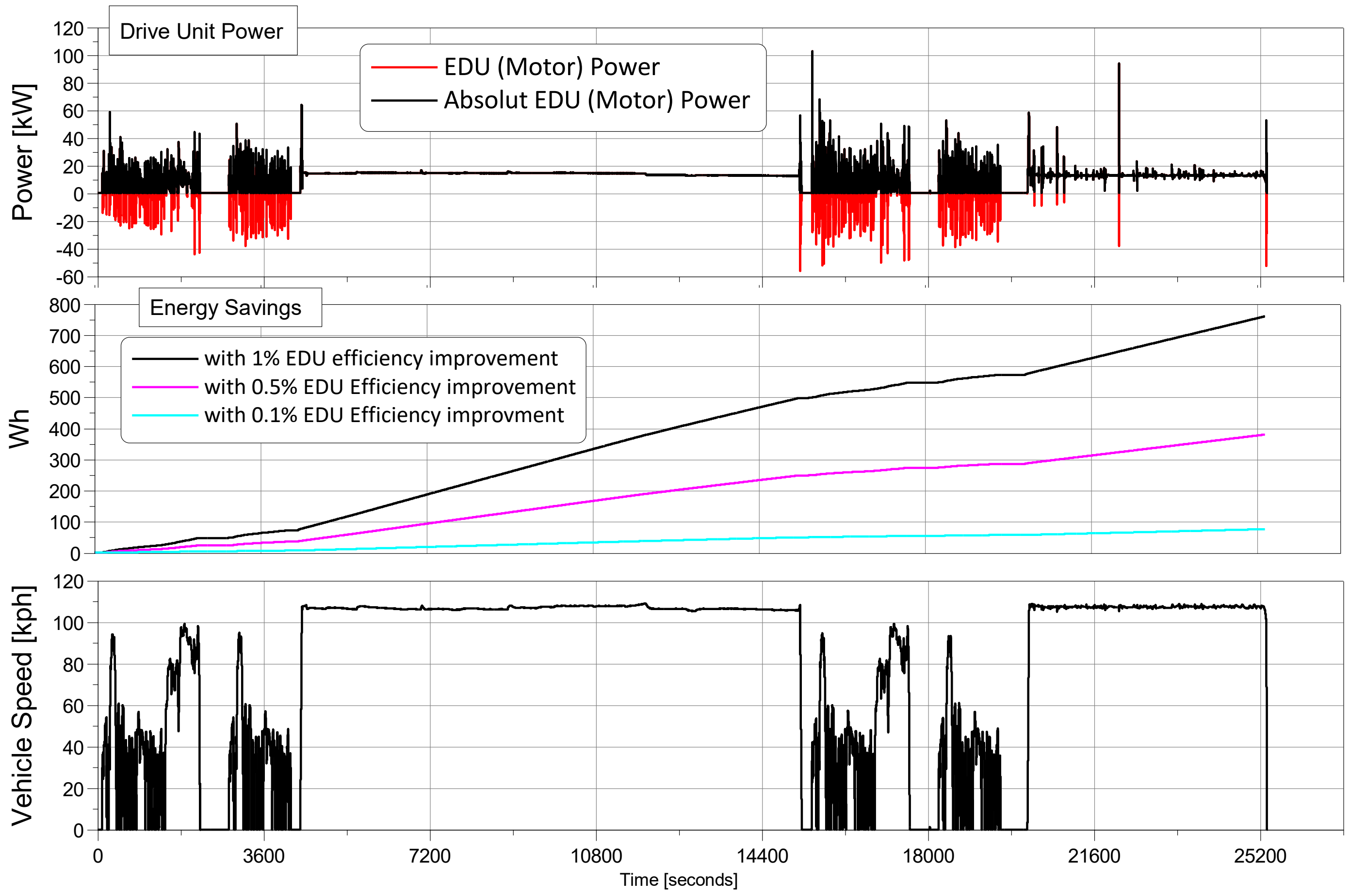
Based on EDU propulsion power (motor power) and overall EDU efficiency improvement, the associated increase in EV range is calculated

ELECTRIC VEHICLE MCT TESTING – PASSENGER CAR



- Based on EDU propulsion power (motor power) and theoretical overall EDU efficiency improvement (1%, 0.5%, 0.1%) power loss and energy loss improvement is calculated
  - With 1% efficiency improvement of the drive unit, 0.76kWh of energy loss is avoided
- Estimation does not take the change of road load into account
  - Further range improvement is expected due to reduction or rolling resistance

Estimated drive range in MCT with expected improvement of EDU efficiency

Efficiency & Range		
City	Highway	Combined
573 mi	401 mi	495 mi
Adjusted Range - Standard 0.7 Adjustment Factor		
347 miles		

- Baseline Range

0.5% EDU efficiency Improvement

Efficiency & Range		
City	Highway	Combined
577 mi	401 mi	498 mi
Adjusted Range - Standard 0.7 Adjustment Factor		
349 miles		

- Noticeable improvement of 3 miles unadjusted
  - 2 miles adjusted range improvement

1% EDU efficiency Improvement

Efficiency & Range		
City	Highway	Combined
582 mi	402 mi	501 mi
Adjusted Range - Standard 0.7 Adjustment Factor		
351 miles		

- Noticeable improvement of 6 miles unadjusted
  - 4 miles adjusted range improvement

AGENDA

Evaluation of E-Fluids for electric drive units

- Simulation based tools are essential for thermal- and fluid development of electric drive units
- Test-based fluid evaluation of drive units is important both on sub-component and EDU system levels
  - Sub-component testing allows for detailed investigation of specific components
  - EDU level evaluations allow for understanding the overall system behavior, and interactions between the sub-components
- E-fluids can play an important role in cooling of the motor and power electronics, and hence overall performance of the EDU
- E-fluids can noticeably influence EDU efficiency, and hence drive range of a BEV
  - Further improvement of drive range is possible with superior E-fluids
- Key targets for further development are:
  - Loss reduction in areas of main vehicle operation
  - Improvement of cold drive unit (and vehicle) behavior
  - Full vehicle thermal management optimization
  - Gear protection while maintaining material capability