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# Charging forward

to bring innovative solutions to market

2024 ARCTIC DRIVE
BorgWarner Winter Development Facility, Arjeplog

**February - March 2024**

# AGENDA

CHARGING FORWARD

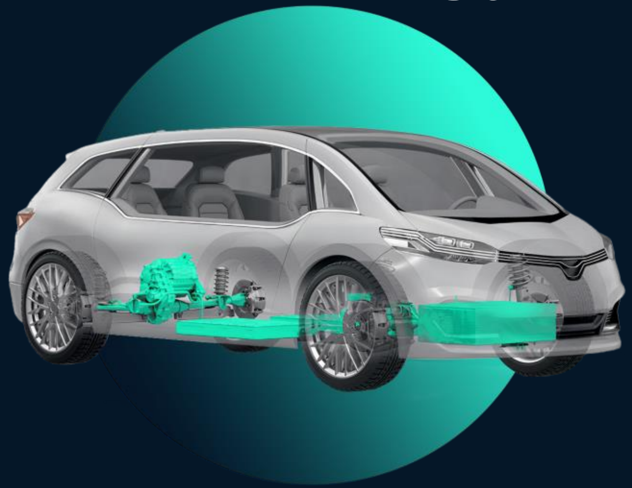
INNOVATIVE and SUSTAINABLE MOBILITY TECHNOLOGIES
The NOW and the FUTURE

TECHNOLOGY DEMONSTRATION DRIVE

FEEDACK and CURRENT TOPICS

WRAP-UP

# Electric Vehicle Technology*



Battery Systems

Chargers

Controllers

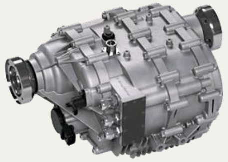
Electric Drive Modules

Electric Drive Motors

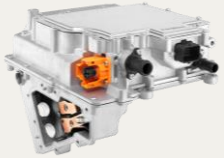
EV Transmissions

P1 Hybrid Architecture

P2 Hybrid Architecture



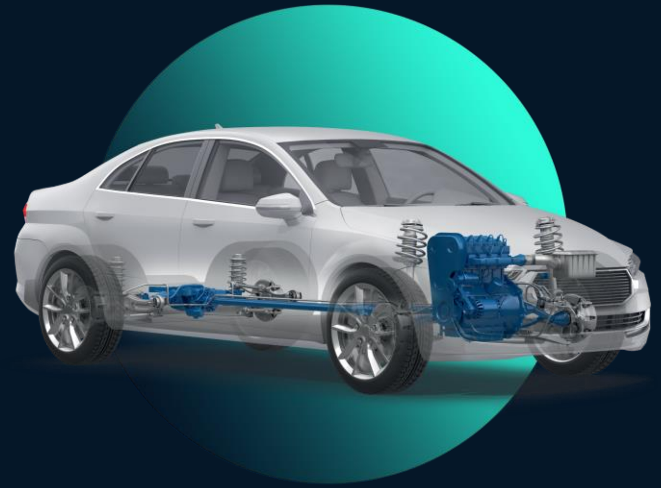
P4 Hybrid Architecture



Power Electronics

Thermal Management

# Foundational Technology

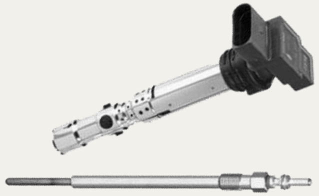


AWD + Cross Axle Systems

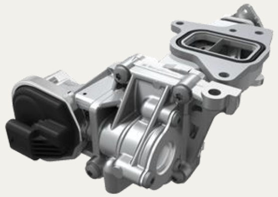
Boosting Technologies

Electric Boosting Technologies

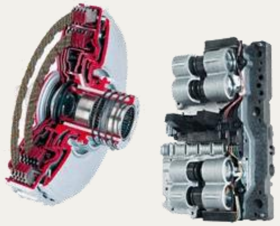
Engine Timing Systems



Ignition Technologies



Intake and Exhaust Gas Management



Transmission Technologies

Valvetrain Systems

# Commercial Vehicle Technology

Battery Systems

Boosting Technologies

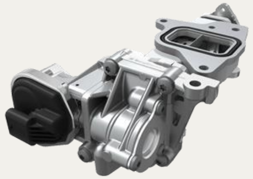
Chargers

Controllers

Electric Drive Modules

Electric Drive Motors

Engine Timing Systems



Intake and Exhaust Gas Management

Power Electronics

Thermal Management



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# CEO Organization Chart

**Fred Lissalde**
President & Chief Executive Officer

**Julie Piazza**
Sr. Executive Assistant

**Dr. Stefan Demmerle**
Vice President of BorgWarner Inc. and President and GM PowerDrive Systems

**Joseph (Joe) Fadool**
Vice President of BorgWarner Inc. and President and GM Emissions, Thermal and Turbo Systems

**Isabelle McKenzie**
Vice President of BorgWarner Inc. and President and GM Morse Systems

**Dr. Volker Weng**
Vice President of BorgWarner Inc. and President and GM Drivetrain and Battery Systems

**Kevin Nowlan**
Executive Vice President and Chief Financial Officer

**Paul Farrell**
Executive Vice President and Chief Strategy Officer

**Tom Tan**
Vice President and President BorgWarner China

**Tonit Calaway**
Executive Vice President, Chief Administrative Officer, General Counsel and Secretary

**Tania Wingfield**
Executive Vice President and Chief Human Resources Officer

# Sustainability Strategy

## Create a Cleaner, More Energy-Efficient World

### Continue

Accelerating Electrification Offerings

Delivering Products for Improved Efficiency and Reduced Emissions

### Advance

Expansion of eMobility Market Offerings

Environmental Product Stewardship

Environmental Aspects of Operations

## Live the BorgWarner Beliefs

### Continue

Employee Health & Safety

Community Education, Equity and Economics

### Advance

Diversity, Equity & Inclusion

Building the Talent Pipeline

Evolving the Skills

Engaging our People

## Partner with and Report to Stakeholders

### Continue

Ethics & Compliance

Product Safety & Quality

Data Privacy & Cybersecurity

### Advance

Sustainable Value Chain

Tech-driven Innovation

# ETC Today

**Location**
Landskrona, Sweden

~ **200** Engineers
**21%** Female

**DBS and PDS**

**Since 1998**

**WINTER FACILITY**
Arjeplog

**TECH CENTER**
Landskrona

**PROVING GROUND**
Ljungbyhed

## STRATEGIES

CHARGING FORWARD 2027

**Product Leadership**

**Innovation**

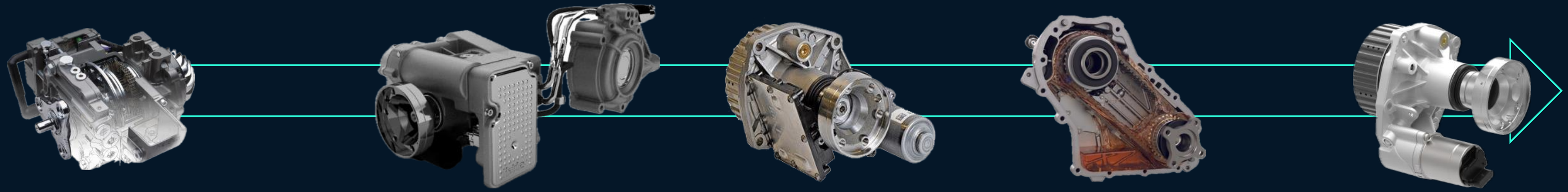
**Sustainability**

**Power to Evolve**
**Competence Transition**

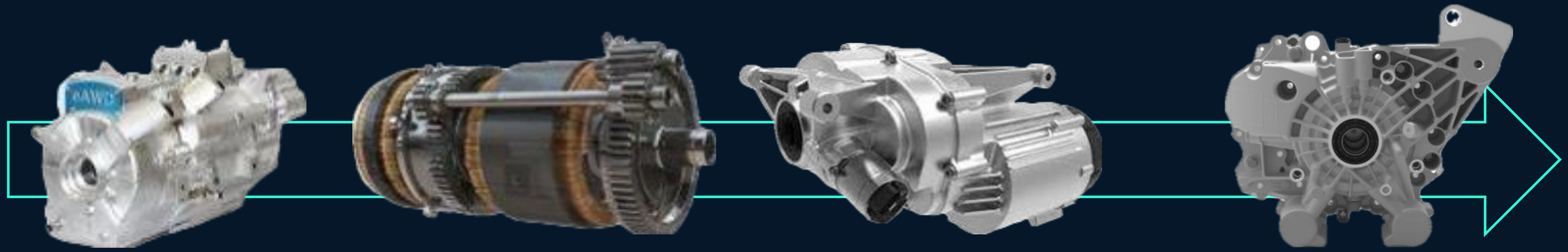
# THE HISTORY Strong Legacy Of Innovation

"Haldex Coupling"

GEN I | GEN II | GEN III | GEN IV/XWD | GEN V/FXD | EHOD Transfer Case | GEN VI



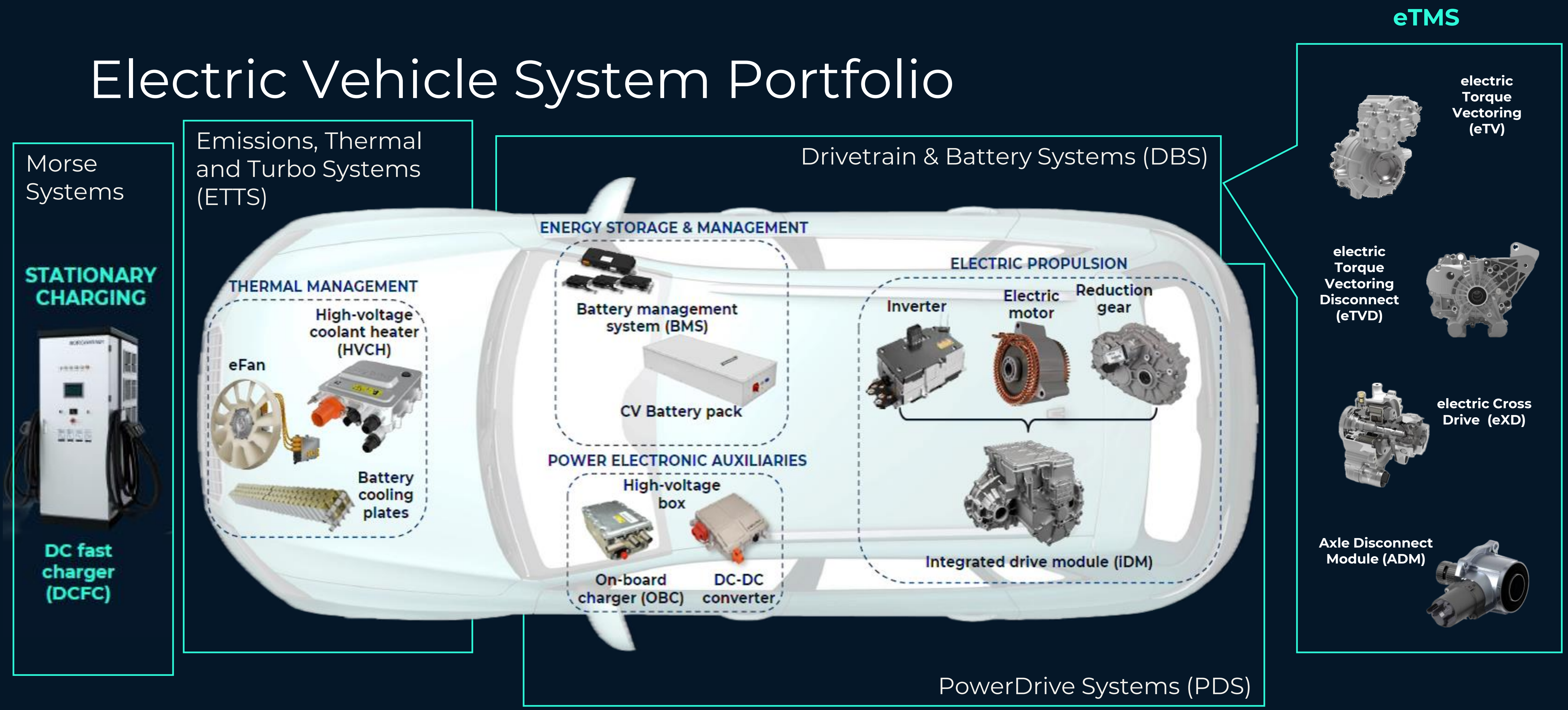
1998 | 2002 | 2004 | 2007 | 2010 | 2011 | 2013 | 2015 | 2018



eAWD | 48V/HV P2/P3/P4 | eTVD/eTV

**ROOTS stretching back to 1880**
**THULIN VERKEN**

# Electric Vehicle System Portfolio



# Technology Trends

# Technology Trends:

## Increased electrification

- Established and proposed regulations will drive higher electrification levels.
- Fleet compliance in major markets will require solutions that go beyond full hybrids

## Sustainability focus

- At vehicle and component level, sustainability based on LCA becomes an objective, not an afterthought
- This drives design and sourcing choices involving cost and performance trade-offs

## SW defined vehicles

- SW becomes more and more a differentiator and drives customer buying decisions
- Separation of HW & SW development opens system improvement opportunities

# Technology Trends:

## Controller Architectures

- Simplification and centralization of domain controllers
- Increase in on-board computing power
- Future introduction of Ethernet

## LV bus moves to 48V

- 48V allows to increase the LV bus power without a significant wiring penalty
- Higher computing power needs and auxiliary systems associated with ADAS and safety are the main drivers

## High efficiency

- System efficiency is key for electrified vehicles
- Strategies to push the efficiency boundaries at component and system level involve both HW & SW solutions

# Technology Trends:

### Smart thermal management

- Improved centralized demand oriented thermal control
- Optimization in the use of available thermal sources
- Integration of thermal management system and powertrain components
- New refrigerants

### Charging power and alternatives

- DCFC power and availability increases significantly
- Vehicle capacity to charger at higher C-rates follows through
- Wireless charging starts to gain traction in some applications and use cases

### Materials development

- Strong research focus on materials and methods to improve performance, sustainability and efficiency
- Battery chemistry, high Si-Steel, magnets with low/no RE, conductors with higher conductivity than copper, etc.

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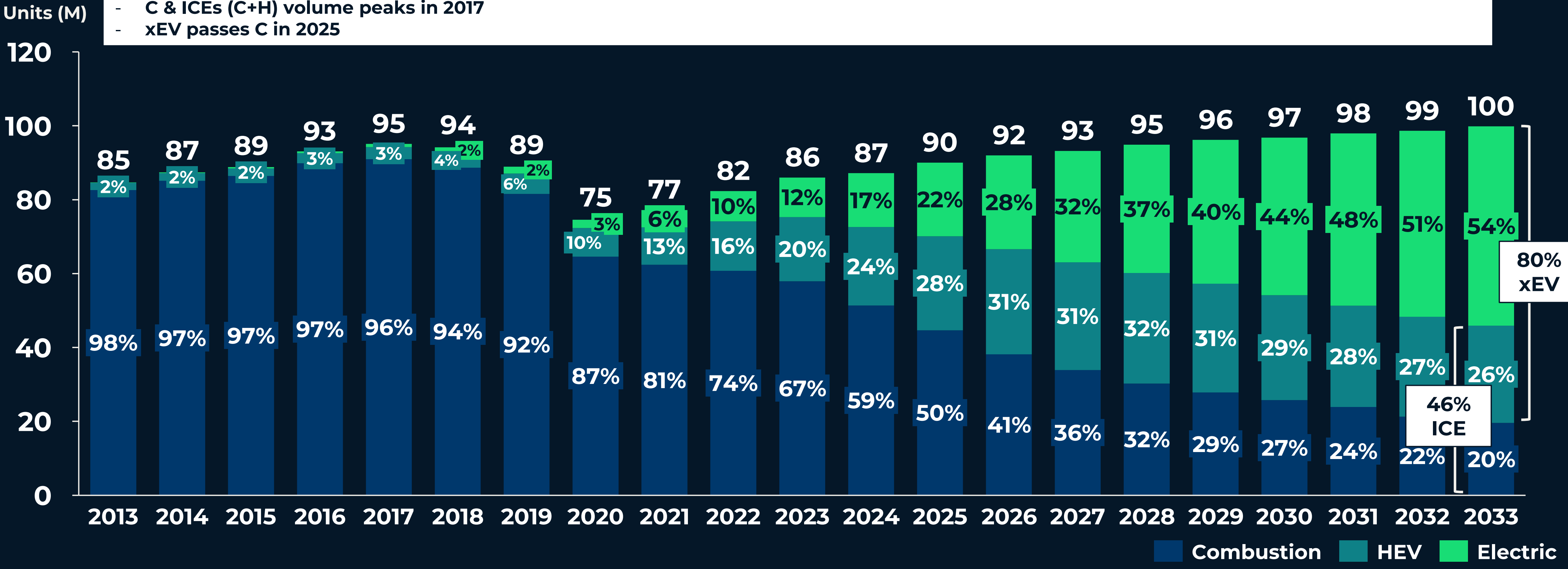
# Market Trends

# Global LV Propulsion Outlook

***Baseline Fcst.**

- Slowed market recovery from COVID-19 pandemic due to continued supply chain disruptions
- Weakened long term macro environment due in part to widening impacts of Russia/ Ukraine crisis (nat. gas supply) and elevated inflation
- C & ICEs (C+H) volume peaks in 2017
- xEV passes C in 2025



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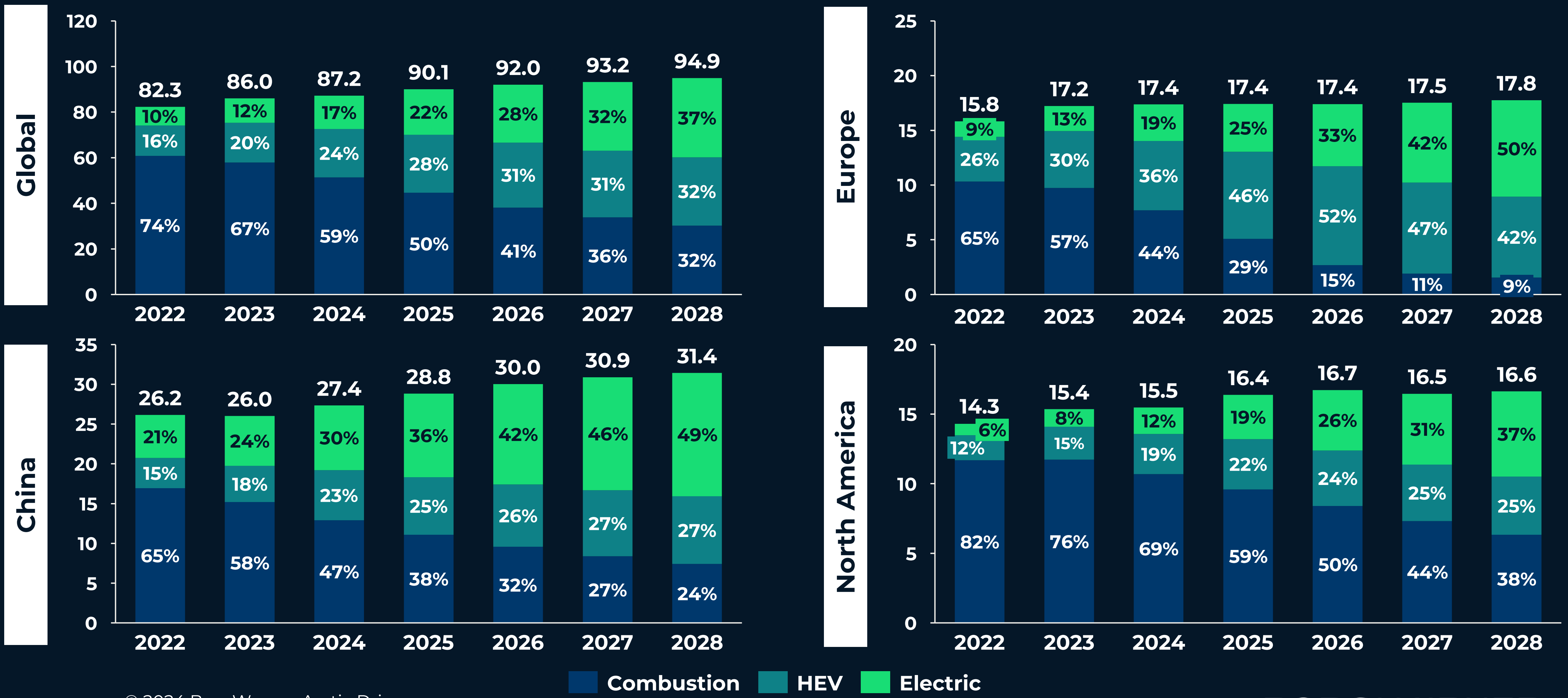
# Global LV Propulsion Outlook

*Baseline Fcst.



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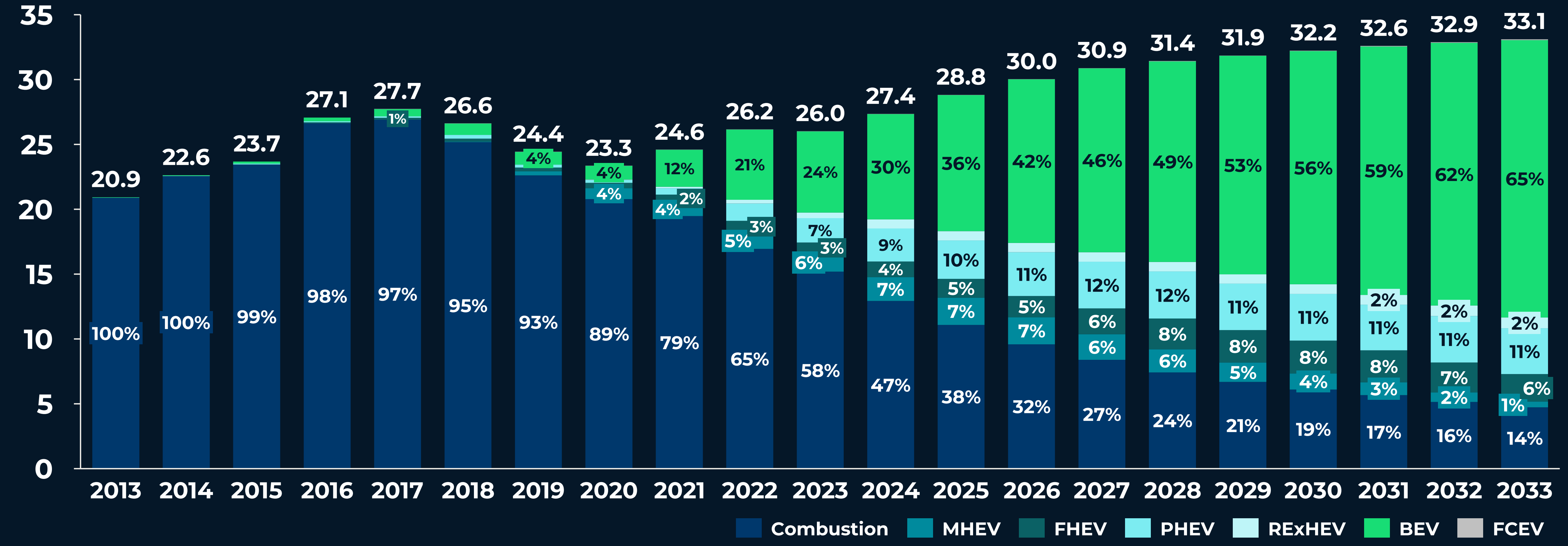
# Global LV Propulsion Outlook - China

*Baseline Fcst.

- Govt. incentives and improvements in semiconductor supply result in upside for ‘22
- Stimulus effects and indications of changes in BEV availability/preference boost volumes in outer years

Units (M)



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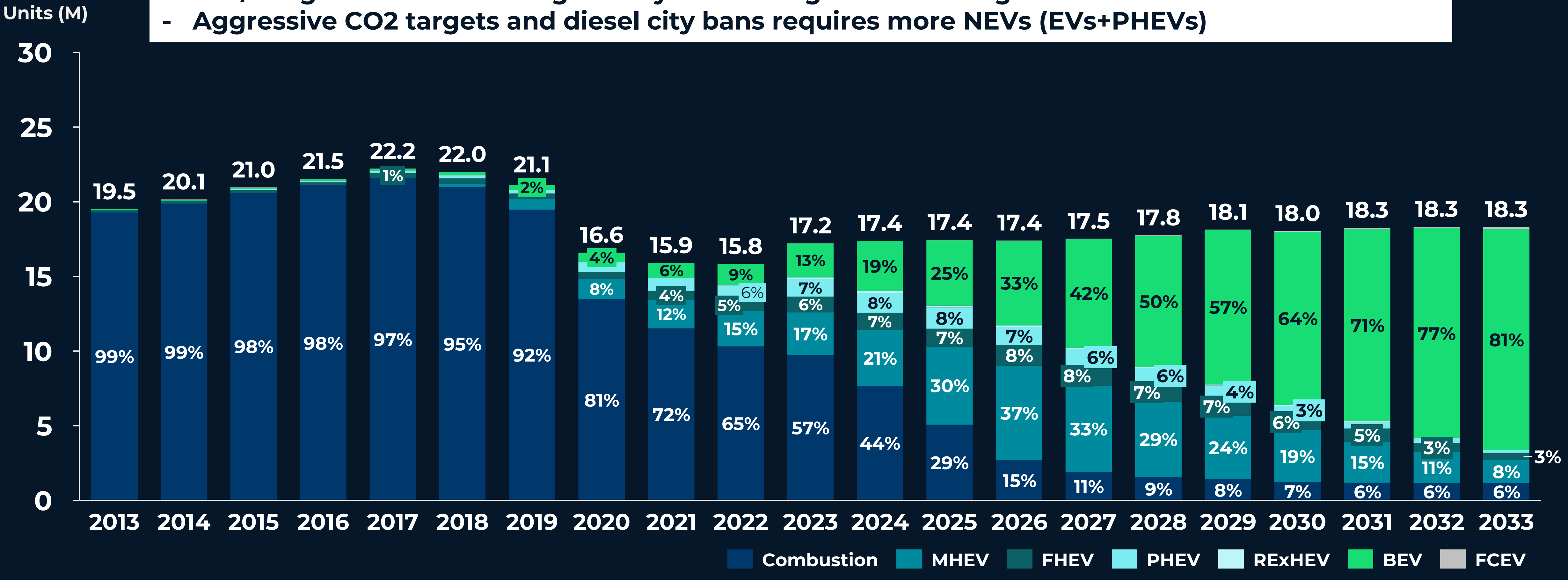
# Global LV Propulsion Outlook - Europe

*Baseline Fcst.

- Despite short term improvement, potential downside risk remains as a result of Ukraine crisis
- Mid/Long-term outlook weighted by weakening macro setting
- Aggressive CO2 targets and diesel city bans requires more NEVs (EVs+PHEVs)



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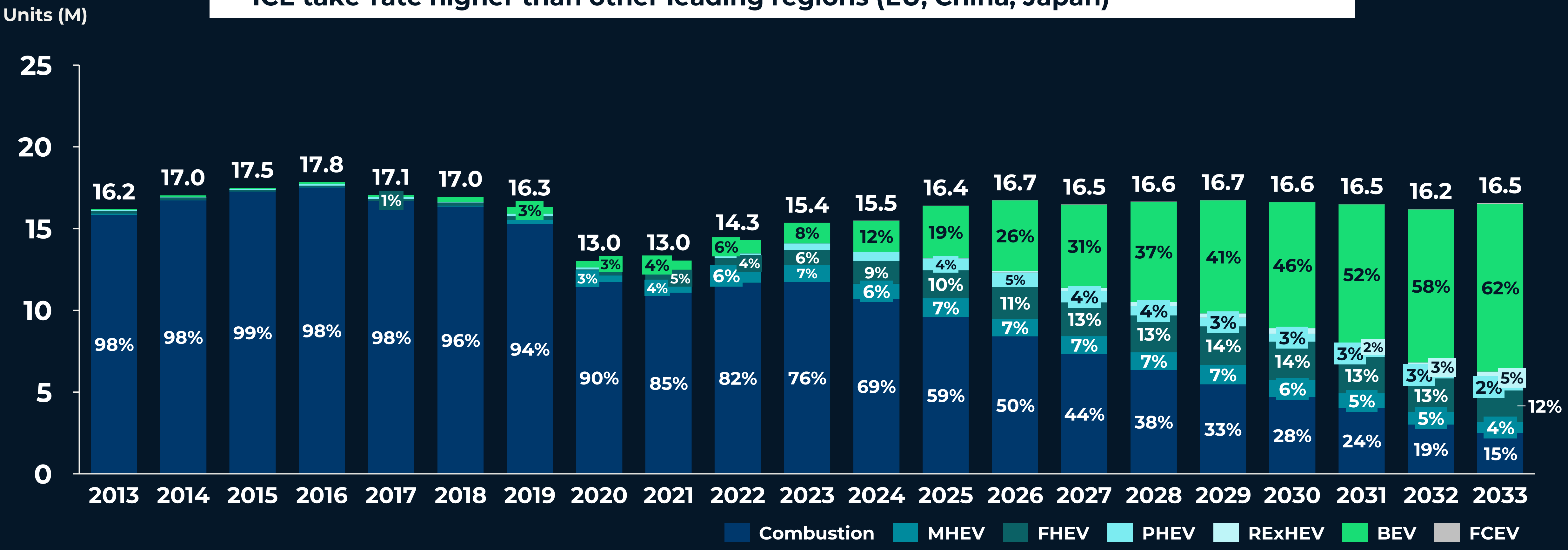
# Global LV Propulsion Outlook - North America

*Baseline Fcst.

- Varying OEM strategies drive relatively even market opportunities for all xEV types
- ICE take-rate higher than other leading regions (EU, China, Japan)



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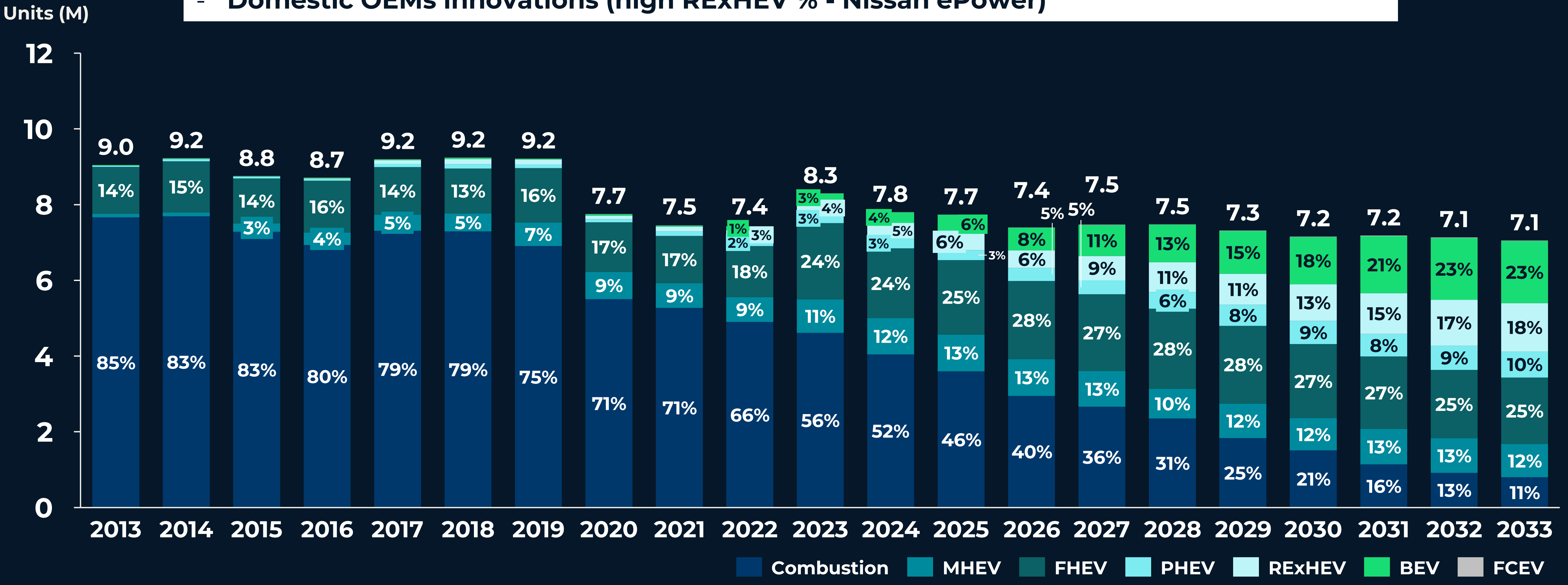
# Global LV Propulsion Outlook - Japan

*Baseline Fcst.

- ~20% global Hybrid volume today, driven by Full-Hybrid DHTs (Power Split, Direct, etc.)
- Domestic OEMs innovations (high RExHEV % - Nissan ePower)



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# EV Torque Management Systems

Vehicle introduction

# Introduction
## Electric Vehicles

**Challenges**

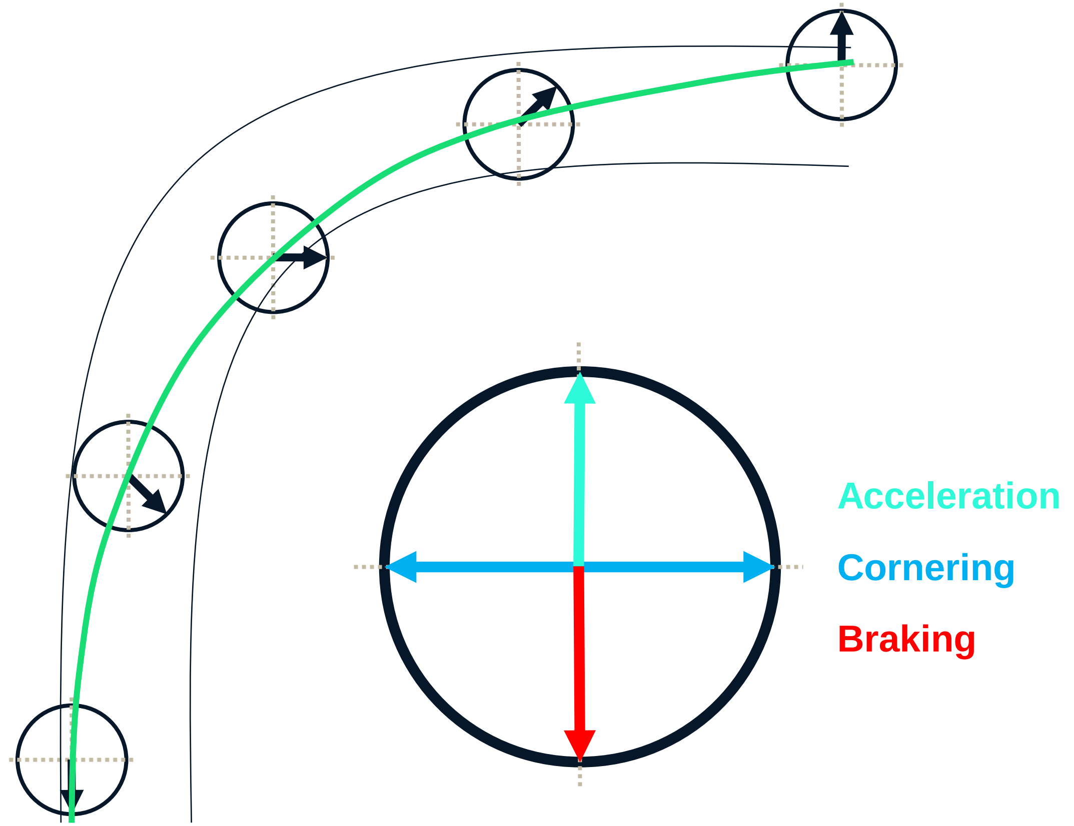
- High driveline torque capacity with fast response times
- Higher vehicle weight
- Increased stress to the tires

**Torque Management Solutions**

- Torque distribution to the wheel with best influence of vehicle behavior
- Increased vehicle stability
- Improved traction during launch and increased acceleration capacity

# Basic Tire Theory
## The Friction Circle

- The lateral and longitudinal grip of the tires can simplified be described by the friction circle
- If consuming more of the longitudinal level of grip, the available lateral grip level will also be reduced



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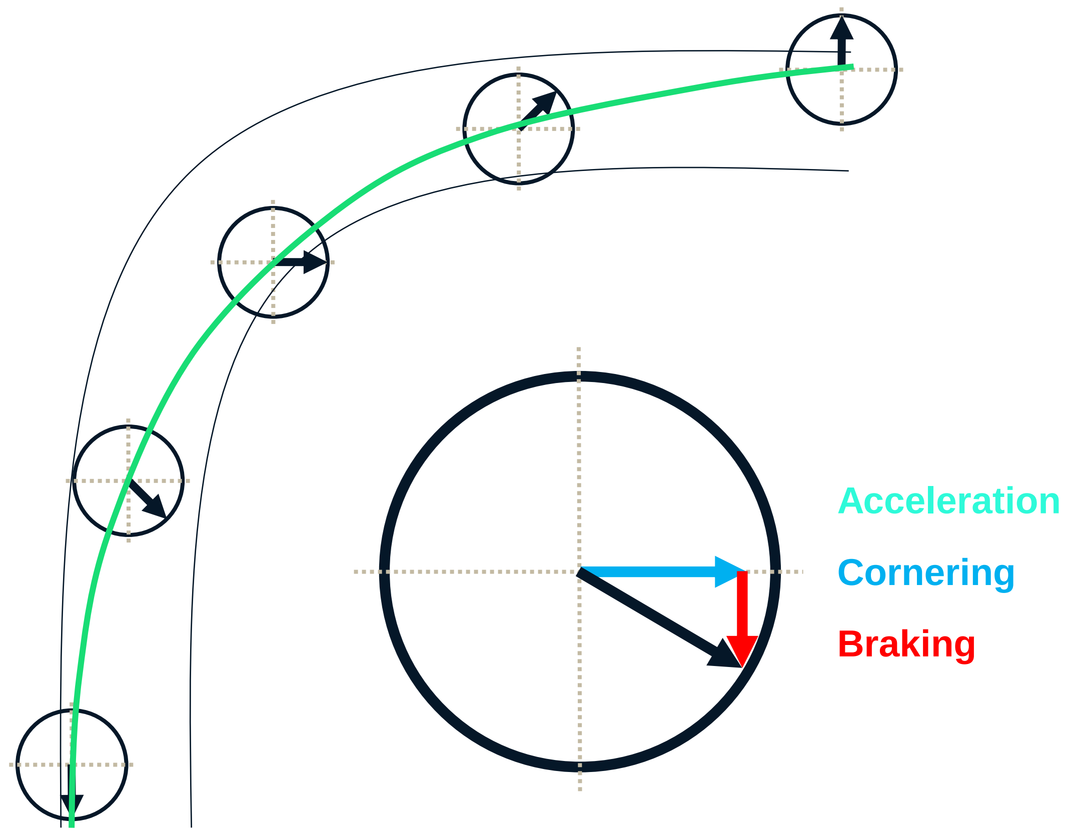

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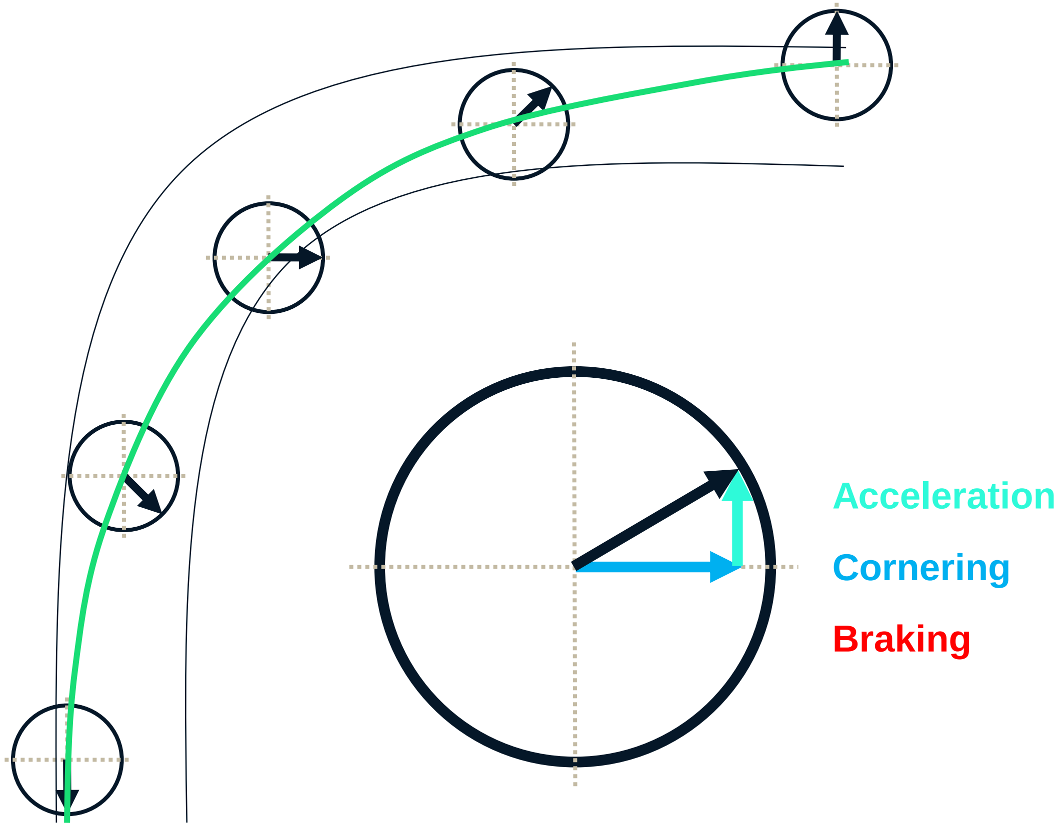
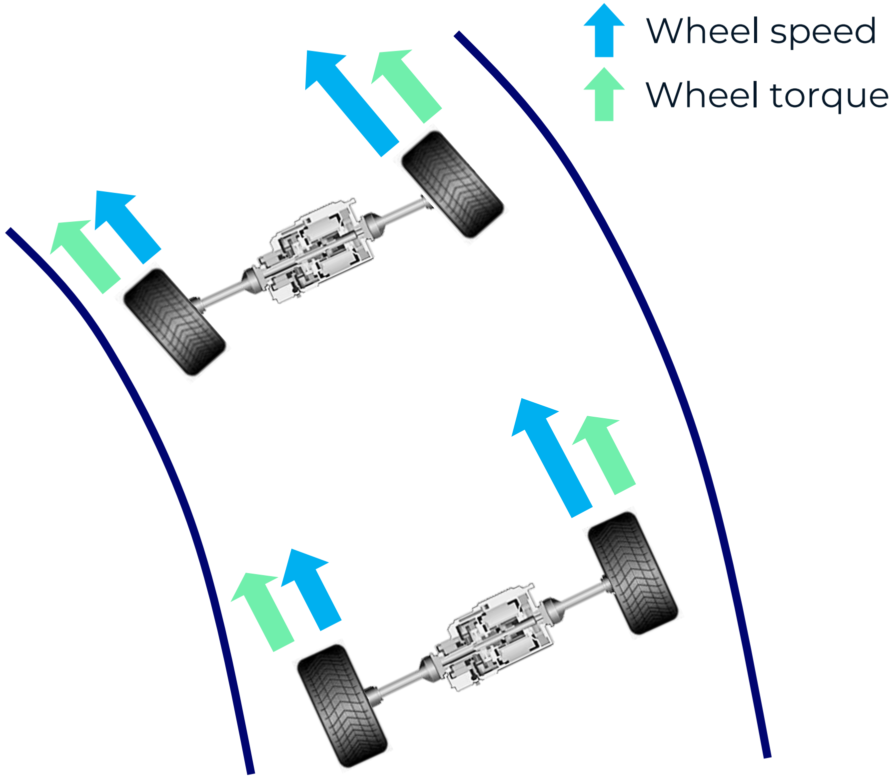


# Open Differential
## Basic Functions




- Allow different rotational speed on left and right wheels to enable cornering without windup
- Enables same torque transfer to inner and outer wheel during straight ahead driving and driving around corners

$$\omega_{Input} = \frac{\omega_{Left} + \omega_{Right}}{2}$$

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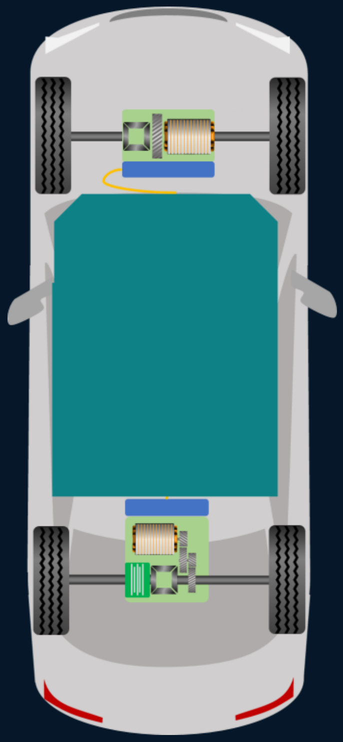
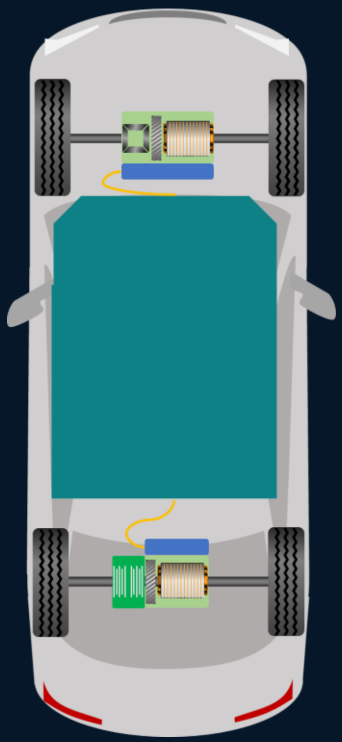
# Torque Management Systems

## Portfolio – Roadmap – Advanced

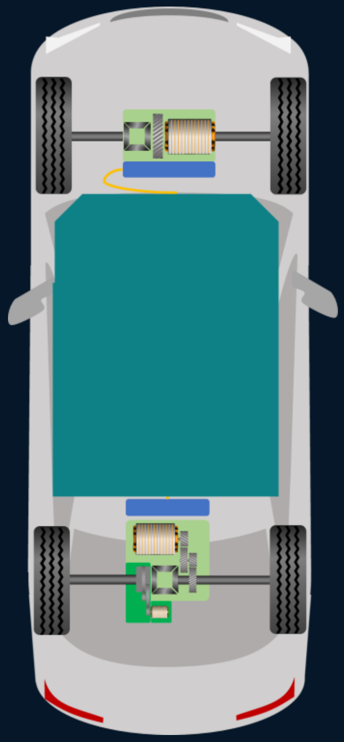
# Torque Management Systems
## Overview



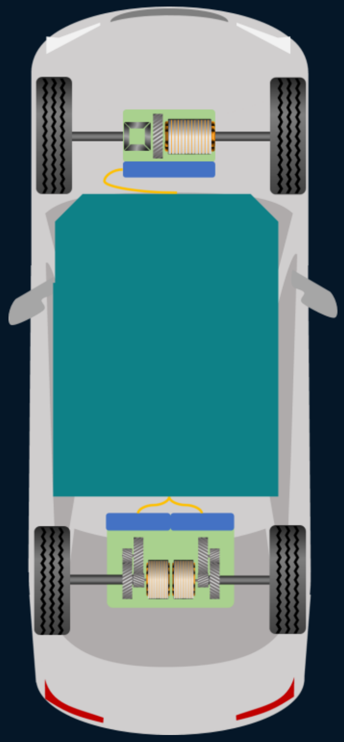
electric Cross Drive



electric Torque Vectoring and Disconnect

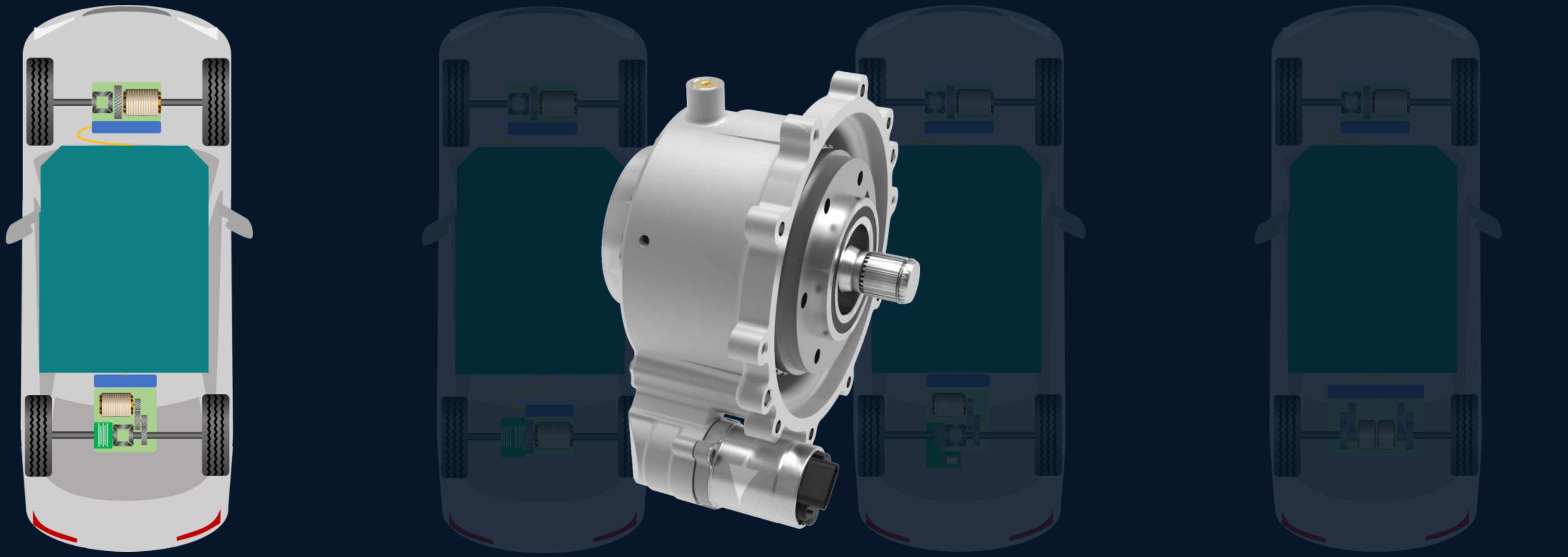


electric Torque Vectoring



2-Motor Torque Vectoring

# Torque Management Systems
## eXD – electric Cross Drive



electric Cross Drive

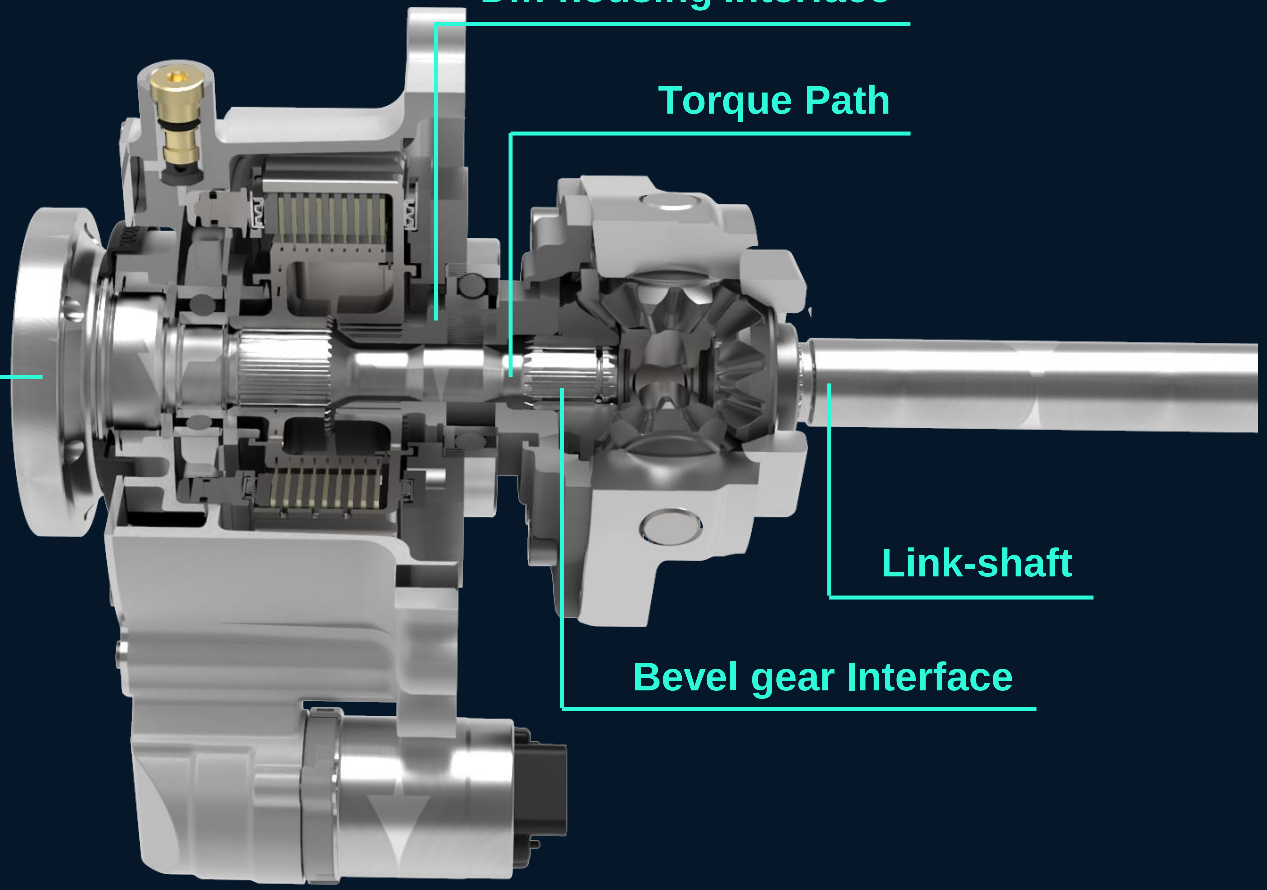
electric Torque Vectoring and Disconnect

electric Torque Vectoring

2-Motor Torque Vectoring

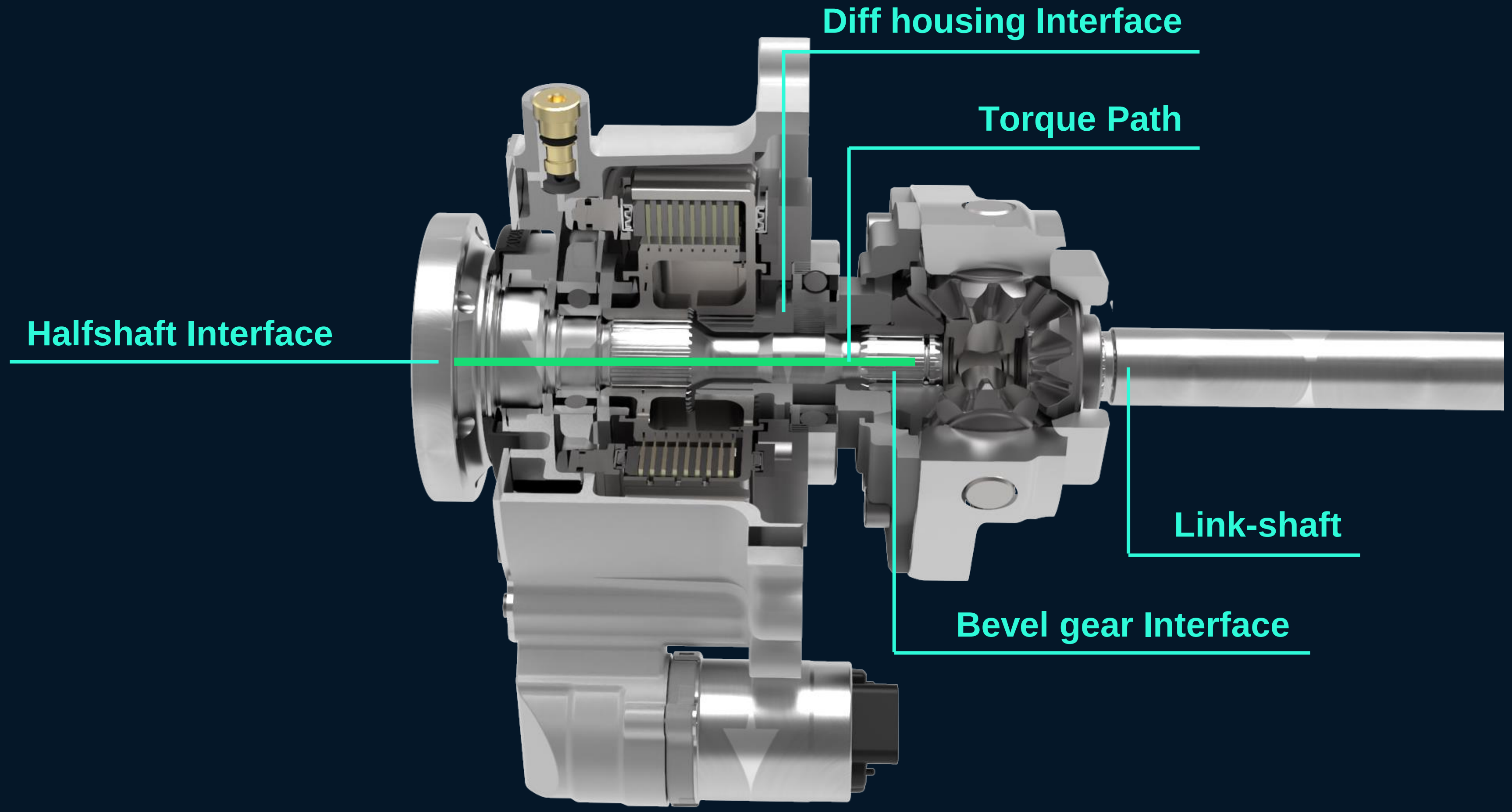
# Hardware Description

## eXD – electric Cross Drive



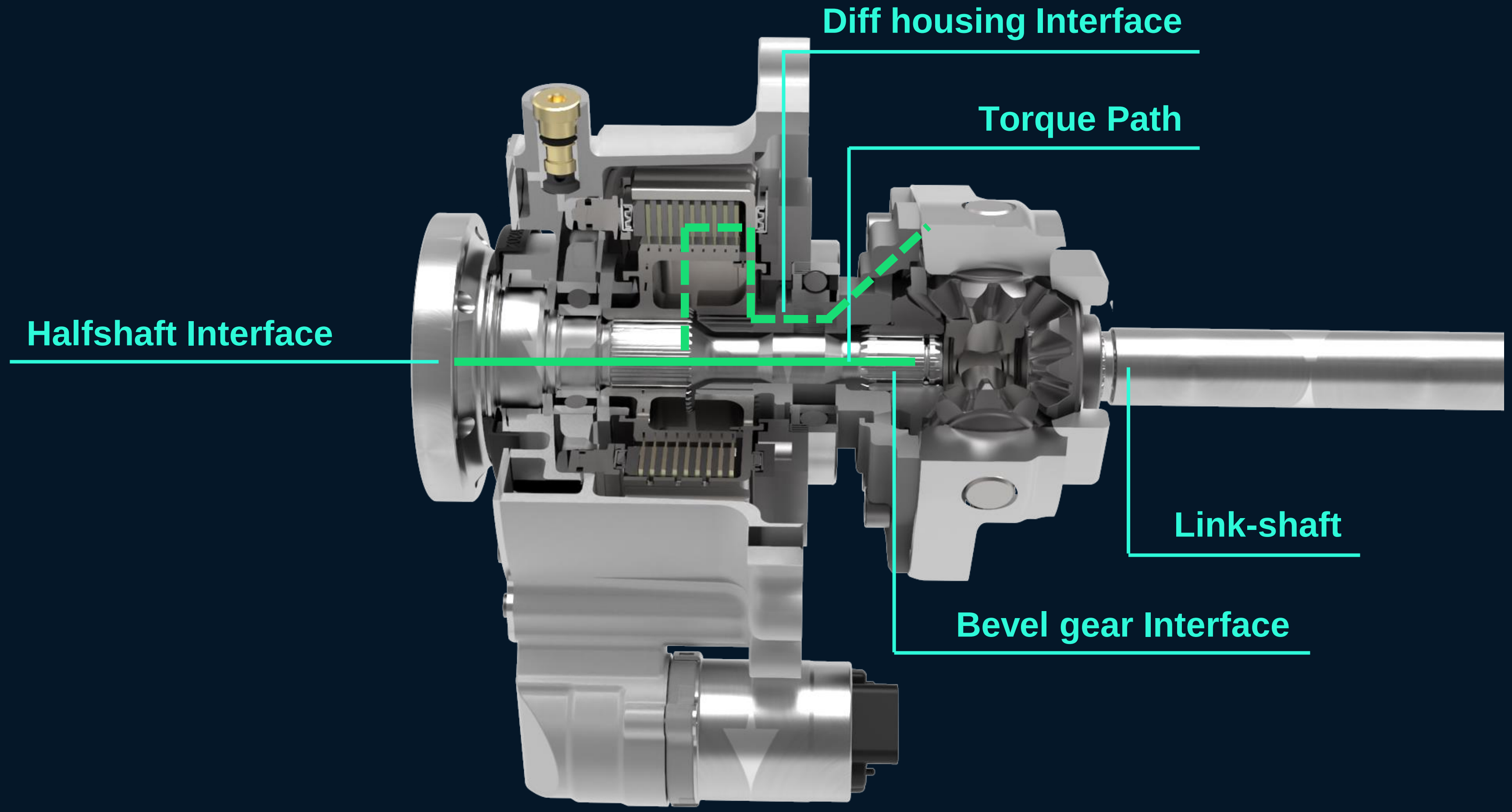
# Torque Path, System Inactive

## eXD – electric Cross Drive

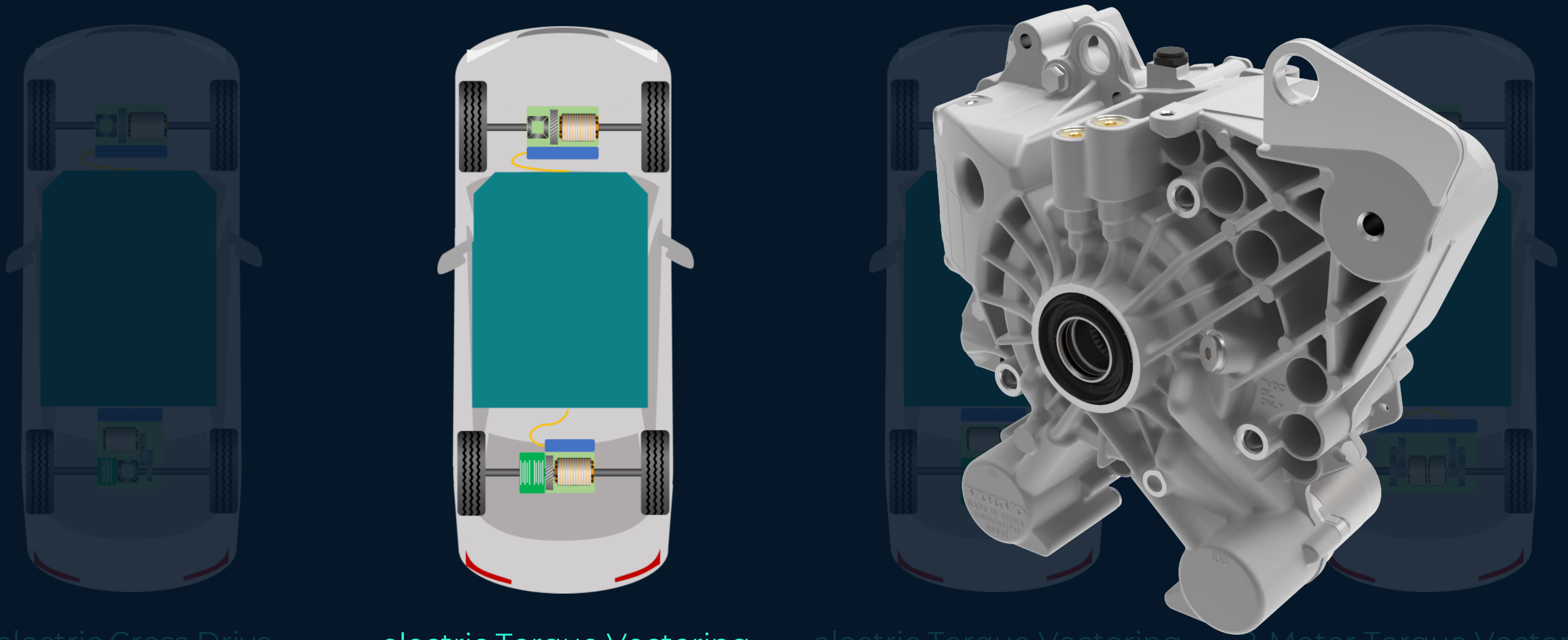


# Torque Path, System Active

## eXD – electric Cross Drive



# Torque Management Systems
## eTVD – electric Torque Vectoring and Disconnect



electric Cross Drive

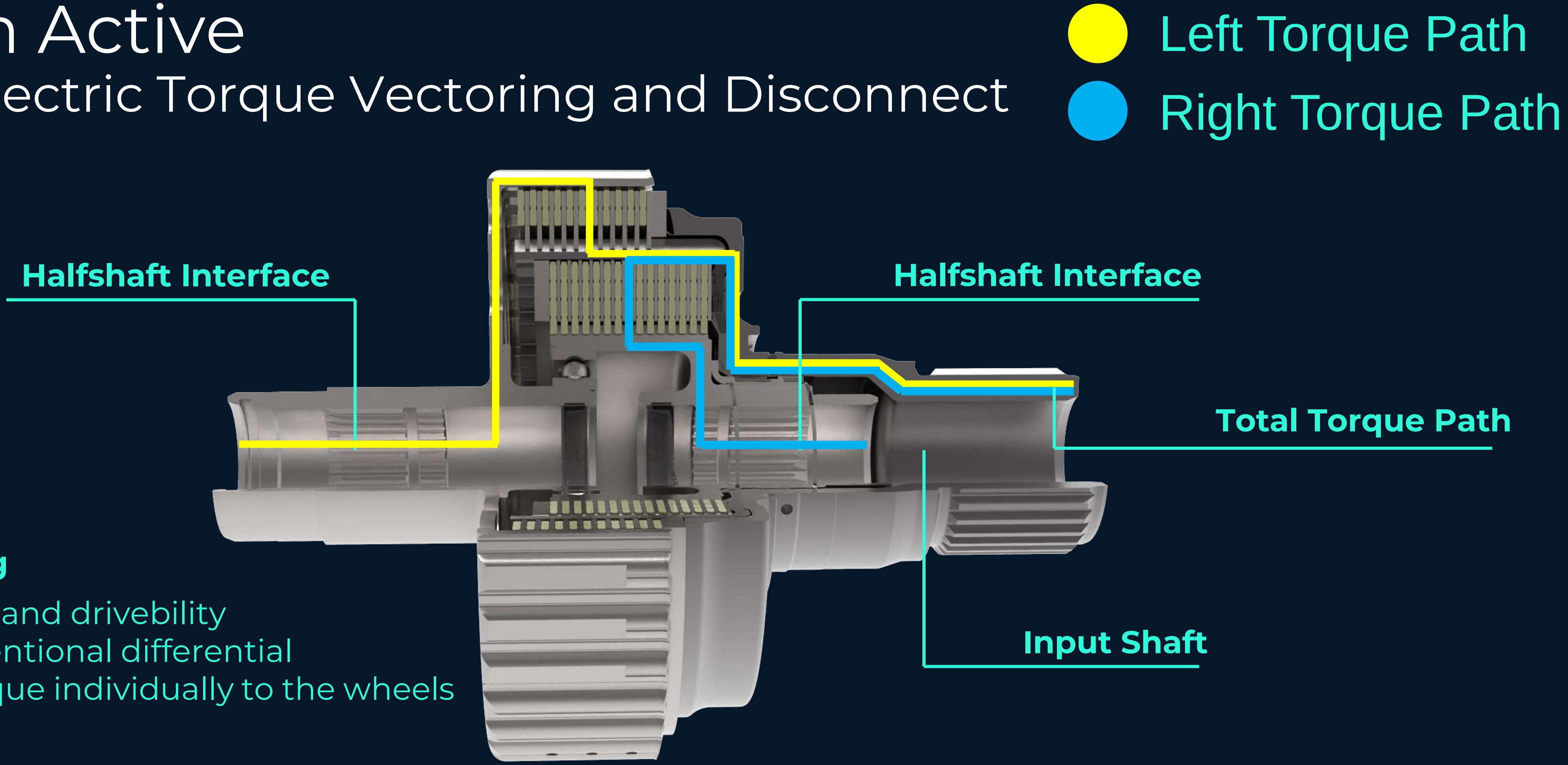
electric Torque Vectoring and Disconnect

electric Torque Vectoring

2-Motor Torque Vectoring

# System Active

## eTVD – electric Torque Vectoring and Disconnect




**Torque Vectoring**

- Superior safety and drivebility
- Replaces conventional differential
- Distributes torque individually to the wheels

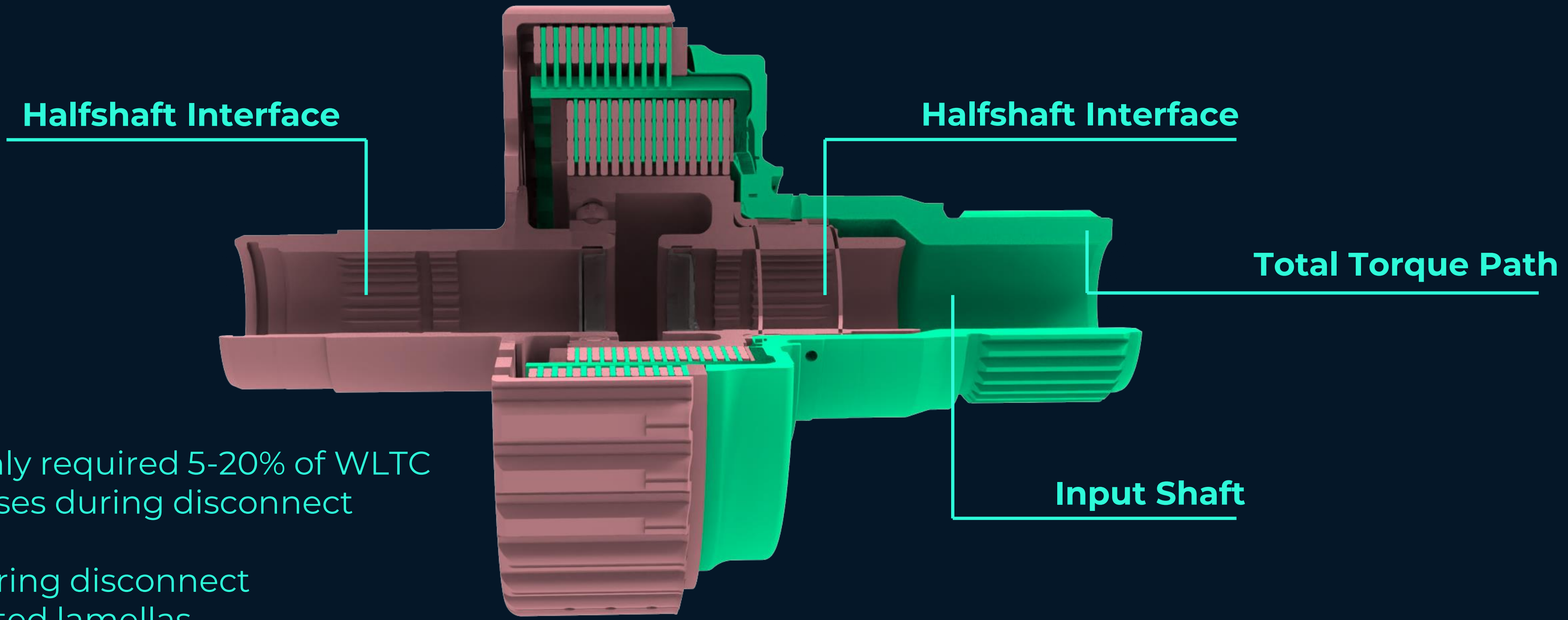
**BEV advantages**

- More precise speed & torque control
- Independent control between front and rear axle

# Efficiency mode

## eTVD – electric Torque Vectoring and Disconnect

Rotating parts
Stationary parts

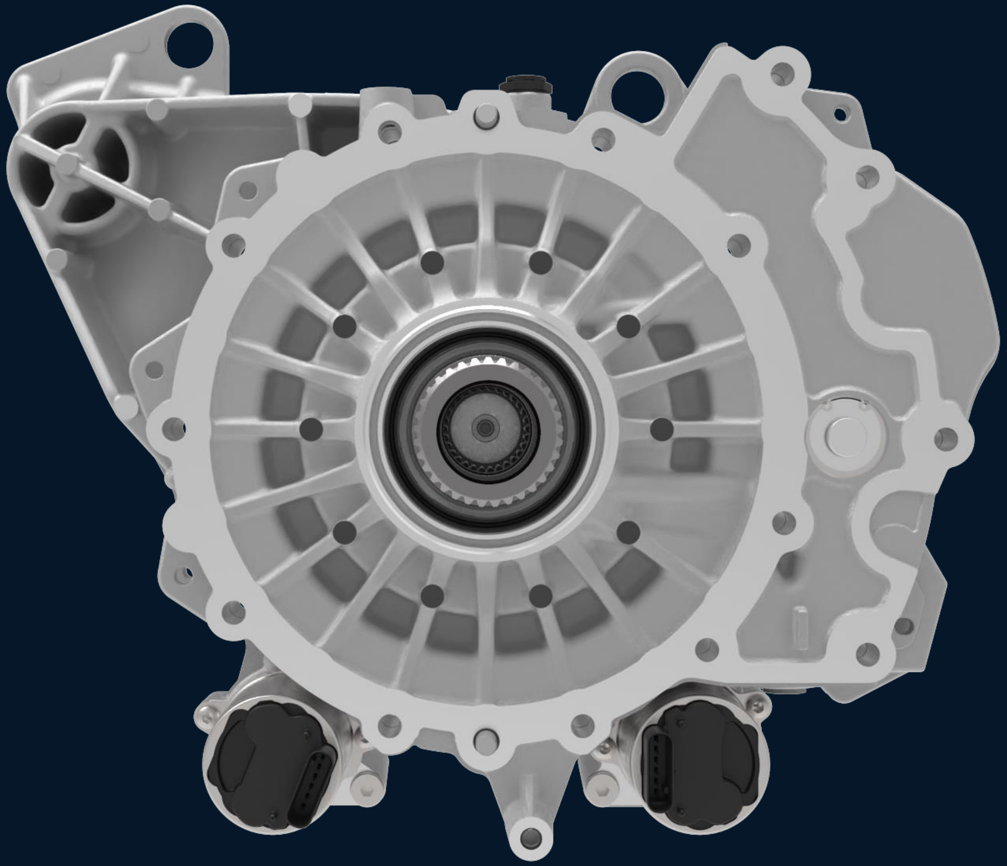



**Efficiency**

- Active mode only required 5-20% of WLTC
- 8% reduced losses during disconnect

- Sleep mode during disconnect
- Actively separated lamellas
- Reduced splash losses
- Two piston areas per piston to optimize connect time

# Hardware Design – eTVD





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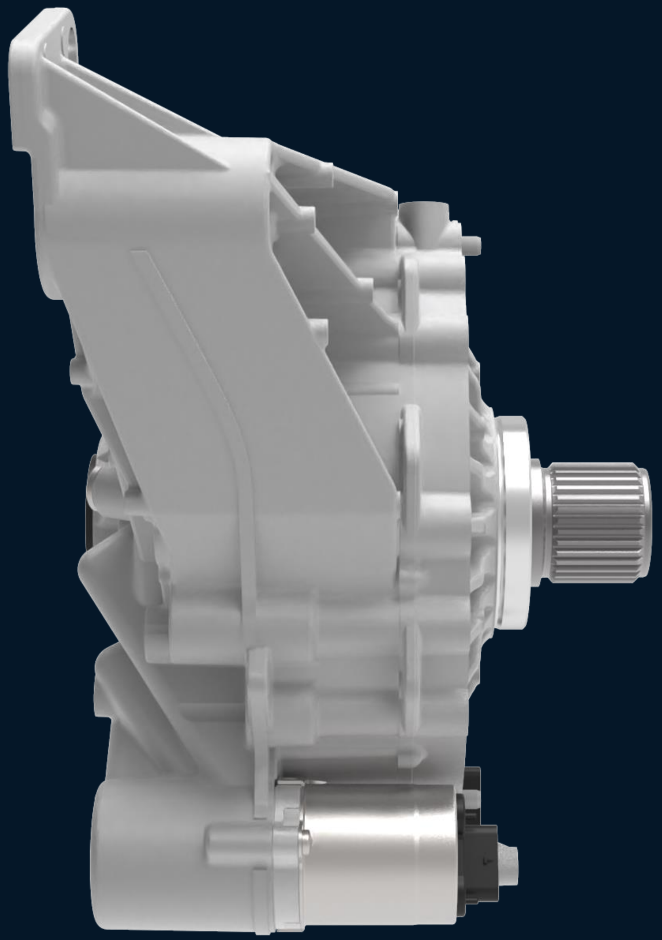
# Hardware Design – eTVD





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# Hardware Design – eTVD

# Hardware Design – eTVD



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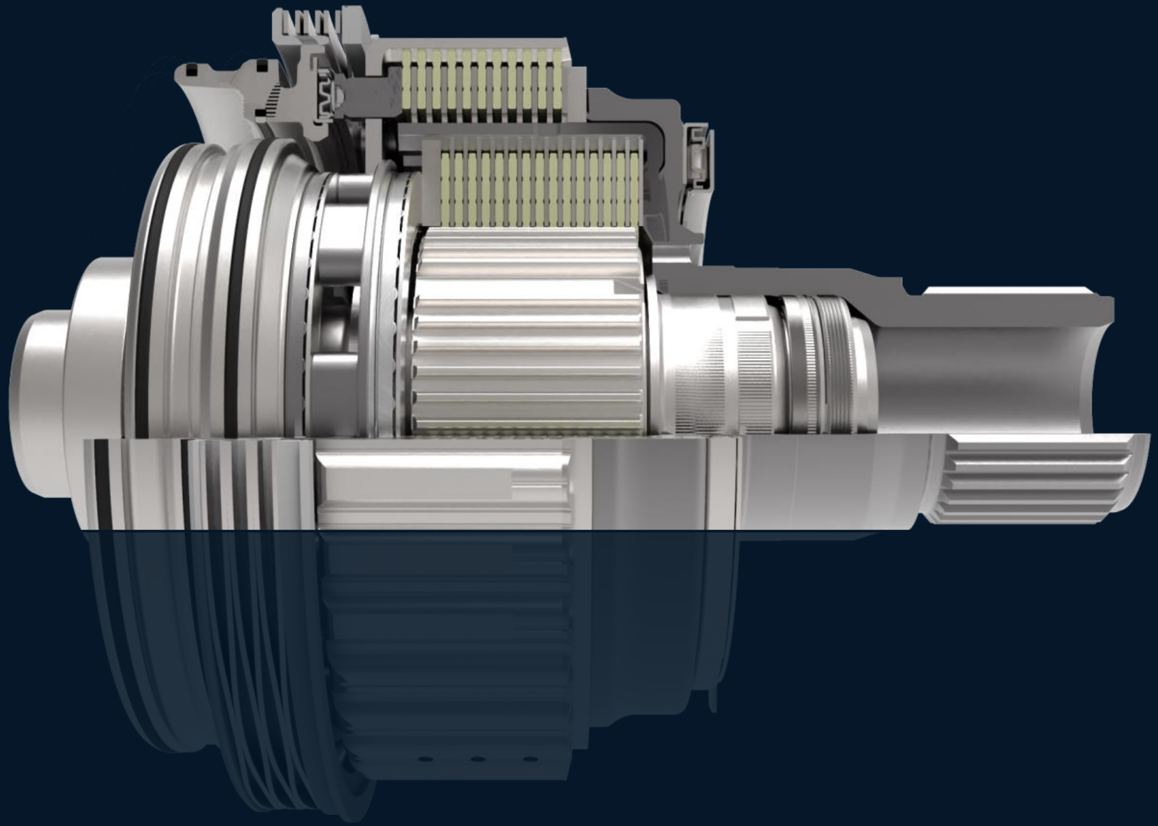
# Hardware Design – eTVD

## Lamellas – Performance Mode





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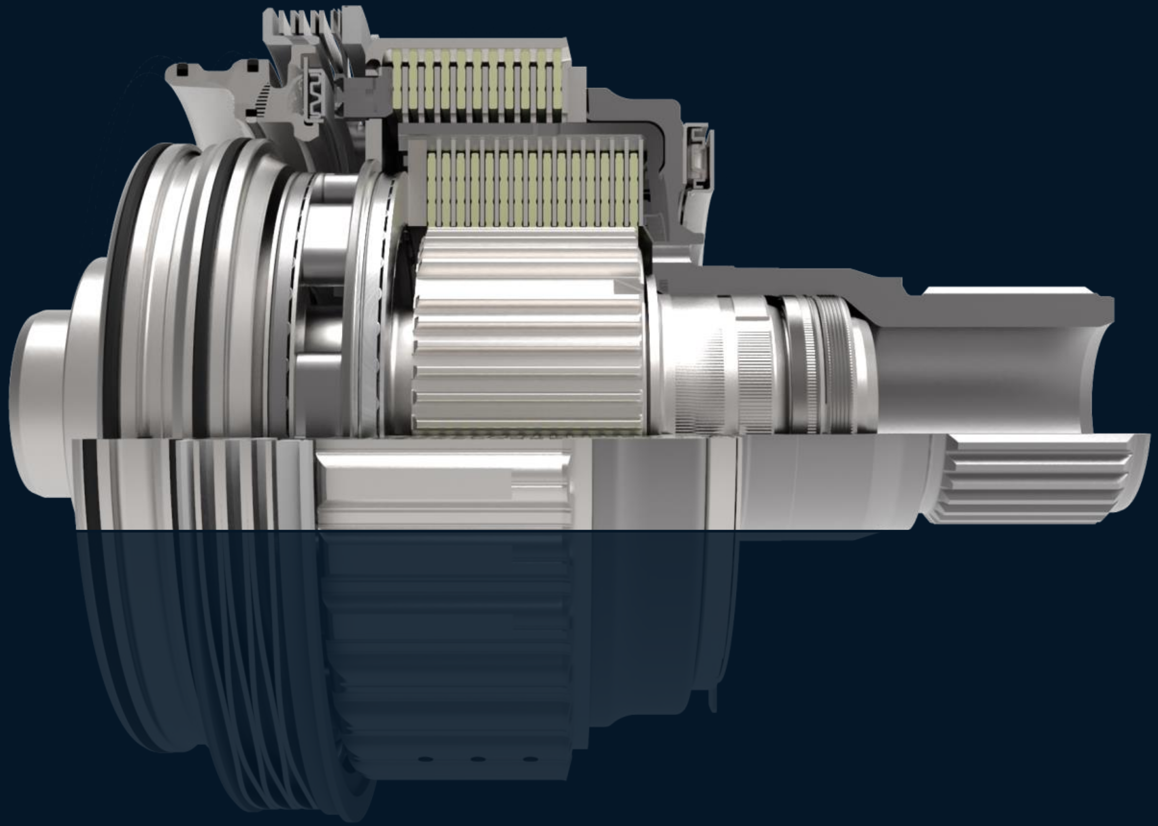
# Hardware Design – eTVD
## Lamellas – Efficiency Mode





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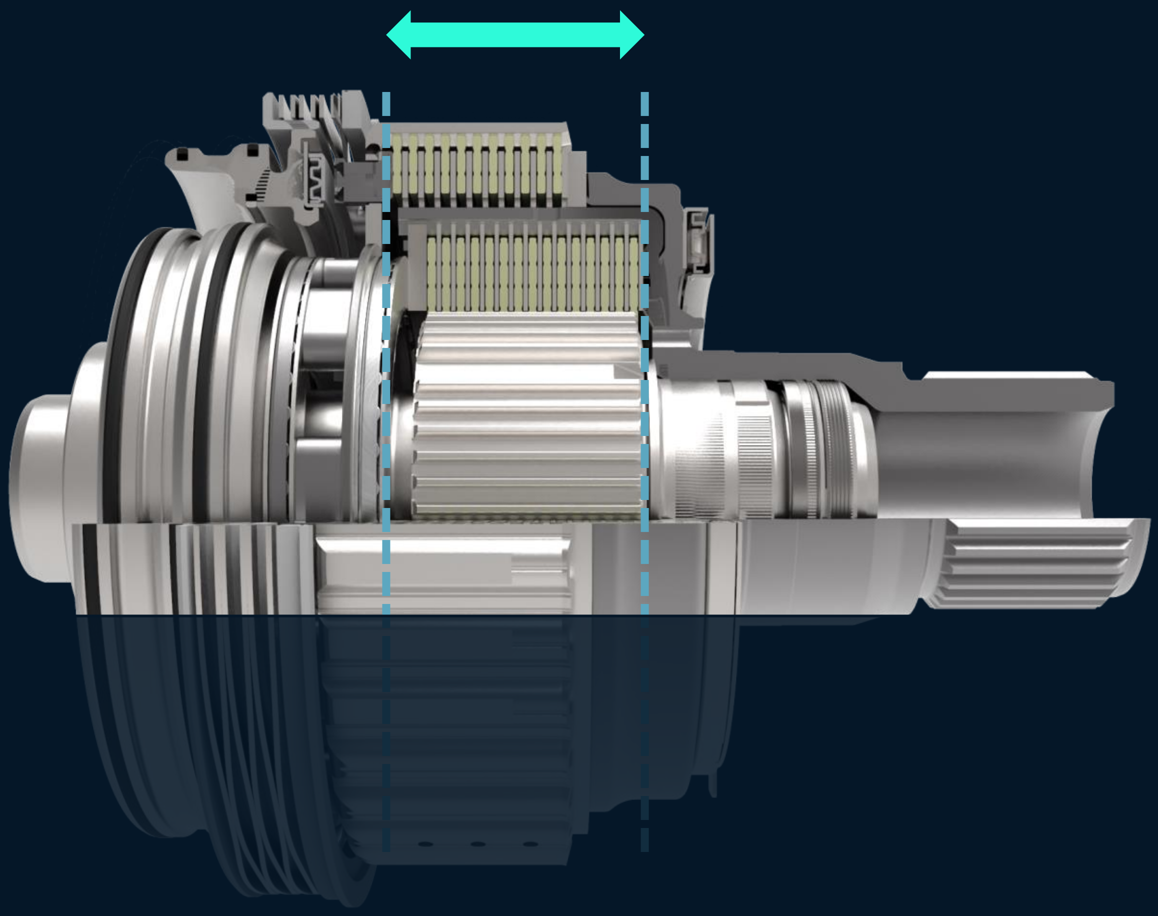
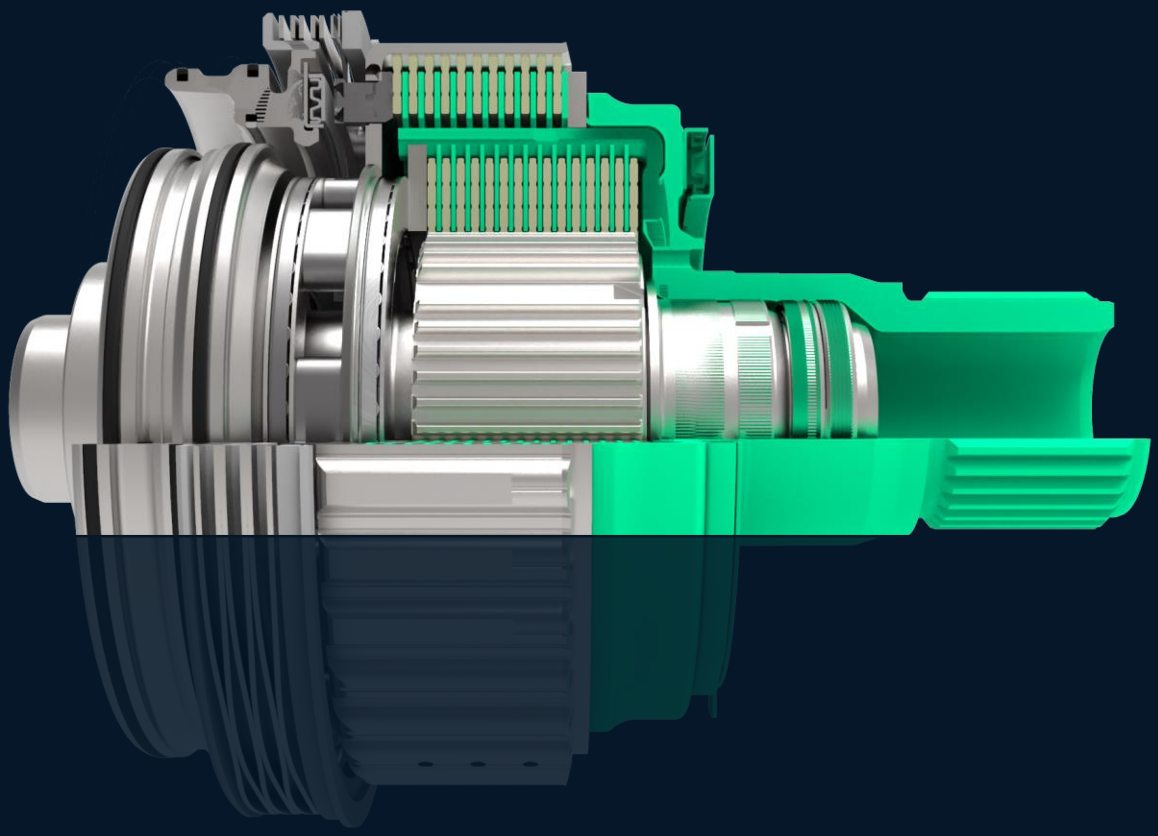
# Hardware Design – eTVD
## Lamellas – Efficiency Mode



# Hardware Design

## Disconnected parts – Efficiency Mode





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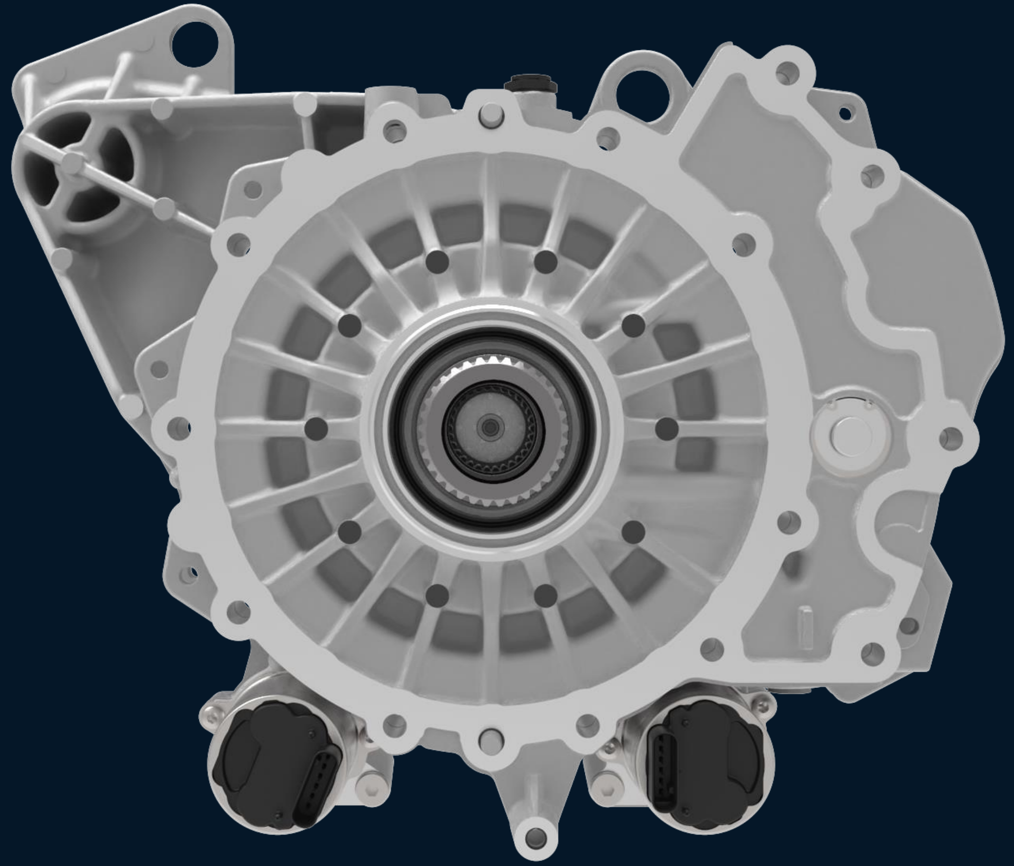
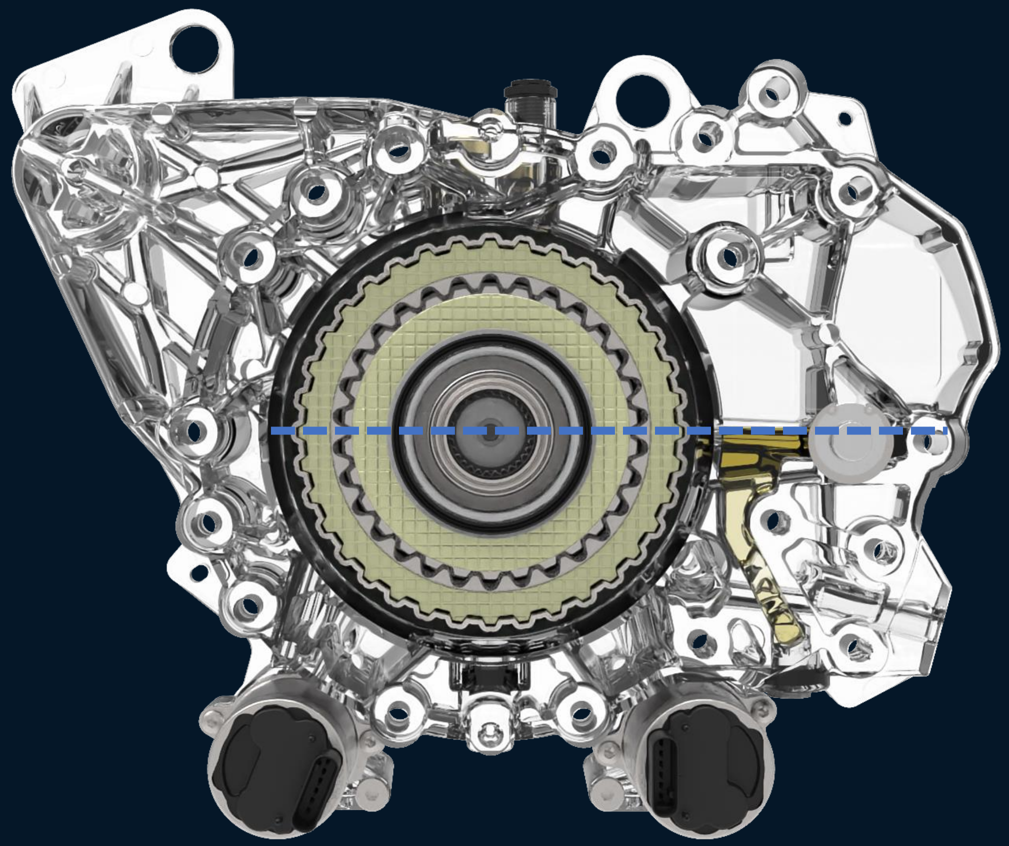
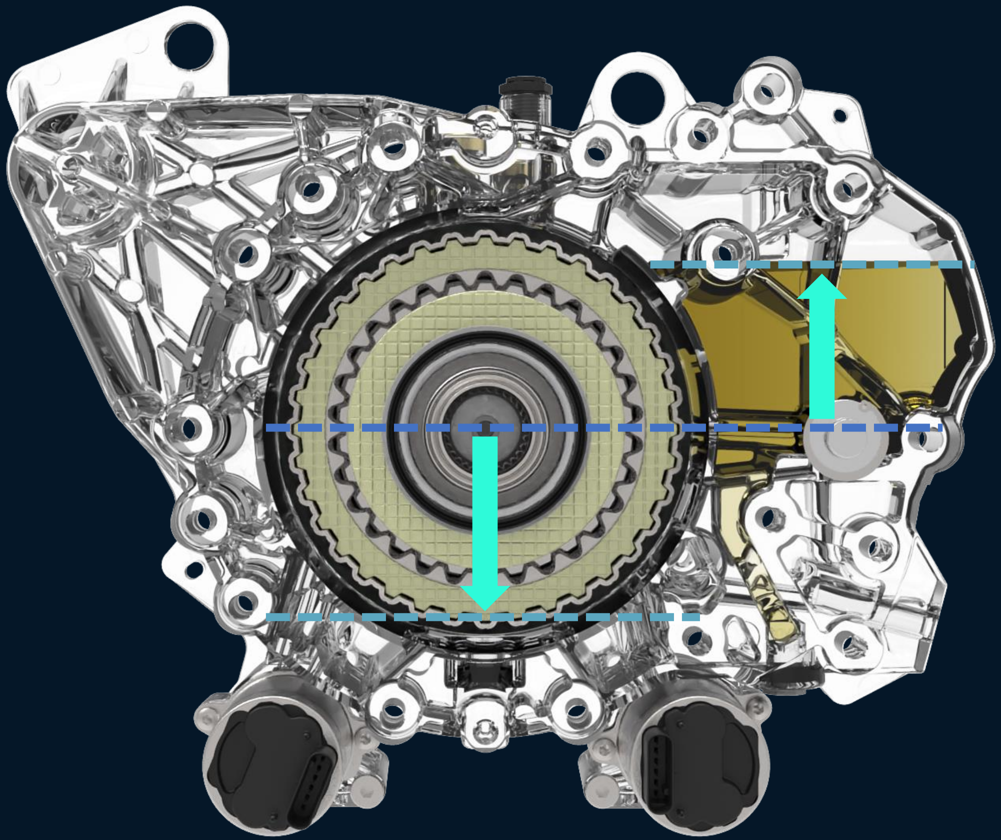
# Hardware Design – eTVD



# Hardware Design – eTVD
## Oil management – Performance Mode



# Hardware Design – eTVD
## Oil management – Efficiency Mode





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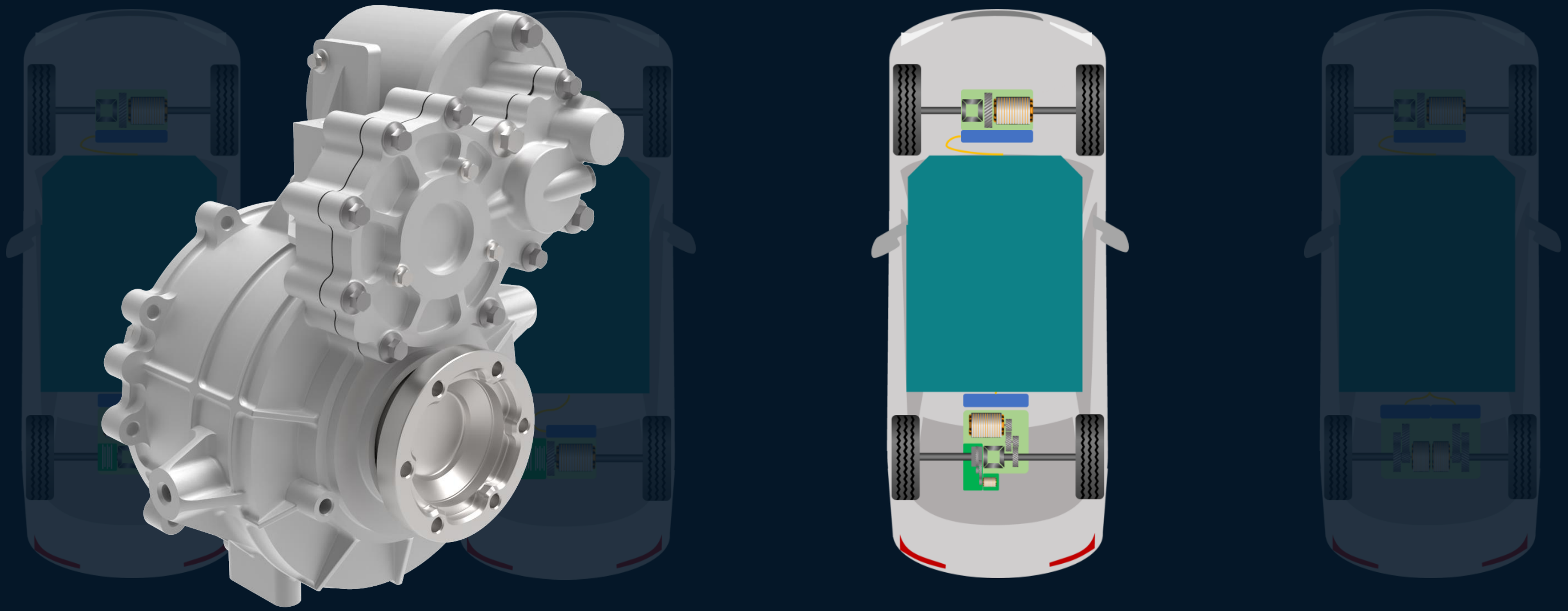
# Torque Management Systems

## eTV – electric Torque Vectoring



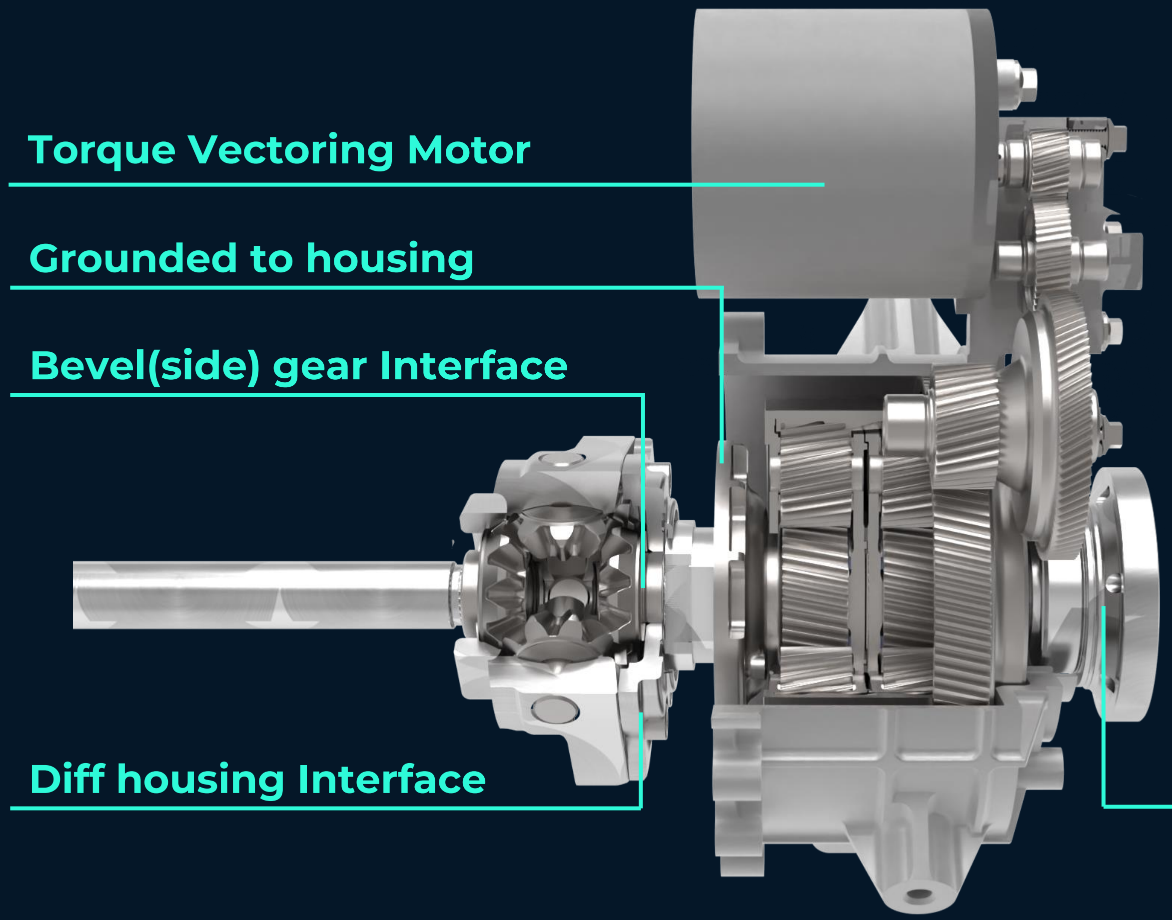
electric Cross Drive

electric Torque Vectoring and Disconnect

electric Torque Vectoring

2-Motor Torque Vectoring

# eTV Overview

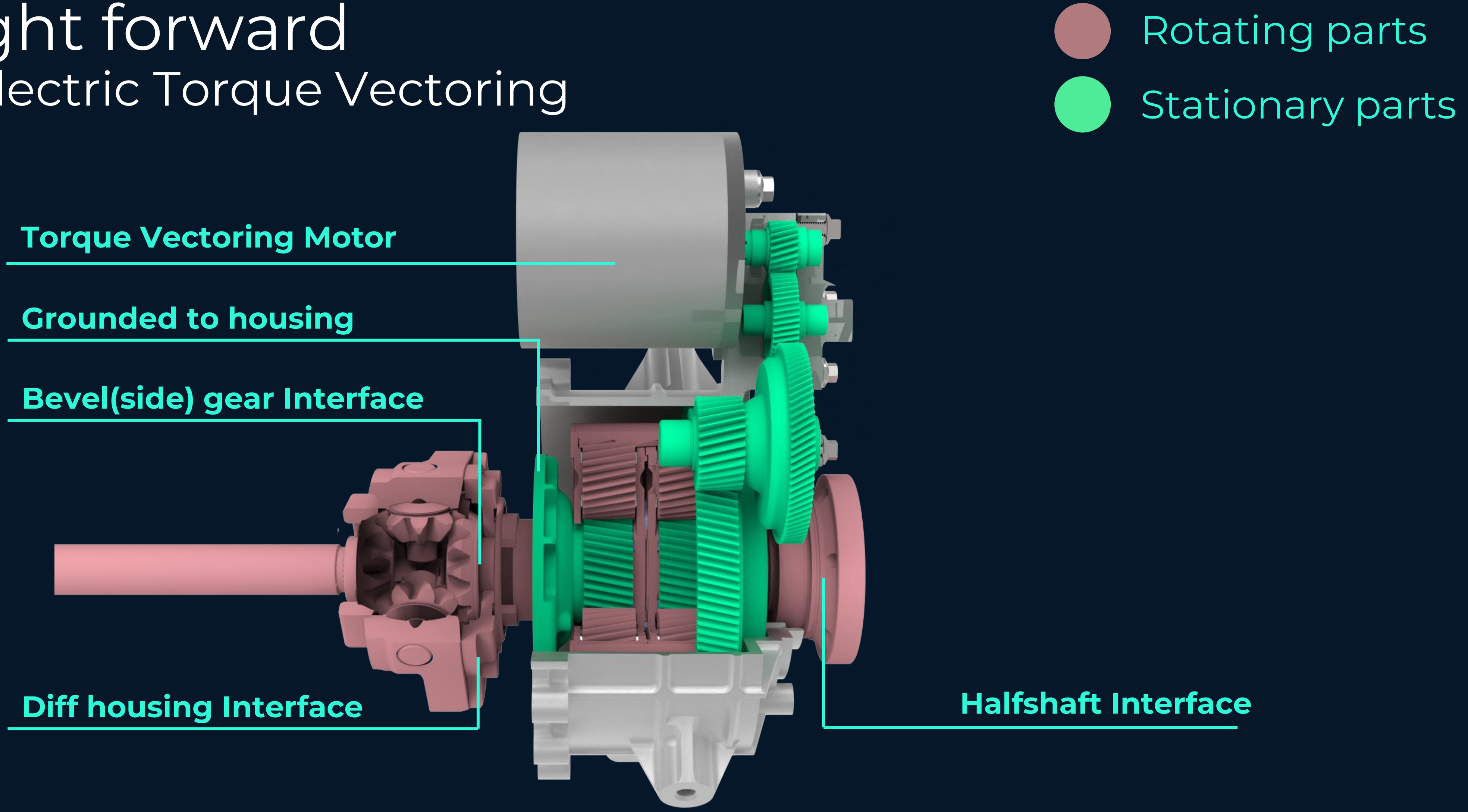



**Super imposed torque vectoring**

- Independent of propulsion torque from traction motor
- Outperforms equal 2-motor setup
- Compact and modular design for easy adoption
- Torque management up to 2500Nm available between 0-300kph
- Fast response time <50ms
- Efficient with low drag losses ~1%

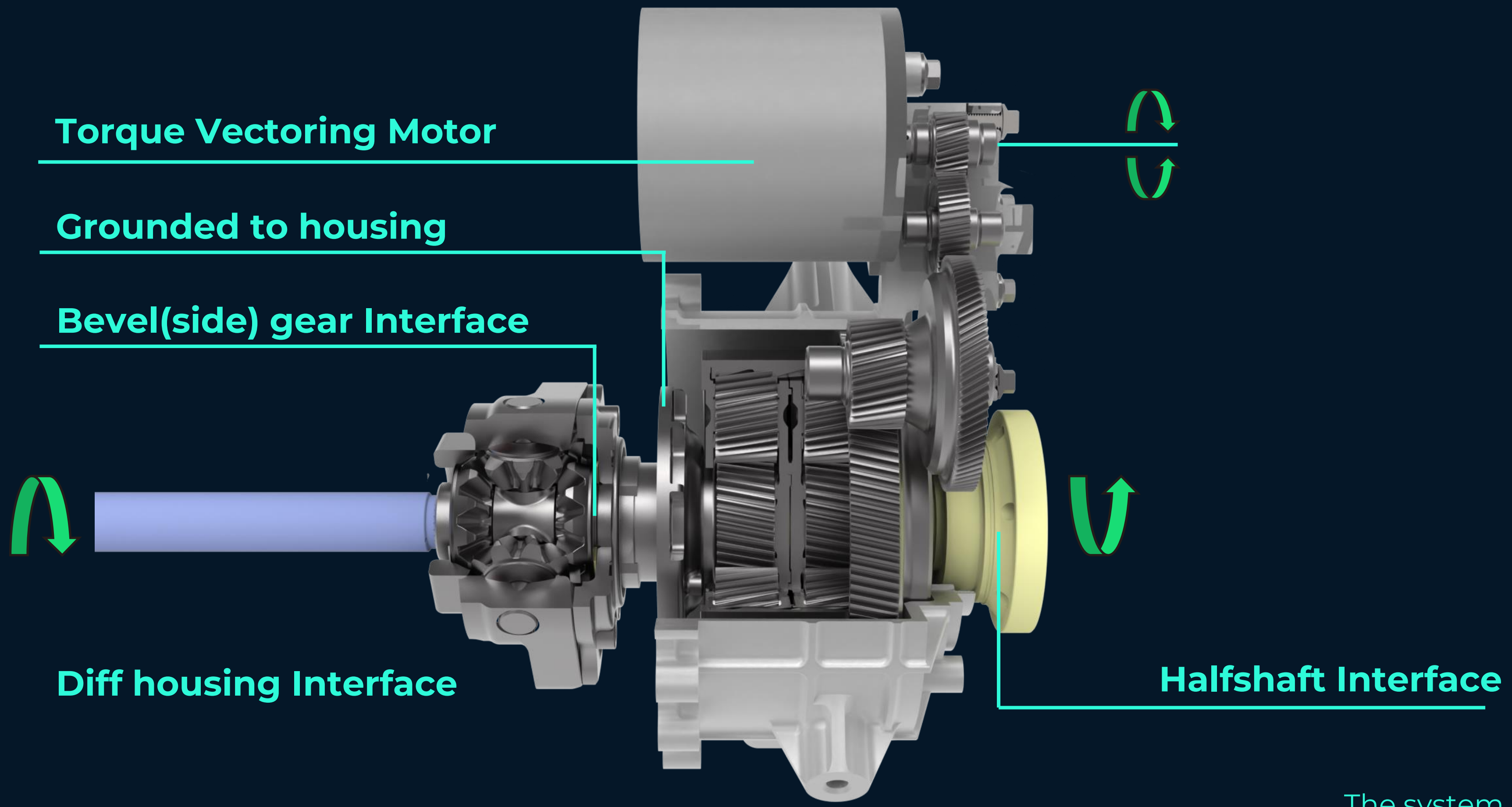
# Straight forward

## eTV – electric Torque Vectoring



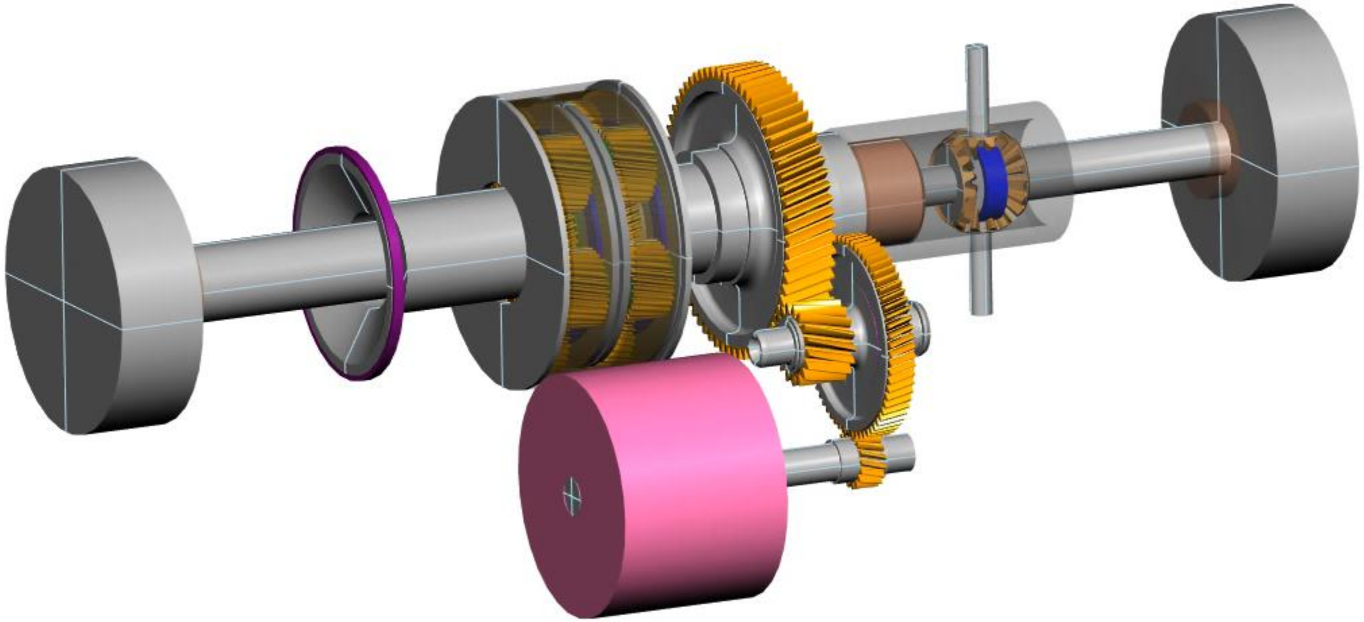
# Torque Vectoring Active

## eTV – electric Torque Vectoring

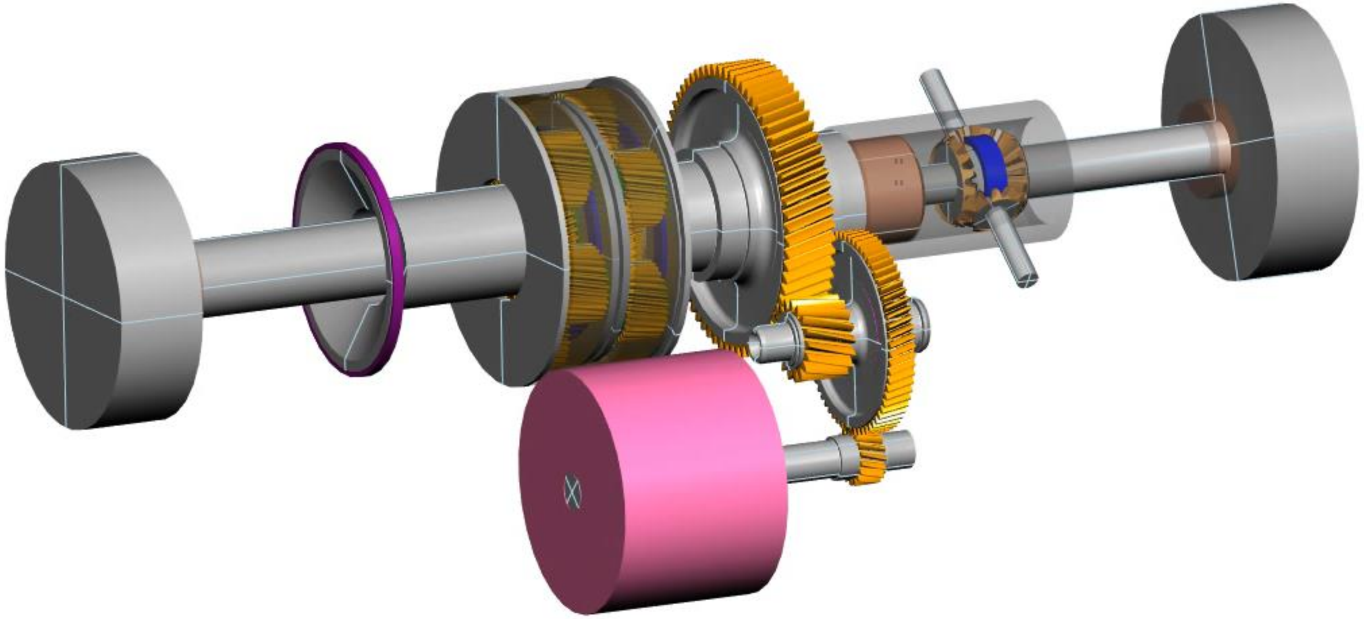



The system is found in the blue Polestar

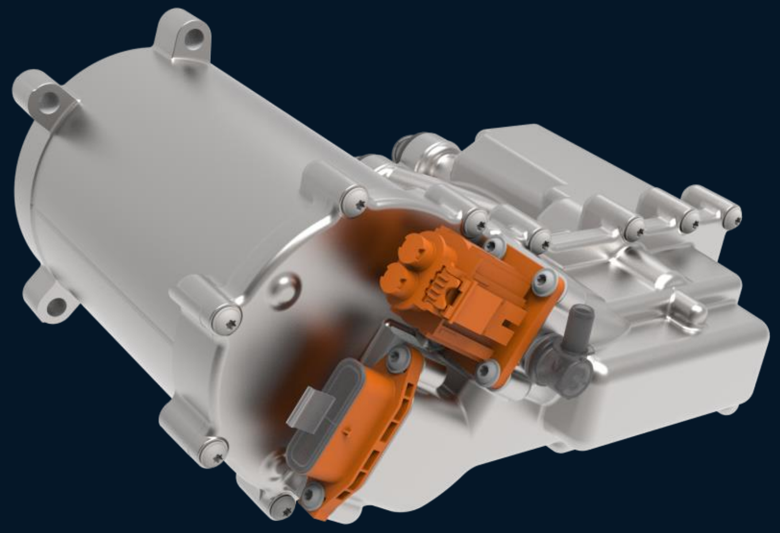
# Straight ahead



# Hard turn left



# eTV Actuator - Concept
## Integrated Smart Drive Module



### Inverter

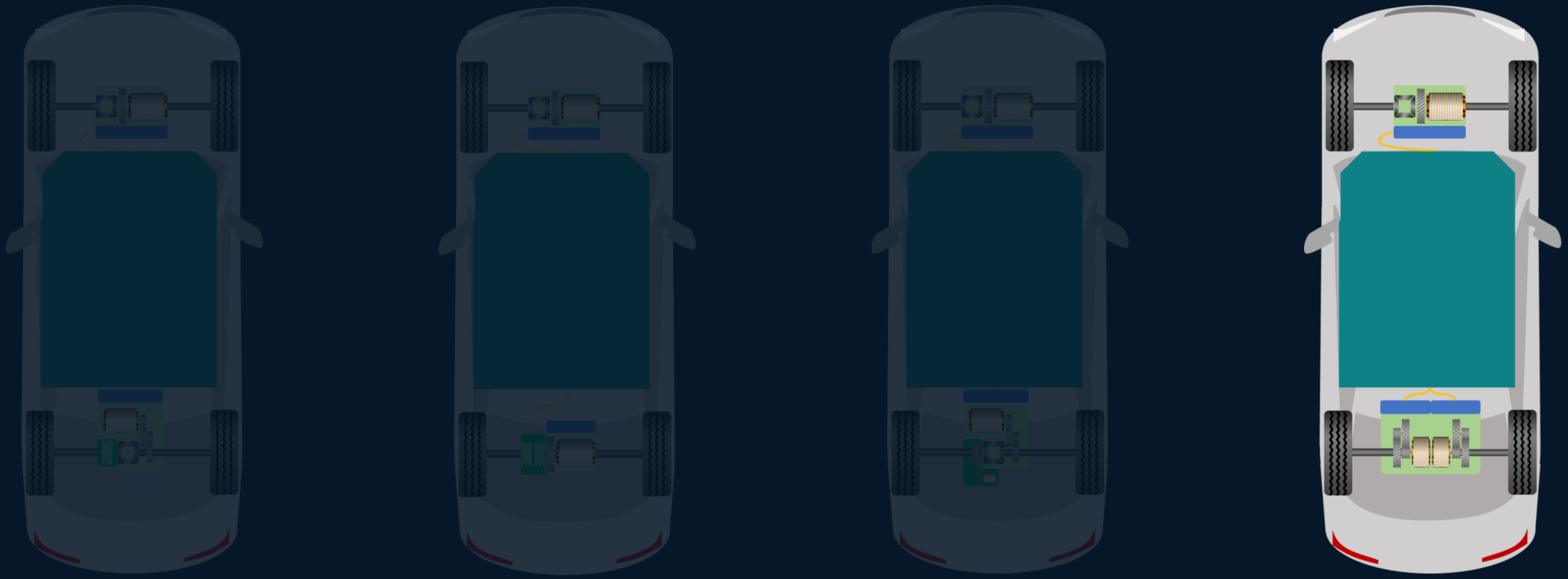
- HW designed for ASIL D
- Aurix Tricore - Multicore CPU
- Multi-board design for flexible packaging
- Fast response: <1 ms

### E-motor (IPM)

- 800V architecture (400-960V)
- 11kW
- Max peak torque 50Nm (15Nm continuously)
- Operational speed >10.000rpm
- Externally induced abuse speed 20.000rpm

# Torque Management Systems

## 2-Motor Torque Vectoring



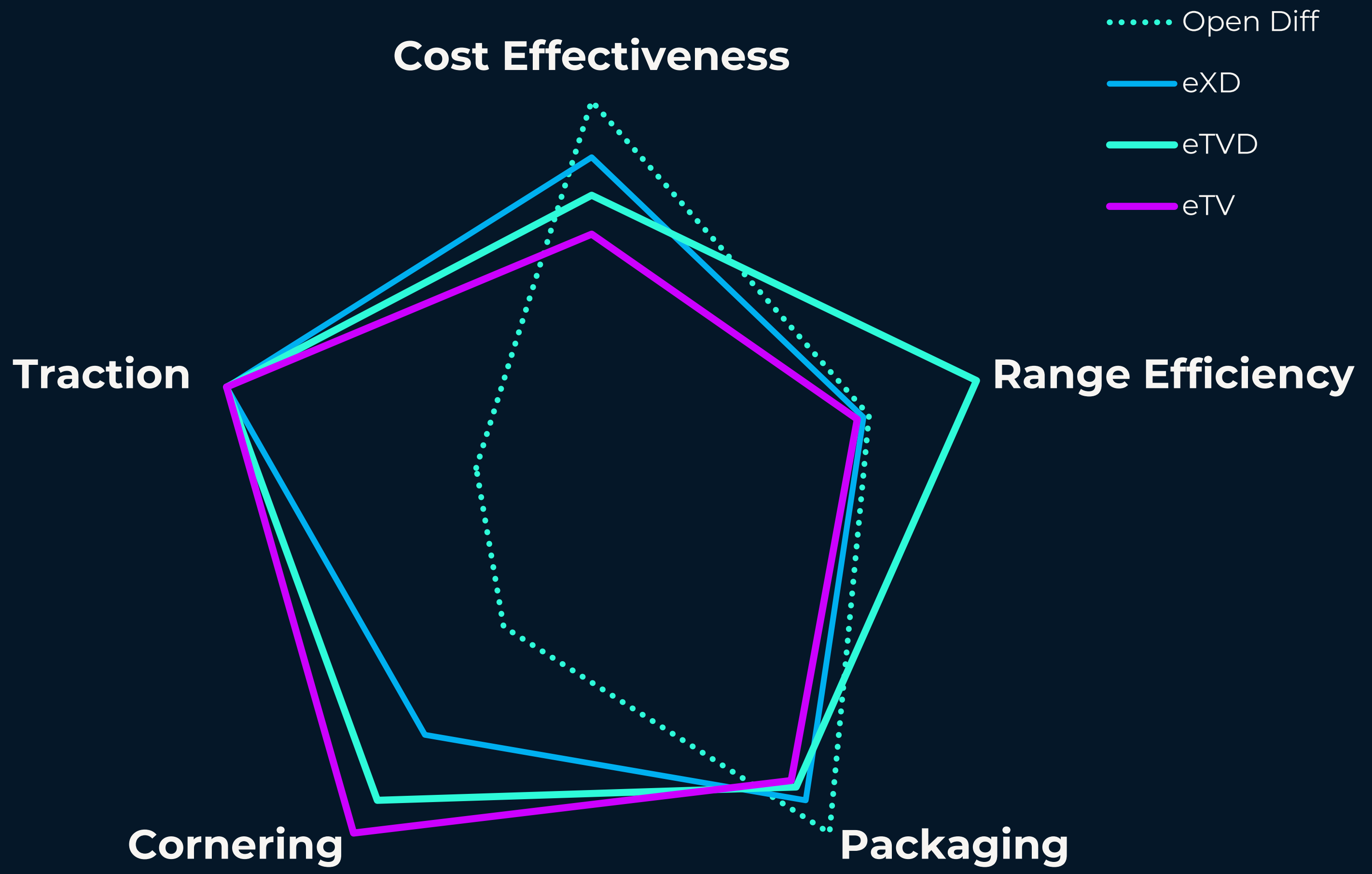
electric Cross Drive

electric Torque Vectoring and Disconnect

electric Torque Vectoring

2-Motor Torque Vectoring

# System Comparison



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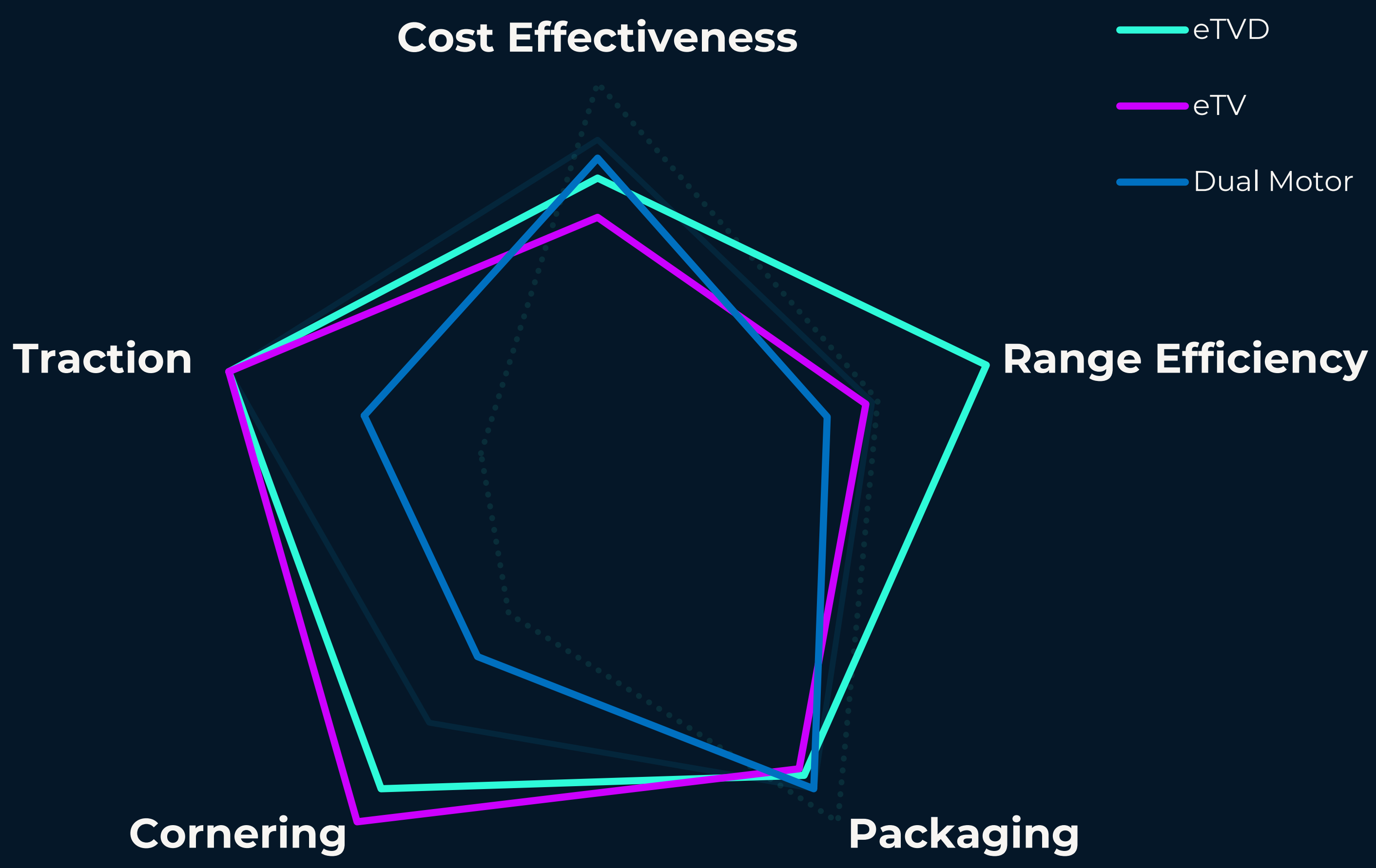
# System Comparison
## Torque Vectoring



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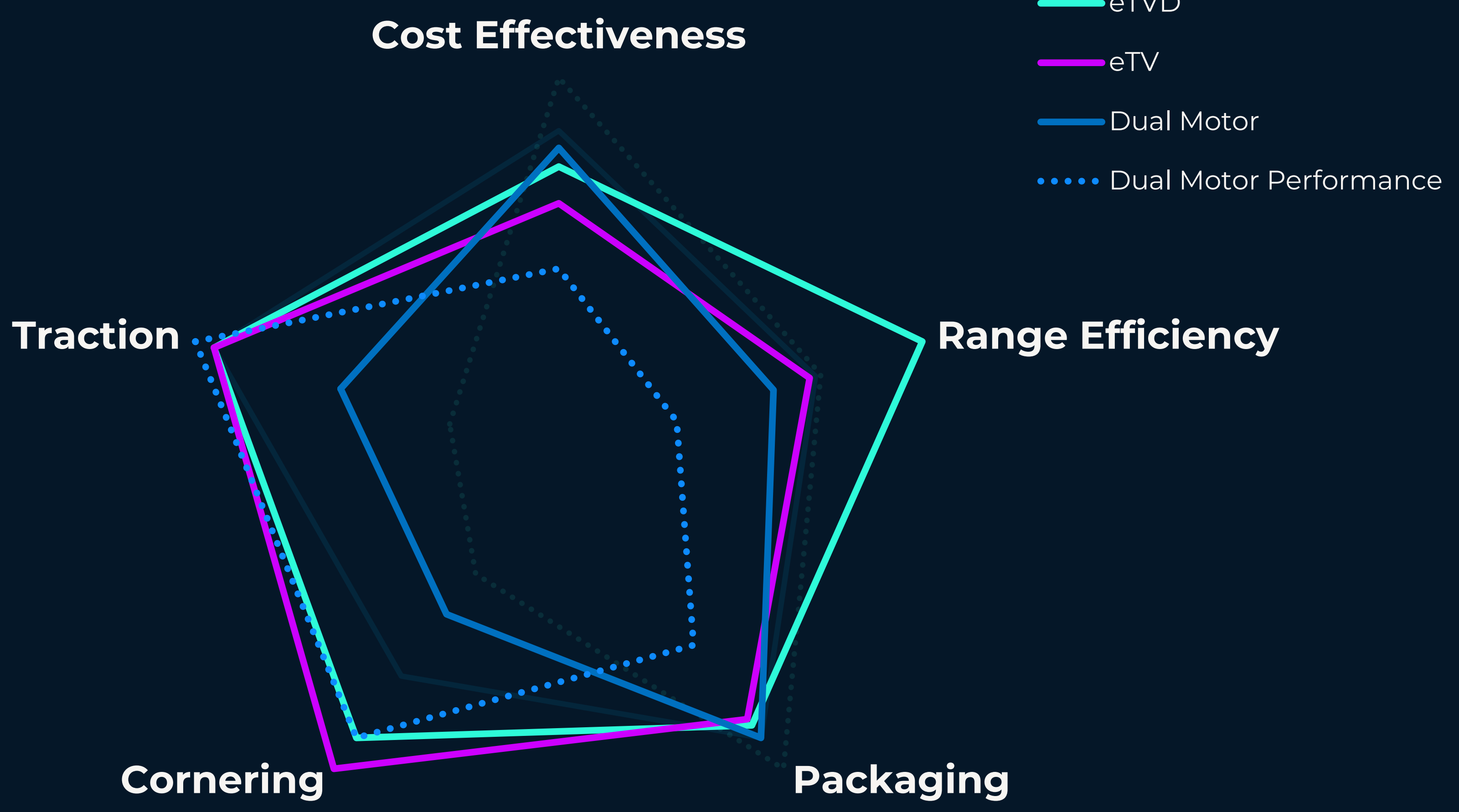
# System Comparison
## Torque Vectoring



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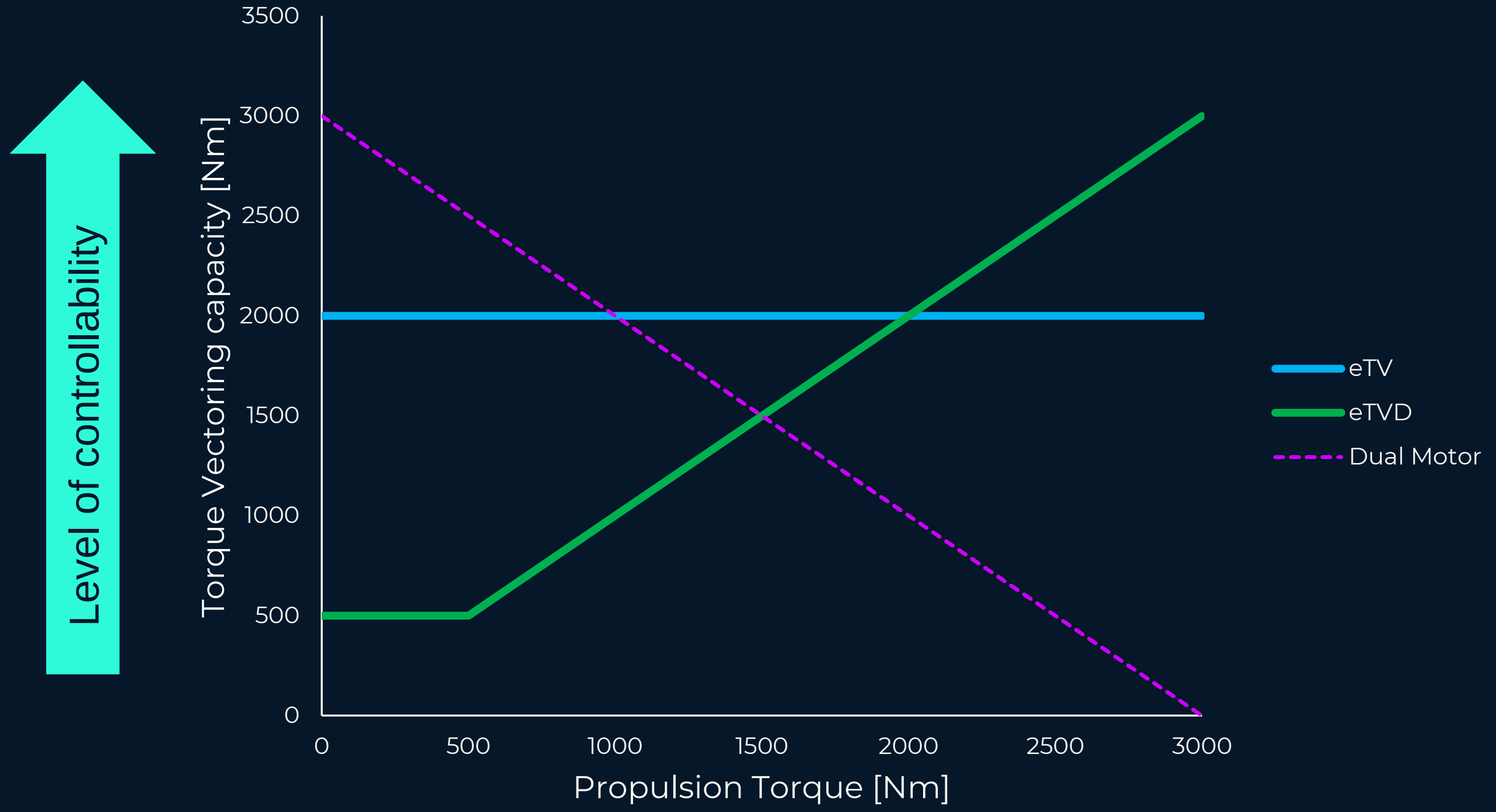
# Available Torque Vectoring

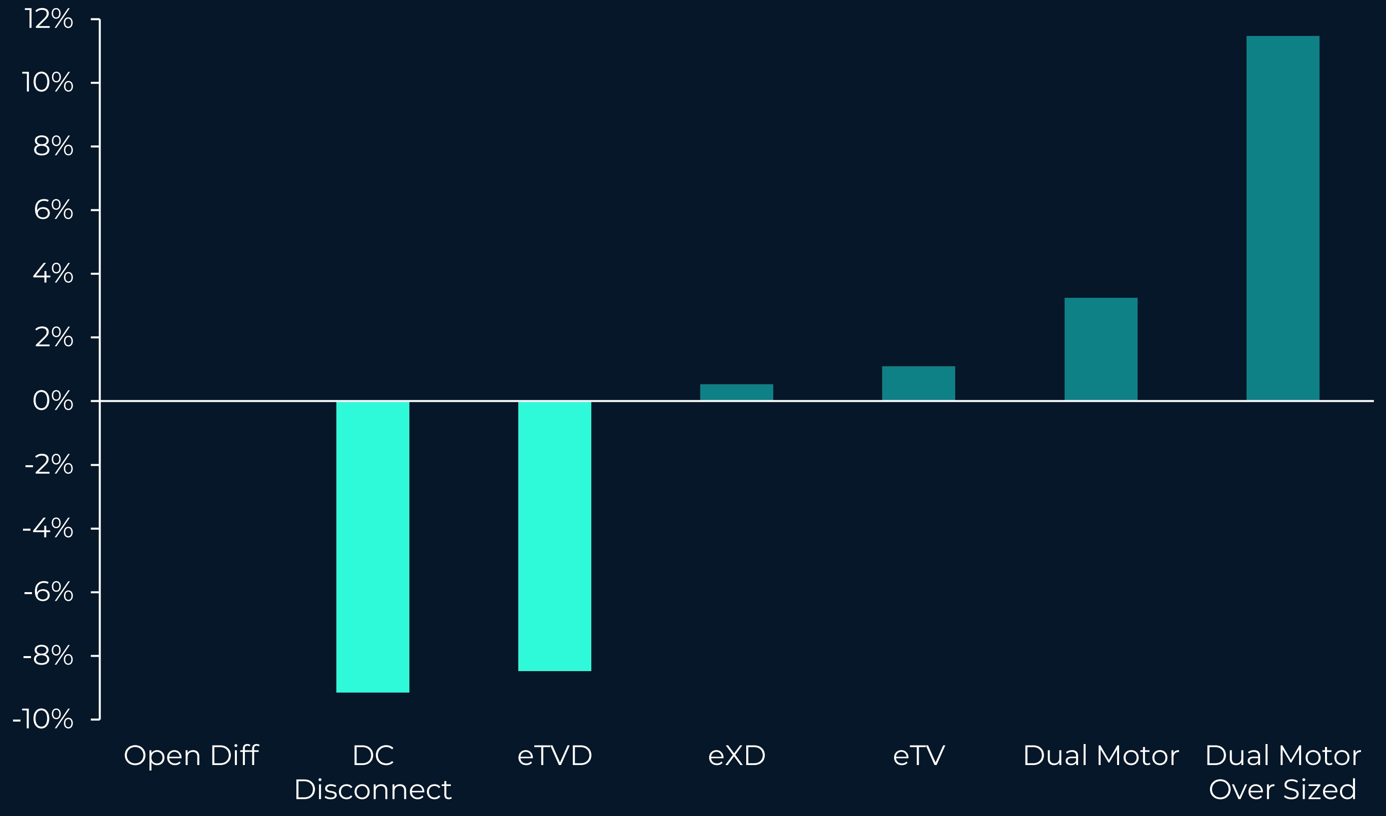
## System comparison




- **eTV**
  eTV provides Torque Vectoring fully independent from the requested propulsion torque
- **eTVD**
  The eTVD system distributes the available propulsion torque to each wheel to create Torque Vectoring
- **Dual Motor**
  Maximum e-Motor torque is shared between propulsion and Torque Vectoring. Oversized motors needed to provide sufficient Torque Vectoring during acceleration

# Efficiency

## Energy Consumption WLTP




## Vehicle configuration

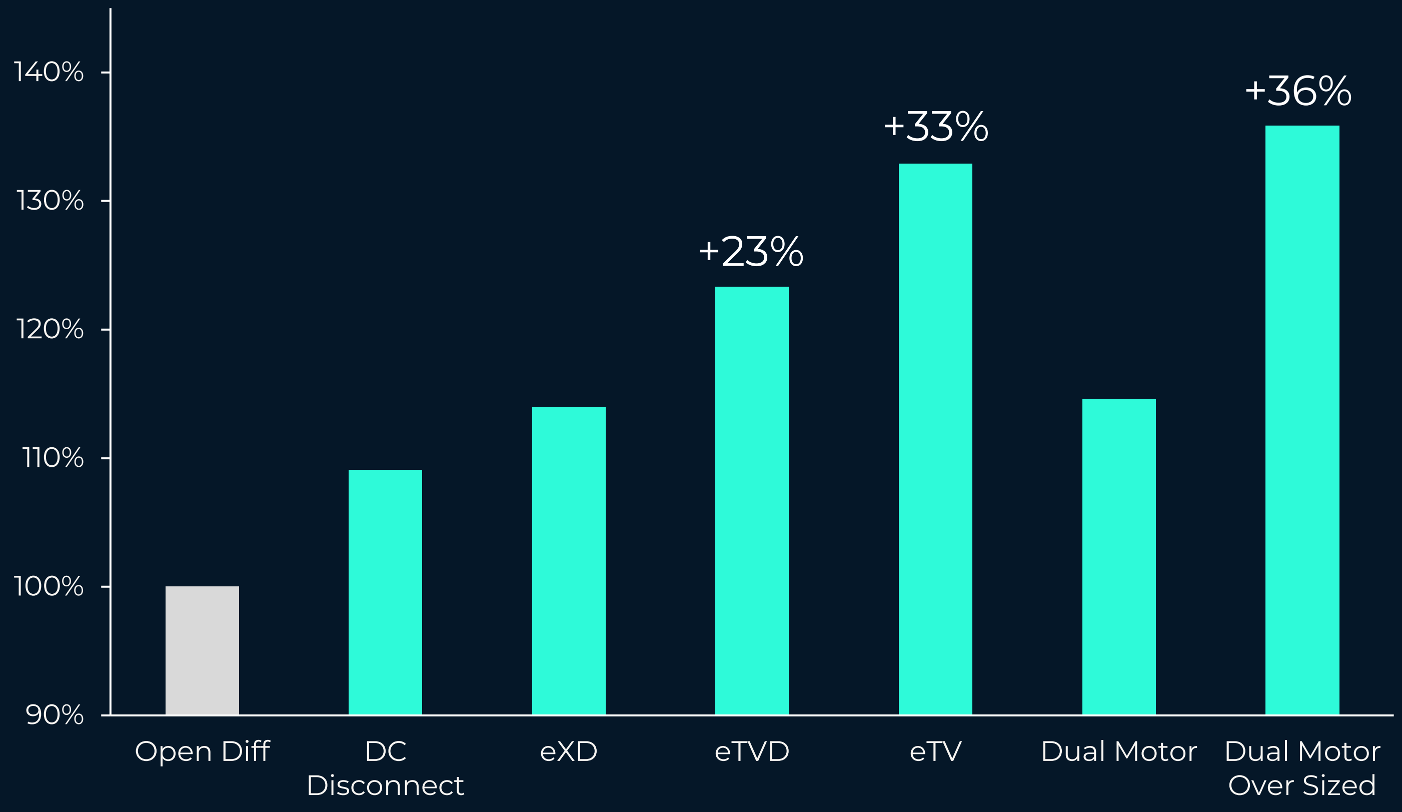
- Midsize SUV, 2500kg
- AWD
- PMSM 170kW per axle

▸ **eXD and eTV**
Low additional losses, due to minimal delta speed during normal driving scenarios

▸ **eTVD**
The only system with higher efficiency and higher performance

▸ **Dual Motor**
Highest energy consumption due to additional losses in motor and transmission

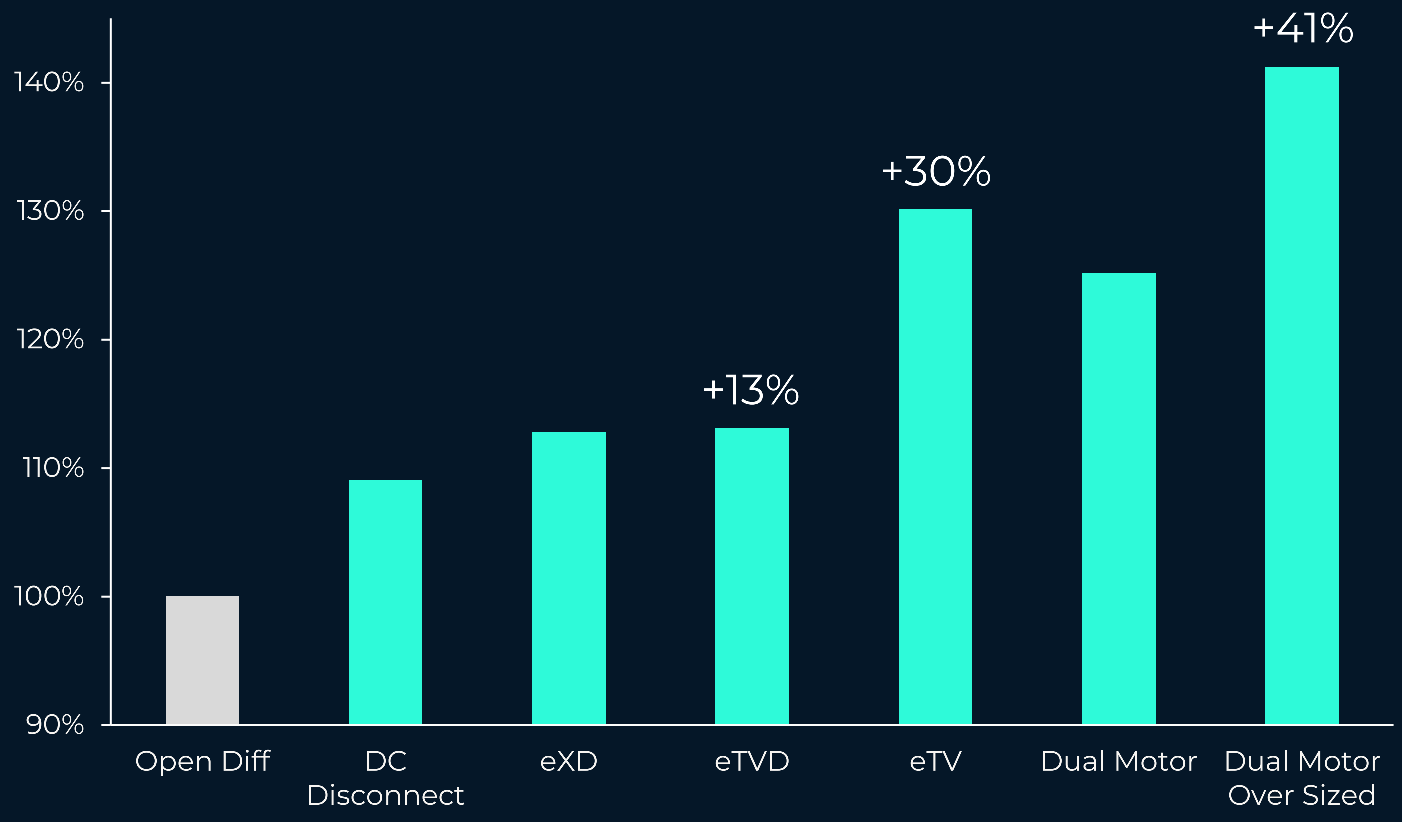
# Cost Comparison
## Complete RDU




Cost comparison performed on a single iDM with open differential as reference.

- **eXD**
  Lowest price of the products in the performance segment
- **eTVD**
  Combines performance and efficiency in a cost-efficient way
- **eTV**
  Highest price and highest additional performance
- **Dual Motor**
  Significant cost penalty for large motors.
  Cost level is very dependent on size of the motors

# Cost Comparison
## Complete RDU including Disconnect




Cost comparison performed on a  single iDM with open differential as reference

eTVD is the only Torque Vectoring system with a built in disconnect function for increased efficiency.

To reach a similar efficiency level for the other systems, additional disconnect hardware is needed.
This increases the cost and complexity.

# Efficient Traction
## Safety and comfort

Conventional Traction Control Systems use friction brakes to reduce the disadvantages of open differentials

Adding an eTMS Systems leads to

- Superior traction at normal and slippery conditions without brake interventions
- Less wear on friction brakes and tires results in less particle emissions
- Comfort and premium feeling

# Efficient Traction
## Slippery Hill Example

Climbing 20% inclination split mue hill in Arjeplog, Sweden

- eXD inactive
  - TCS Wheel Brake Active
  - Average Torque: 1950 Nm
  - Average Power: 11.2 kW
- eXD Active
  - Bypassing differential
  - Average Torque: 1250 Nm
  - Average Power:  7.1 kW

# Efficient Performance
## Vehicle Controllability

BEVs normally suffer from high vehicle weight, resulting in decreased lateral performance

Adding an eTMS Systems leads to

- Increased ability to follow requested path through corners and T-junctions
- Minimized risk for over or understeer in roundabouts even at acceleration during lane changes
- Firm and tight feeling of the steering
- Vehicle feels lighter

# Efficient Performance
## Cornering example

- Open Differential (Reduced Traction)
  - Max Wheel Torque: ±1780 Nm
- eXD Active
  - Max Wheel Torque: ± 2670 Nm
  - Actuation power loss: <200W
- Brake based Traction Control (Calculated)
  - Max Wheel Torque: 2670 Nm
  - Friction braked torque: 900 Nm
  - eMotor Torque: 3770 Nm
  - Brake based power loss: 40kW

*Example:*
*Driving at dry conditions in 55km/h through a corner.*
*Mid-sized SUV with lateral acceleration of 5m/s2.*

# Efficient Performance
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*Example:*
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*Mid-sized SUV with lateral acceleration of 5m/s2.*



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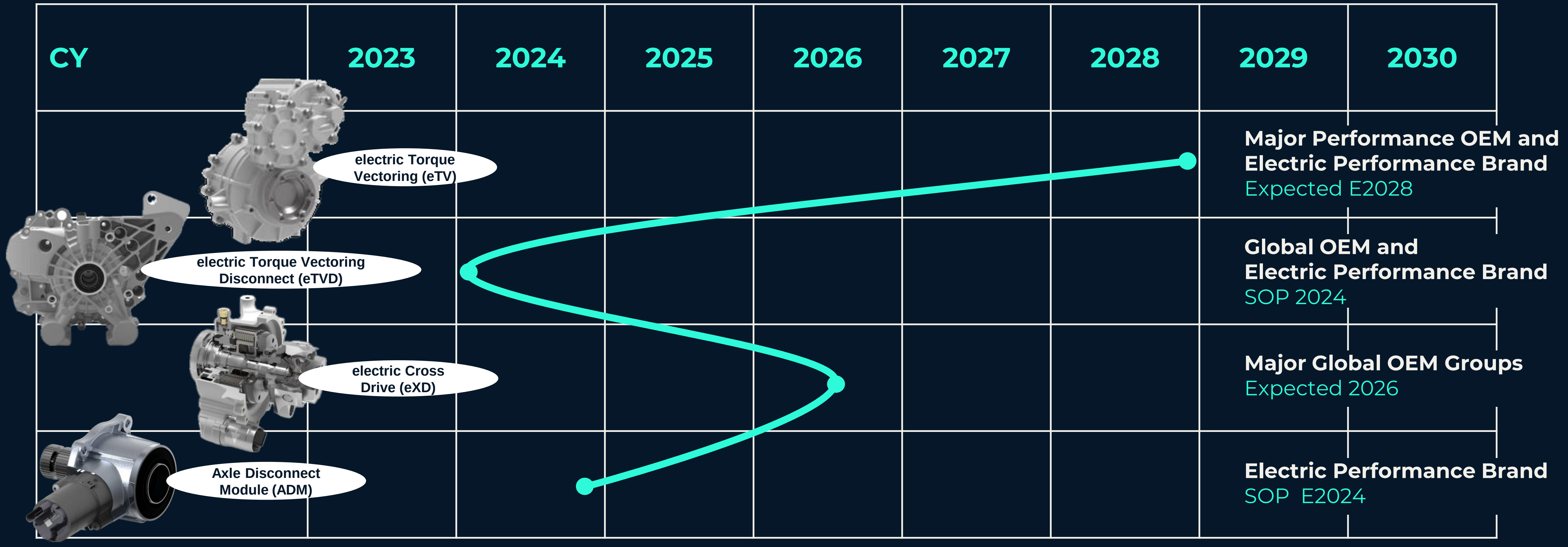
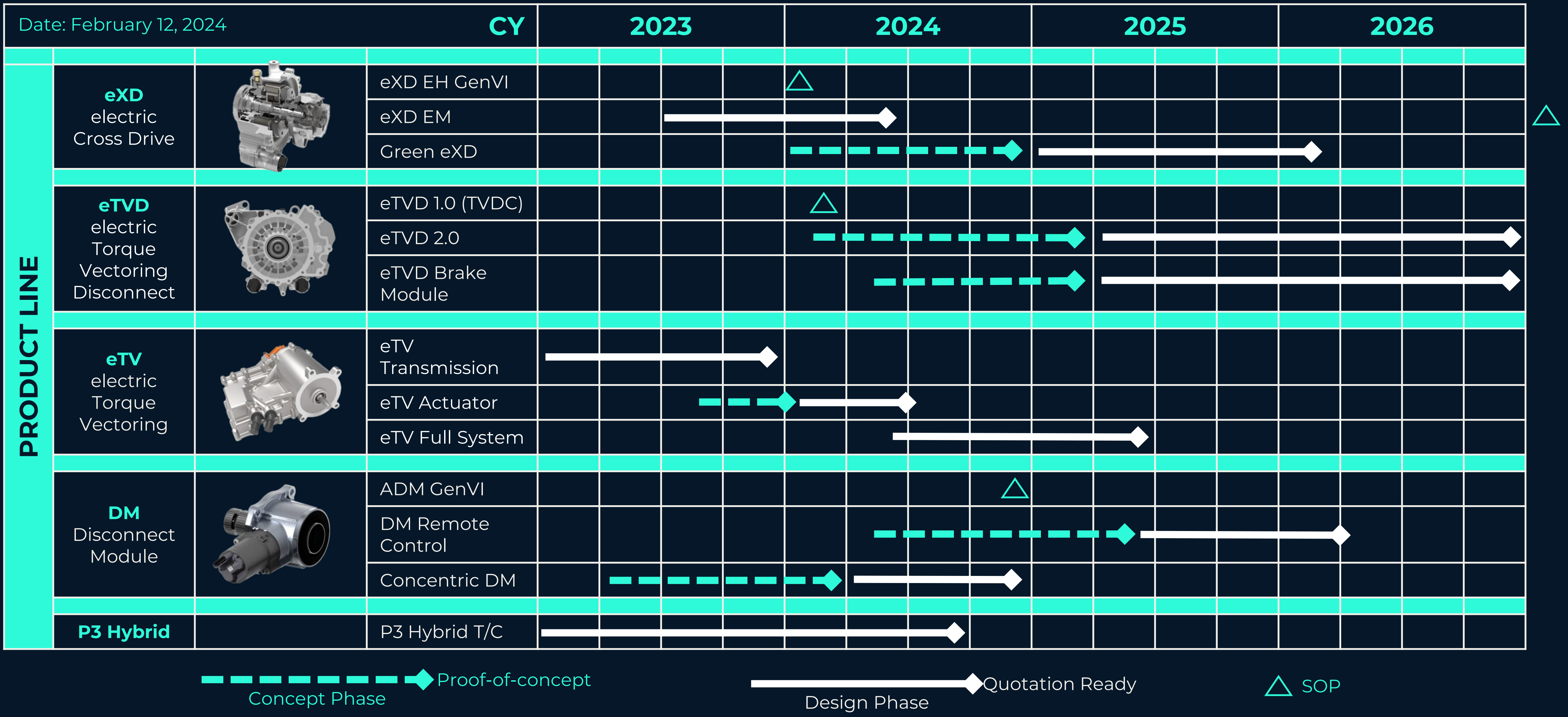
# THE NOW and THE FUTURE Portfolio Launch Outlook

## EV Torque Management



# eTMS Global Product Roadmap



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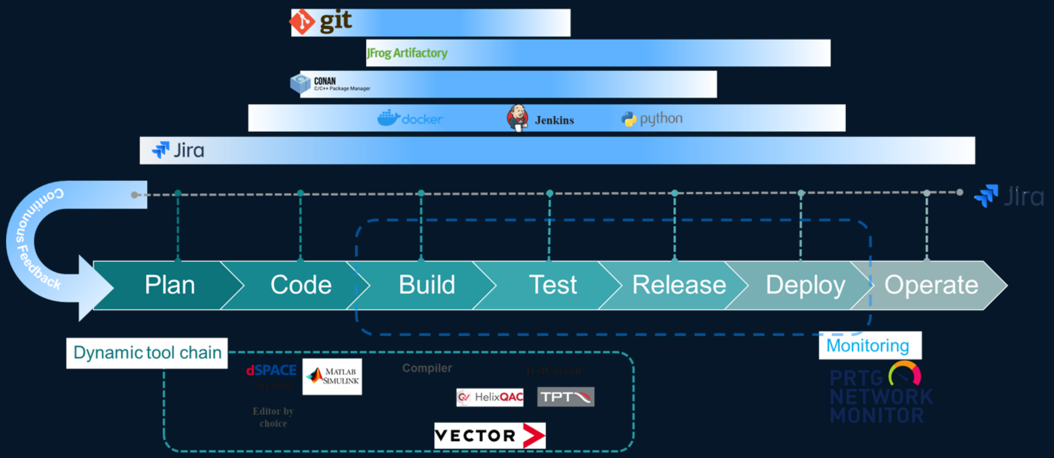
## SOFTWARE FACTORY

# SOFTWARE DEVELOPMENT
# Center of Excellence




Market is moving from hardware defined software to software defined components and vehicles

Software is increasing in importance and becoming essential to sell hardware

With limited resources we need to be efficient on how we develop and maintain software

**Enhanced Software Development Capability**

VALUE FOR CUSTOMER

Increased Software Quality & Robustness

Secure Maintainability for up 15 years

Shorter Time to Market

Enable True Commonality and Reuse

Efficient Use of SW Development Resources

Platform for Multiproduct Support

COMPETITIVENESS

# Vehicle Control Software
## Strategy and Background

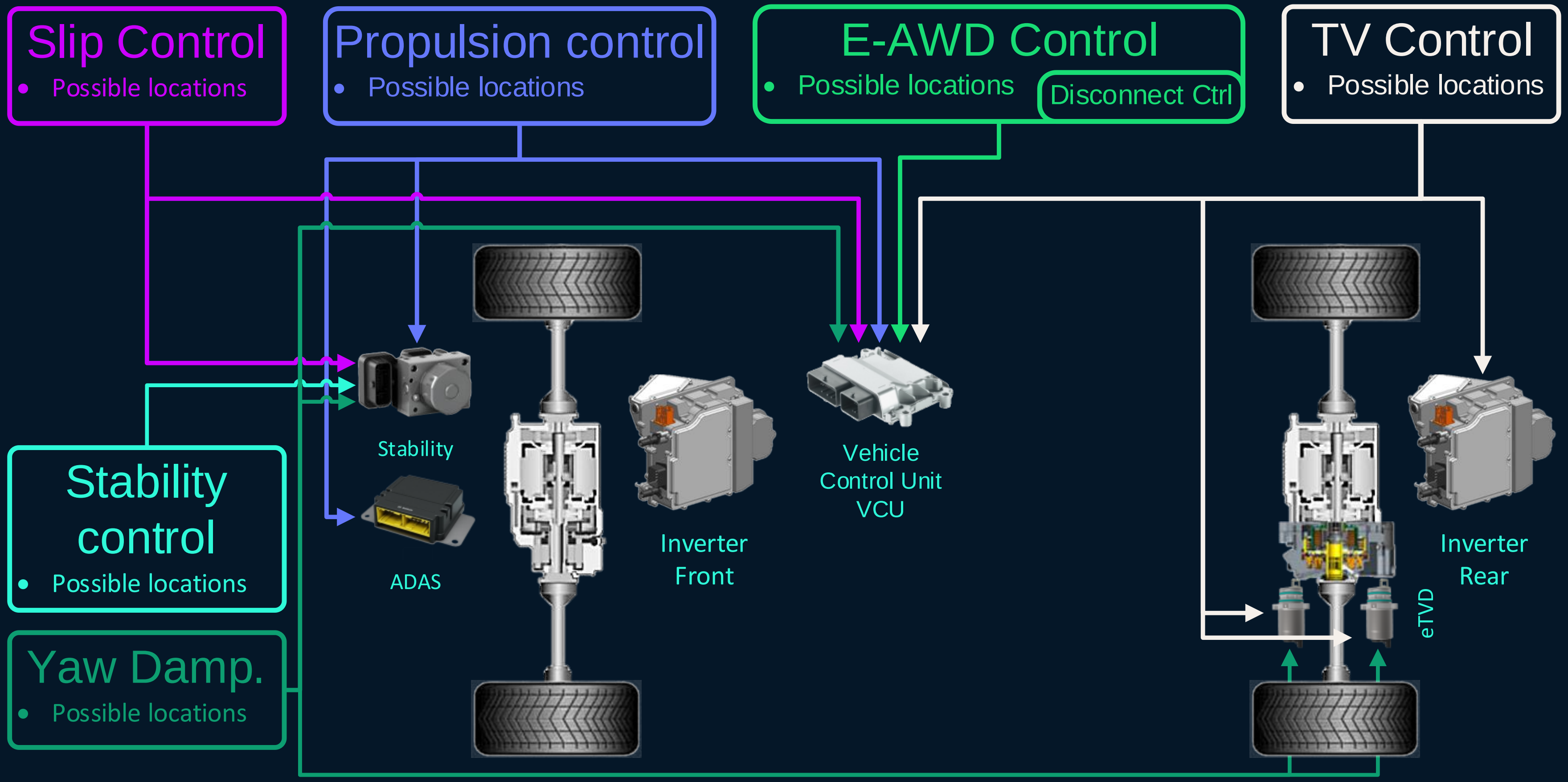
*Vehicle Dynamics is the vehicle motion response, to driver input and environmental disturbances*

- Background
  - The system reacts on driver requested inputs in combination with actual vehicle state signals to maximize the performance
- Preemptive torque distribution
  - The software calculates and predicts the vehicle behavior to give the driver a premium experience in any given situation
  - A feedback loop is used as a safety net if any unexpected situation occurs

# Vehicle Control Software
## Creating additional value

- Modularity
  - Same software can be used for multiple vehicle platforms, with different tuning options available
- Connected Vehicles
  - Adjusted sensitivity based on available cloud data, i.e slippery road segments
  - Disconnect Strategy influenced by the route from the GPS system
- Brand DNA
  - Customized tuning together with our experts as standard deliver the important brand feeling for every OEM

# Vehicle Control Software
## Functional description



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# Sustainability

Our commitment - LCA – Green eFXD

## Scope 1 & 2 reduction

**-85%** by 2030 from 2021 base year

## Scope 3 reduction

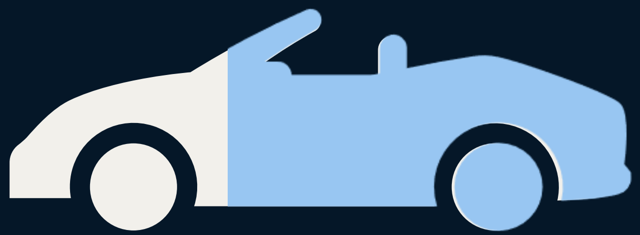
**-25%** by 2030 from 2021 base year

SCIENCE BASED TARGETS
DRIVING AMBITIOUS CORPORATE CLIMATE ACTION

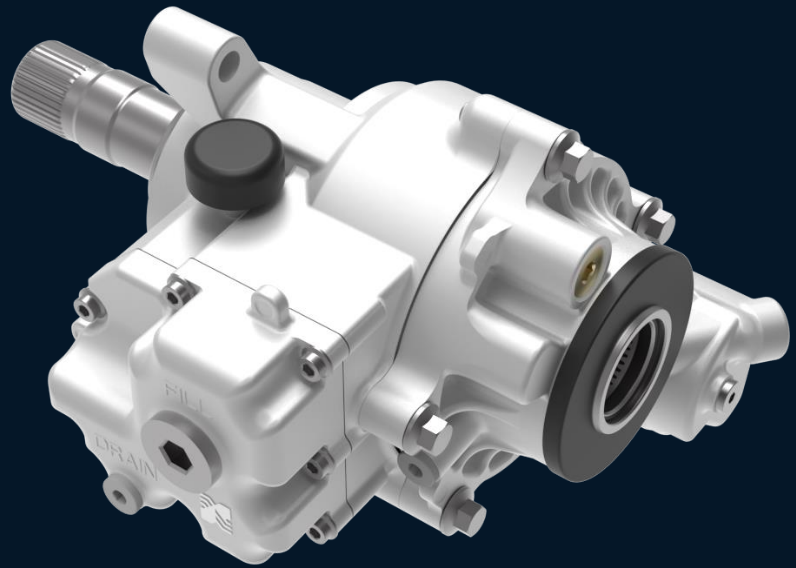
Validated by SBTi in August 2023!

# ≈60%

of a BEV total $CO_2$ footprint comes from the material production



# eFXD



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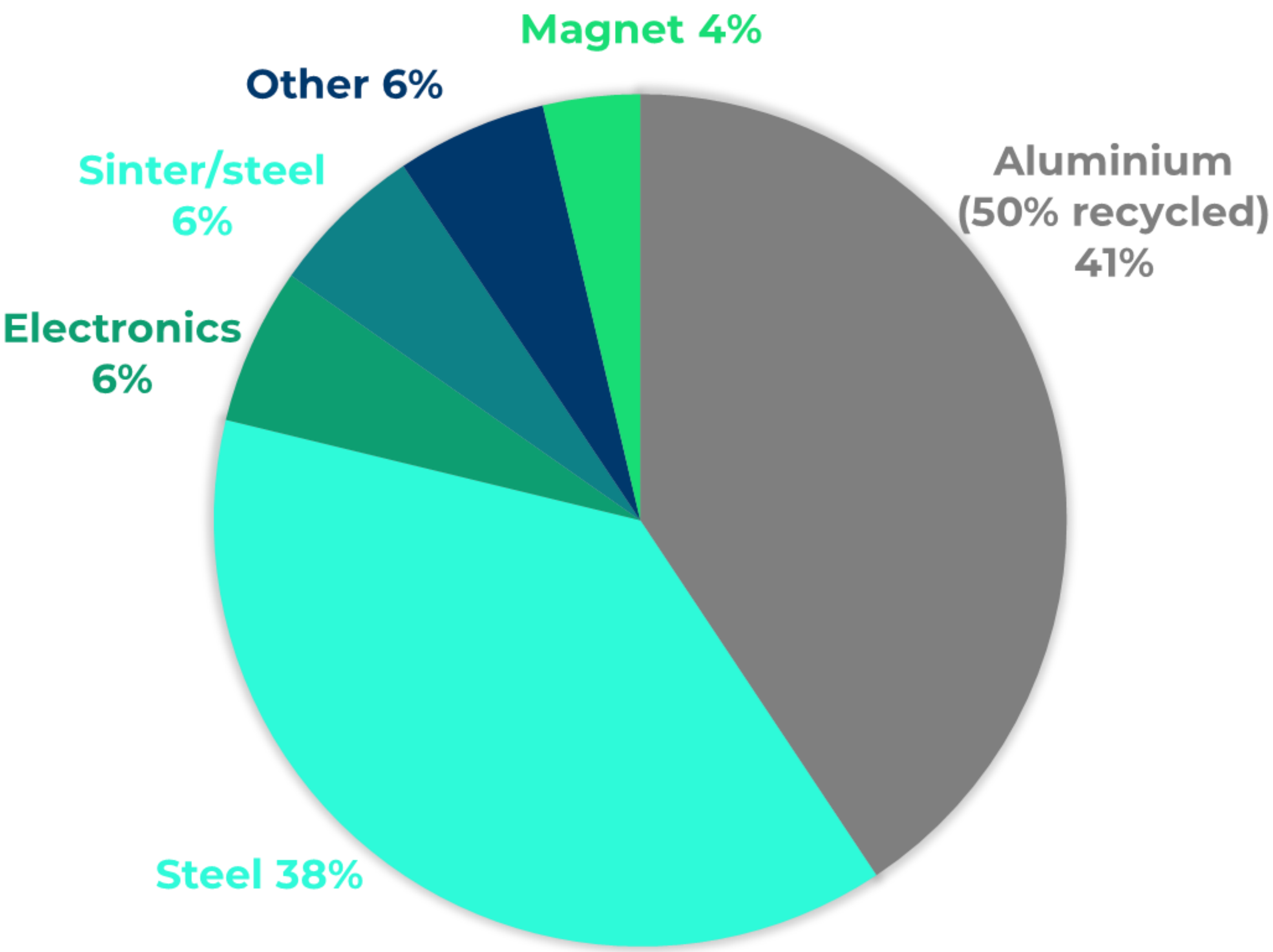
# Material related emissons
kg CO2 eq.

**45 kg $CO_2$ eq.**

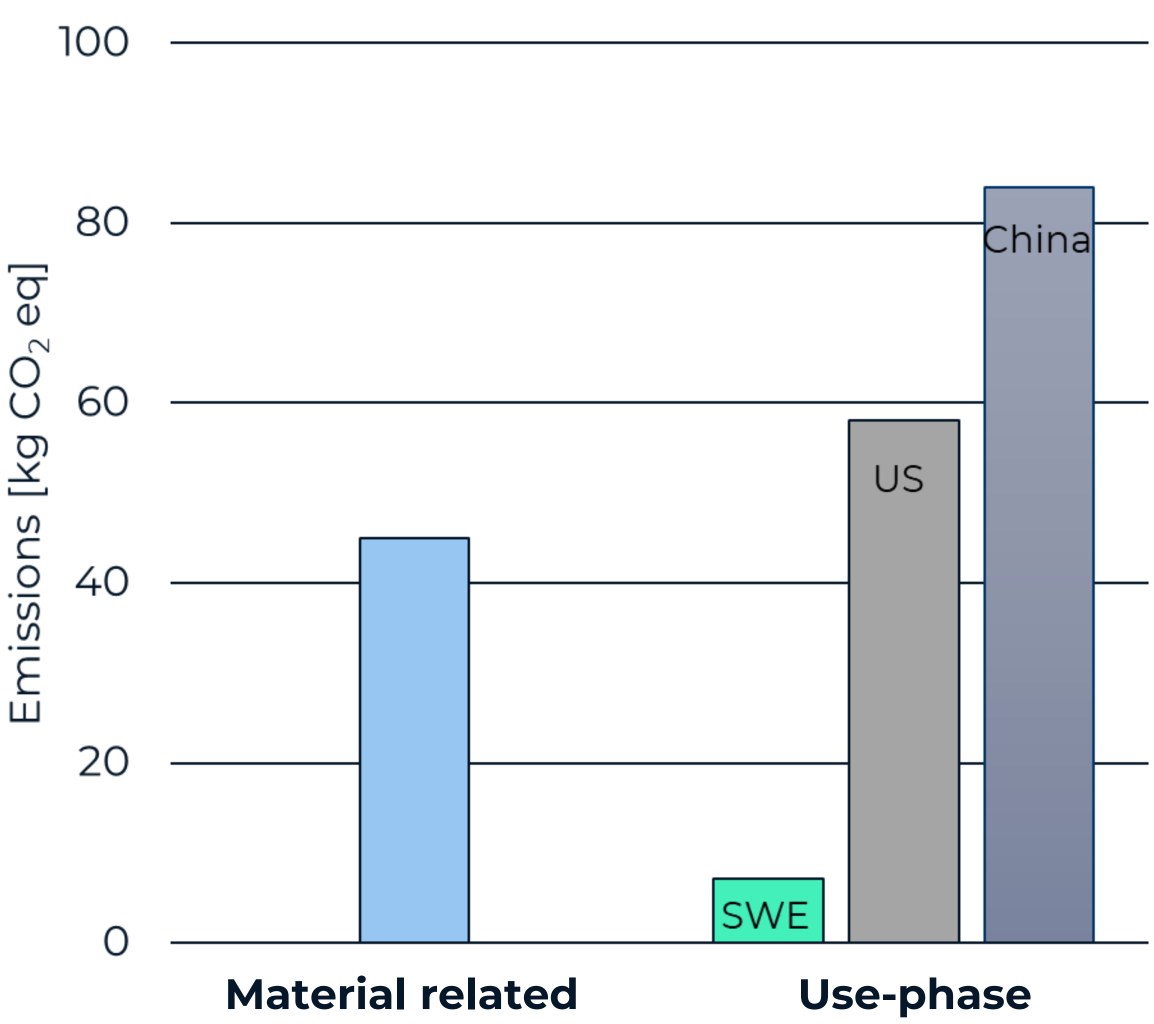





Emissions breakdown by material

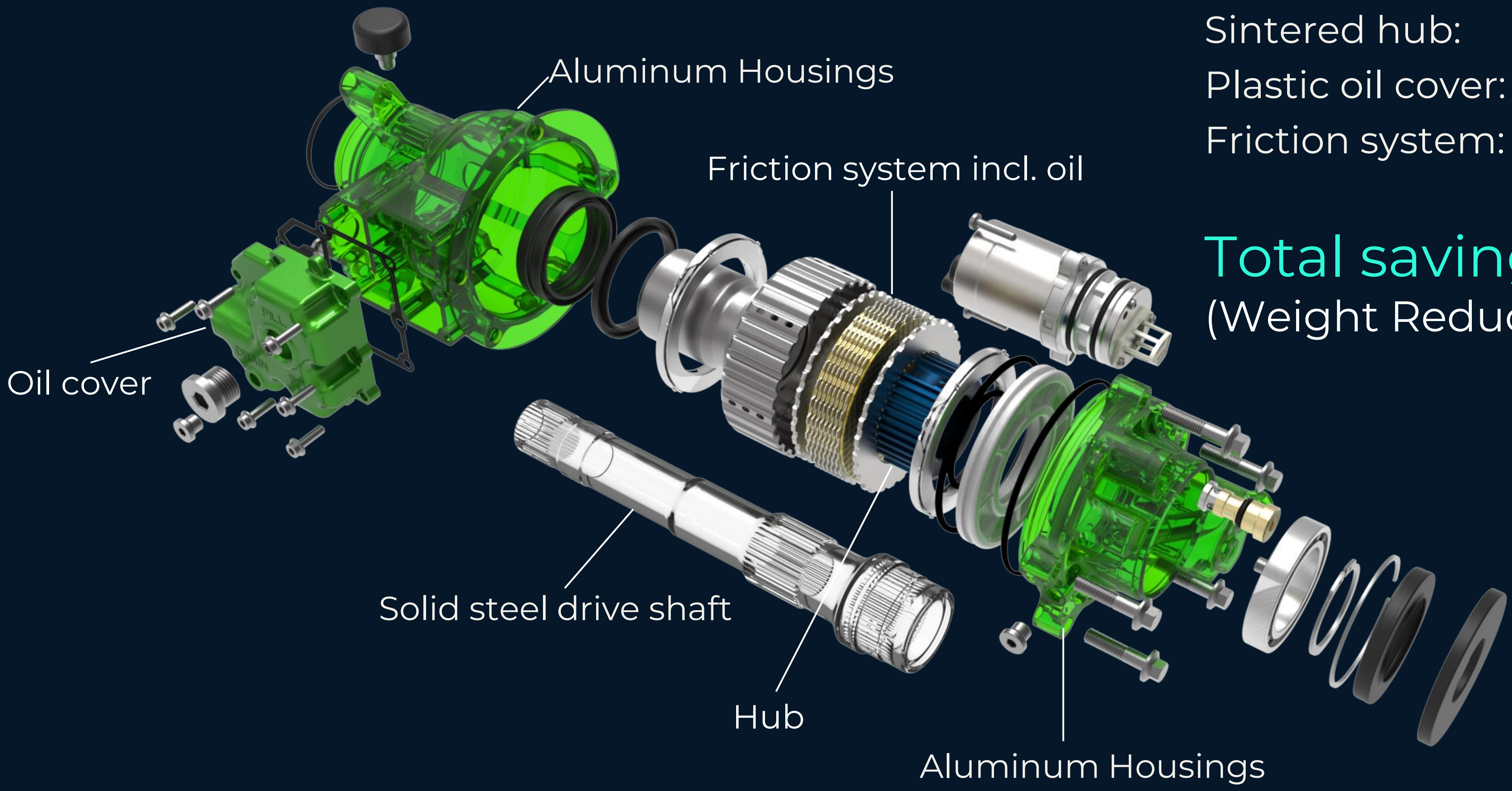
## Material related vs. **use-phase**

# Up to 84 kg $CO_2$ eq




$CO_2$ eq emission allocated to eXD over lifetime (250 000 km) depending on grid mix

# $CO_2$ reduced components




| | |
|---|---|
| Plastic housings: | -10.3 kg $CO_2$ |
| Hollow drive shaft: | -2.5 kg $CO_2$ |
| Sintered hub: | -1.3 kg $CO_2$ |
| Plastic oil cover: | -1.4 kg $CO_2$ |
| Friction system: | -0.32 kg $CO_2$ |
| | ------------------- |
| **Total saving:** | **-35% $CO_2$** |
| (Weight Reduction: | 16%) |



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# PowerDrive Systems

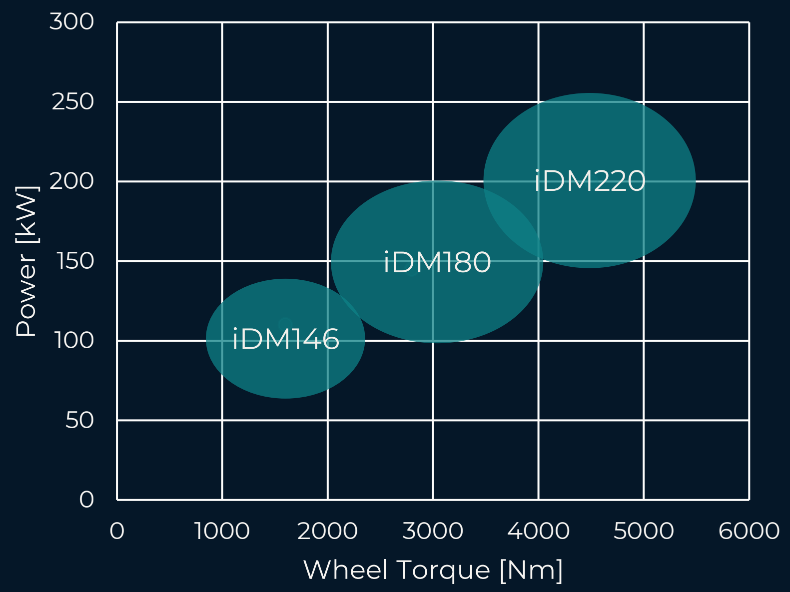
2024 BorgWarner Arctic Drive, Arjeplog, Sweden

# One Pagers – All Products

# iDM – integrated Drive Module

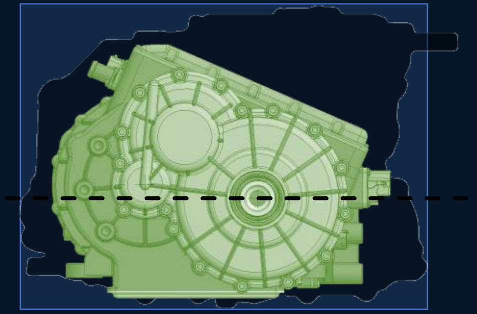
**Flexible Architecture + Reusable Building Blocks**

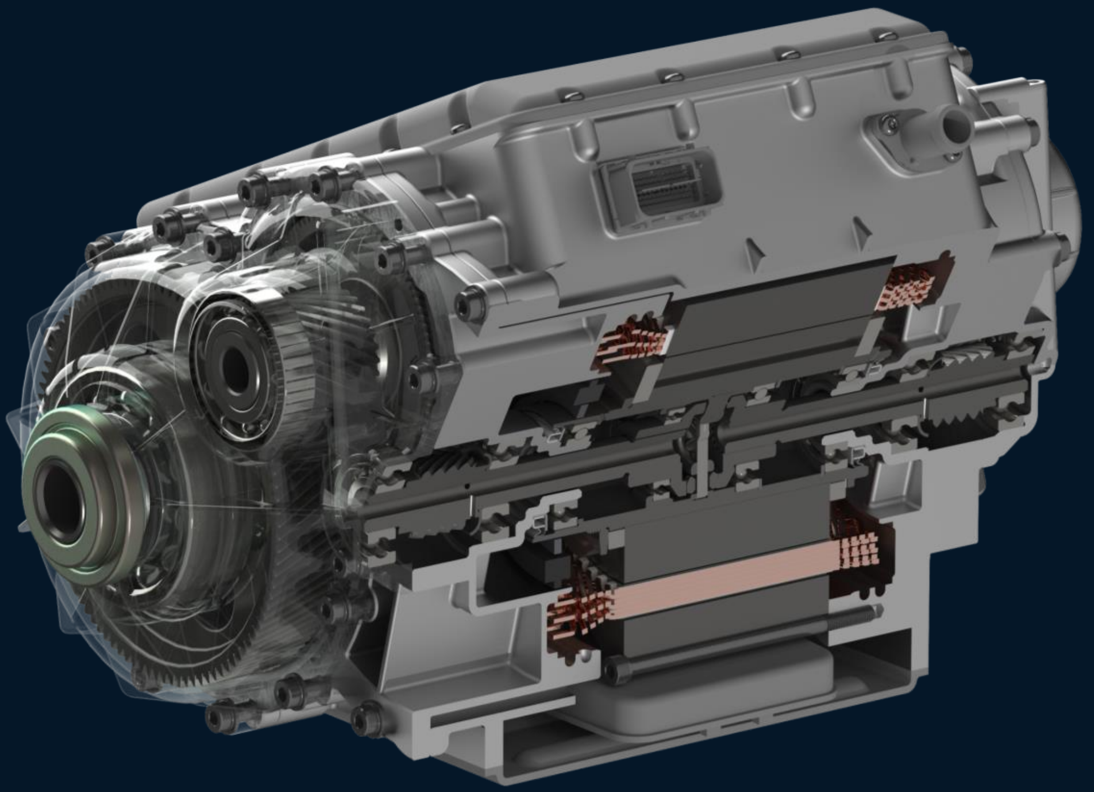
- Deployment of proven and tested components
- Flexible system voltage, torque, power and packaging
  - **eMotor**
    - PMSM with low or no HRE-magnet or IM
    - Oil cooled or water cooled
  - **Inverter**
    - Si or SiC based on BW Viper Power Modules
    - Semi-integrated in main housing
  - **Gearbox**
    - Co-axial or off-axis layshaft transmission
    - Different Disconnect solutions available
- Full SW and controls capability
- Development and production in EU, US and China



# Advanced: 800V Ultra Compact High Speed iDM

**Dual Gearbox + Integrated Diff**
- Gear ratio: > 13.0
- Integrated Differential
- High speed bearings



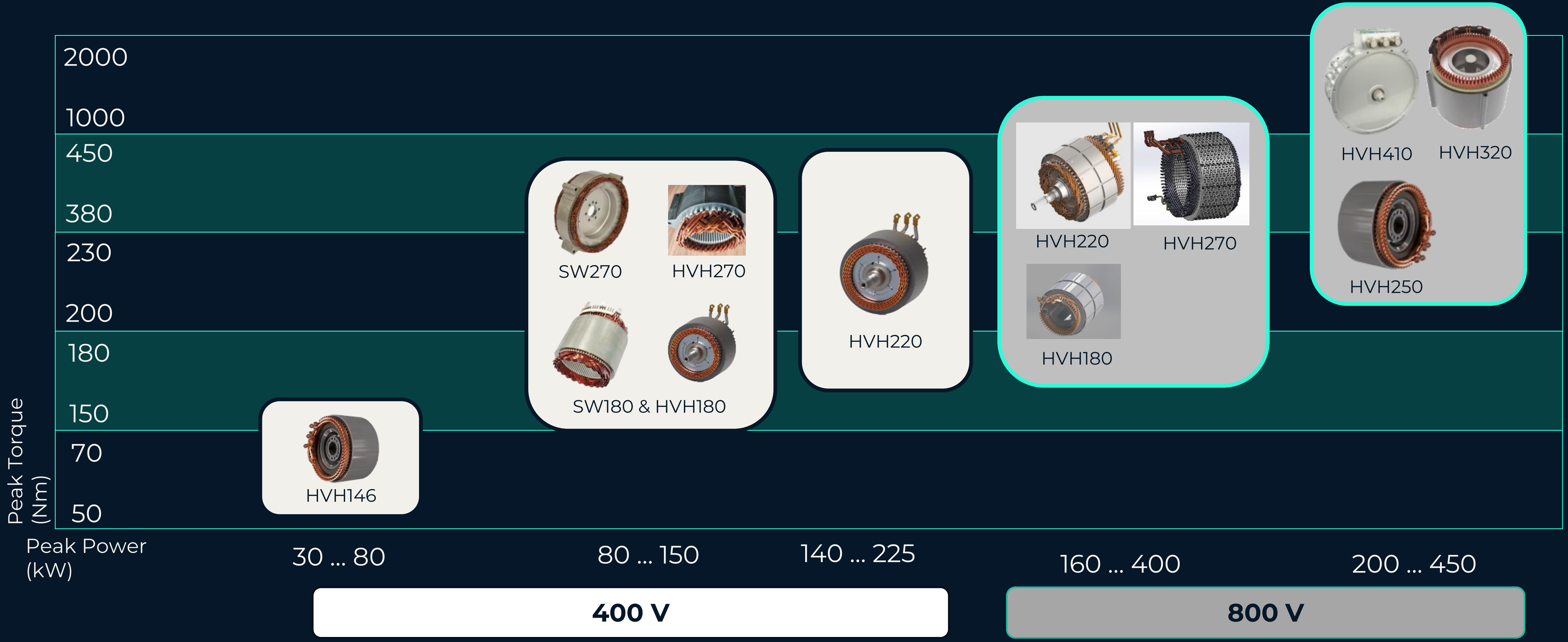


**Fully integrated inverter**
- 800V SiC high current density
- Planer component placement
- Compact assembly (< 4kg)

**High Speed eMachine**
- Pk Torque: > 250Nm
- Max Speed: ~23,000rpm
- 245kW @ 650 Vdc
- Submerged end coil cooling

**D-seg iDM with B-seg Packaging**
- Box Volume reduced by 24%

# eMotor - Overview



# Advanced: 800V EESM; iDM with Compact Power flow

- RE free iDM with compact form-factor using integrated electronics and controls

Externally Excited Wound Rotor

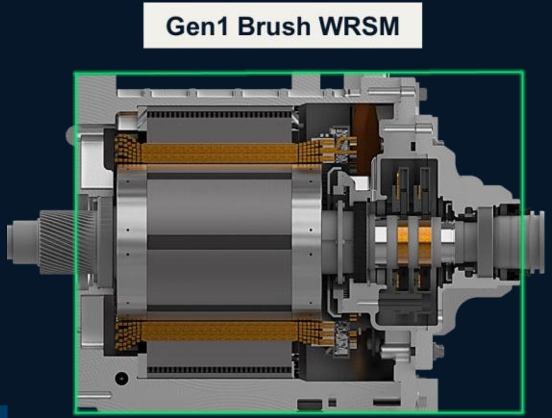
Ultra compact coaxial power flow

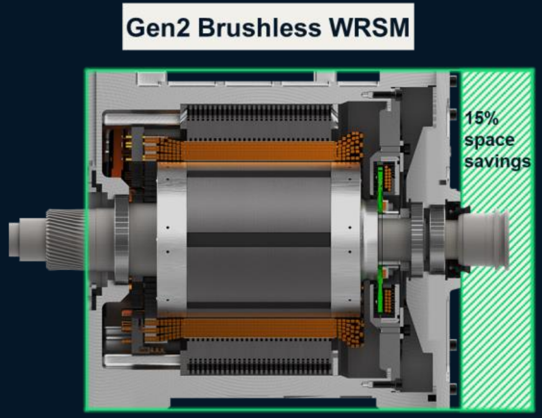
Integrated stator – rotor excitation controls

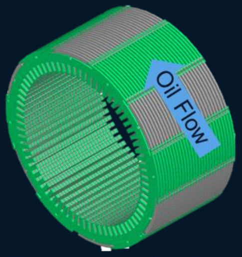
Stator cooling - 25% more torque, Interpolar rotor cooling

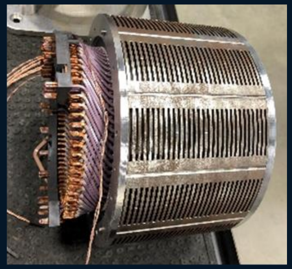
Gen 1 with brushed excitation

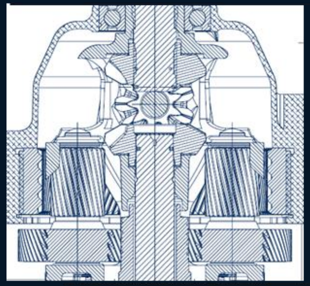
Gen 2 with brushless rotary transformer

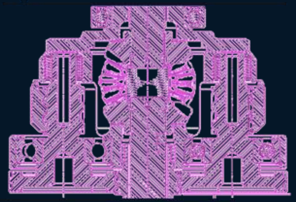


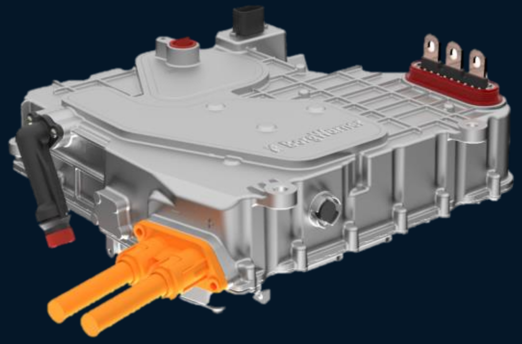







# Inverter Overview



- #1 non-captive supplier by 2025
- Market leader in 800V and SiC
- Strategic supplier partnership on SiC


**CY 2021-2026**
> 22 applications

Single or Dual Inverter
Combo with Boost Converter

400 & 800V

300 – 900
Arms Peak

Si & SiC

6-13 L

7-15 kg

**BorgWarner Inverter portfolio covers all market needs**



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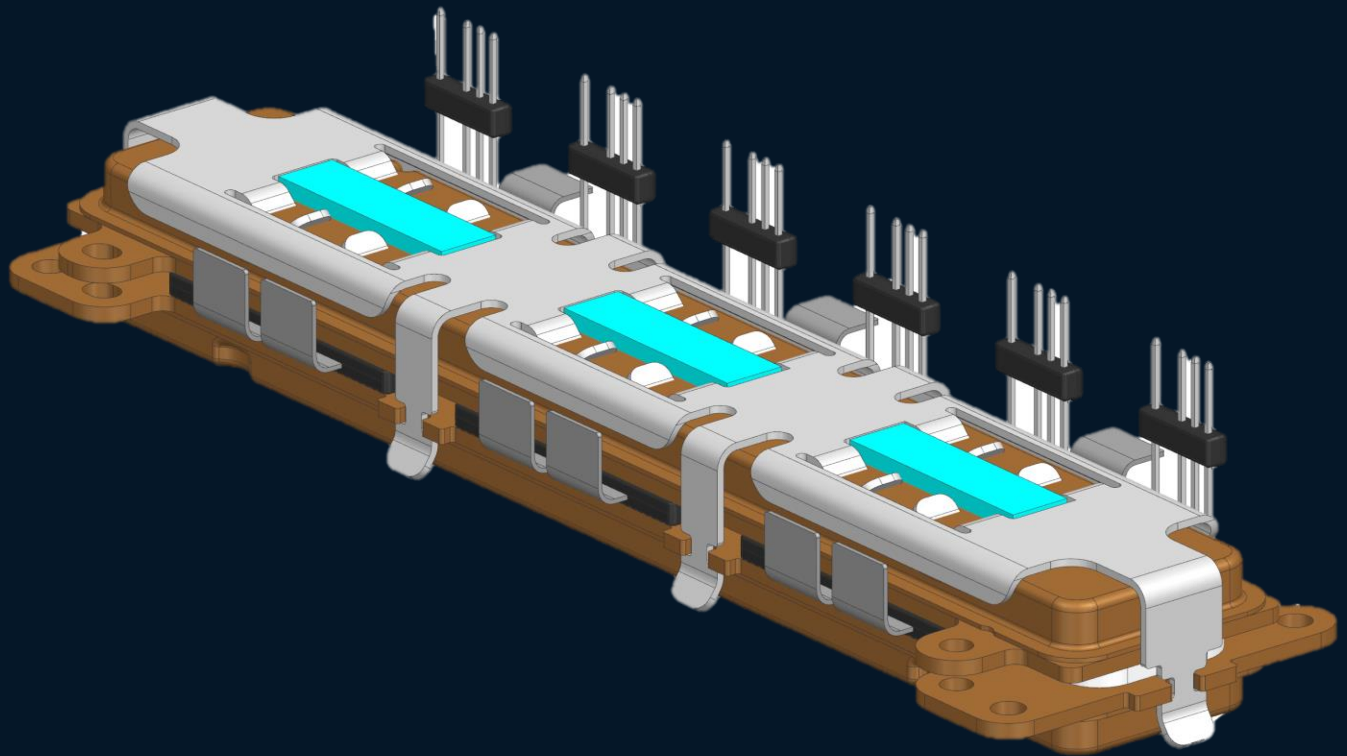
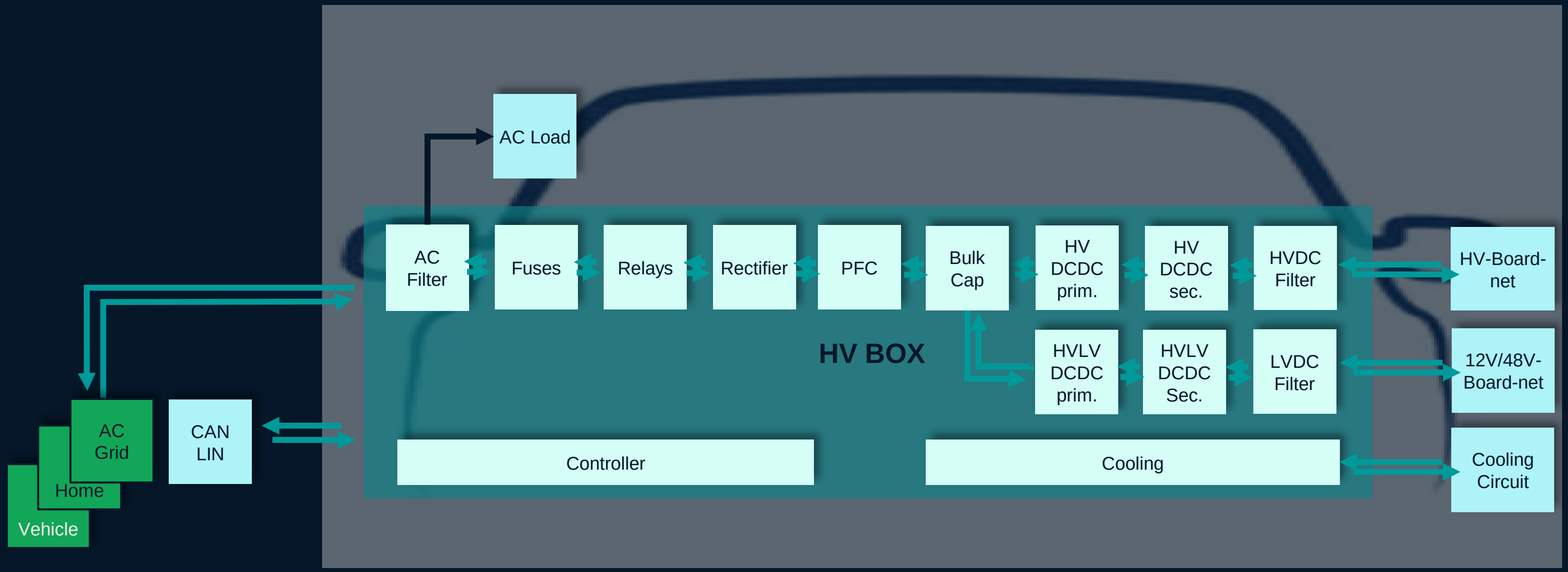
# Power Module Overview

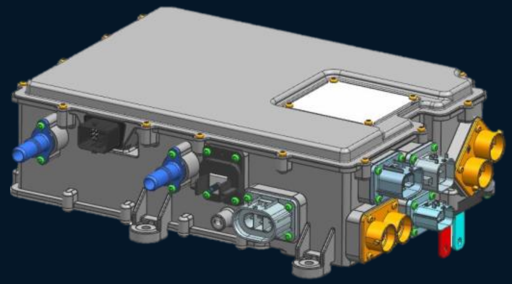
- Power dense design
- Unique Double side cooled
- Cu or AL heatsinks
- Scalable & “future proof”
  - SiC and Si support
- Highest A/mm2
- Market leading $/Amp



# HV-Box Overview

- OBC, Power Conversion of AC to DC for Onboard Charging of Vehicle Battery Pack (400V/800V)
- DC/DC, Power Conversion of HV-LV DCDC for Auxillary Vehilce Power (12V or 48V vehicle power)
- V2X, Power Conversion of DC to AC for Inverter Mode (V2X: Vehicle-to-Load, Vehicle-to-Vehicle, Vehicle-to-Grid)



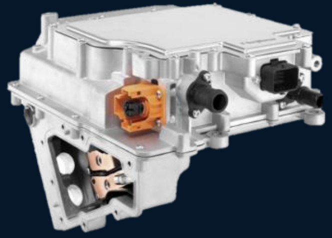



# iDM - integrated Drive Module

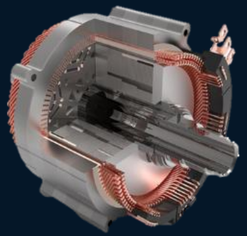
# Integrated Drive Module (iDM) - System Supplier

BorgWarner Product, Development & System Integration Know How

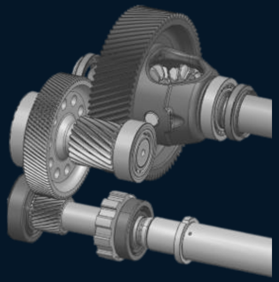
**Inverter**



**E-Motor**



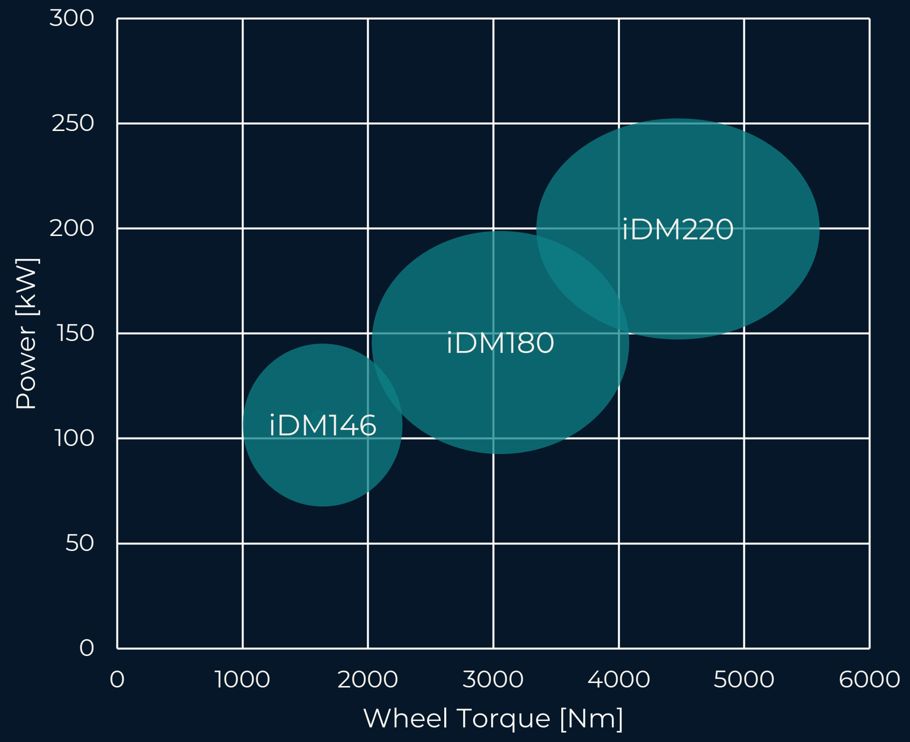
**Transmission**



**Software**

**iDM**

# iDM Product Family




- Both 400V and 800V possible

**Flexible Architecture + Reusable Building Blocks**

- Deployment of proven and tested components
- Competitive development timing
- Component synergies
- Usage of common processes, standards, and tools
- Domain teams with deep knowledge / key competencies

# Integrated Systems Portfolio

## EXPERIENCE DRIVEN MARKET LEADER

### Co-Axial iDM

High Voltage
Passenger Car - BEV
SOP 2020

Ford

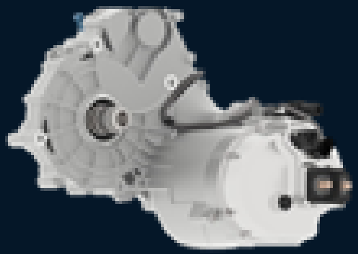
### P2 On Axis

High Voltage
Passenger Car - P2
SOP 2020

CHANGAN

### P3 Module

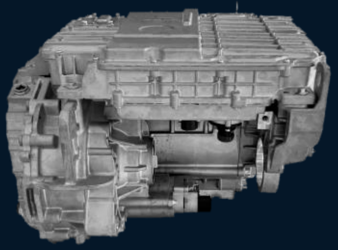
Passenger Car – P3
SOP 2024



**Major EU OEM**

### iDM146

High Voltage
Passenger Car - P4/BEV
SOP 2023



HYUNDAI

### iDM220

High Voltage
Passenger Car - BEV
SOP 2023

Li Auto

# iDM180 Concept Development

## EFFICIENCY, COST AND WEIGHT OPTIMIZED PRIMARY DRIVE UNIT

**System**

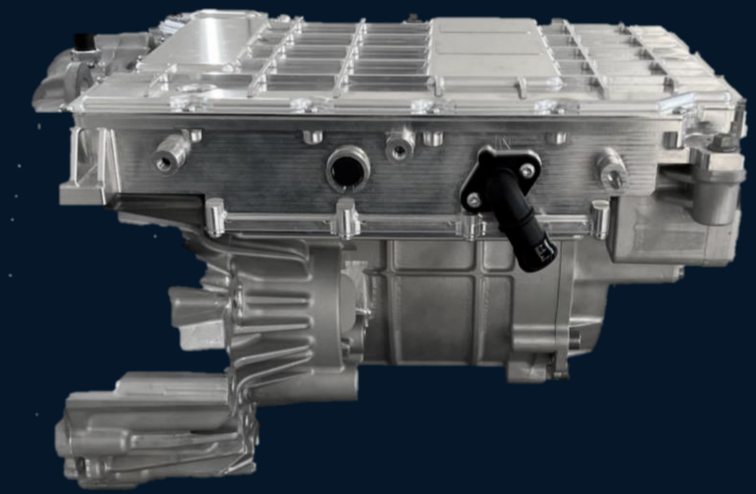
| | |
|---|---|
| • System Voltage | **800V** |
| • Peak torque | **>4000 Nm** |
| • Peak power | **>150 kW** |
| • Peak efficiency | **> 95,5% *** |
| • Weight | **< 83kg** |
| • Water/Oil cooled | |
| • Full SW incl. driveline controls | |

**Compliance**
- ASPICE L2 (SYS+SW)
- ASIL C(D)
- AUTOSAR R20-11

**eMotor**
- PMSM, hairpin, 180 OD
- Heavy rear earth free
- Oil cooled

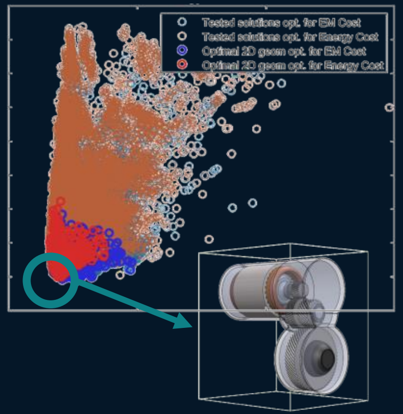
**Inverter**
- Peak current 350Arms
- SiC Power Modules

**Gearbox**
- Off Axis Design
- Ratio 12.085
- Optional park-lock and disconnect



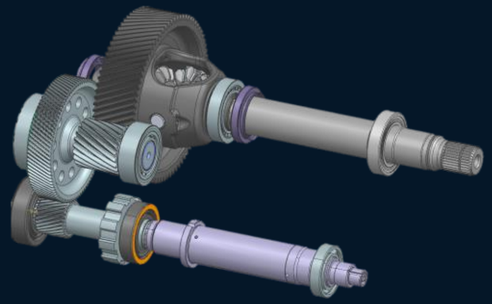
* e.g. D-Segment vehicle average WLTC loss is <750W

# Loss Reduction Measures, iDM180 Concept




## System Optimization

- Thousands of motors with optimized gear ratio and inverters compared

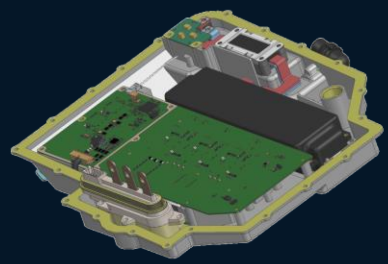


## Gearbox

- Optimized high-speed bearing concept
- Reduced preloaded bearings
- Dry sump solution with minimal splash losses
- Smart cooling and lubrication strategy

## Motor & Inverter

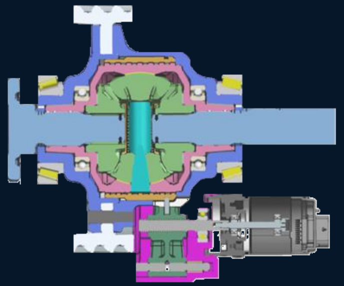
- Thinner Laminations
- Stator back-iron oil cooling
- Rotor oil cooling



## Motor Controls

- BorgWarner Viper 8 Power Modules
  - Variable Gate Strength
  - Lowered Hotel Losses
- Switch frequency Optimization
- Multiple modulation techniques

# Disconnect Solutions for Secondary Drive Unit



**Differential Disconnect**

- Disconnects differential gears from differential housing
- Optimized for low drag
  - No preloaded bearing losses in disconnect mode
- BLDC Actuator
- In concept development
  - Development vehicle available Q3 2024

**Axle Disconnect**

- Disconnects one of the half-shafts
- Cost optimized
- In production since 2022

**Input shaft disconnect**

- Solenoid based, 48V
- SOP 2024

# PowerDrive Systems Global Footprint

**EU Tech Centers covers:** System, SW, Inverters, Gearbox and regional lead on eMotors

**EU has production of** 3in1 Systems, Inverters, eMotors and Transmissions

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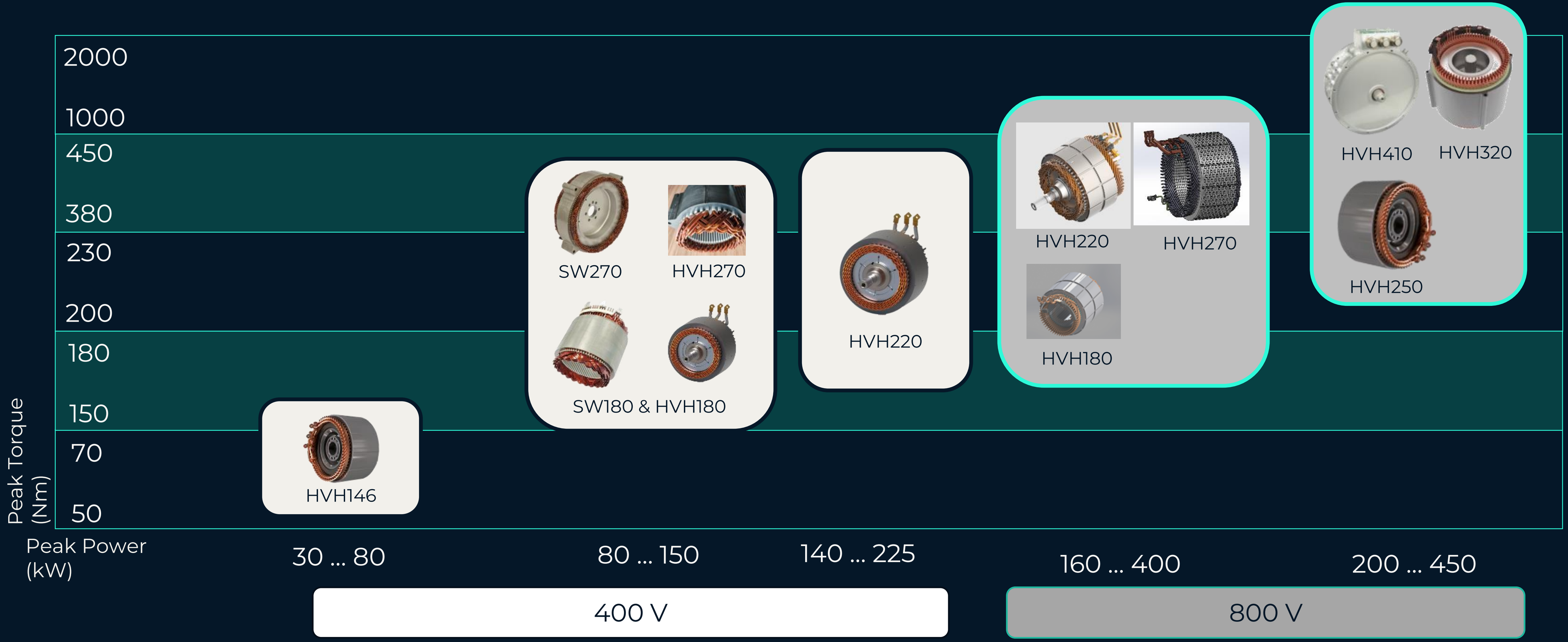
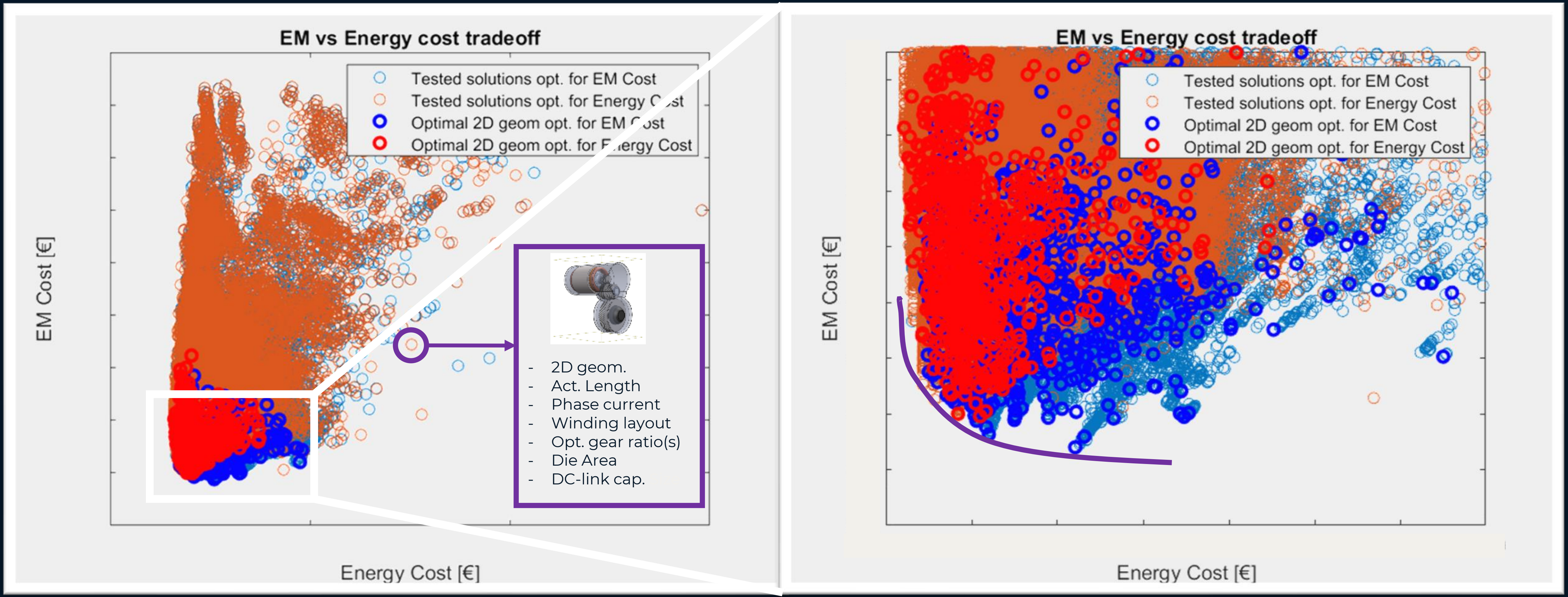
# eMotor

# eMotor - Product Families



# Trade-off between energy consumption and EM cost



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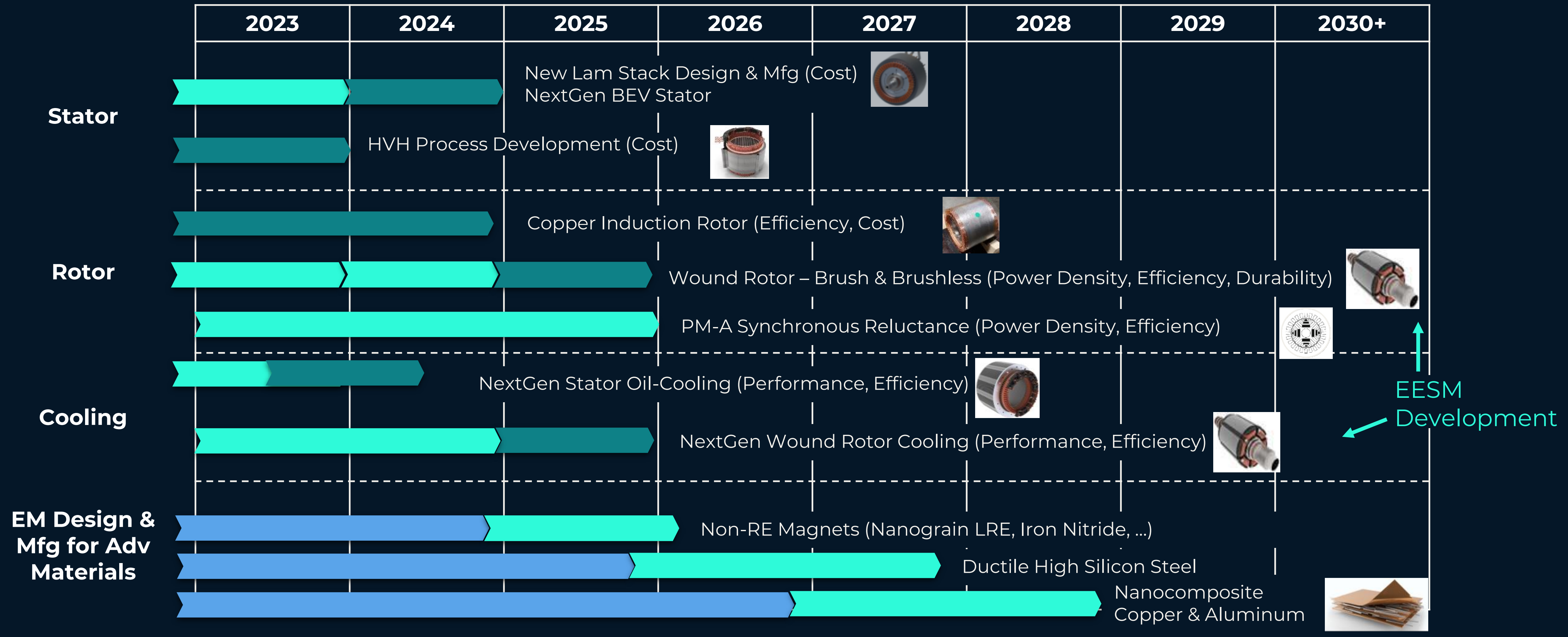
# eMotor Technology Roadmap

Exploration | Feasibility | Assurance



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# BorgWarner – IPM eMotor Roadmap Magnet

| | 2023 | 2024 | 2025 | 2026 | 2028 | 2030 |
|---|---|---|---|---|---|---|

NdFeB

**Magnet**
- Grain boundary diffusion
- Jet milling lower grain size
- 3D coercivity design
- Jet milling < 3um grain size

HRE content → Dy 0% / Tb 0%

**PSM motor**
- Lam stack design
- Optimized ASC exposure
- Adv. Magnet shape
- Rotor Cooling
- Low max magnet temp.

**System**
- Optimized ASC control

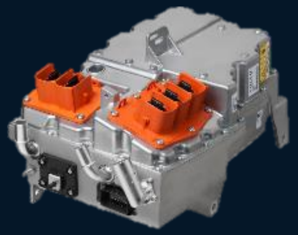
B | C | SOP Ready

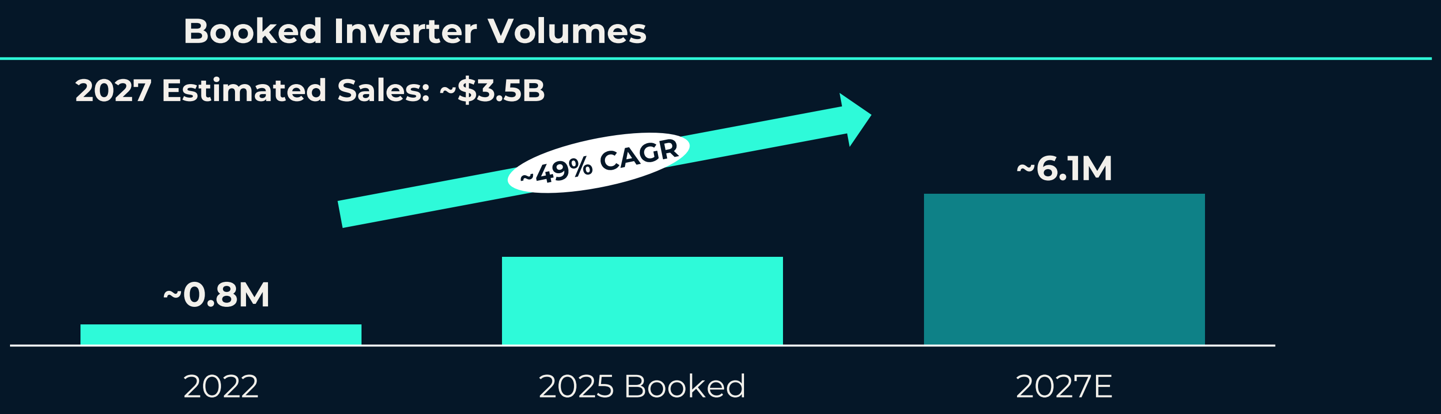
- BW key technologies enabling anticipated market intro of HRE free PSM eMotor
- Removing HRE is a key subject for sustainability

**BorgWarner eMotor without Heavy Rare Earth is on its path to market introduction**

# Inverter

# Significant Bookings Across eProduct Categories

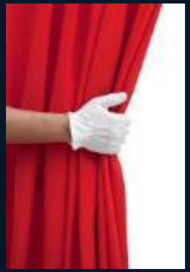




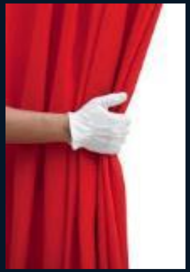

- #1 non-captive supplier by mid-decade (BEV and xEV) with growth expected to be significantly faster than market
- 29 Inverter application SOP's between 2015 and 2025
- Market leader in advanced solutions including 800V and SiC
- Strategic supplier partnership to ensure SiC device supply

# Inverters In-Progress

## 2023

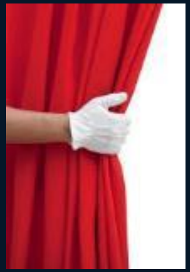



**Single Inverter**
330 - 444V
600 Arms Peak
230 Arms Cont.
Si
<7 Liters
8.5 kg

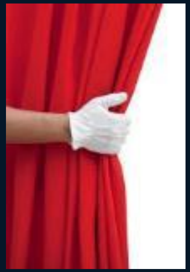



**Dual Inverter w / boost**
194 - 450V
400/400 Arms P
230/240 Arms C
Si / Si
13 Liters
14.5 kg

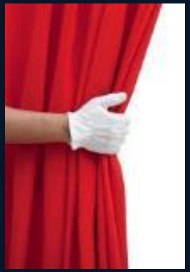
## 2024



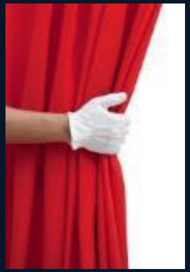

**Inverter Trans. Cntr.**
260 - 835V
300 Arms Peak
160 Arms Cont.
SiC
6.2 Liters
7 kg




**Single Inverter**
250 - 470V
510 Arms Peak
260 Arms Cont.
SiC
6.0 Liters
7.5 kg

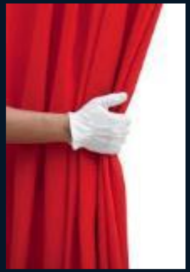



**Single Inverter**
250 - 470V
750 Arms Peak
350 Arms Cont.
SiC
6.0 Liters
8.5 kg



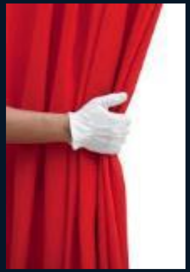

**Single Inverter w/Boost**
450 - 880V
425 Arms Peak
225 Arms Cont.
Si
<9 Liters
<10 kg

## 2025





**Inverter Trans. Cntr.**
260 - 835V
440 Arms Peak
200 Arms Cont.
SiC
8 Liters
10 kg

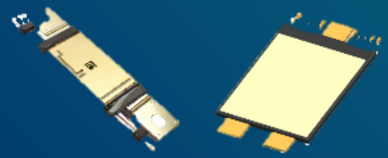




**Inverter Trans. Cntr.**
260 - 835V
540 Arms Peak
230 Arms Cont.
SiC
8 Liters
10 kg

# BorgWarner – Power Electronics Foundation

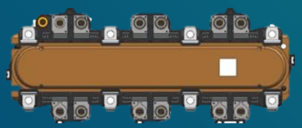
## Viper



High Performance Power Switch

- Industry leading compact power switch
- Scalable & “future proof”
  - SiC and Si support
- High reliability
  - Zero wire bonds
- High performance

## Power Module



Viper w/ Thermal Management

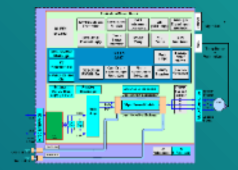
- Power dense design
- Unique Double side cooled
- Highest A/mm2

## ASICs

Custom In-house ASIC Design Capability

- Reduce part count
- Extends processor capabilities
- Enables common architecture

## Software System Solutions



Scalable Architecture

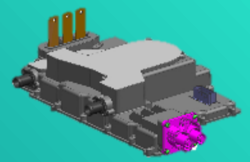
- Fully integrated controls solution for optimal efficiency and performance
- Custom scalable system and software solutions
- Process driven organization with demonstrated capability to ASPICE L2

## Functional Safety & Cybersecurity

ISO26262 and ISO21434 Capability

- ASIL C & D
- Established functional safety driven culture

## 800V Leader



Industry Leading Power Dense Inverter

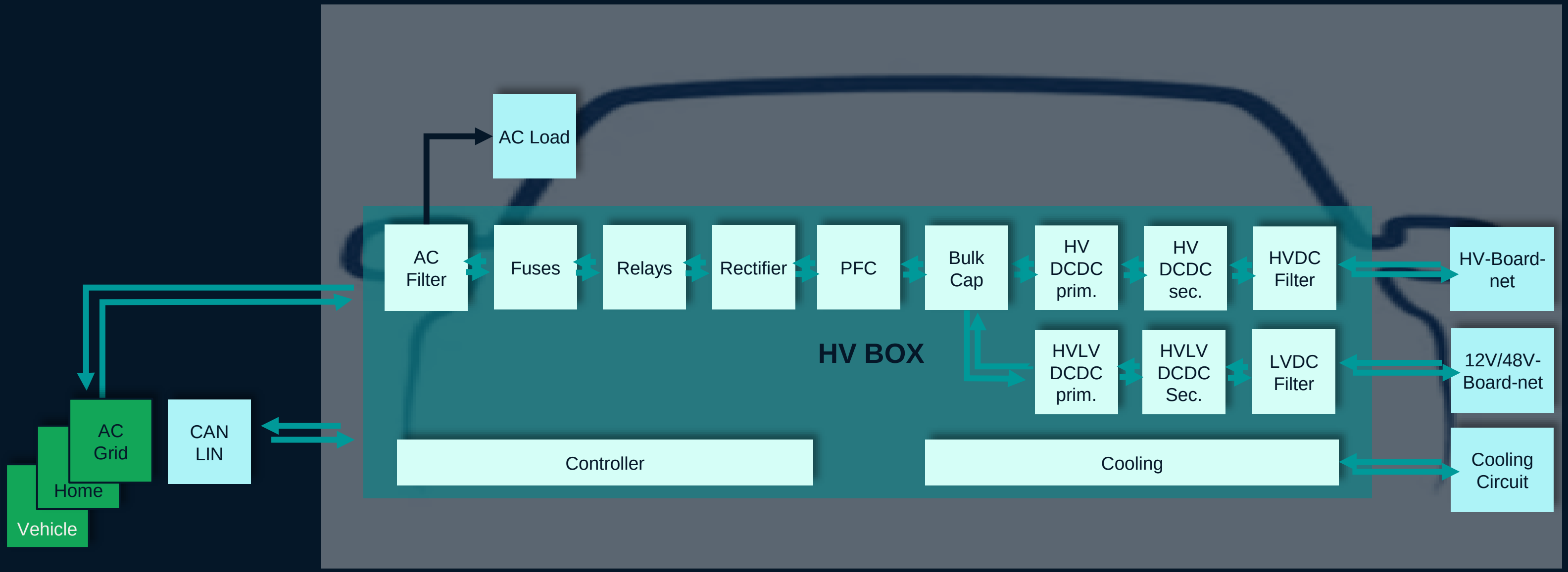
- Multiple 800V programs with multiple major global OEM’s
- Highly reliable compact design

**BorgWarner Power Electronics made of mature and full range of building blocks**

# HV-Box
## (OBC + DC/DC)

# HV-Box Product Definition (Onboard Charger & DC/DC)

- OBC, Power Conversion of AC to DC for Onboard Charging of Vehicle Battery Pack (400V/800V)
- DC/DC, Power Conversion of HV-LV DCDC for Auxillary Vehilce Power (12V or 48V vehicle power)
- V2X, Power Conversion of DC to AC for Inverter Mode (V2X: Vehicle-to-Load, Vehicle-to-Vehicle, Vehicle-to-Grid)



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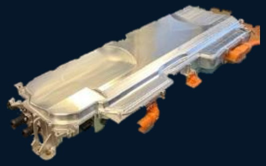
# HV-Box Product Evolution



<u>2015</u>
OBC 400V, 3,5kW
production

PHEV ACDC OBC on Applications

DCDC Converter Series Applications
- PHEV Inverter with int. HVLV DCDC
- HVLV DCDC stand alone solutions

Learnings/Transfer from PE Applications
- Top Side Cooled SiC Modules
- 800V Technology
- Precharge Functionality
- Digital Control Architecture
- Supply Base
- Validation concepts and infrastructure

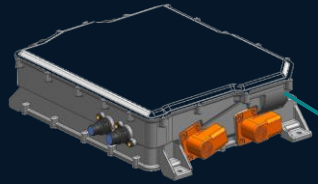
IMD & RCM

E-Fuse

2020

Cold plate mounted
solution
(no internal cooler)

IMD & RCM
HV Safety

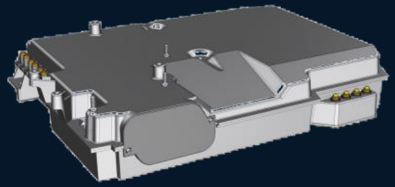


OBC 800V, 19,2/22kW
Development sample

2021

Center of Competence OBC/HV-Box
- Dedicated team in Kokomo and Lux
- Platform Development
- V2H, V2G, V2L
- global Grids

2022



<u>2023</u>
HV-Box 800V, BD, 11&22 kW
3 customer A-phase programs
Development samples



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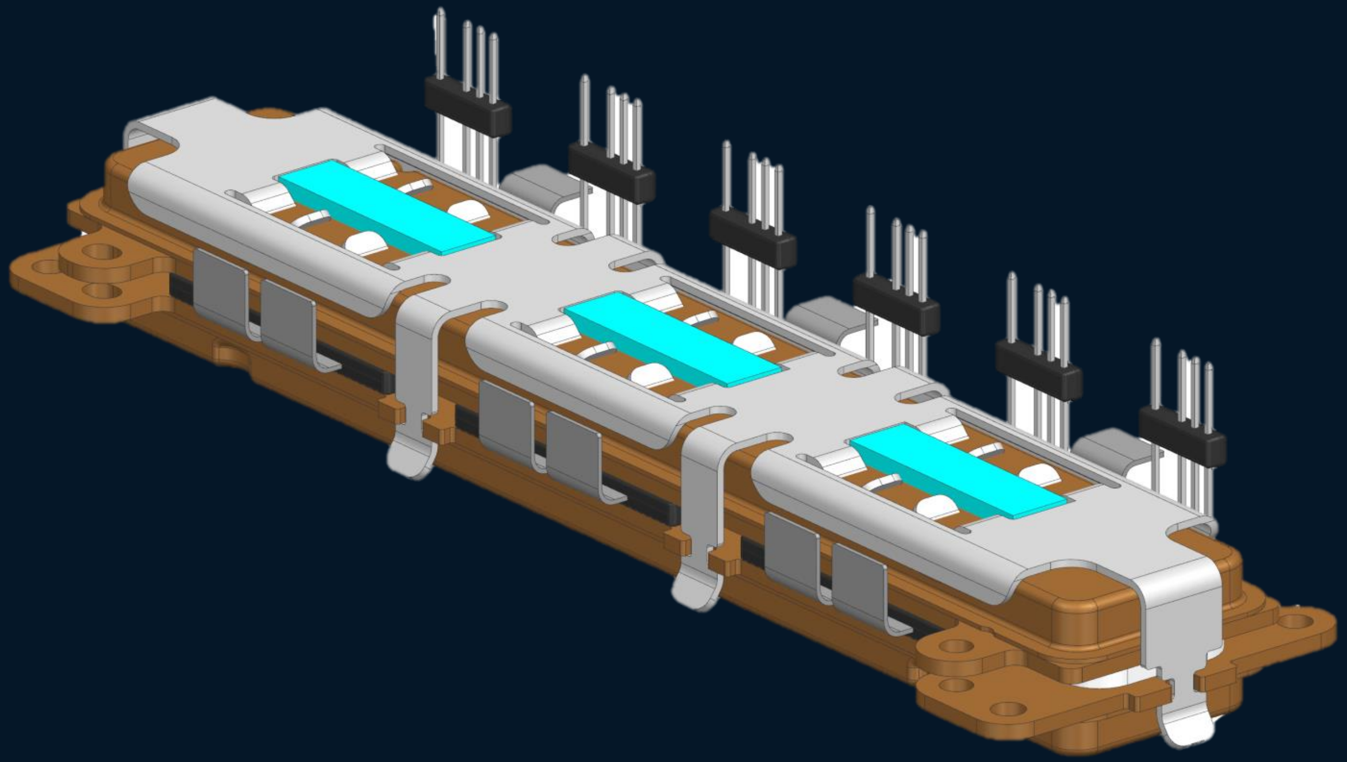
# Power Module

# Power Module Overview

- Power dense design
- Unique Double side cooled
- Cu or AL heatsinks
- Scalable & “future proof”
  - SiC and Si support
- Highest A/mm2
- Market leading Amp/$



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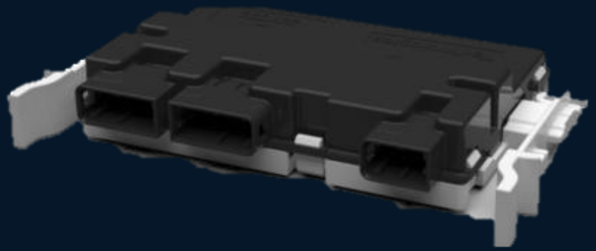
# BMS

# Battery Controller Systems

- Battery Management System Controller for electric vehicle (EV) applications.
- Common Features
  - High Speed Microprocessor
  - Internal and external Watchdogs
  - Measures End to End Pack Voltage
  - Current sensor interfaces for measuring HV current
  - High-Voltage isolation detection
  - HV Interlock Loop monitoring/control
  - Synchronization with Cell monitoring controller
  - Contactor Controls
  - Pack Temperature
  - Pump control



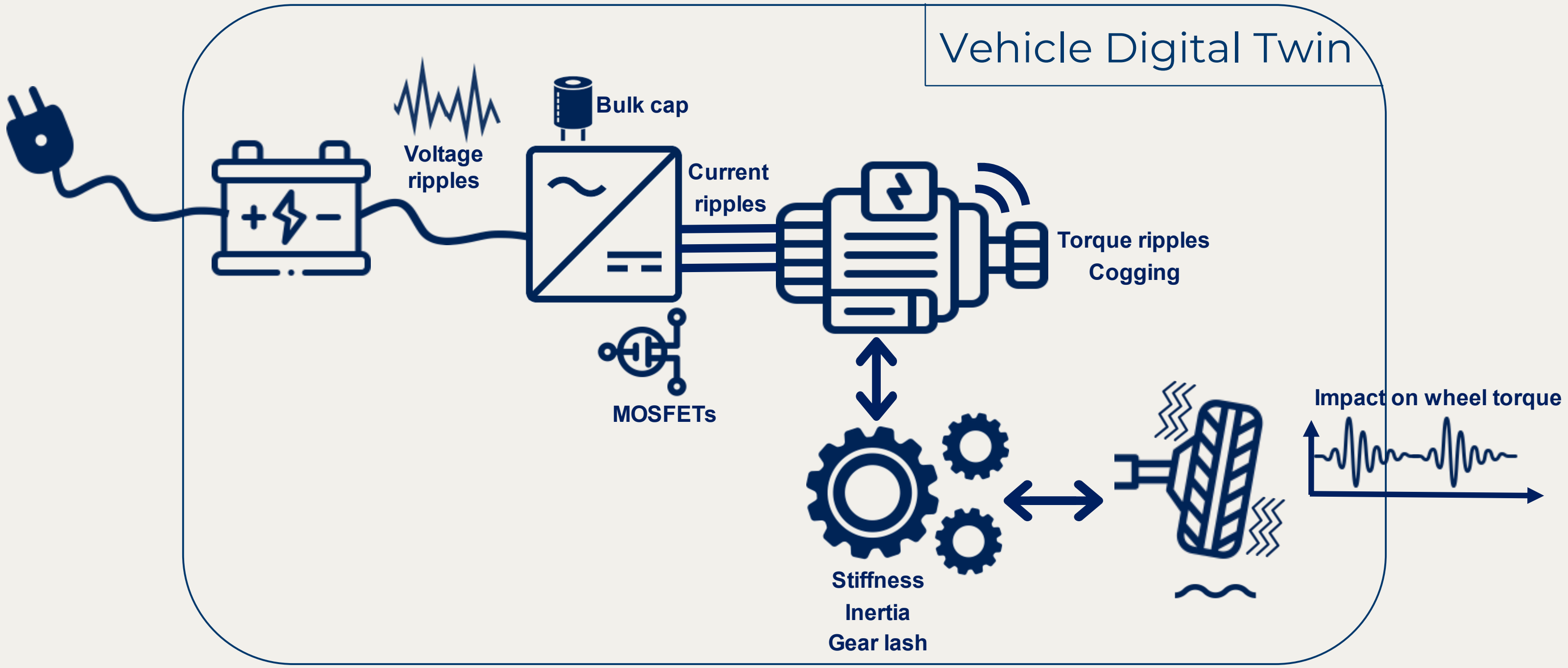
Communication Interfaces
- CAN-FD
- CAN-PN
- LIN
- FlexRay

Mechanical
- IP 40D
- Outline: 200 X 150 X 35mm

# Digital Twin

# Digital Twin

- A multiphysics vehicle model
- Embedded in a single software framework using Amesim
- Composed with sub-models / sub-DT developed and verified individually
- Compatible with different modeling level of details
- Able to assess technology impacts on different physics at vehicle level



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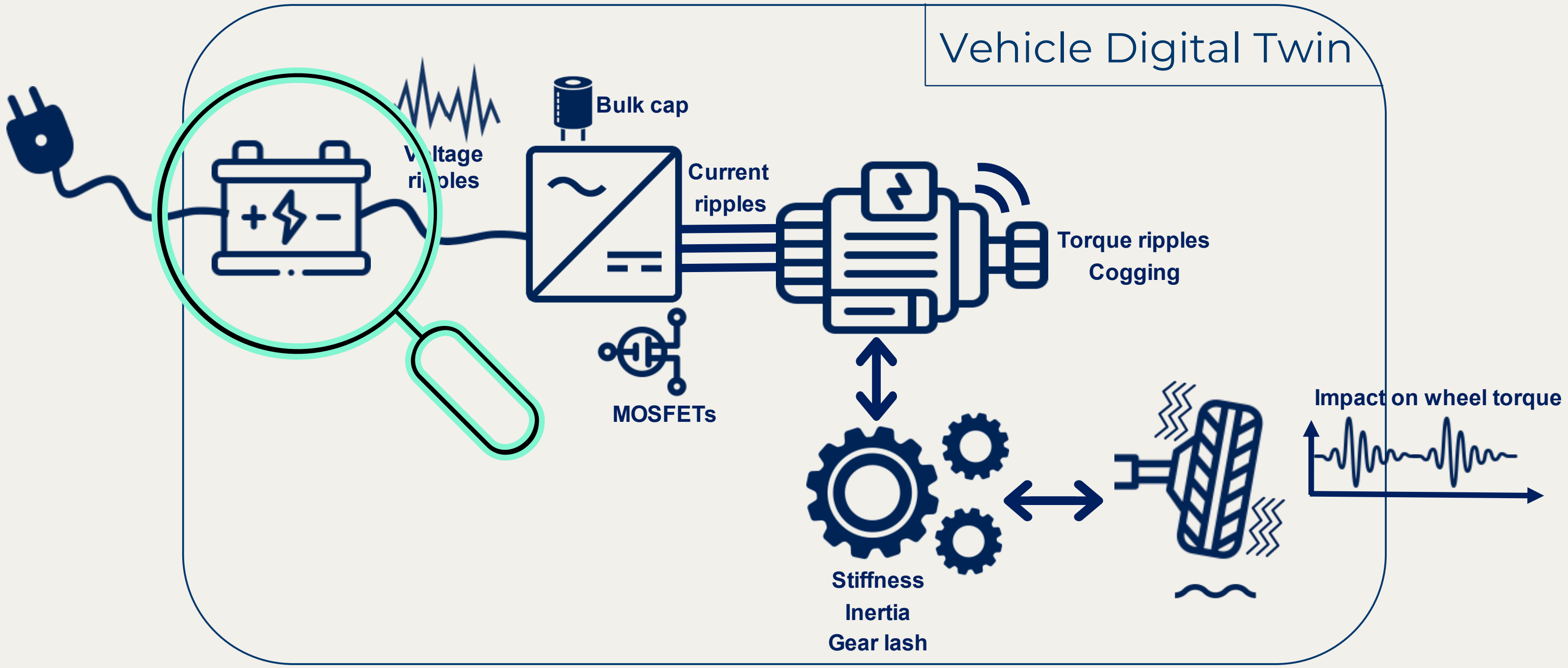

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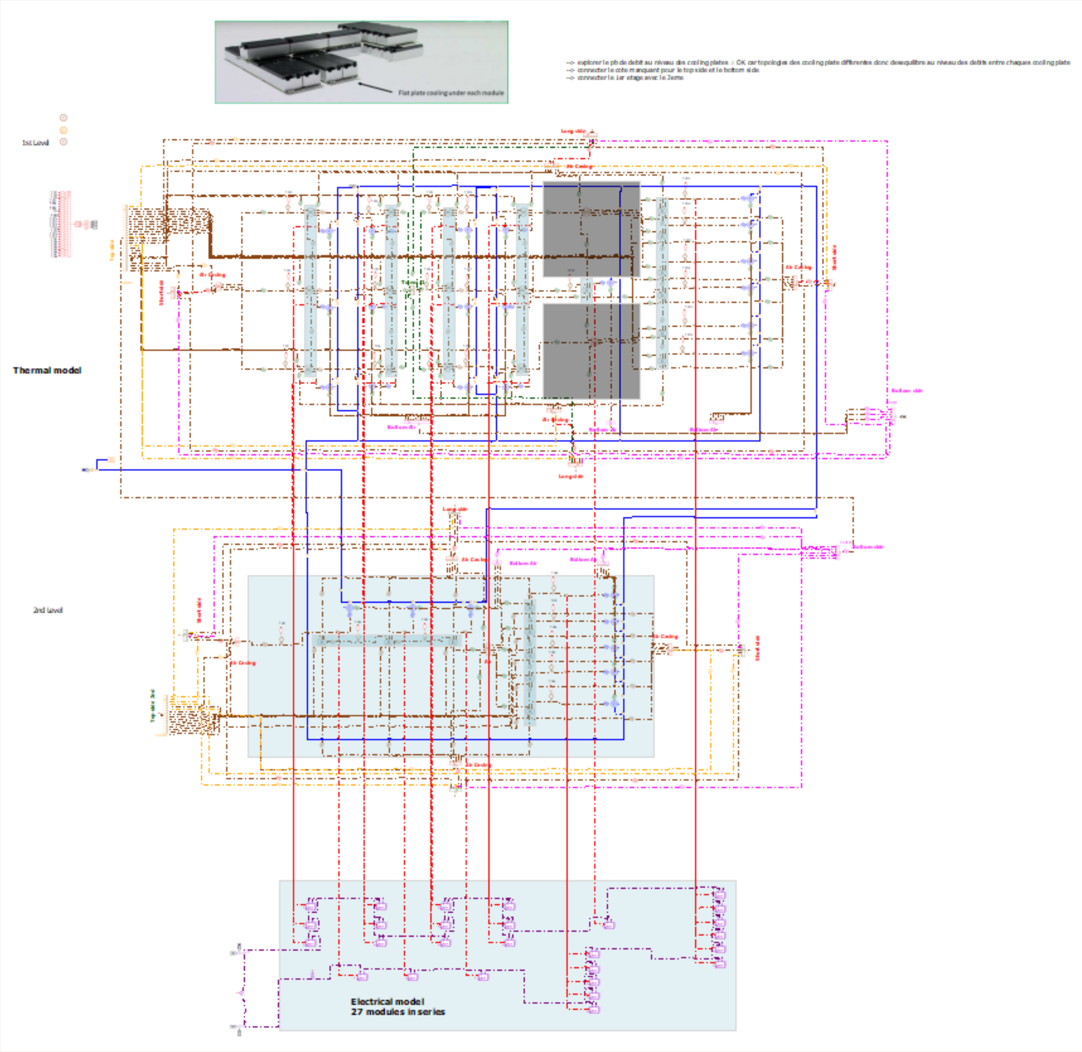
Battery pack model



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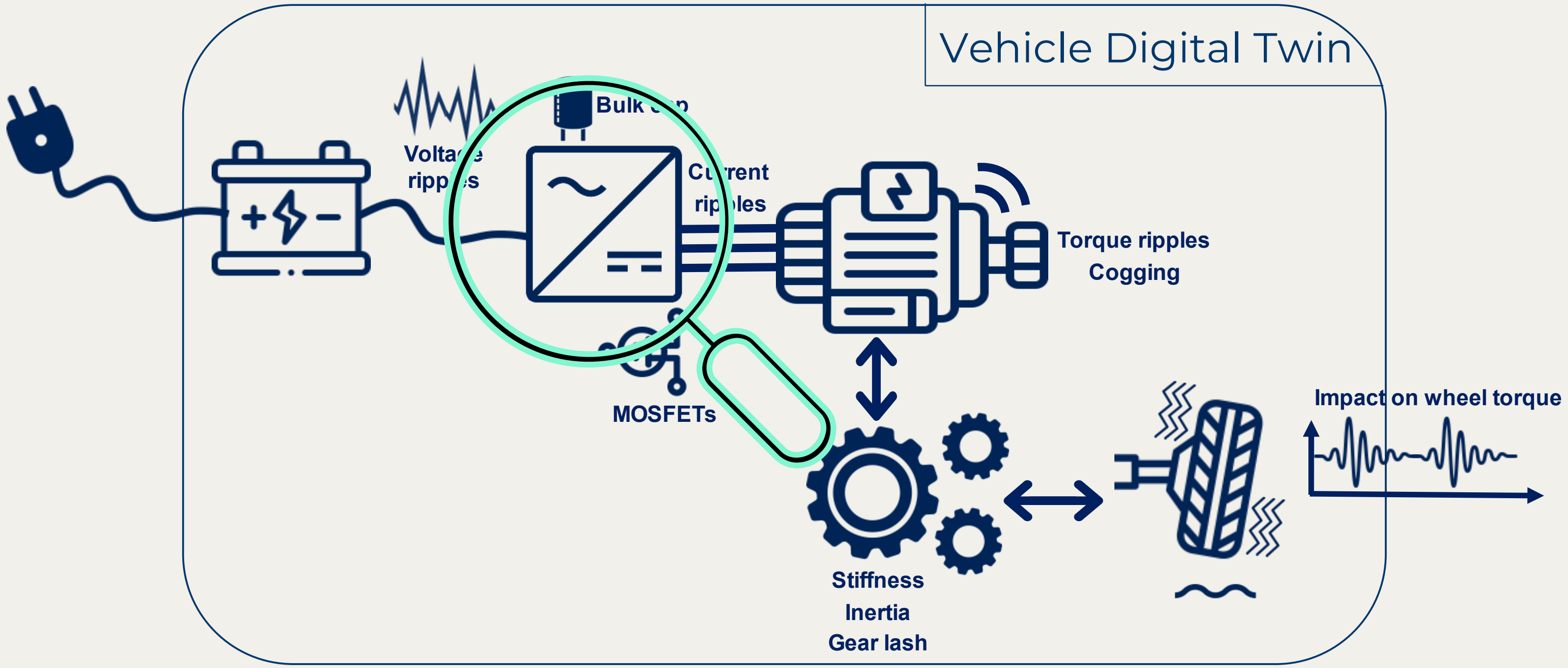




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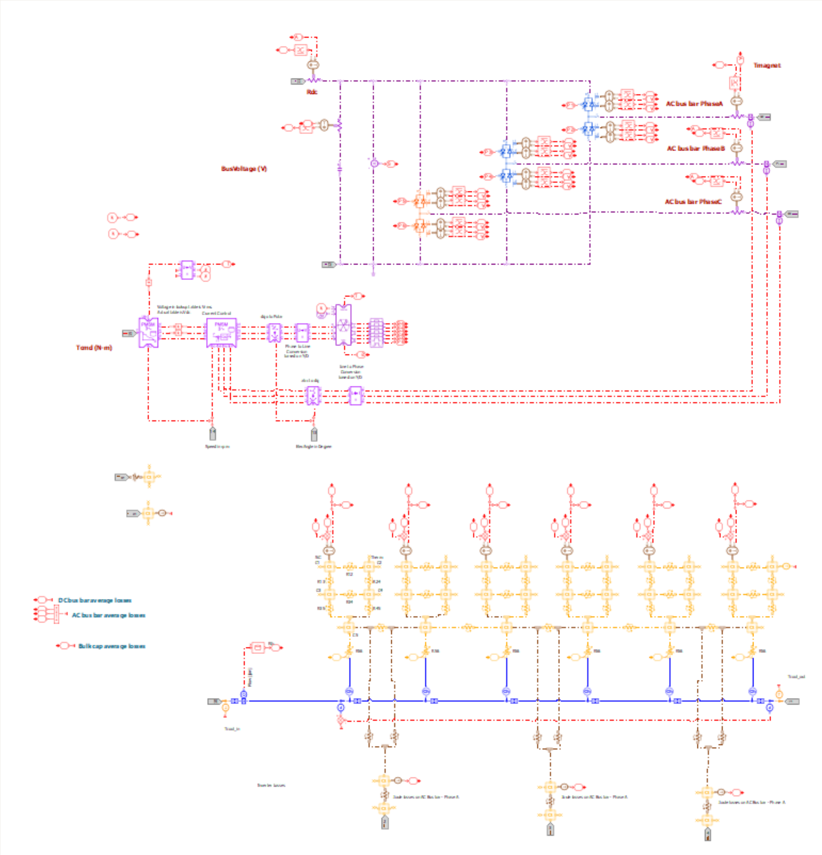
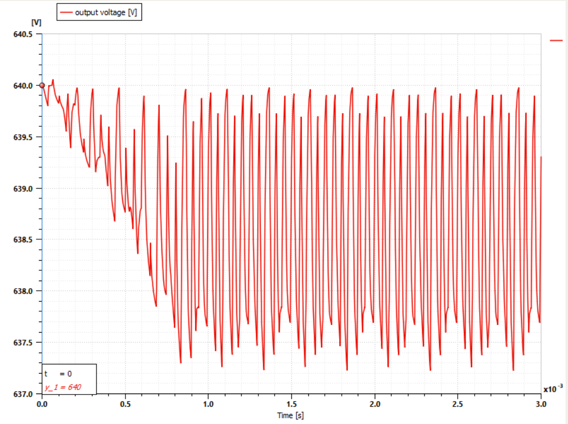
Inverter model



Bulk cap current ripples



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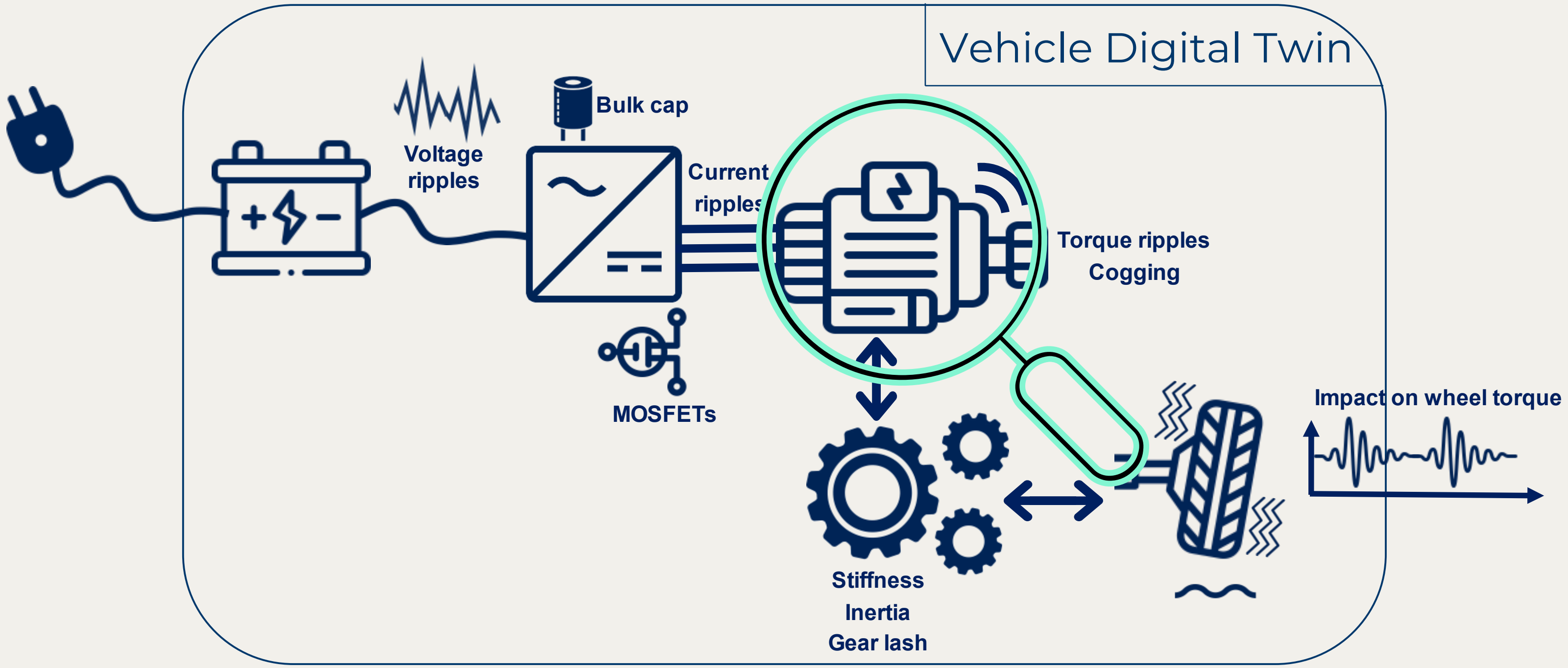




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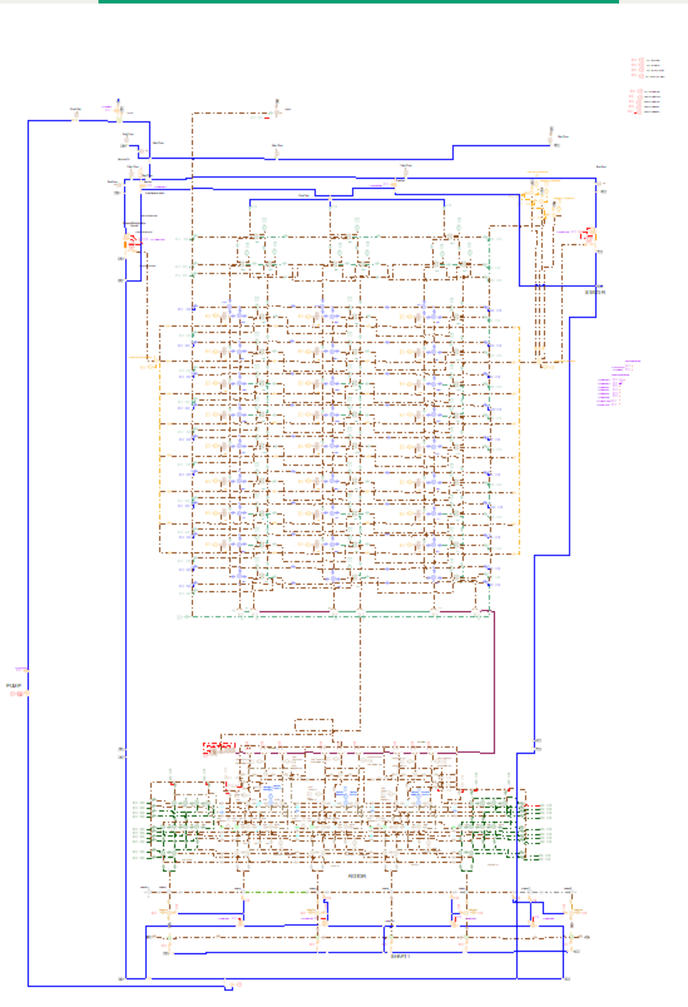
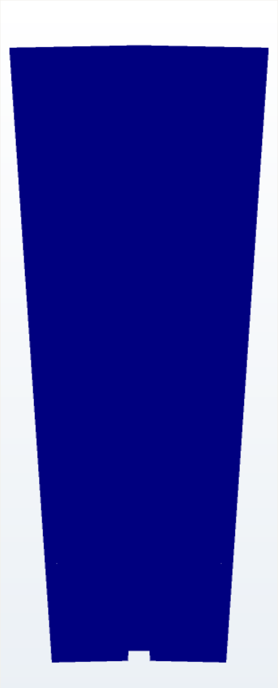
EMotor model





stator thermal simulation

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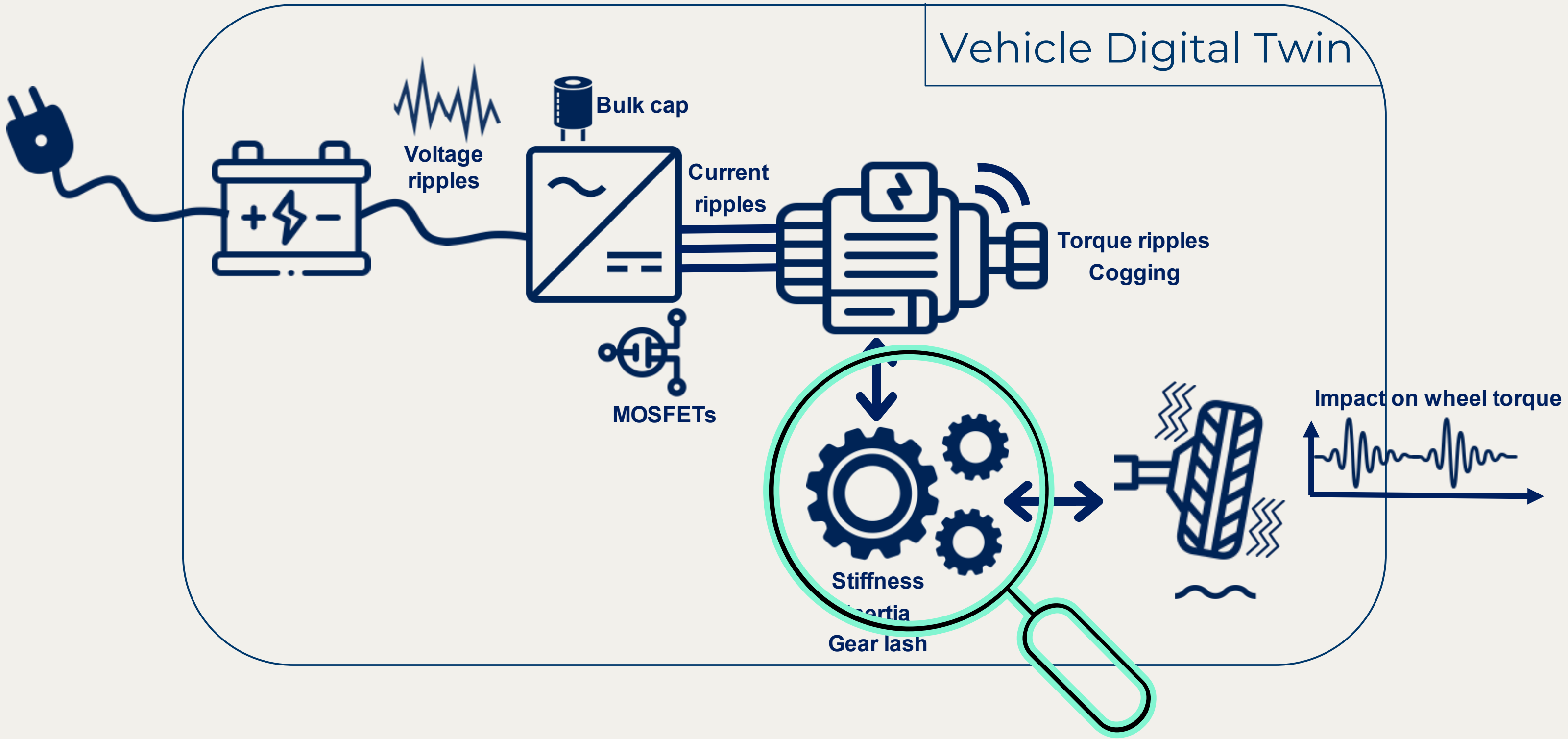




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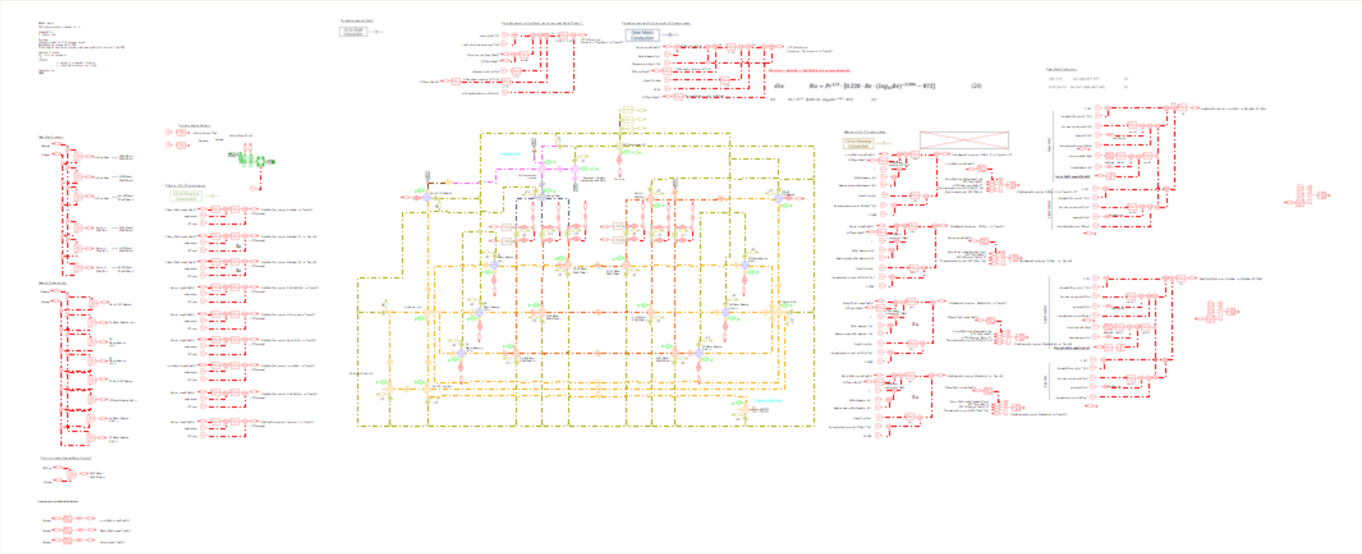
Transmission model



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# Advanced EESM iDM

# EESM's compared to PMSM

### EESM Strengths

- No rare earth
- High efficiency at high speed and low loads
- Low material cost
- High power factor
- Low $CO_2$ production in materials & manufacturing

### BorgWarner Approach:

- Enhanced stator and rotor cooling
- Brushless resonant inductive excitation system
- Compatibility with compact gearboxes

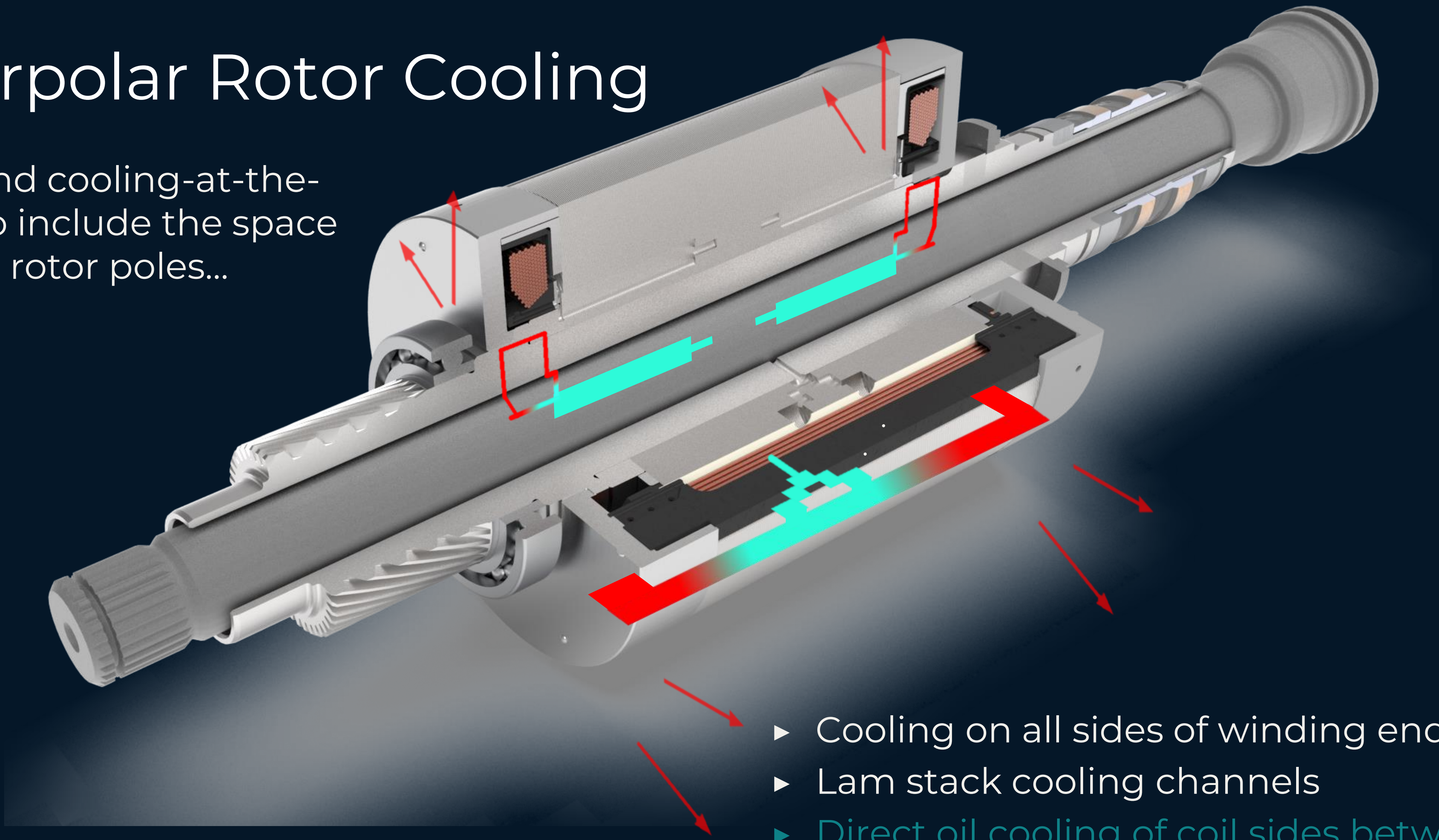
### EESM Challenges

- Rotor excitation needed
- Drive cycle efficiency
- Power density
- Continuous power
- Compatibility with concentric layshaft & coaxial gearboxes

EESM = Externally-Excited Synchronous Machine
PMSM = Permanent Magnet Synchronous Machine

# Interpolar Rotor Cooling

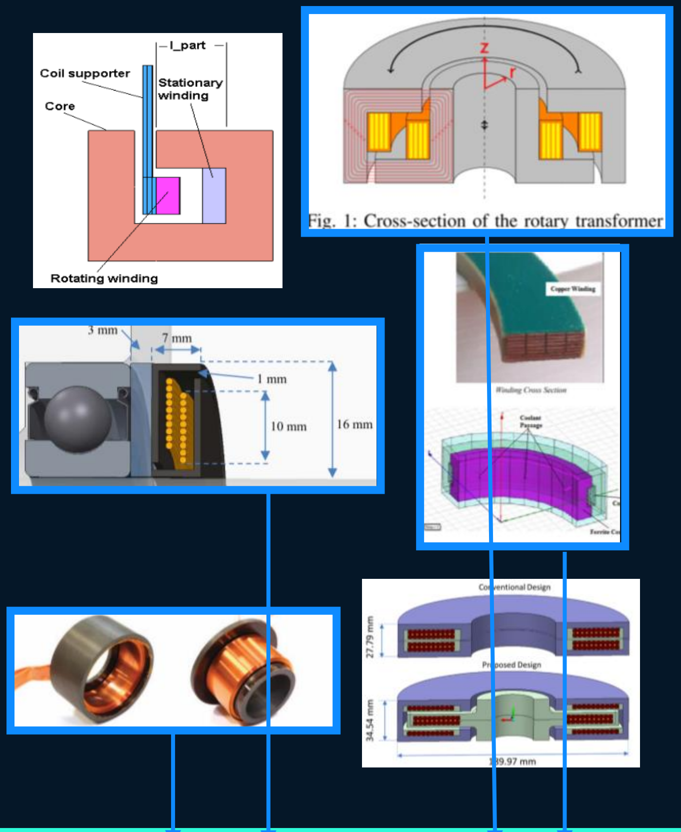
We extend cooling-at-the-source to include the space between rotor poles...



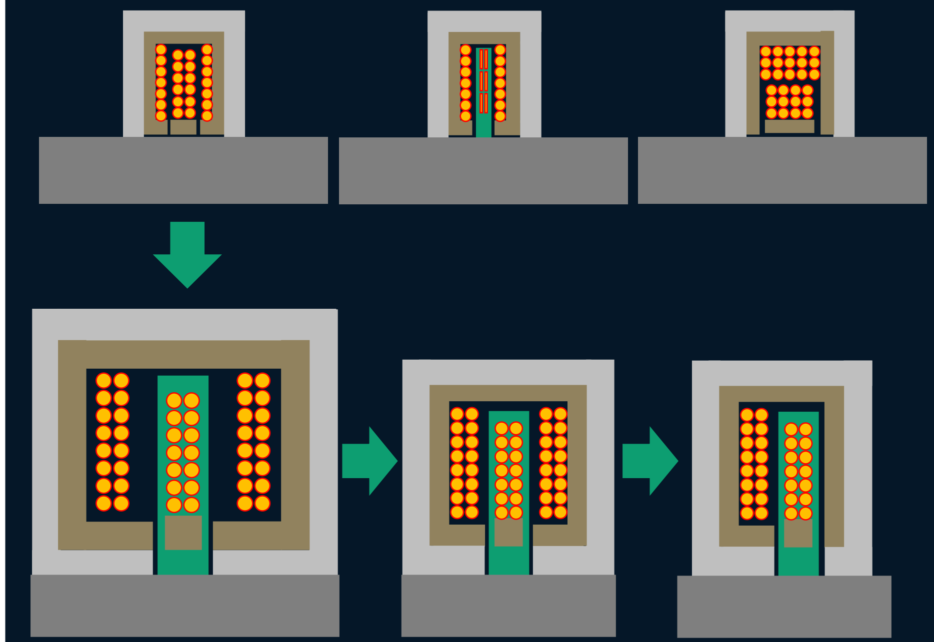
- Cooling on all sides of winding end turns
- Lam stack cooling channels
- Direct oil cooling of coil sides between poles

# Rotary Transformer: Concept Selection

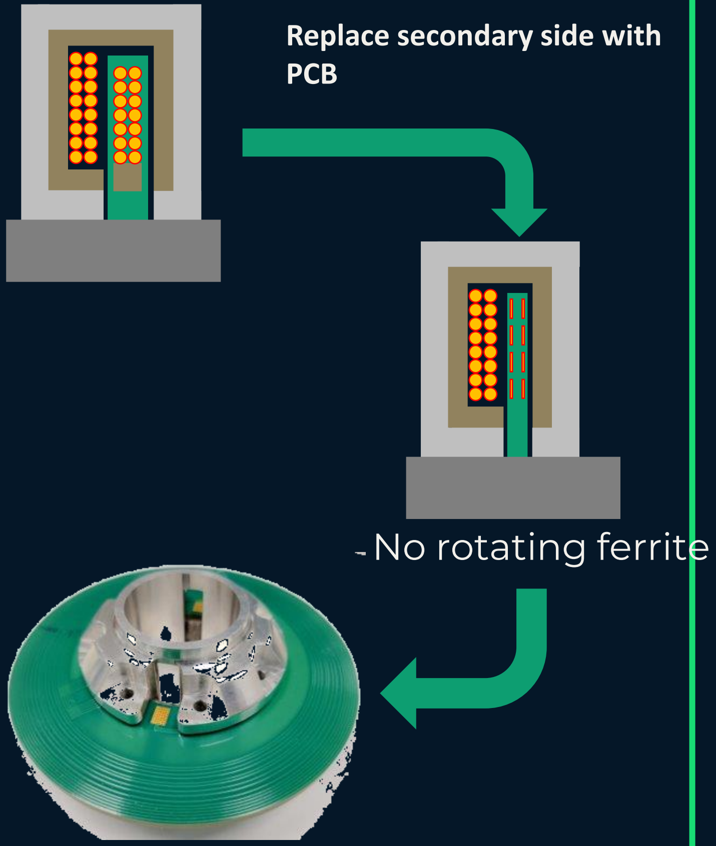
## Literature review & preliminary down selection




## Concept selection and refinement

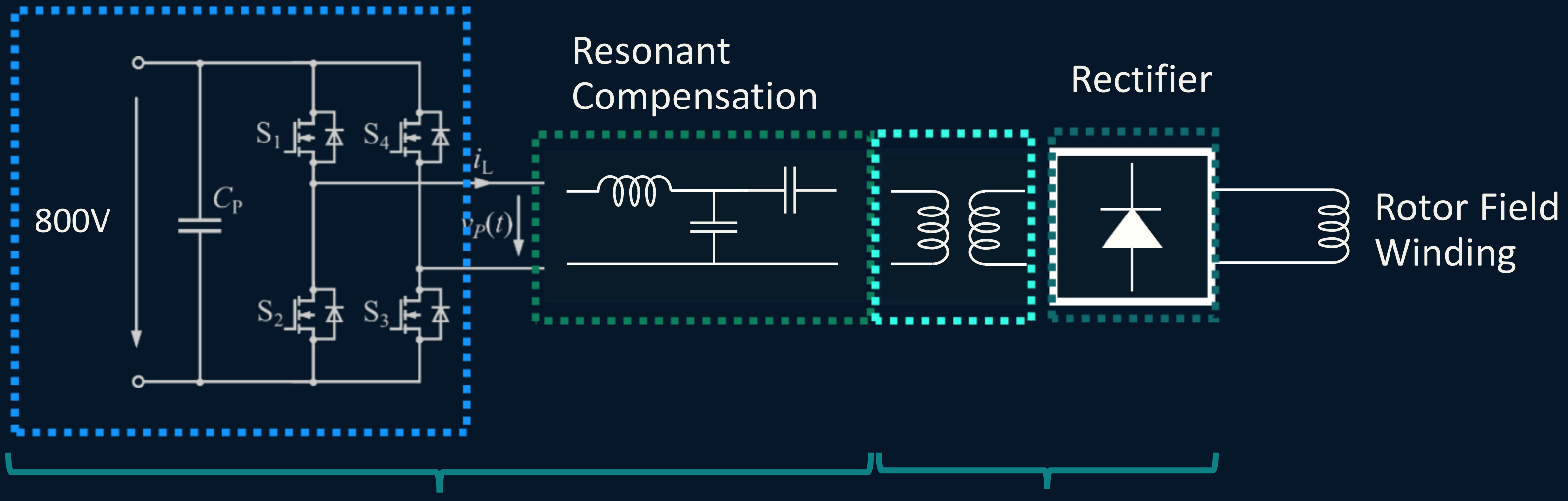


## Final concept development




High shaft diameter needed for concentric iDM applications limit the use of designs with rotating ferrites that are not fully supported.

# BorgWarner Brushless Module




1φ SiC Inverter

800V capable

Rotary Transformer and Rectifier

BorgWarner HVH220 EESM

# Brushless Excitation System – Key Innovations

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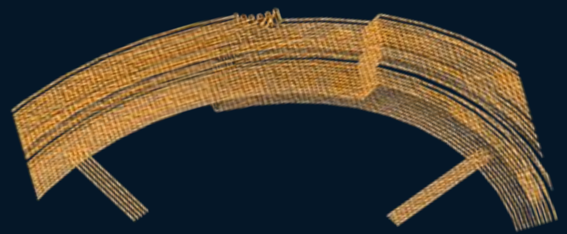
- Leader in R&D for automotive eMotors and power electronics.
- System, application and manufacturing know-how.

OAK RIDGE National Laboratory

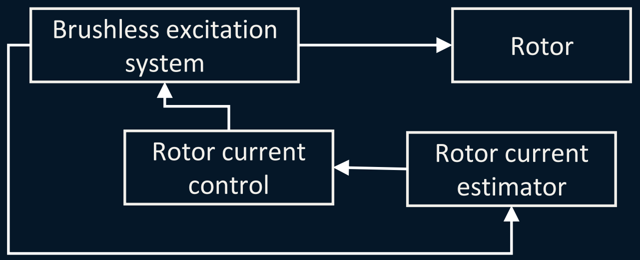
- Leading institution on power electronics research.
- Ample experience in wireless power transfer.

Patented single PCB construction on receiver side

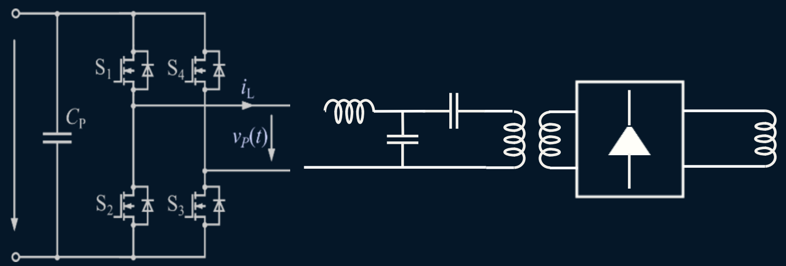
Patented PCB-trace layout for minimizing AC losses



Patented optimized controls without need for rotor current sensor

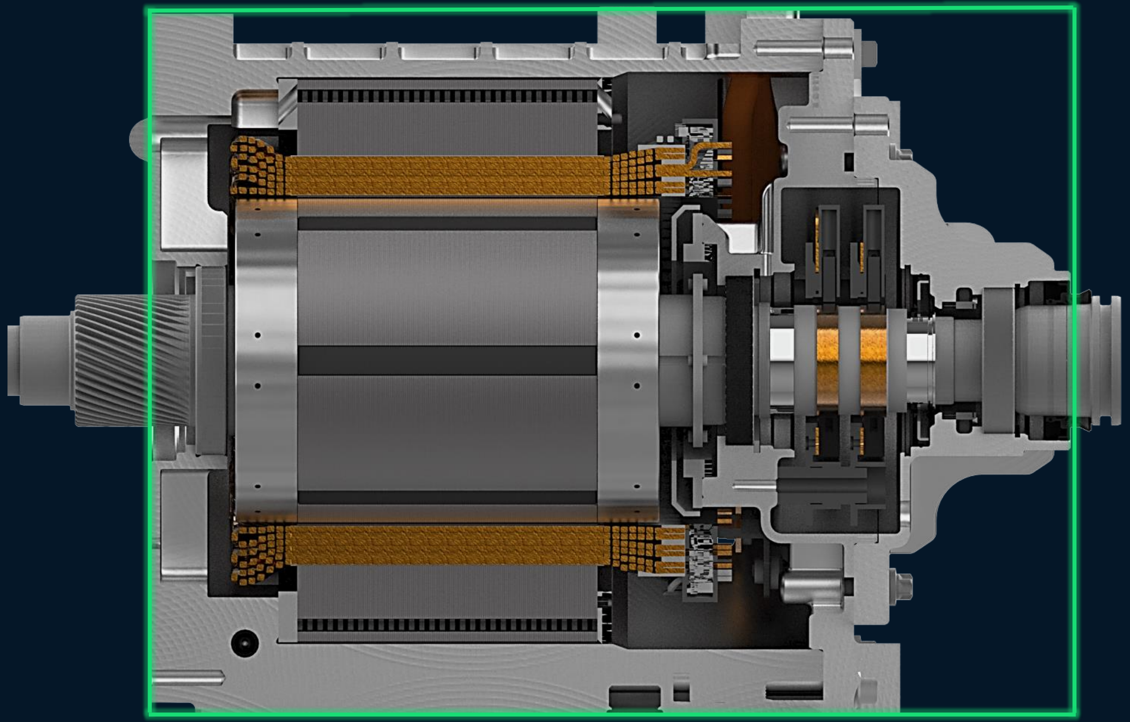



Resonant converter with patented tuning network locating all components on non-rotating side



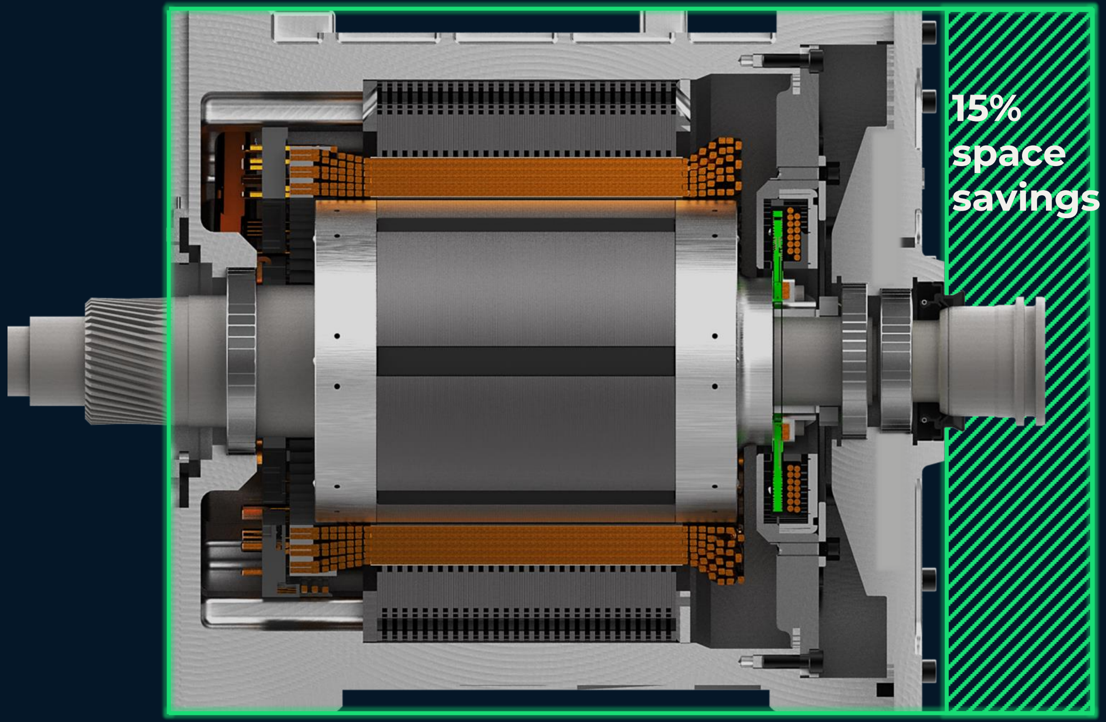
# Reducing EESM Size

## Gen1 Brush EESM



- Brushes & slip rings must be sealed off from oil spray

## Gen2 Brushless EESM




- Rotary transformer and rectifier take up less space than brushes
- Can be located in oil spray area, reducing overall eMotor size
- Reduces drag loss due to shaft seals



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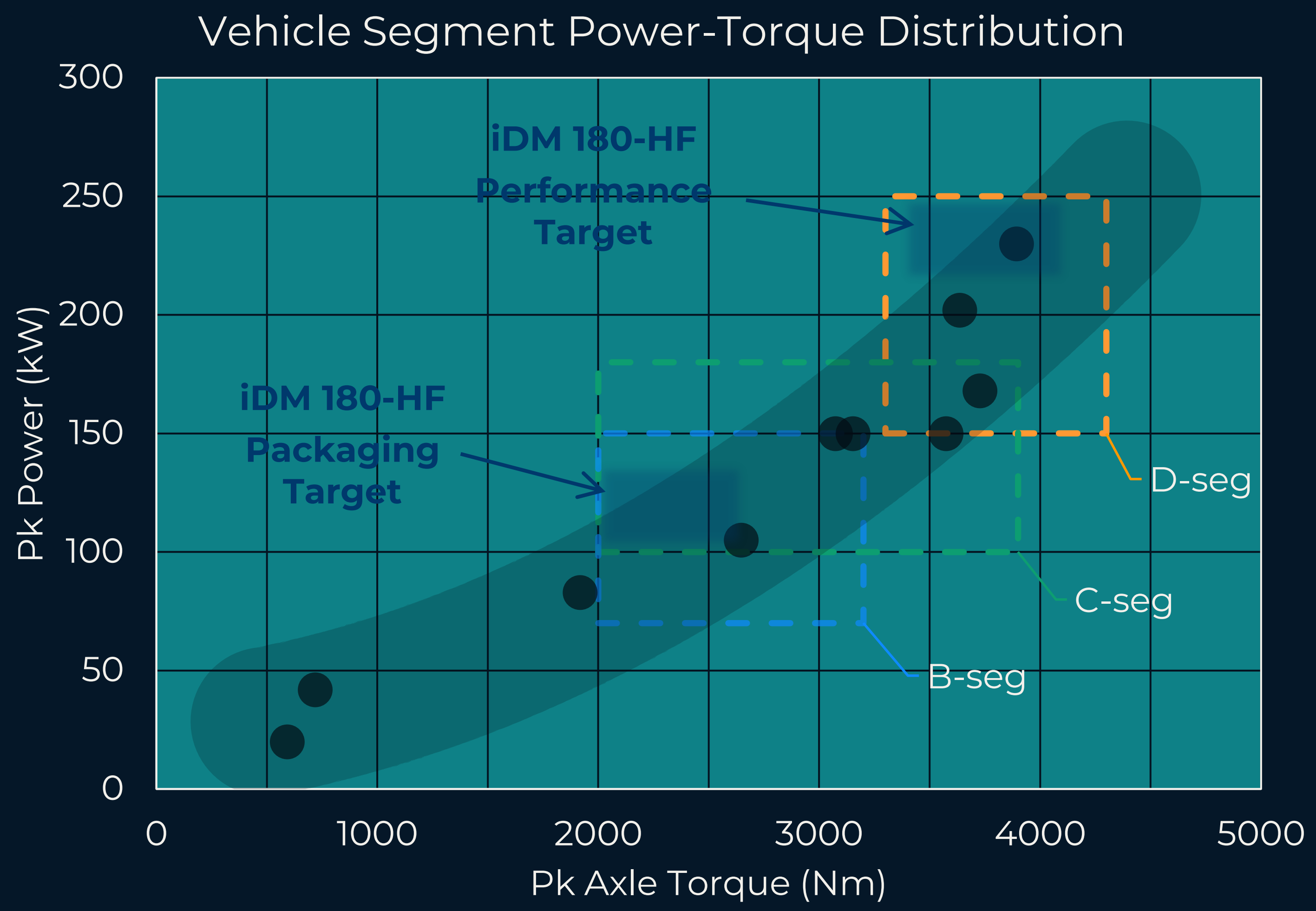
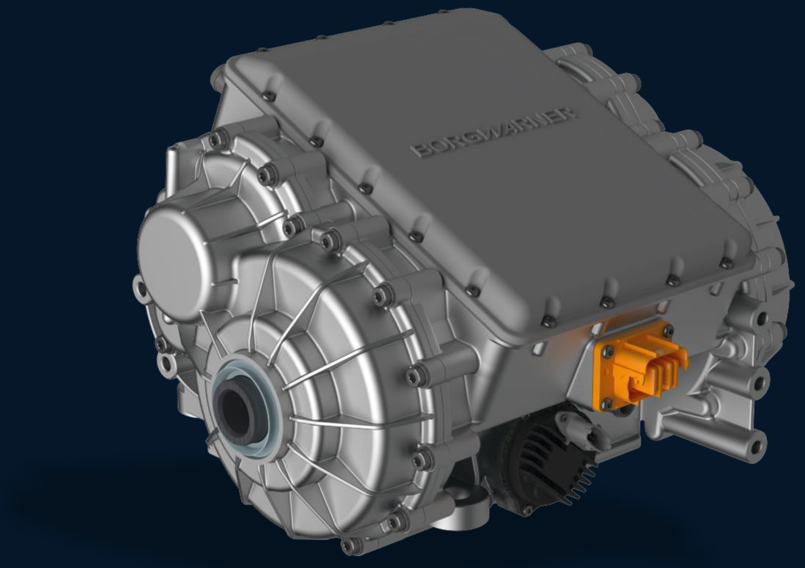
# Advanced HFHE iDM

# System Target



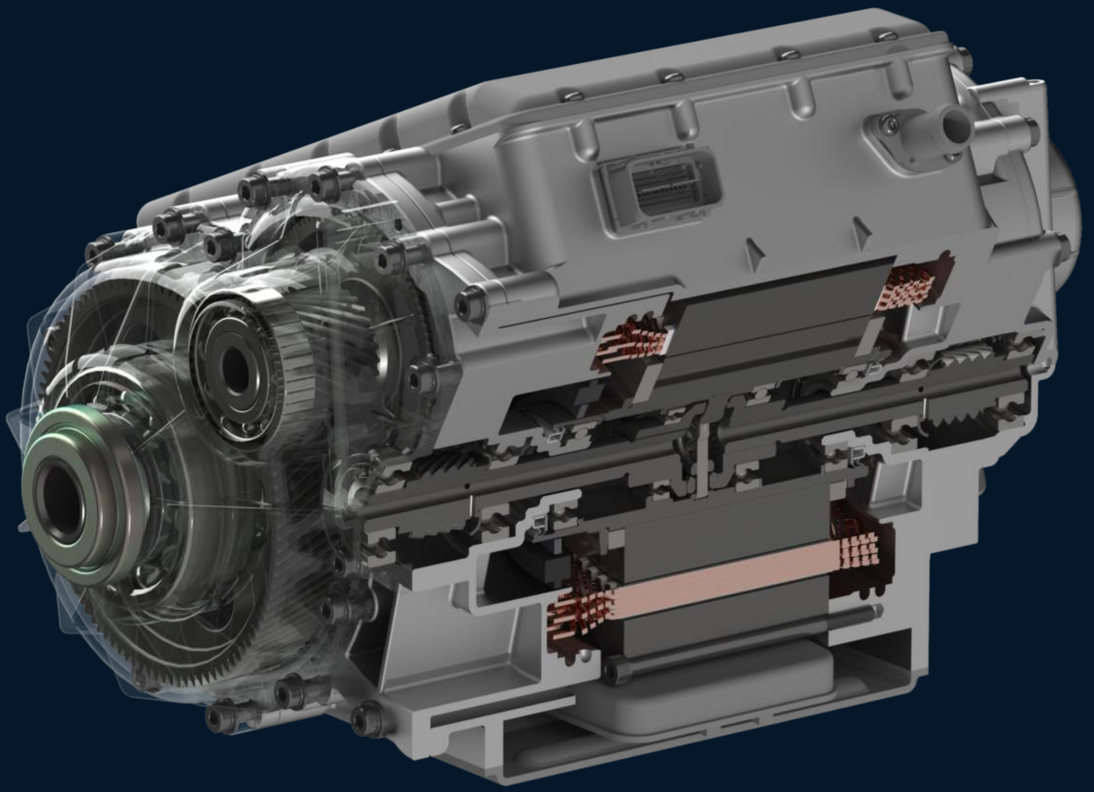



- D-segment vehicle performance
- B-segment packaging size

# iDM180-HF (250kW variant)

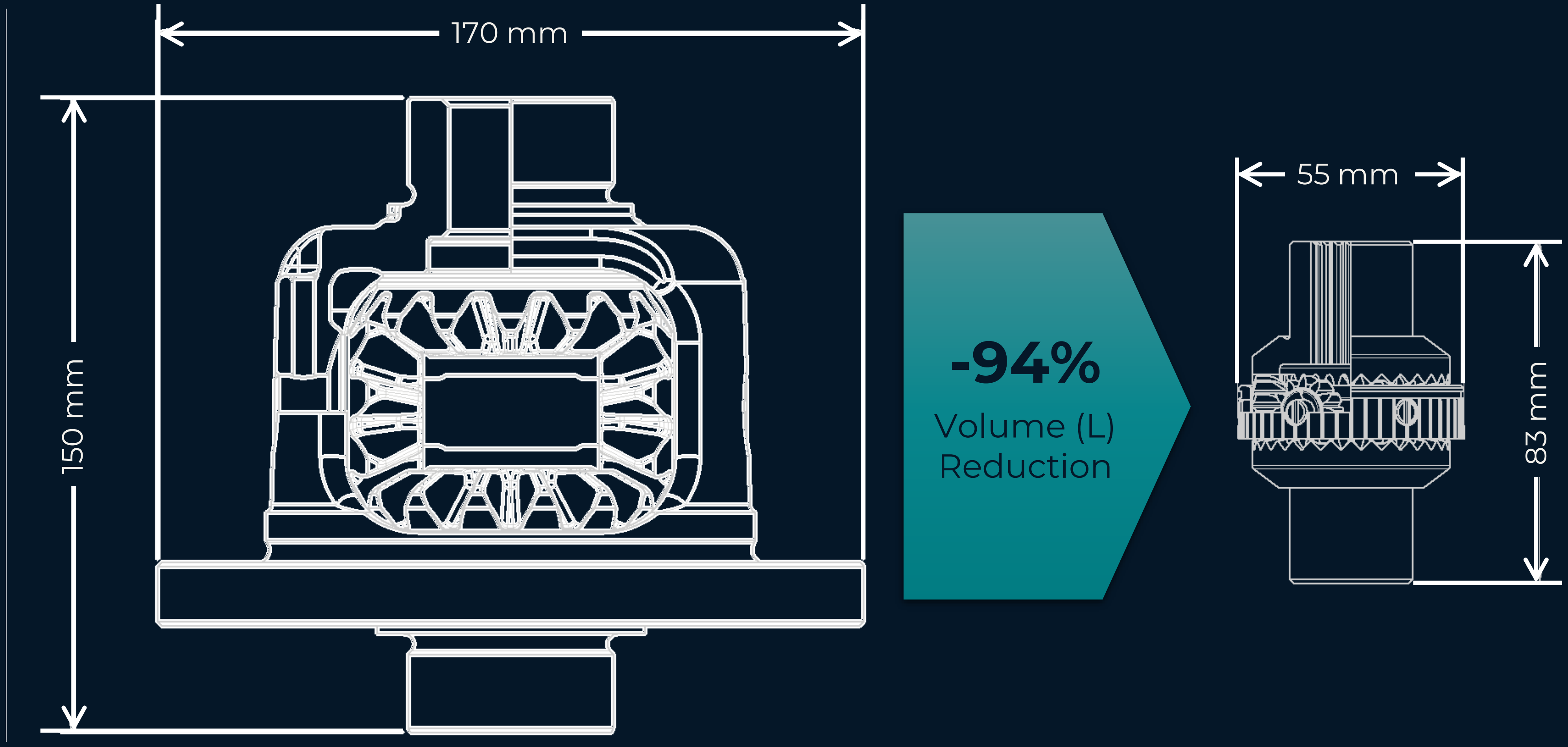
**Fully integrated inverter**
- 800V SiC high current density
- Low stray inductance
- Planer component placement
- Compact assembly (< 4kg)

**Dual Gearbox + Integrated Diff**
- Gear ratio: > 13.0
- Integrated Differential
- High speed bearings
- Volume reduction by > 10%



**High Speed eMachine**
- Pk Torque: > 250Nm
- Max Speed: ~23,000rpm
- Current density: > 33 Arm/mm2
- 245kW @ 650 Vdc
- Submerged end coil cooling

# High Speed Differential



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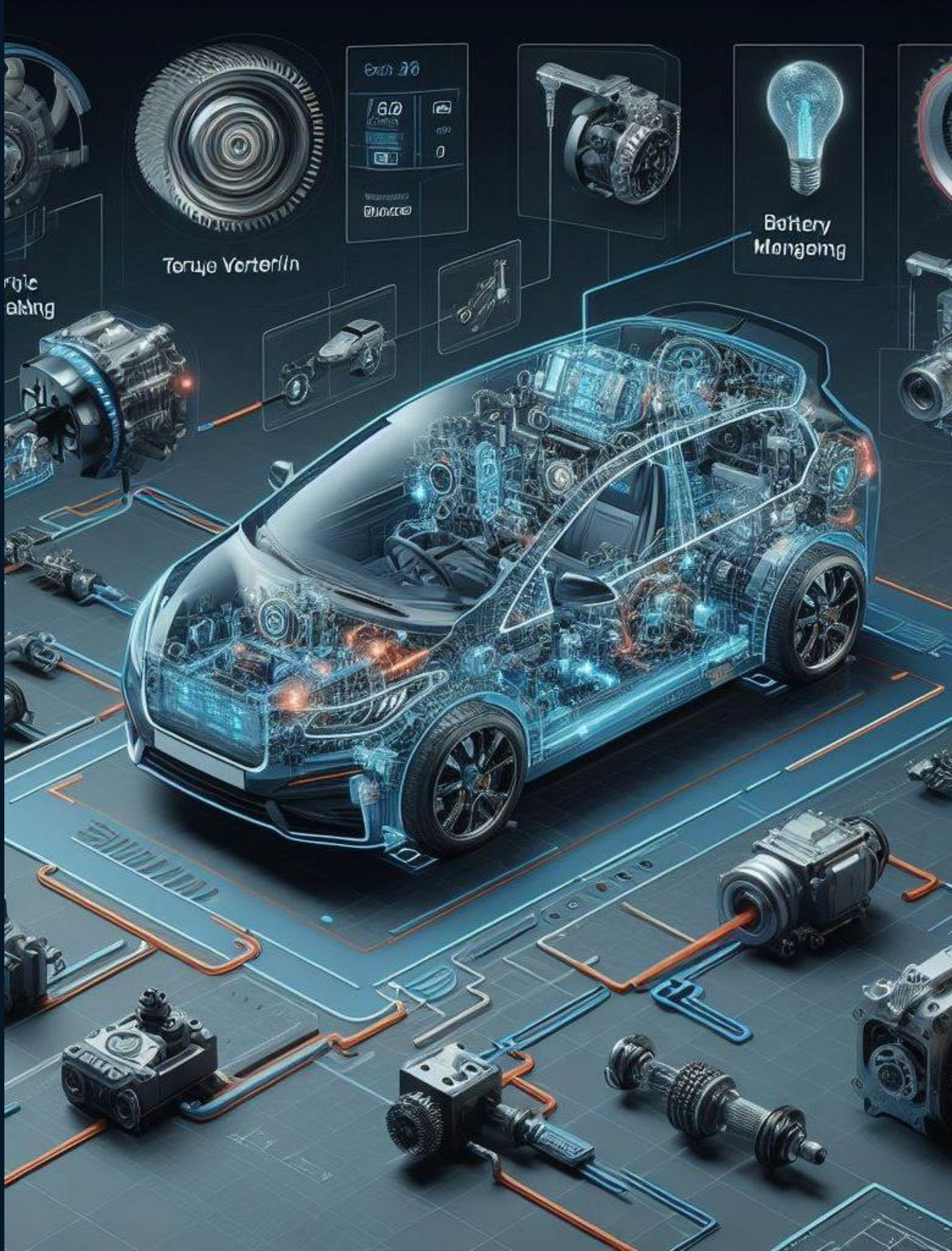
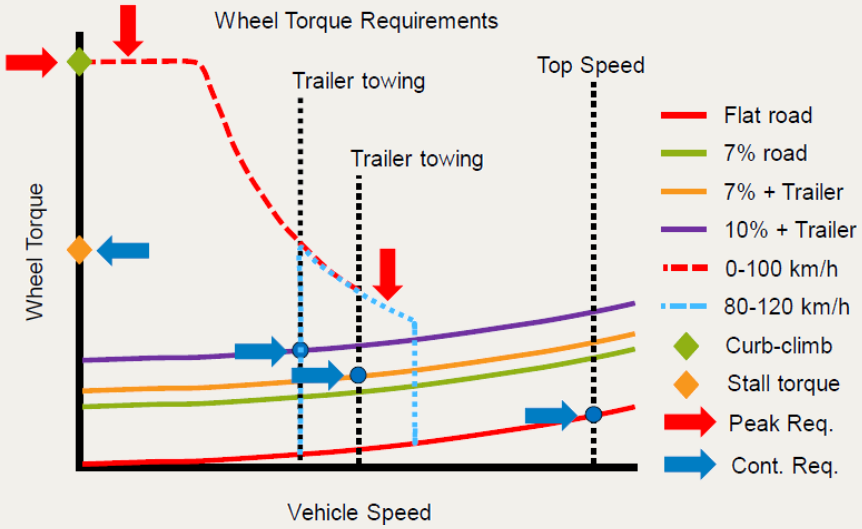
# Advanced Developments:
# Electric Powertrains

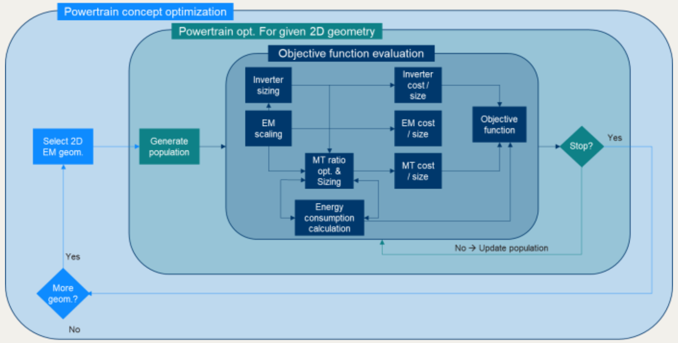


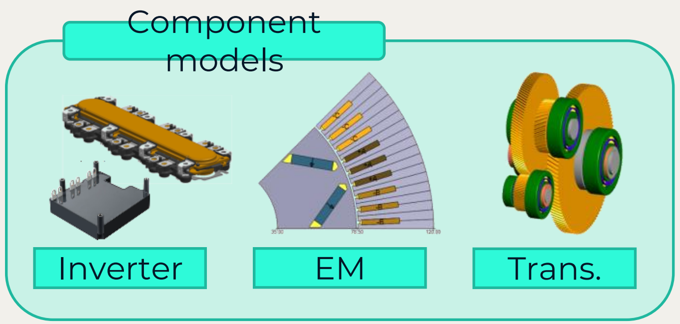
# Main objective: translate wheel requirements into preliminary powertrain designs

## Vehicle level requirements

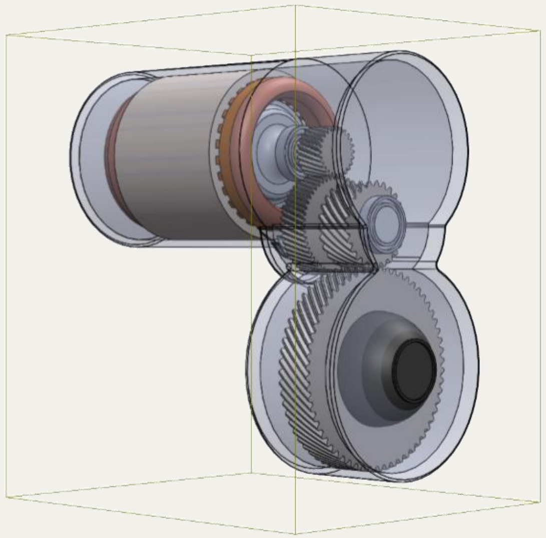



## System optimization




## Preliminary design





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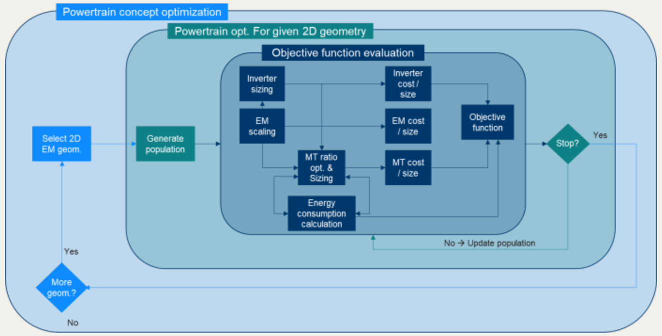
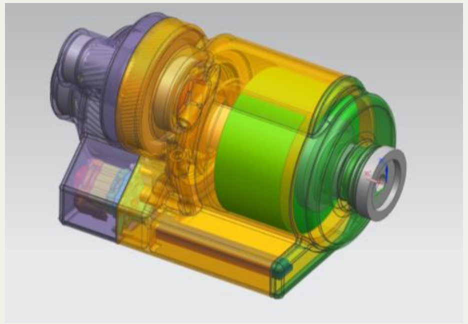
# Electric powertrain development workflow

## Concept optimization

Initial specifications and requirements

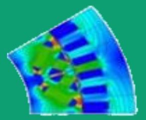



Preliminary design – key attributes defined



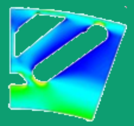
## Detailed analysis and component optimization and refinement

**EM Multi-objective GA optimization**

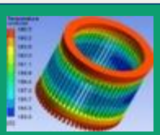


Magnetic

Weight



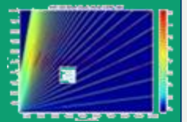
Structural



Thermal

Size

NVH



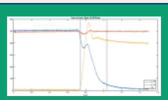
BOM

Inertia

**PEC Design and Opt.**

Circuit simulations:
Currents - Voltages - Losses

Thermal simulations:
Temperatures – Stresses - Expected lifetime



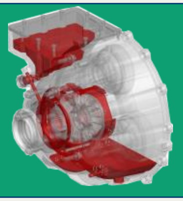
Component characterization :
Currents - Voltages - Losses

**Trans. Design and Opt.**

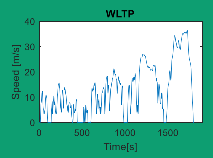
FEA Structural simulations:
Stresses – expected life

Fluid Dynamic simulations:
Lubrication and cooling

NVH simulations



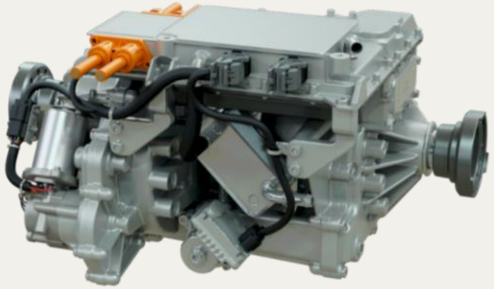
**System and Vehicle Simulations**




- Overall energy consumption
- Loss separation
- Vehicle performance
- System NVH
- System Thermal Management

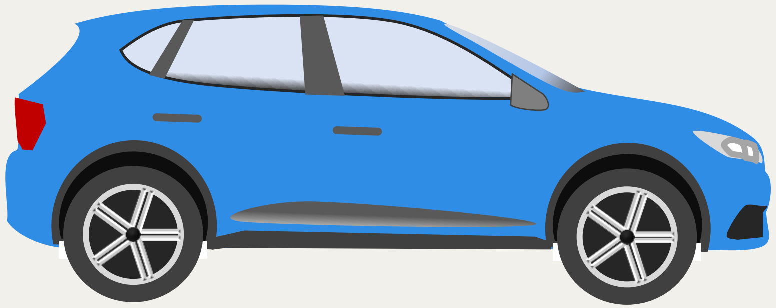
## Validation and verification

Prototype bench testing – model calibration

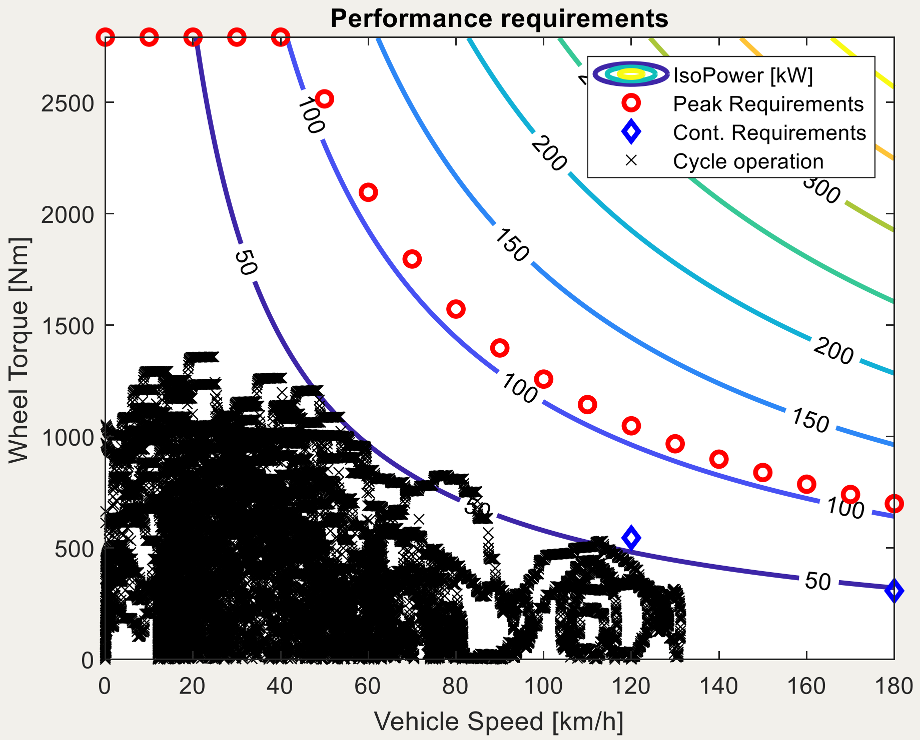


Vehicle level testing – control calibration

# Application example: C segment vehicle



| Parameter | Value |
|---|---|
| Vehicle mass | 2000 [kg] |
| Wheel radius | 0.32 [m] |
| Drag coef. | 0.23 [-] |
| Roll coef. | 0.009 [-] |
| Front. Area | 2.22 [m^2] |




- RWD vehicle
- Initial EM database consisting of ~1000 2D geom.
- Single V-IPMSM, Oil-cooling
- Single speed transmission
- Nominal Vdc – 800V
- Two optimization objectives:
  - EM cost
  - Energy consumption
- Overloading time 60s from 60 deg. C

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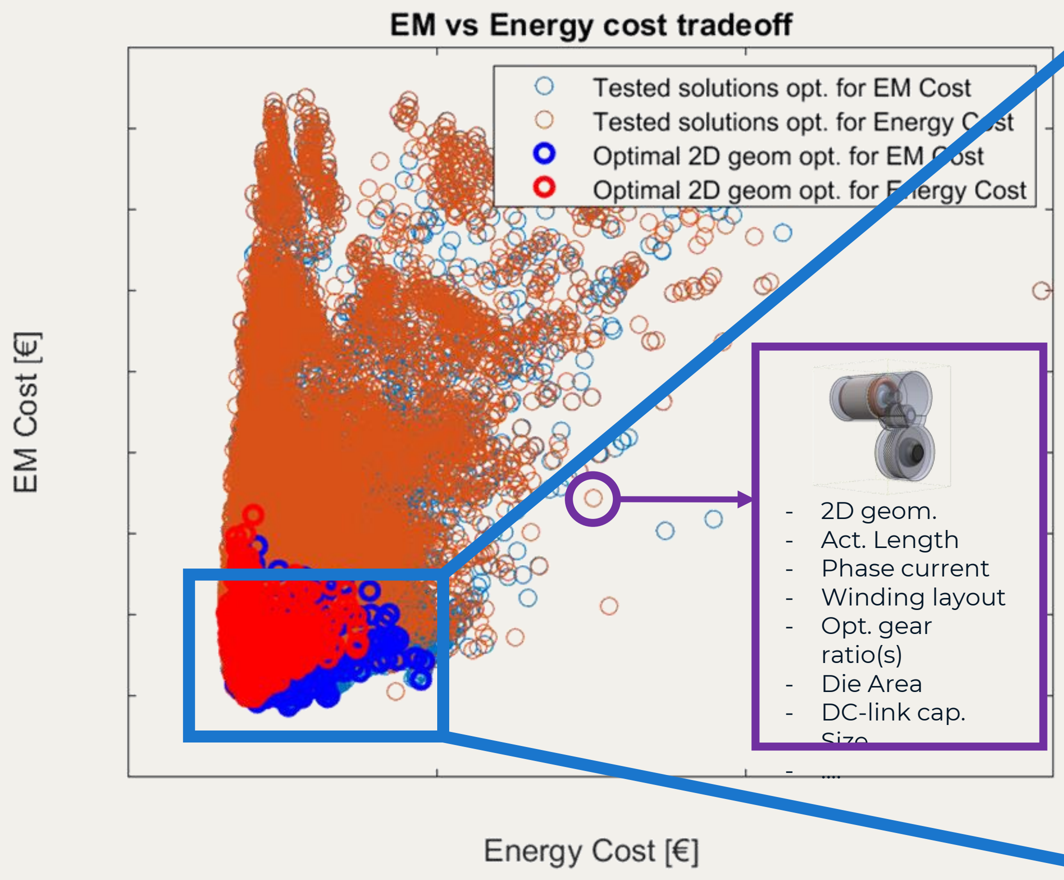
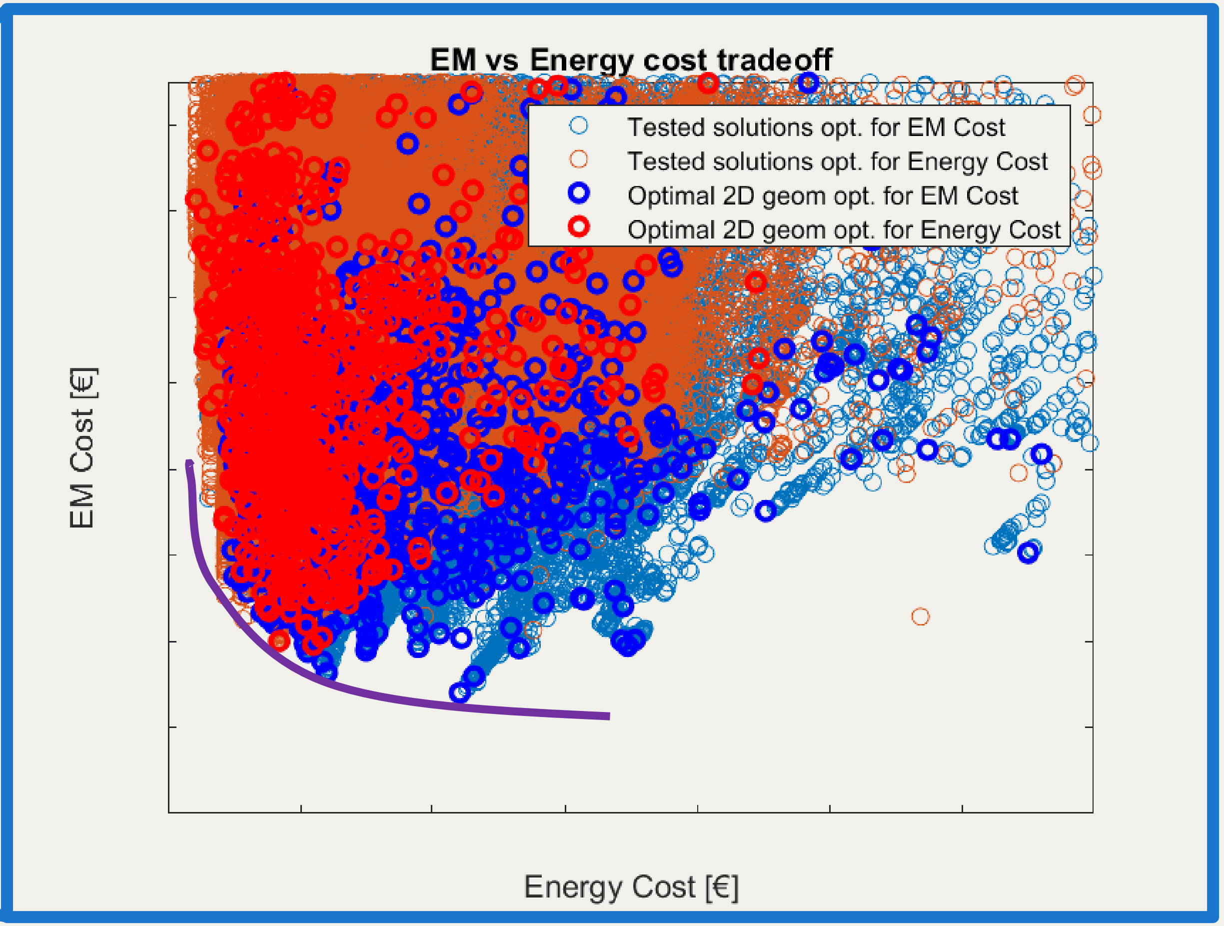
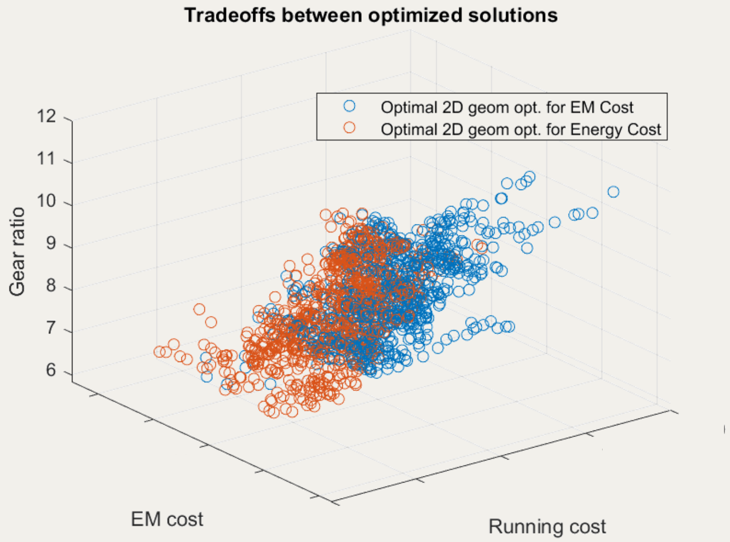
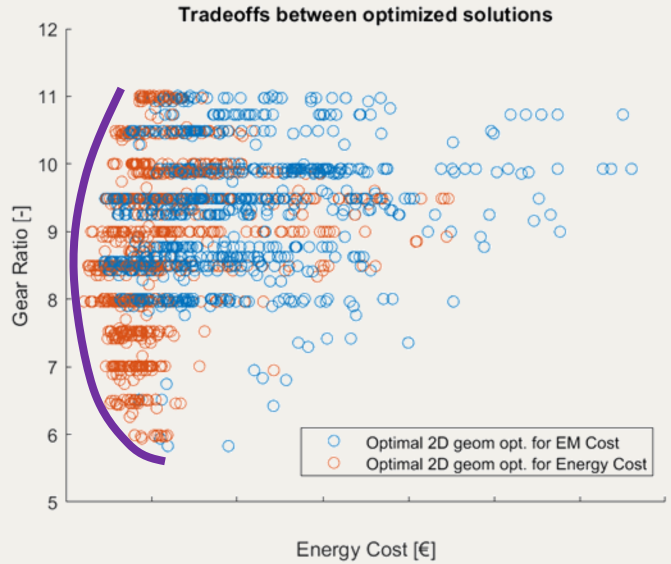
# Trade-offs between energy consumption and EM cost

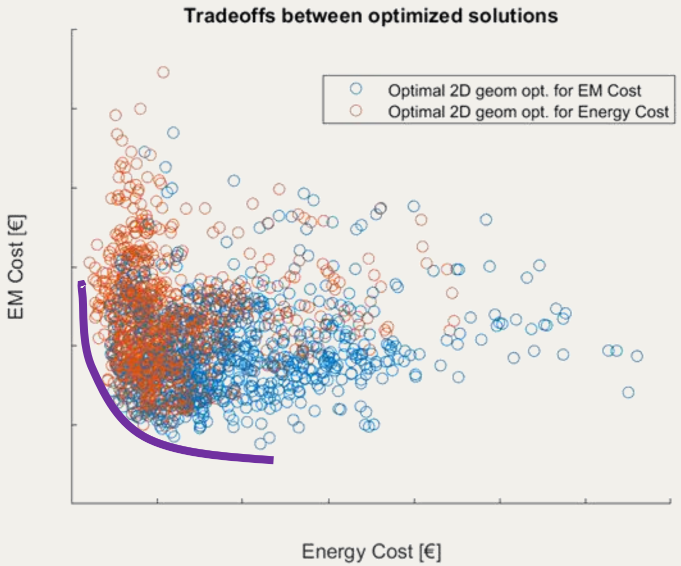


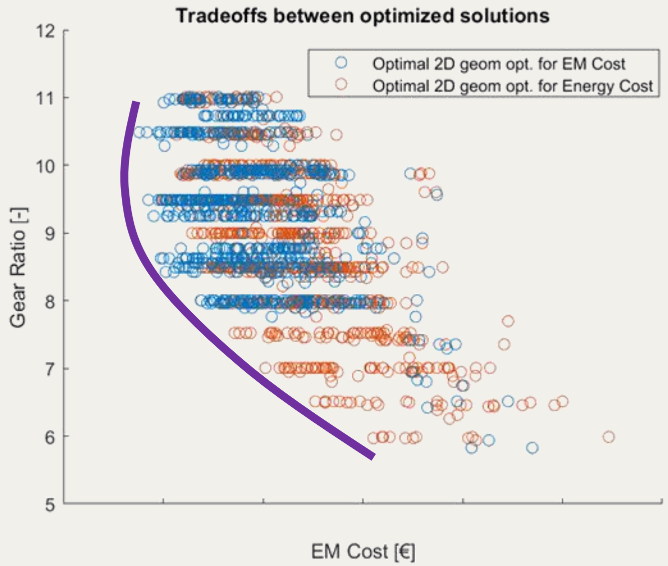



# Analysis of optimal results




- Clear trade-off between optimization objectives
- For the included geometries, higher transmission ratios reduce EM cost at a slight detriment of energy cost.
- Lower ratios and larger machines operating at lower speeds improve energy consumption.



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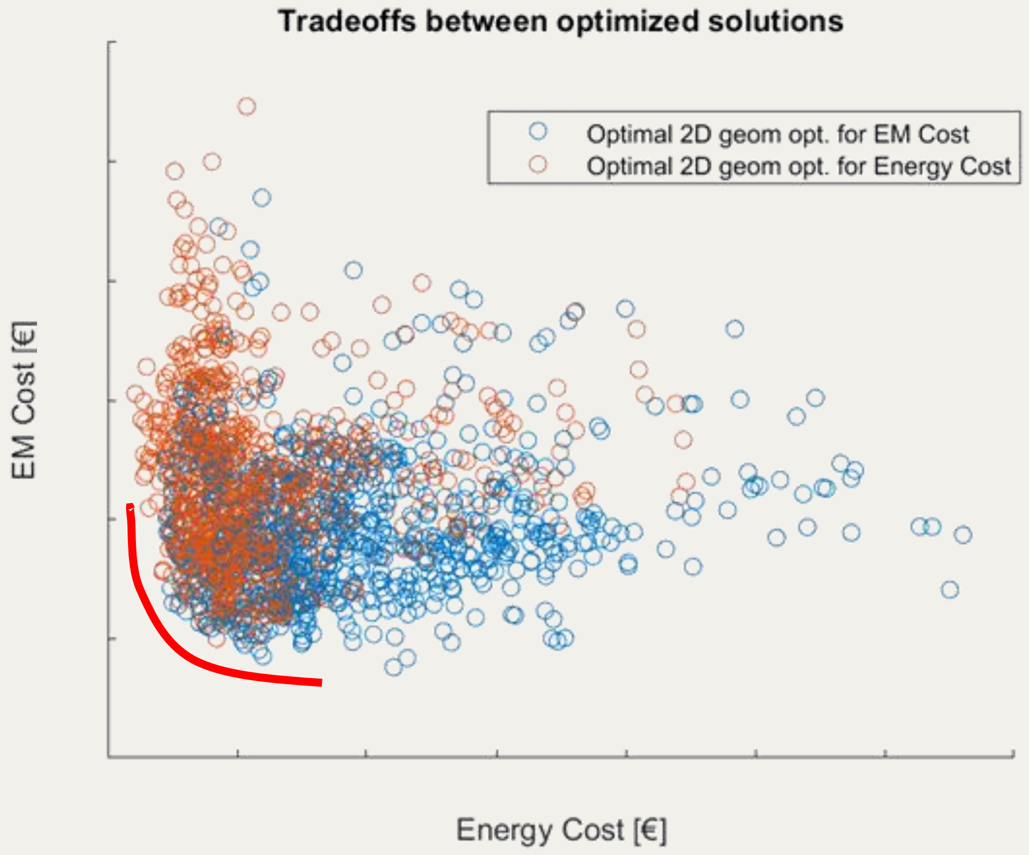
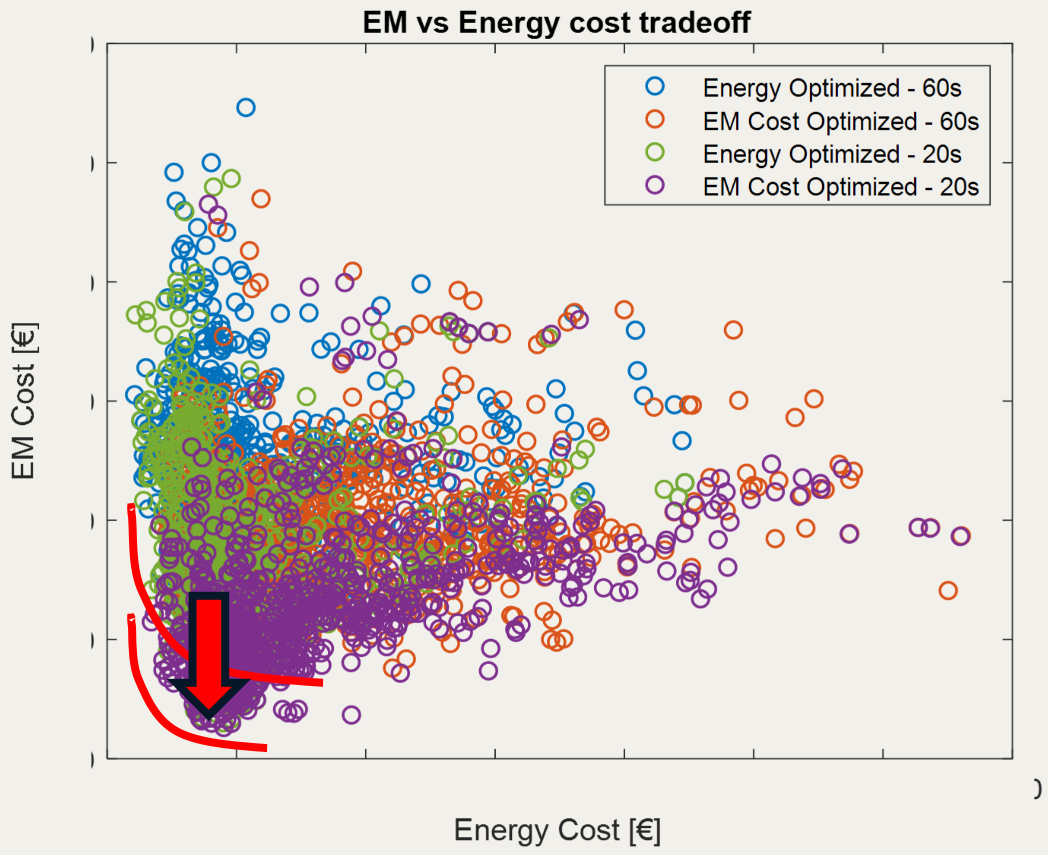
# Impact of overloading requirements

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# Technology Demonstrators

2024 BorgWarner Arctic Drive, Arjeplog, Sweden

# TECHNOLOGY integrated Drive Module (iDM)

▸ VEHICLE PLATFORM **WELTMEISTER (WM) EX5**

**VEHICLE SPECIFICATION**

Front Propulsion
- Motor Type PMSM
- Motor Power 120 kW
- Wheel Torque 2 800 Nm

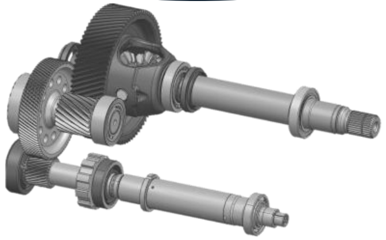
Battery
- Nominal Voltage 400 V


| KEY FEATURES and BENEFITS |
|---|
| INTEGRATED DRIEVE MODULE (iDM) |
| WATER-COOLED ONE-SPEED GEARBOX |
| SLIP AND ANTI-JERK CONTROLS |
| OPTIONAL PARKLOCK |

Applicable BorgWarner Portfolio

iDM

GEARBOX



Inverter

# Reference Vehicle - eLSD

▸ VEHICLE PLATFORM **Kia EV6 GT**

**VEHICLE SPECIFICATION**
Dual Motor - 430kW

Front Propulsion
- Open Differential
- Motor Power 160 kW

Rear Propulsion
- eLSD (None BorgWarner)
- Motor Power 270 kW

Battery
- Nominal Voltage 800 V
- Capacity 77 kWh


| **KEY FEATURES** |
| --- |
| eLSD at Rear axle (None BorgWarner) |
| Standard Production Vehicle |

# TECHNOLOGY electric Cross Drive (eXD)

▸ VEHICLE PLATFORM **Volvo C40 Recharge**

**VEHICLE SPECIFICATION**
Dual Motor

Front Propulsion
- Retrofitted eXD (eFXD)
- Integrated eXD Torque 2 500 Nm
- Motor Type PMSM
- Motor Power 170 kW
- Wheel Torque 3 300 Nm

Rear Propulsion
- Retrofitted eXD (eRXD)
- Integrated eXD Torque 2 500 Nm
- Motor Type PMSM
- Motor Power 170 kW
- Wheel Torque 3 300 Nm

Battery
- Nominal Voltage 400 V
- Capacity 78 kWh


| KEY FEATURES and BENEFITS |
|---|
| INTEGRATED DRIVE MODULE (iDM) FEATURING eXD |
| VEHICLE DYNAMICS CONTROL SOFTWARE HANDLING SLIP CONTROLLER, LONGITUDINAL AND LATERAL TORQUE |
| CUSTOMER INTERFACE FOR VEHICLE TUNING ON-THE-FLY |
| POSSIBILITY TO EMULATE MULTIPLE VEHICLE PROPULSION ARCHITECTURES |

**Applicable BorgWarner Portfolio**

eXD

iDM

Vehicle Controls

# TECHNOLOGY electric Torque Vectoring Disconnect (eTVD) 2.0

▸ VEHICLE PLATFORM **Polestar 2**

**VEHICLE SPECIFICATION**
Dual Motor

Front Propulsion
- Motor Type PMSM
- Motor Power 150 kW
- Wheel Torque 3 000 Nm

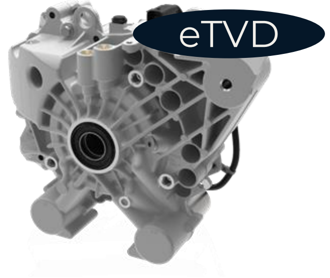
Rear Propulsion
- Retrofitted eTVD 2.0
- Torque per Wheel 2 600 Nm
- Motor Type PMSM
- Motor Power 200 kW
- Wheel Torque 4 300 Nm

Battery
- Nominal Voltage 400 V
- Capacity 78 kWh


| KEY FEATURES and BENEFITS |
|---|
| ELECTRIC TORQUE VECTORING DISCONNECT (eTVD) – DUAL CLUTCH SYSTEM |
| VEHICLE DYNAMICS CONTROL SOFTWARE HANDLING SLIP CONTROLLER, LONGITUDINAL AND LATERAL TORQUE |
| CUSTOMER INTERFACE FOR VEHICLE TUNING ON-THE-FLY |

**Applicable BorgWarner Portfolio**

eTVD



Inverter

Vehicle Controls

# TECHNOLOGY iDM w/ electric Torque Vectoring (eTV)

▸ VEHICLE PLATFORM **Polestar 2**

**VEHICLE SPECIFICATION**
Dual Motor

Front Propulsion
- Motor Type PMSM
- Motor Power 150 kW
- Wheel Torque 3 000 Nm

Rear Propulsion
- Retrofitted eTV
- eTV Torque 2 000 Nm
- Motor Type PMSM
- Motor Power 170 kW
- Wheel Torque 3 300 Nm
- Inverter SiC

Battery
- Nominal Voltage 400 V
- Capacity 78 kWh


| **KEY FEATURES and BENEFITS** |
| --- |
| ELECTRIC TORQUE VECTORING (eTV) – ELECTRIC MOTOR VECTORING |
| FULL IN_HOUSE INTEGRATED DRIVE MODULE SCOPE – INVERTER, MOTOR, GEARBOX |
| VEHICLE DYNAMICS CONTROL SOFTWARE HANDLING SLIP CONTROLLER, LONGITUDINAL AND LATERAL TORQUE |

**Applicable BorgWarner Portfolio**

eTV

iDM

Vehicle Controls



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# Driving Rules

- A BorgWarner expert always attends in the vehicles to support during the drive
- Traffic signs must be observed
  - Stop signs and direction signs are placed at the entrances to the tracks to provide important safety information
- Don't drive beyond your skills
  - All drivers are responsible for their own driving and must keep safety first in mind
  - The BorgWarner co-driver is obliged to abort the drive if safety is compromised

# Winter test facility - Arjeplog
## Garage and Office




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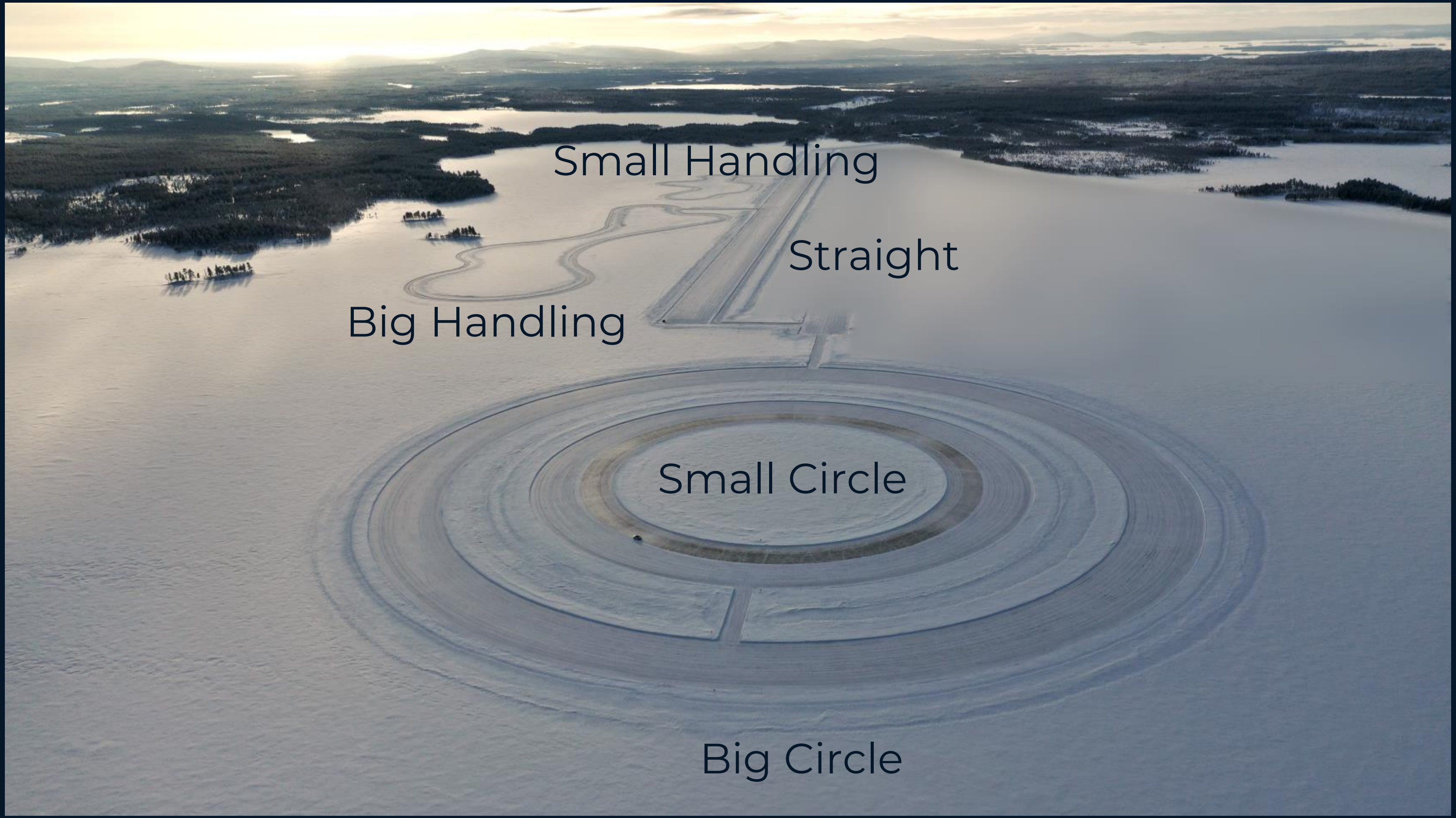
# Winter test facility - Arjeplog
## Overview



# Winter test facility - Arjeplog

## Small Handling

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# Winter test facility - Arjeplog
## Big Handling




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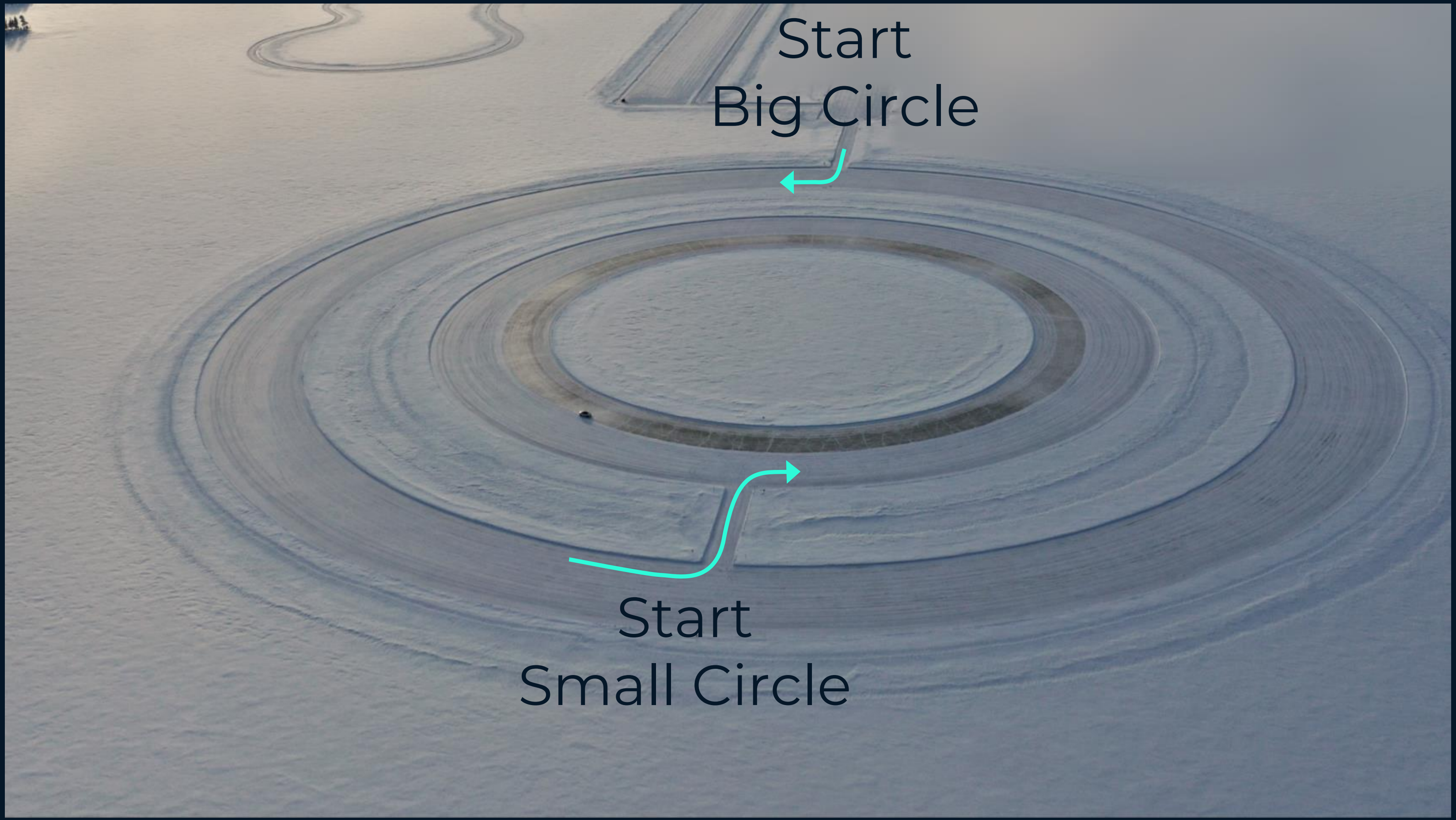
# Winter test facility - Arjeplog

## Circles



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# Winter test facility - Arjeplog
## Straight / Dynamic Area



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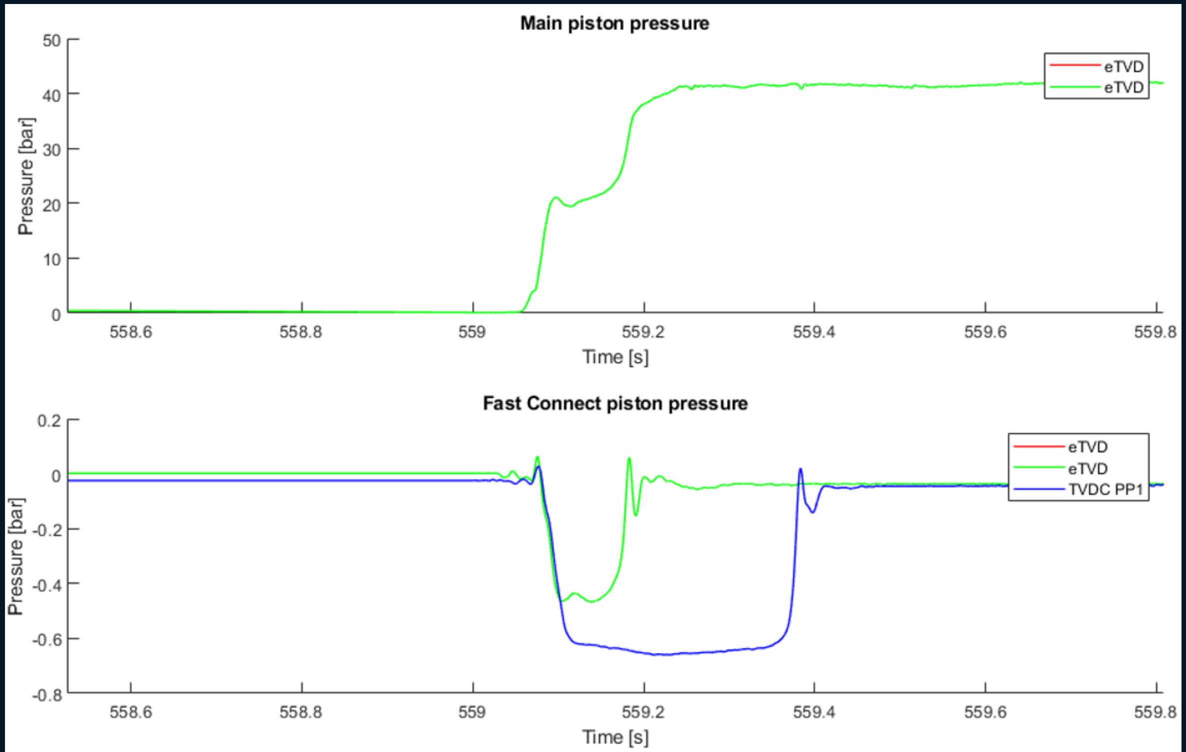
# eTVD – performance upgrade

- System performance is improved by optimizing the hydraulic layout
  - Flow restrictions/tight sectors removed
- Connect time is reduced by >200ms
  - Time to kisspoint reduced by 55%
  - Time to torque transfer (300Nm) reduced by >30%
  - Time to torque transfer (300Nm): 400 ms
  - Time to max torque: 600ms



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