Electrify & Optimize: Revving Up E-Powertrain Design and Analysis

GAMMA TECHNOLOGIES

The Engineering Challenge

GT

Battery, Motor, & Inverter Design Trade-offs

The Electrified Powertrain triplet (battery, motor, inverter) need to be designed and sized together:
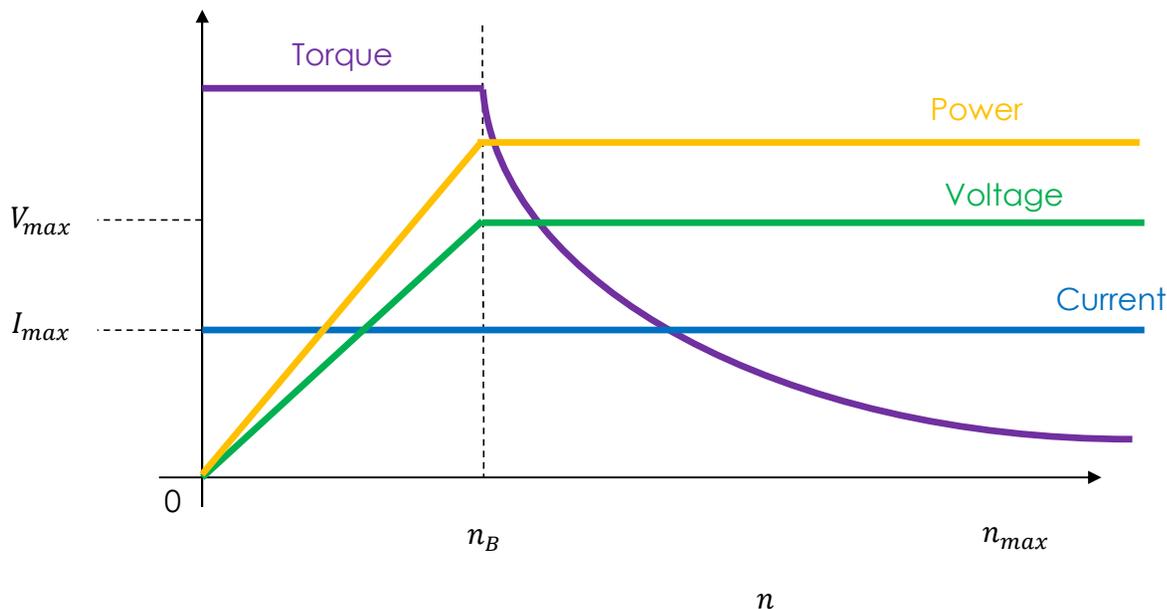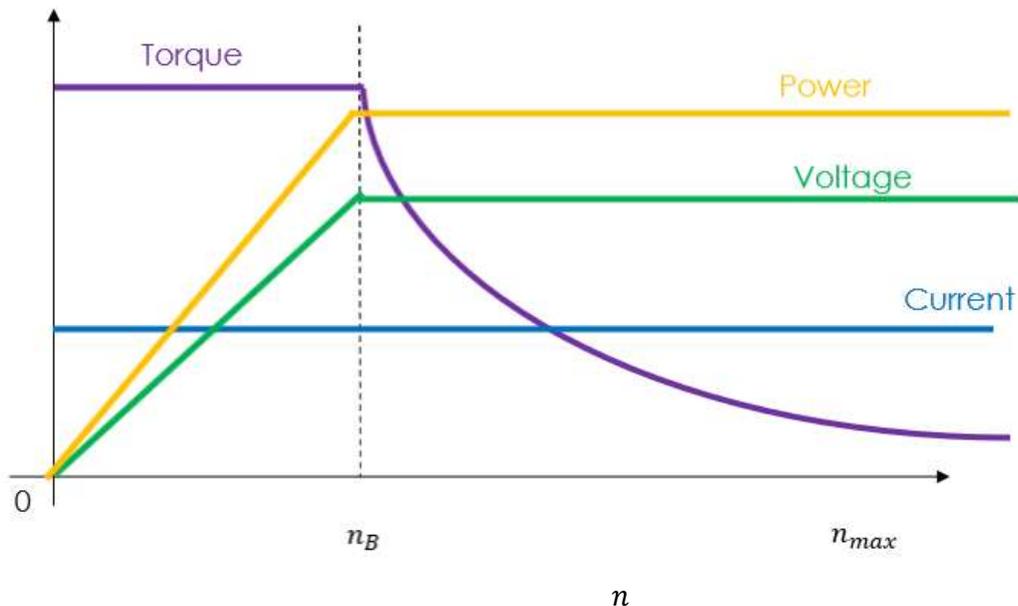
V_{max}: Limits of battery
- Battery Chemistry
- N_{Series}

I_{max}: Limits of battery and motor
- $N_{Parallel}$
- Motor thermal security

Battery, Motor, & Inverter Design Trade-offs

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V_{max}: Limits of battery
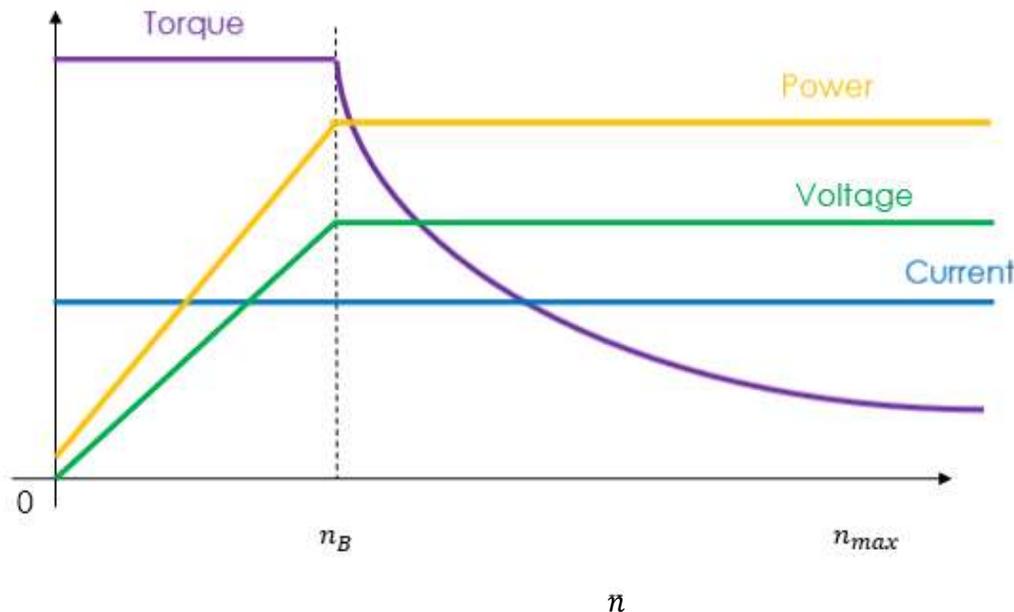- Battery Chemistry
- N_{Series}

I_{max}: Limits of battery and motor
- $N_{Parallel}$
- Motor thermal security

What if: Increased Battery Voltage?

Battery, Motor, & Inverter Design Trade-offs

The Electrified Powertrain triplet (battery, motor, inverter) need to be designed and sized together:

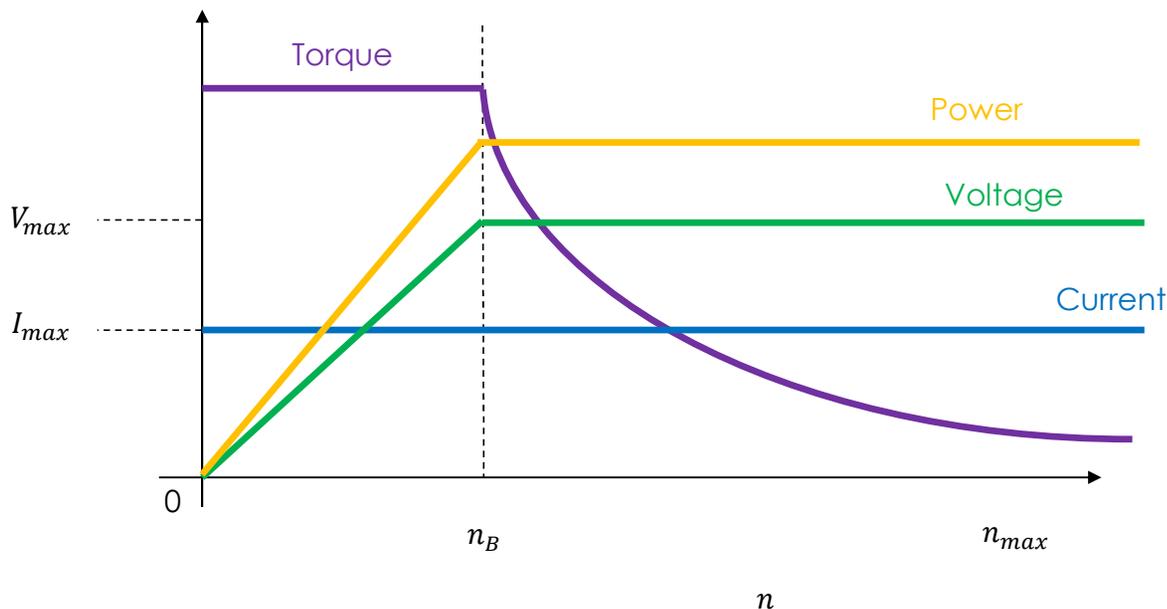V_{max}: Limits of battery
- Battery Chemistry
- N_{Series}

I_{max}: Limits of battery and motor
- $N_{Parallel}$
- Motor thermal security

What if: Improved motor cooling?

Battery, Motor, & Inverter Design Trade-offs

The Electrified Powertrain triplet (battery, motor, inverter) need to be designed and sized together:
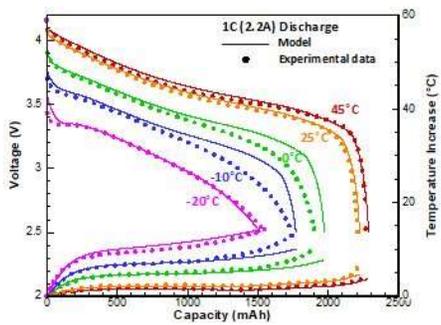

At what cost?
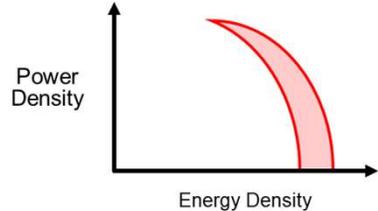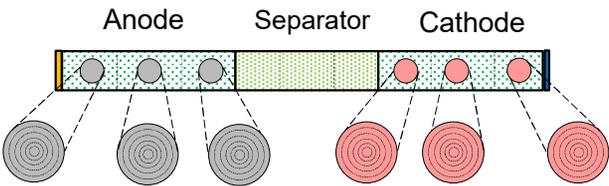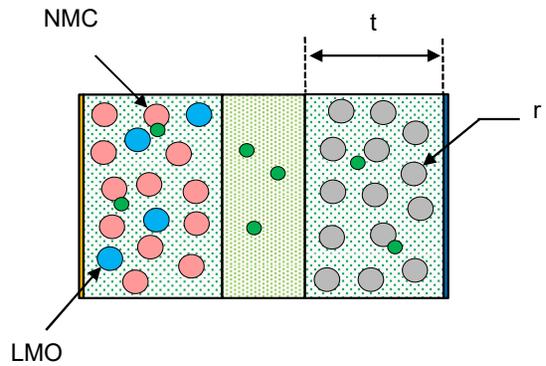- More expensive
- Heavier (worse BEV efficiency)
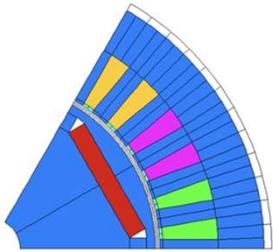
How can we study all of these tradeoffs together???

Solution Introduction

GT

GT-AutoLion

Performance

Degradation

Safety

NMC

LMO

t

r

Power Density

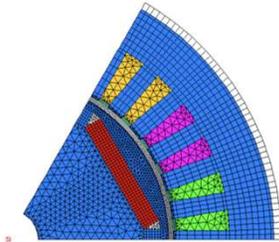Energy Density

Anode   Separator   Cathode

GT-FEMAG
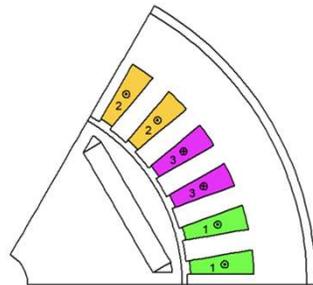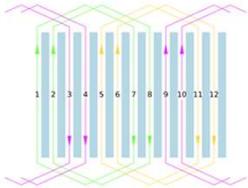
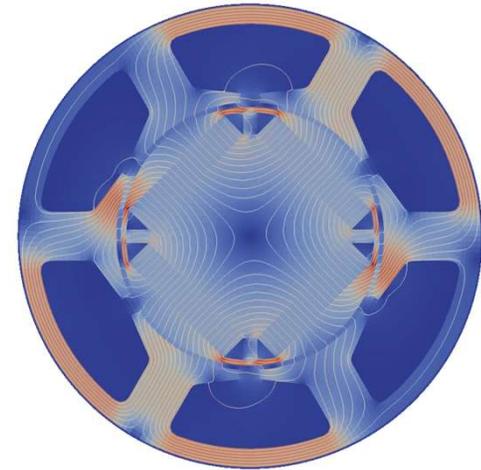GT-FEMAG is a 2D Finite Element simulation of electromagnetics for motor design

Flexible Geometry Definition

Industry-leading mesh technology

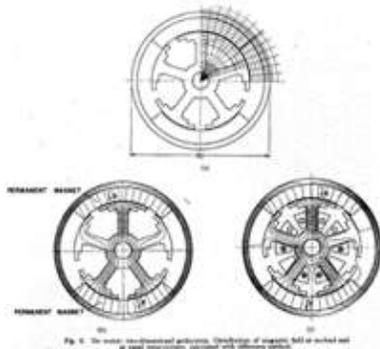2D Magnetic Flux

Flexible Winding Layouts

What is FEMAG?

2D Finite Element simulation of electromagnetics for motor design

Mature & Accurate: under development since 1982

Dr.-Ing. Konrad Reichert
2006 IEEE Nikola Tesla Awardee

ETH Zurich

Flexible: model all motor types or general e-mag problems

IM/ASM   ESM

RSM   SPMSM   IPM

Coil

Airgap

Multi-physics: includes 2D thermal & mechanical modeling

GT
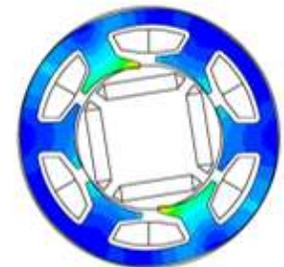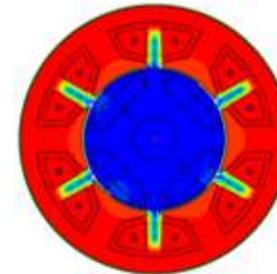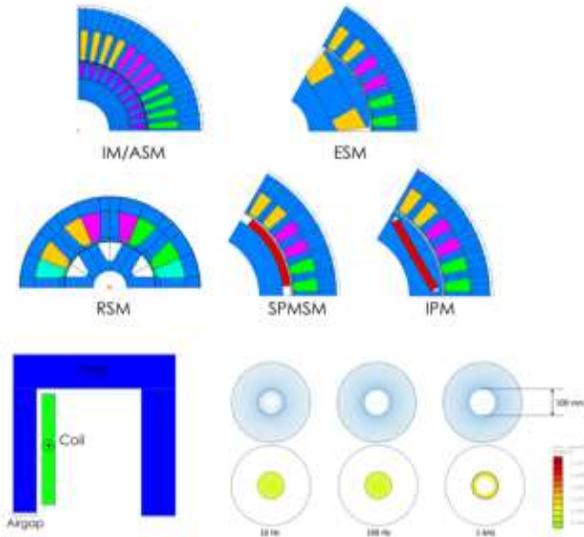
GT-PowerForge

GT-PowerForge for converter design stage:

**Power Converter
Design Parameters**

Topologies

Magnetics / Filter

Switching
frequency

Component
Selection

?

Controls

Cooling
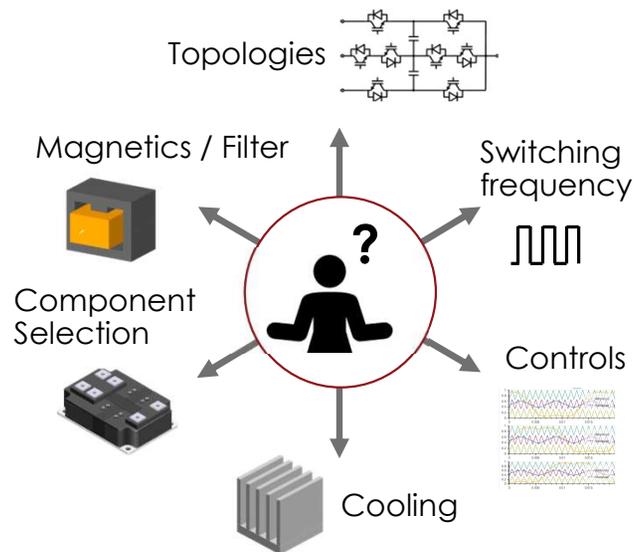
**How to properly explore
design space?**
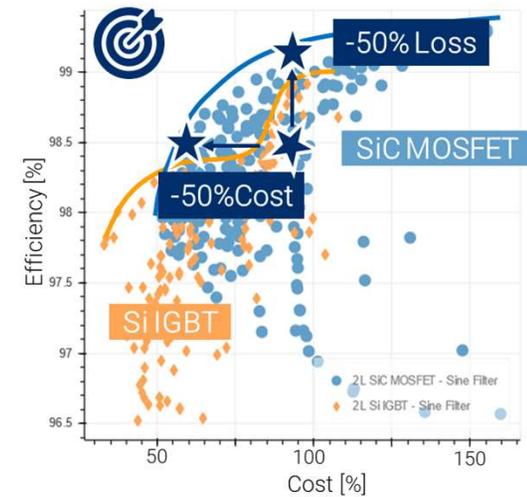
More Accurate Benchmark solutions

Mass (%)

Power loss (%)
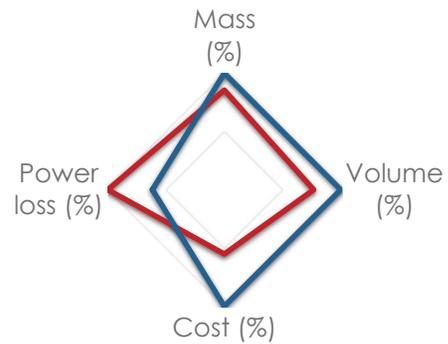
Volume (%)

Cost (%)

Efficiency - Weight - Volume - Cost Power density - Specific power
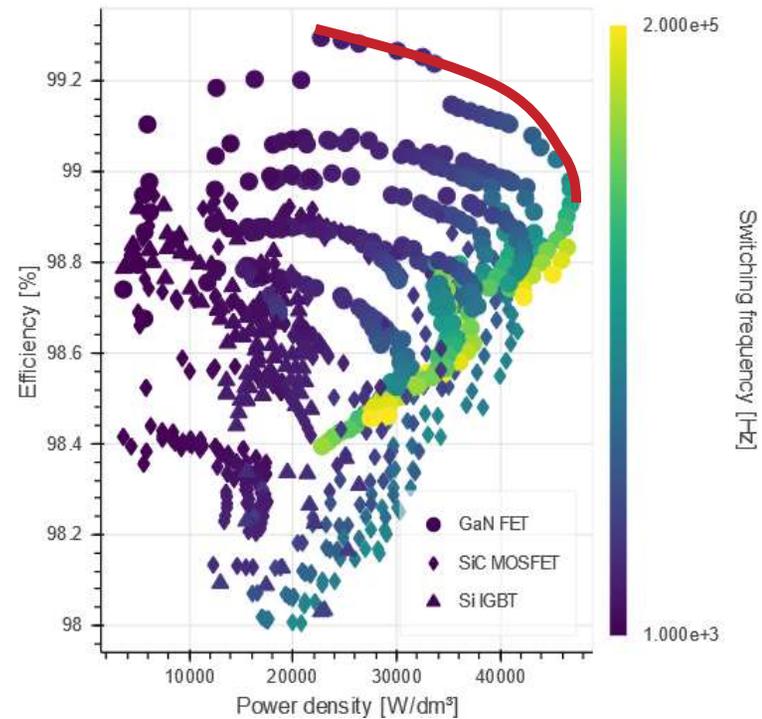
E-Powertrain Design Analysis in GT-SUITE

Anode   Separator   Cathode

Cooling

DC Differential Mode Filter

Macrocell 3
Macrocell 2
Macrocell 1

AC3 Differential Mode Filter

Switching controller

GT
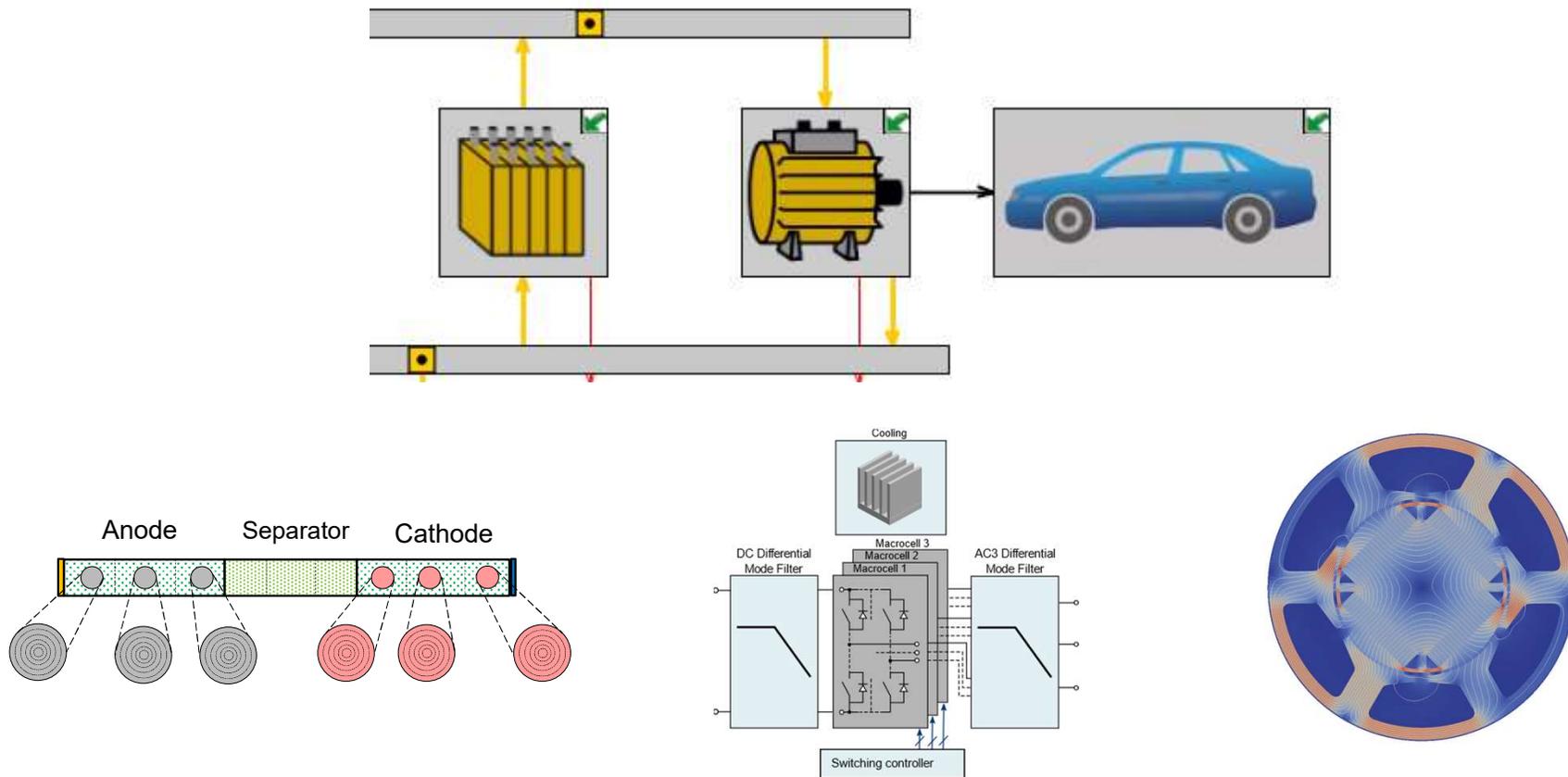
Application Example

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Reference Powertrain

Vehicle
(Sedan body)
- C_d: 0.29
- FA: 1.95m^2
- Tires: 215/50R17
- *Calculated mass*

Motor
- 8-Pole IPM
- *Number of stator slots*
- *Airgap*
- *Width of Magnets*

Battery
- Cell:
  - NCM811
  - 21700 cylindrical
  - 4.8 Ah
  - 3.5 V
- *Variable Pack*
  - *# Series Cells*
  - *# Parallel Cells*

Inverter
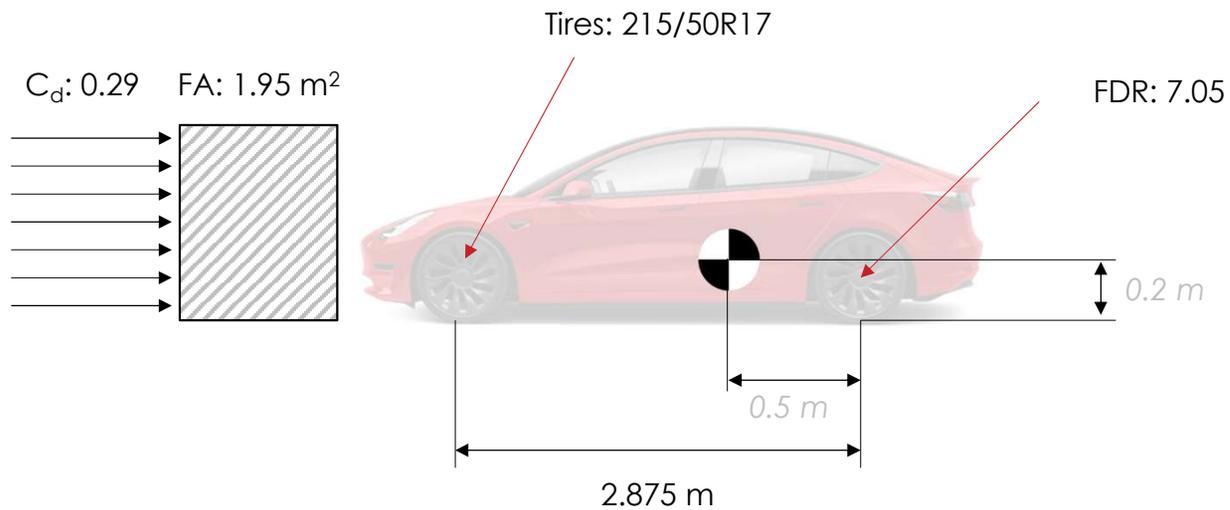- *2 options:*
  - *SiC MOSFET*
  - *Si IGBT*

Legend
- Locked Parameter
- Parameter to Vary

GT

Vehicle

Parameters for vehicle model include:

Tires: 215/50R17

C_d: 0.29   FA: 1.95 m^2

FDR: 7.05

0.2 m

0.5 m

2.875 m

Mass of Vehicle: 1250 kg + Battery Mass

Assumed Values

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Vehicle Model Tests & Metrics
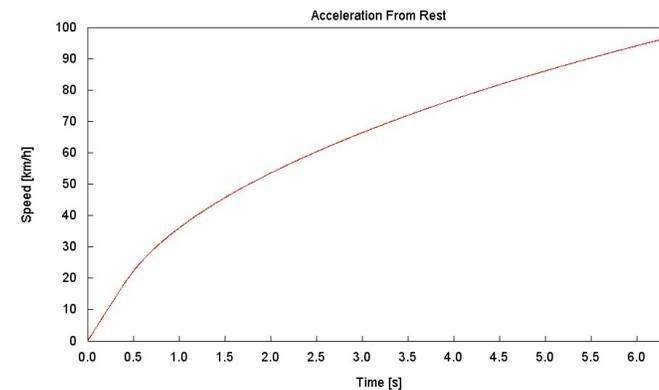
Two tests setup to calculate vehicle-level metrics

Vehicle Range

SAE J1634 EV Range Test
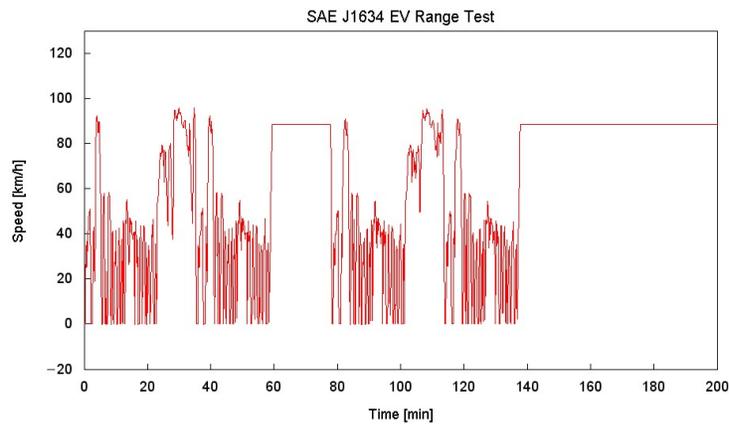
- *BEV Range*
- *BEV Efficiency (kWh/100km)*
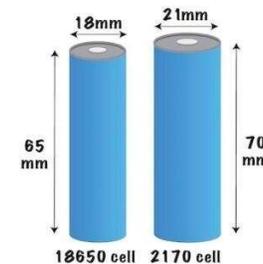
Acceleration test

Acceleration From Rest

- *Time to Distance (0-100 kph)*
- *¼ mile (400m, time, max speed)*
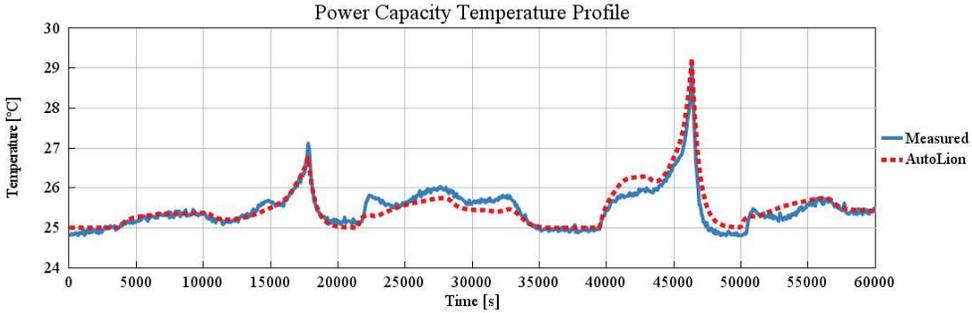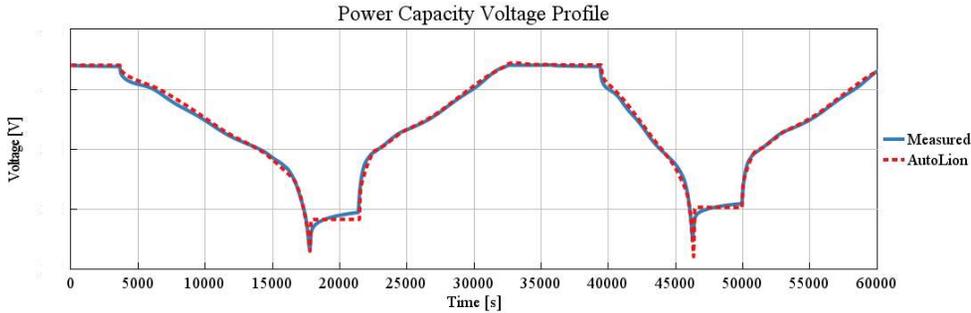- *Top Speed*

Lithium-ion cell

- NCM811 Cathode, Graphite Anode

- 21700 cylindrical

- 4.8 Ah

- 3.5 V

- **~70 grams** per cell
  - *We assume **~110 grams** per cell for pack*
  - *Integration Factor of about **60%** to account for busbars, cooling strategy, BMS, etc.*

- **€1.25** per cell

GT

Battery Model

Using cell dimensions, AutoLion material database, and experimental results*, AutoLion model was calibrated**

Experimental results provided by Southwest Research Institute's battery testing consortium, Electrified Vehicle and Energy Storage Evaluation (EVESE)
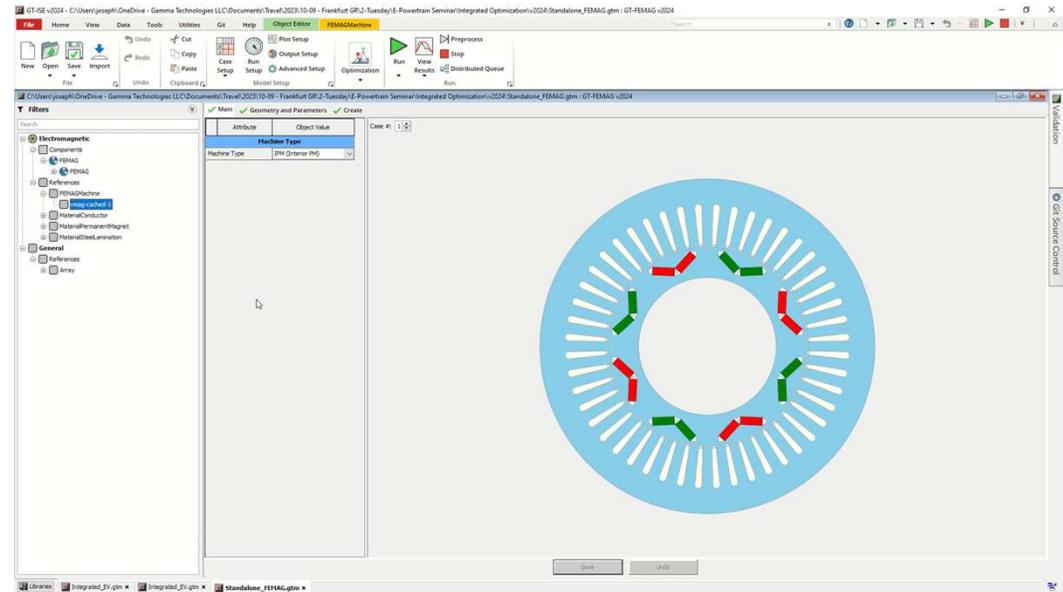
Traction Motor

Baseline IPM Design

Main Motor Parameters	
Motor Type	IPM (internal permanent magnet)
Magnet Shape	V-style
Number of stator slots	48
Number of pole pairs	4
Number of phases	3
Outer Diameter	270 mm
Bore Diameter	162 mm
Length	84 mm

Traction Motors

8 Total Designs to be compared at vehicle-level

Design Option	Baseline Option	Advanced Option	Additional Cost
Number of Stator Slots	24 Slots	48 Slots	€200
Magnet Width	18 mm	25 mm	€600
Airgap	1.5 mm	0.75 mm	€200

GT

Traction Motor

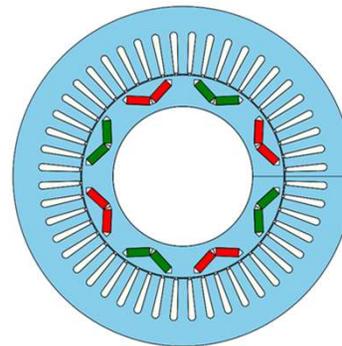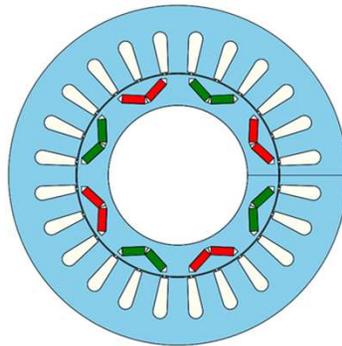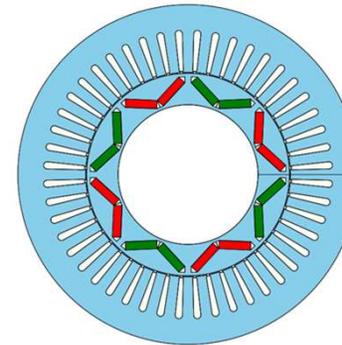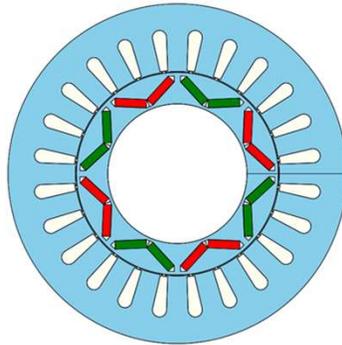## Using 8 Different Traction Motor Designs

24 Stator Slots　　　　　48 Stator Slots

Small Magnets
(18mm width)

Large Magnets
(25mm width)

x 2 different air gaps
(0.75 mm, 1.5 mm)

GT

Traction Inverter Design

Designed & Analyzed over 3,016 designs in an afternoon

- 28 switches
  - 9 Si IGBTs
  - 16 SiC MOSFETs
  - 3 GaNs
- 10 switching frequencies
- # Parallel Switches: 1, 2, 3, 4
- Space Vector & Sine PWM
- 2-level & 3-level topologies
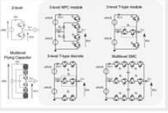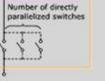
Benchmark results   Sweep history

☐	Name
☐	**MOSDET SiC 2-level SV** (640 designs)
☐	**MOSFET SiC 2-level - SPWM** (640 designs)
☐	**GaN 3-level** (456 designs)
☐	**MOSFET Si 3-level** (160 designs)
☐	**MOSFET SiC 3-level** (400 designs)
☐	**IGBT** (720 designs)
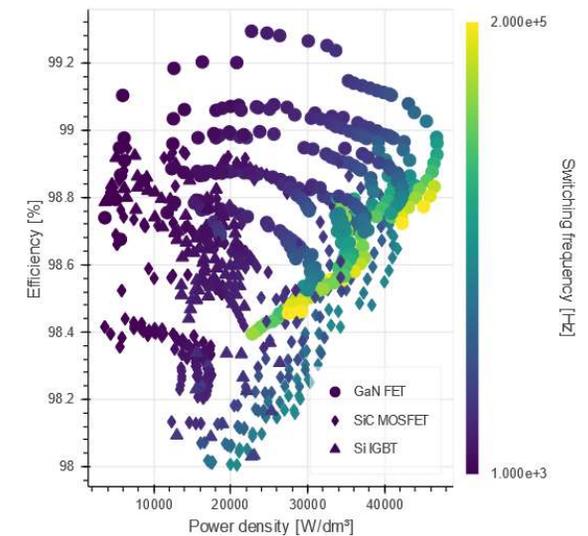
Traction Inverter(s)

Exported maps for 2 Designs to be compared at vehicle-level

		Design 1	Design 2
Switch Technology		SiC MOSFET	Si IGBT
Inverter Topology		2-level	2-level
# of directly parallelized switches		4	3
Switching Frequency		10 kHz	10 kHz
Modulation Strategy		Sine PWM	Sine PWM
Estimated cost		€800	€500

Integration

Battery, Inverter, and Motor integrated into vehicle model with controls in GT-SUITE
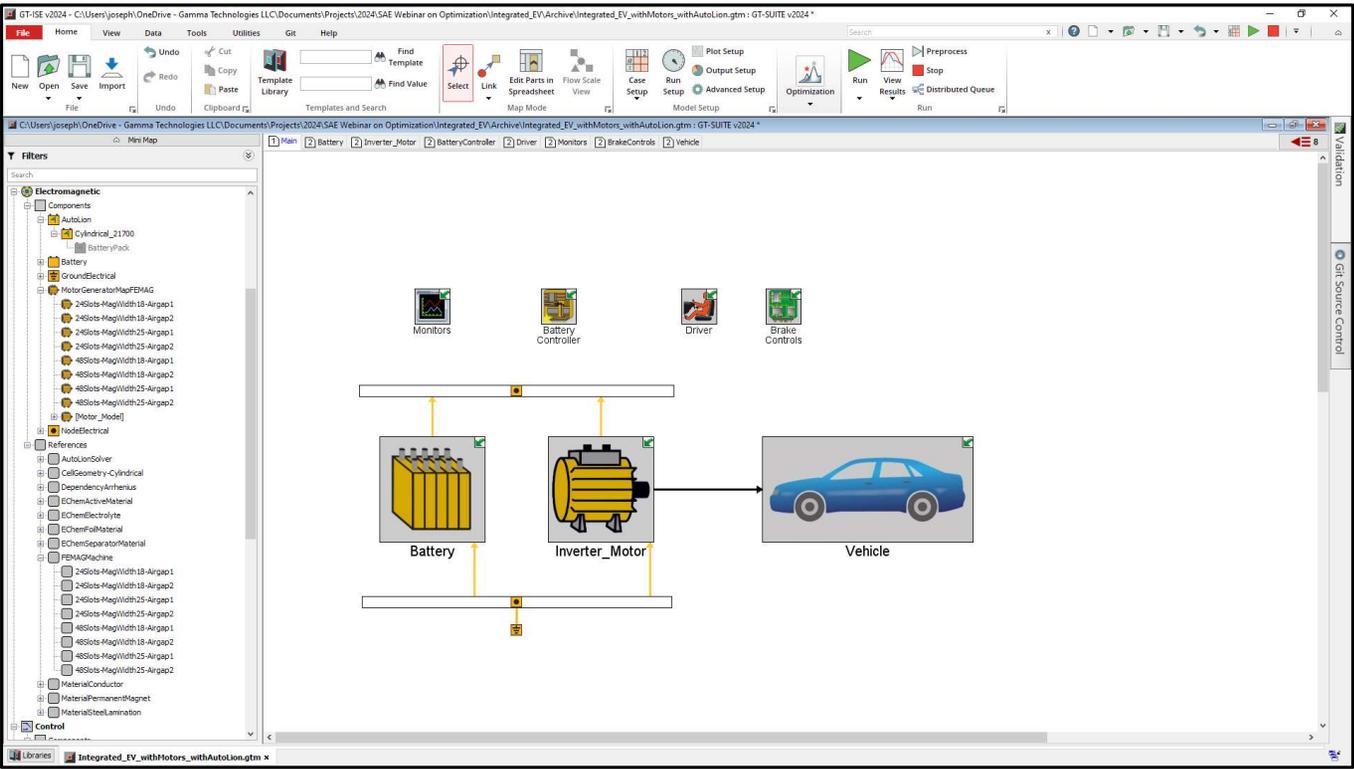
# Integrated
Model Results

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GT Design of Experiments

With GT Design of Experiments, setup a full factorial of electric powertrains, resulting in **400 powertrain designs** compared
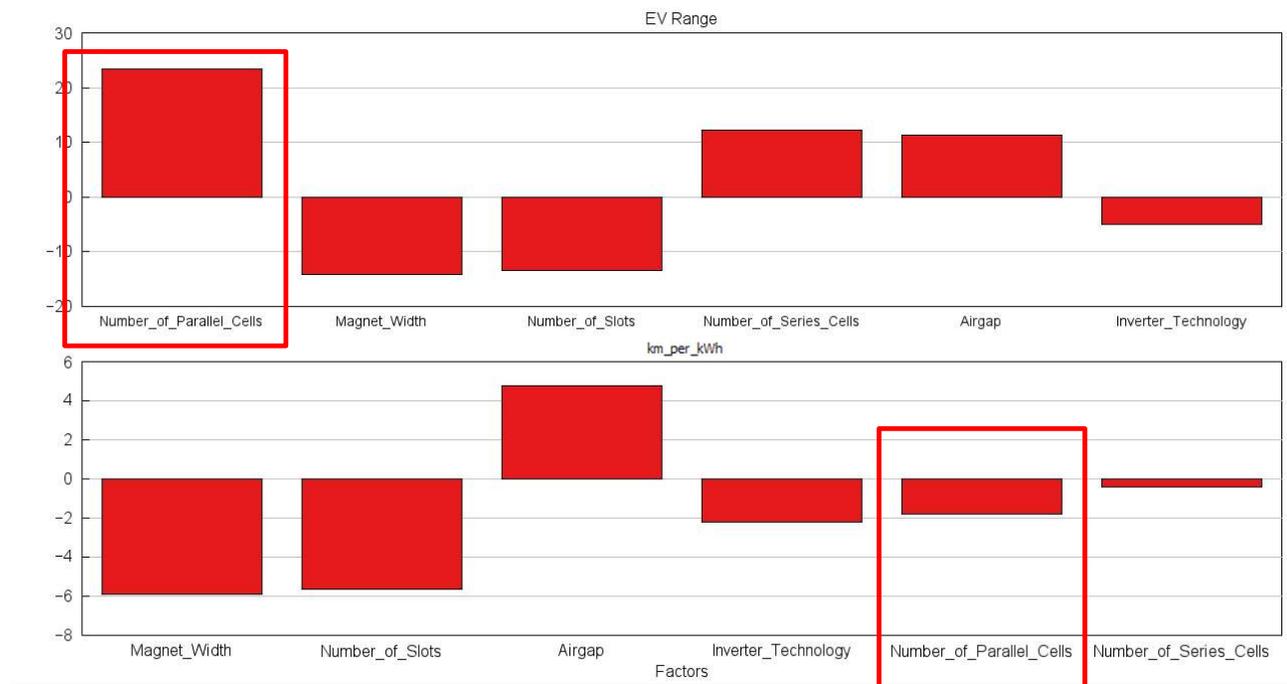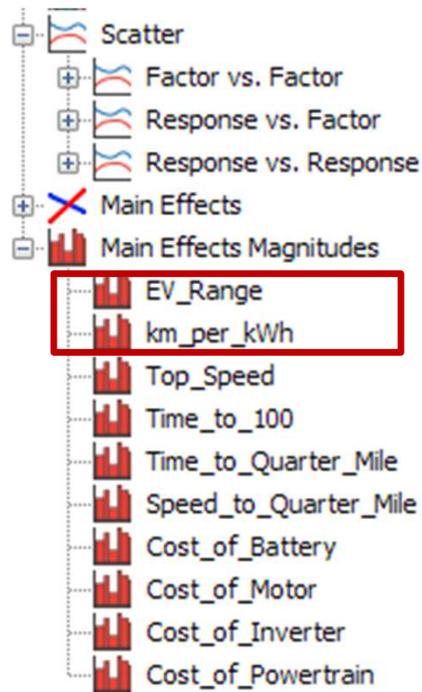
Factor	Number of Levels	Values
# Parallel Cells	5	44, 45, 46, 47, 48
# Series Cells	5	94, 95, 96, 97, 98
Inverter Technology	2	SiC MOSFET, Si IGBT
# Stator Slots	2	24, 48
Magnet Width	2	18mm, 25mm
Airgap	2	0.75 mm, 1.5 mm

GT Design of Experiments

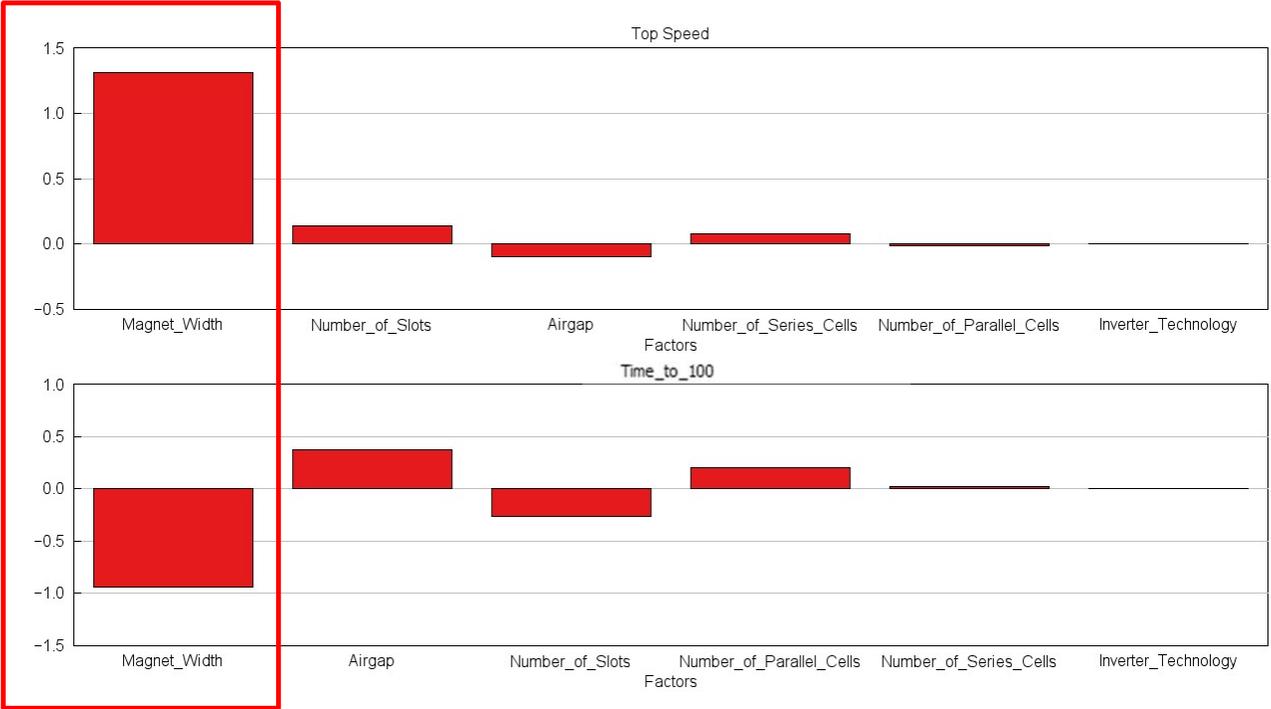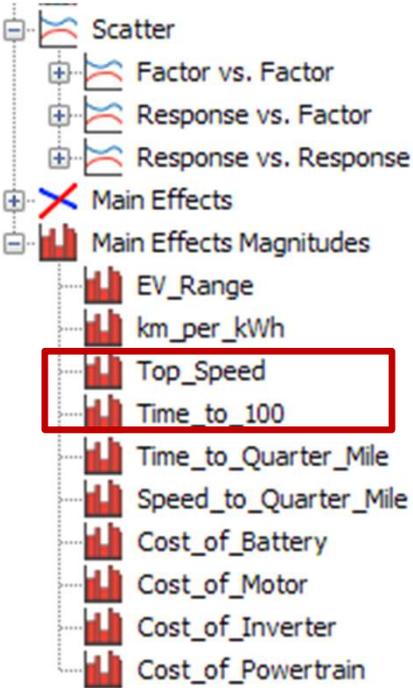Post-processed results with GT's built-in DOE Post-Processor
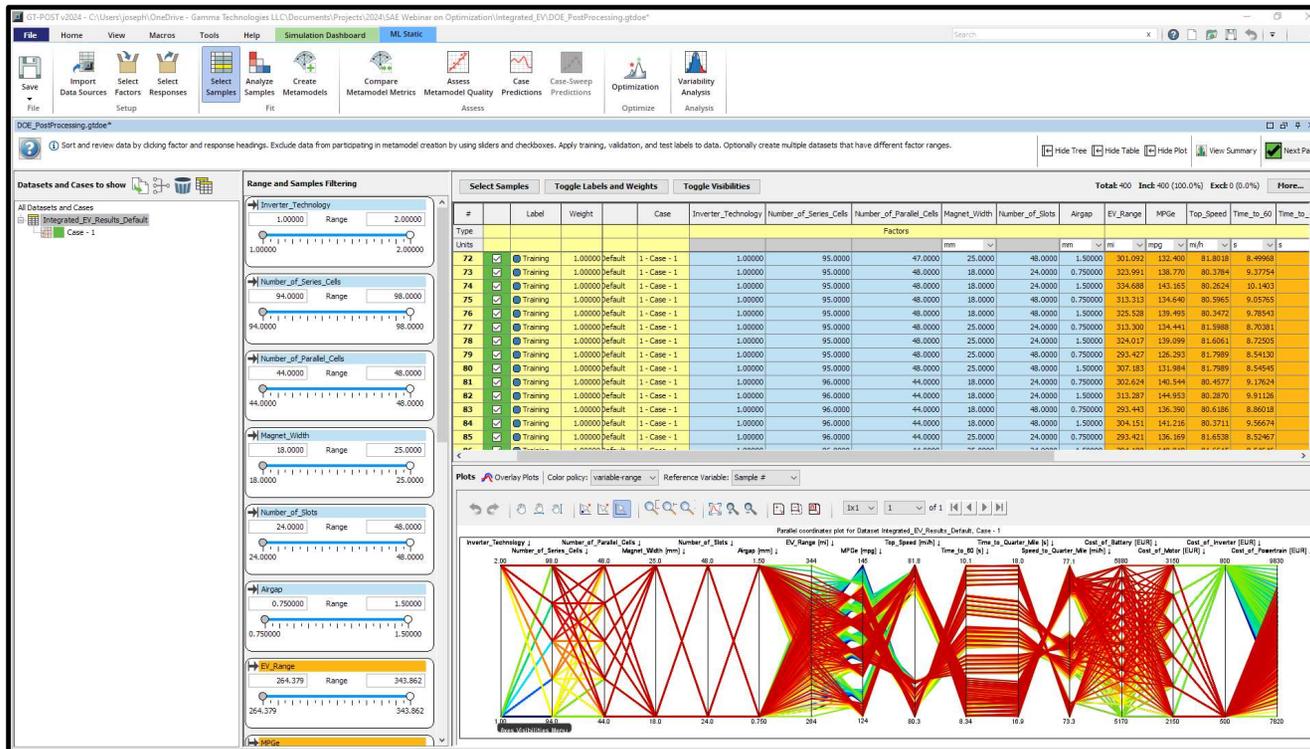
DOE Post-Processing: Sensitivity Analysis

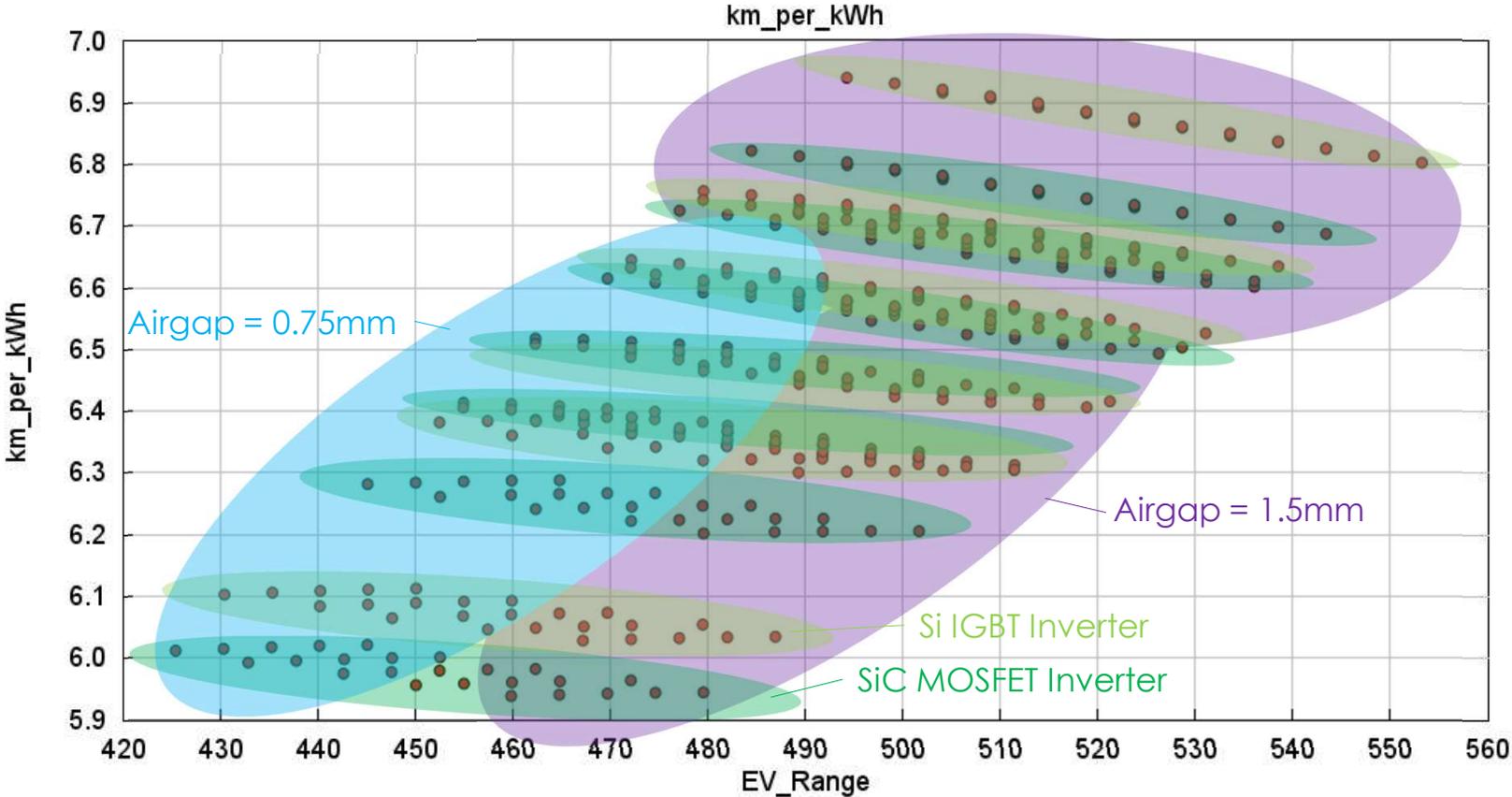0 - base line; x - advanced option; + - increase, - - decrease
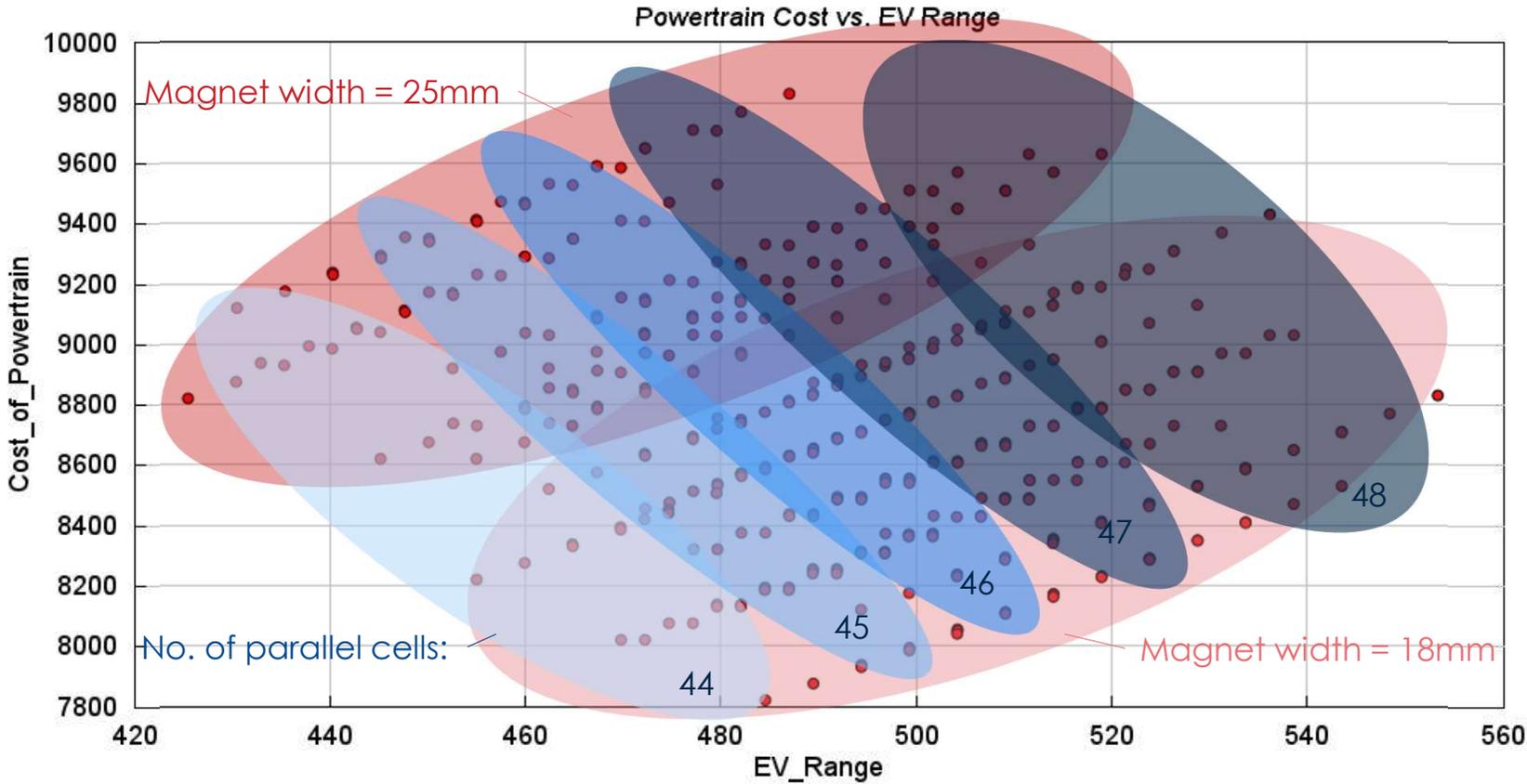
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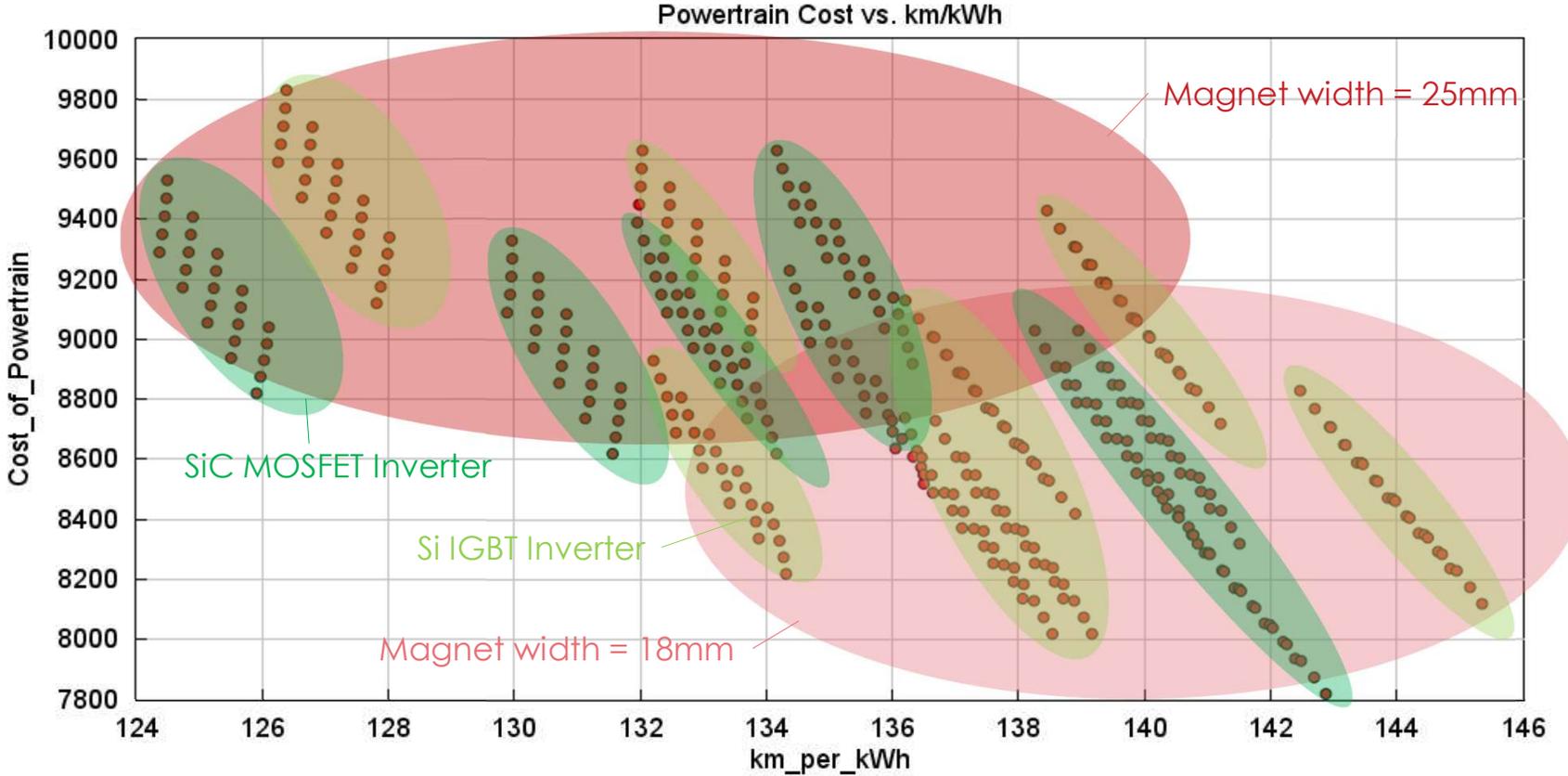0 - base line; x - advanced option; + - increase, - - decrease

Response vs. Response Plots
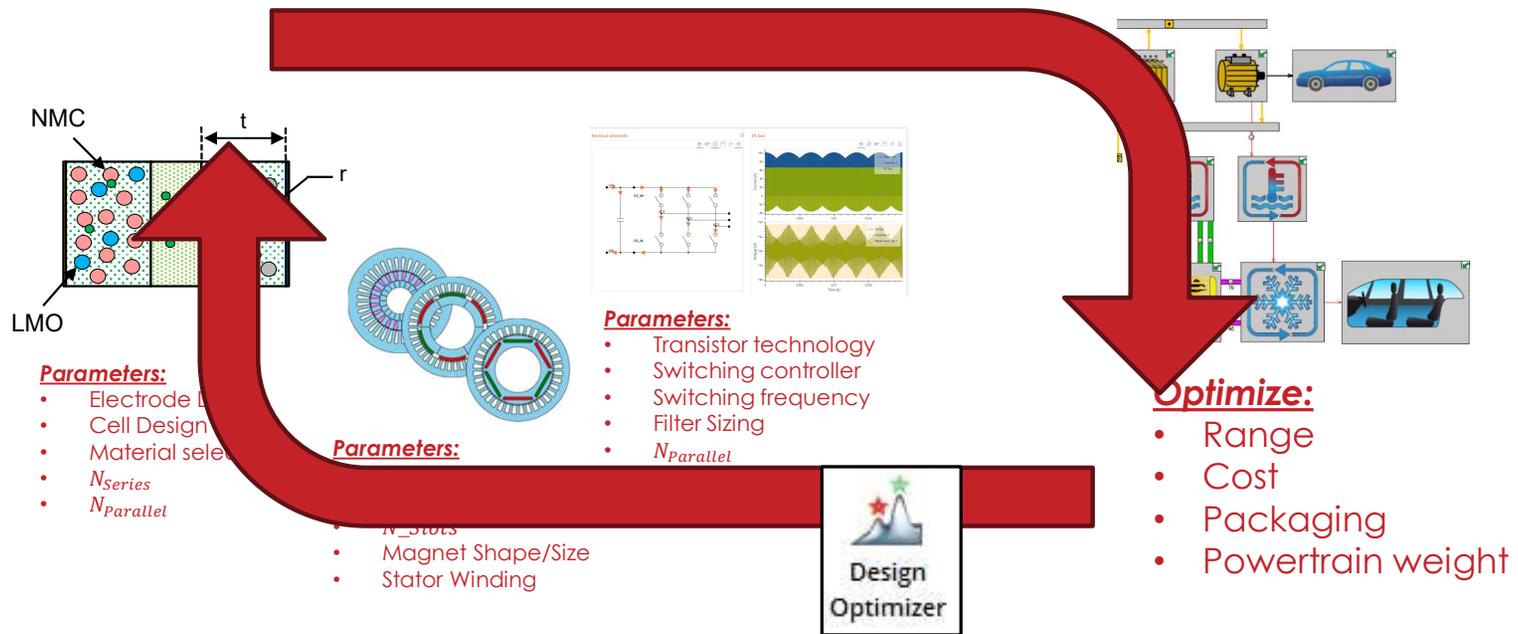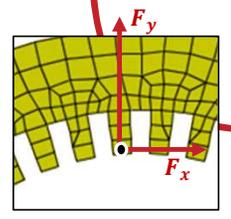
Response vs. Response Plots

Powertrain Cost vs. EV Range

Response vs. Response Plots

Powertrain Cost vs. km/kWh

Magnet width = 25mm

SiC MOSFET Inverter

Si IGBT Inverter

Magnet width = 18mm

Expanding What's Possible

With GT-SUITE, GT-AutoLion, GT-FEMAG, and GT-PowerForge, explore system-level impact of component-level design space
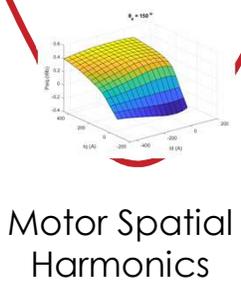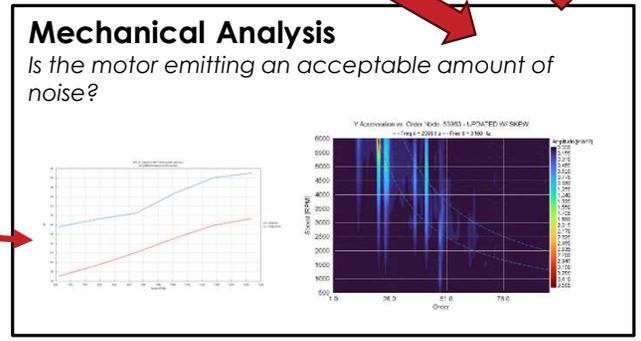

NMC

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LMO

Parameters:
- Electrode L...
- Cell Design
- Material sele...
- N_{Series}
- $N_{Parallel}$

Parameters:
- N_Slots
- Magnet Shape/Size
- Stator Winding

Parameters:
- Transistor technology
- Switching controller
- Switching frequency
- Filter Sizing
- $N_{Parallel}$

Design Optimizer

Optimize:
- Range
- Cost
- Packaging
- Powertrain weight

Multi-physics Powertrain Optimization

Inverter Design

E-mag Design

Motor Spatial
Harmonics

Electrical Analysis
Inverter +Motor Analysis, Modulation

Phase Currents

Detailed E-mag
Magnetomotive Force
prediction, HF Motor Losses

Losses

Loss
Maps

Thermal Analysis
*Are the switches and magnets within
acceptable temperature window?*

System-level
Range Prediction

**Investigate
Trade-offs!**

Mechanical Analysis
*Is the motor emitting an acceptable amount of
noise?*

F_y

F_x

Forces on Stator