Low Cost, High-Performance, HRE-Free 3-In-1 Electric Drive Unit

Project ID: elt276

Principal Investigator: David Crecelius
American Axle & Manufacturing (AAM)
June 22, 2021

Project Overview

- **Timeline**
  - Project Start: 10/1/2020
  - Project End: 12/31/2023
  - Percent Complete: 10%
- **Budget**
  - Total Project Funding: $6,250,000 USD
    - Federal Funding: $5,000,000
    - Cost Share Funding: $1,250,000
  - Funding for FY 2020: $0
  - Funding spent to date in FY2021: $527,616
- **VTO Barriers Addressed**
  - Magnet cost and volatility due to rare-earth elements
  - Performance of non-rare-earth electric motors & material optimization
  - High temperature and isolation materials for Wide-Bandgap switching devices
- **Project Participants:**
  - Recipient: American Axle & Manufacturing, Inc. (AAM)
  - Subrecipient: Electricore, Inc. (501c3 Non-Profit)
  - Project Advisor: Mr. Thomas Gross

Relevance

Project Objective

- Research, develop, and test a heavy-rare-earth (HRE) mineral free electric drivetrain for use in vehicle applications capable of the following targets:

Electric Traction Drive System Technical Targets	
Parameter	Target
Cost (1)	≤ $7/kilowatt (kW)
Power Density (2)	≥ 12 kW/liter
Operating Voltage	≥ 600 Vdc

Electric Drive Unit (EDU) Development Goals

- Reduce system cost by eliminating HRE magnet materials through development of higher efficiency induction motors
- Reduce system mass by spinning the electric machine at high RPM's
- Reduce system volume by highly integrating the power inverter into the motor, running at higher voltages, and higher speeds
- Improve Wide-Bandgap (WBG) power device high temperature thermal performance through attachment method development

Notes:

(1) Calculated cost based on 2020 equivalent dollars. The cost does not include cases, shielding, gearbox, or external connectors/connections.

(2) Calculation based on peak power capability for a duration of at least 10 seconds with volume based on overall outer bounding dimensions. Volume does not include cases, shielding, or external connectors/connections.

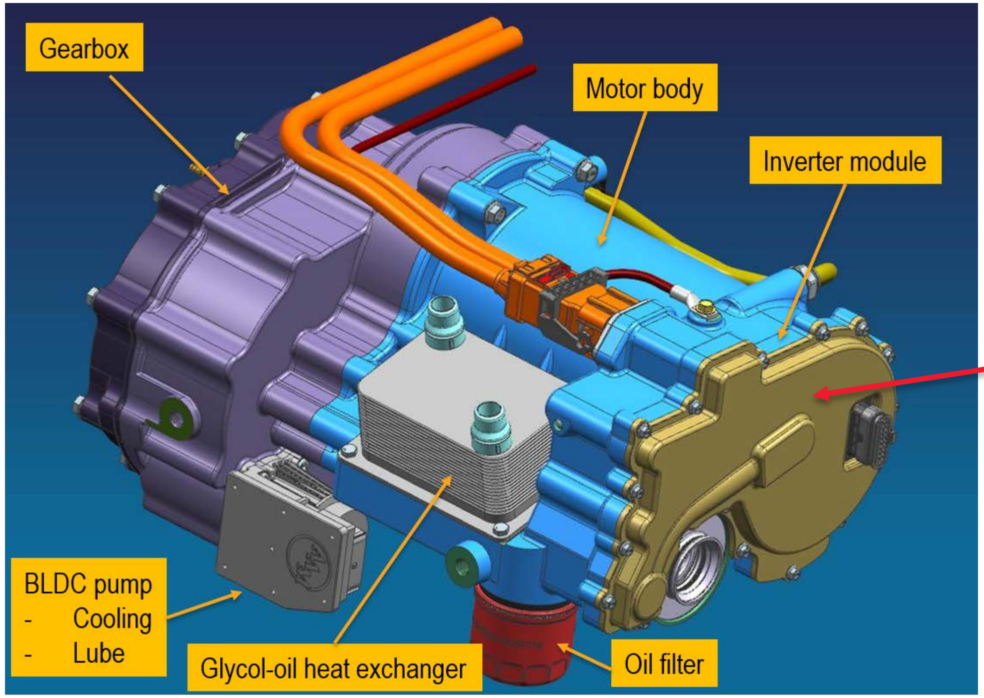
Relevance – Addressing Technical Barriers

- AAM's technology development in 6 areas will address identified VTO barriers for achieving program targets and tie directly to relevant DOE goals of energy security, clean energy, and cost reduction

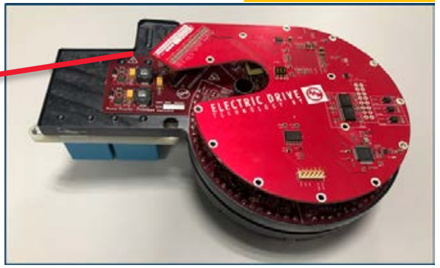
	Technology Development Focus Area	VTO Barrier Addressed
1	30k RPM AC induction motor for increased power density	Magnet cost and volatility due to rare-earth elements & performance
2	Electrically insulated induction rotor bars for increased efficiency	Performance of non-rare earth electric motors
3	Optimized lamination steel for max efficiency vs HRE permanent magnet motor	Material optimization & performance of non-rare earth motors
4	Over-molded stator windings with molded liners for improved slot fill and subsequent improved thermal performance	Performance of non-rare earth electric motors
5	Highly integrated 650V inverter eliminating phase leads for cost and efficiency improvement	Performance of non-rare earth electric motors
6	Silver sintering of discrete SiC devices to heat sinks for thermal efficiency improvement	High temperature and isolation materials for WBG switching devices

Approach – AAM Baseline Technology

- AAM Gen 5.0 3-In-1 EDU
  - Integrated gearbox, motor, ring inverter
  - High speed motor: 24k RPM
  - Induction motor or Permanent Magnet motor
  - Gear reduction: 18:1
  - Peak power: 150kW
  - Peak torque: 3150Nm (Axle)
  - Oil cooled and lubricated
  - Silicon Carbide Inverter
  - Integrated oil pump
  - Nominal DC bus voltage: 350Vdc



Ring Inverter



Technology development within the project will build upon and reference against the AAM baseline Gen 5.0 EDU

Approach – Project Structure

The project is being conducted in three (3) phases:

- Design Development and Technology Research (Budget Period 1)
  - Design, investigate, and develop core technologies
  - Investigate stator lamination and over molding development, high speed motor development, and silicon carbide MOSFET packaging development
  - Investigate, analyze, and assess costs of the developed technologies
  - Select an optimized configuration for prototype build in budget period 2
- Prototype Component Fabrication and Unit Build (Budget Period 2)
  - Fabricate over molded stators, high speed motors, and MOSFET silver sintered attachments
  - Assemble motor-only units and full EDUs for subsequent dyno testing
  - Test the motor-only units on the dyno with the test results being compared to the baseline
- Prototype Testing and Commercialization Planning (Budget Period 3)
  - Test the full EDU on the dyno, with the results being compared to the baseline technology
  - Document the EDU Bill of Materials (BOM) for comparison to benchmarked EDUs and cost targets
  - Prepare a manufacturing and commercialization plan to produce the developed technology in high volume

Approach - Proposed Technical Solutions

VTO Barriers Addressed:

- Inverter Barrier: High temperature and isolation materials for WBG switching devices
  - Technical Solution to Investigate and Develop:
    - Attach discrete SiC MOSFET devices directly to the copper heat sink by a silver sintering process
    - Eliminate traditional thermal interface materials in the MOSFET to heat sink interface

- Motor Barrier: Magnet cost and volatility due to rare-earth elements
  - Technical Solution to Investigate and Develop:
    - Elimination of HRE materials by utilizing a high efficiency & high-speed induction motor (IM) with copper rotor technology

Approach - Proposed Technical Solutions

VTO Barriers Addressed:

- Motor Barrier: Reduced performance of HRE free motors
  - Technical Solutions to Investigate and Develop:
    - Improve performance of IM through utilization of new lamination materials for higher flux capability
    - Improve efficiency of IM by development of insulated copper rotor bars which reduces rotor losses through lamination shorting
    - Enable maximum lamination material utilization in the stator and rotor by investigating a segmented stator design approach
    - Improve motor power density by running at high rotational speeds (up to 30k RPM)
    - Improve motor thermal performance by stator encapsulation and elimination of “air” between windings
    - Design motor and inverter to run at 650Vdc to reduce system cost and improve power density

Approach: Project Milestones – FY21 & FY22

Task No.	Milestone	Description	Anticipated Completion Date
1.2	Mechanical design of over molded stator and copper rotor complete	The mechanical design of the over molded stator and the copper rotor with insulated rotor bars has been completed with detailed drawings and mold flow analysis	12/1/2021
1.3	Electromagnetic design of high-speed induction motor complete	The electromagnetic design of the 30k RPM induction motor, including stator and rotor components, has been completed, with a summary report of motor performance	08/12/2021
1.4	Mechanical design for the motor-only and full EDU complete	The complete mechanical design for the motor-only unit and full 3-In-1 EDU has been completed, with detailed drawings	03/22/2022
Phase I ★ Completion	Design of key technology components completed and verified by analysis and configuration selected	Assessment of the key technology design components has been completed and verified by analytical simulation, with power density ≥ 12kW/L and voltage ≥ 600VDC. A configuration has been selected for the prototype.	03/31/2022
2.1	Fabrication of over molded stators and copper rotors complete	Fabrication of the stators with over molded slots and windings has been completed, with parts ready for final motor/EDU assembly. The copper rotors have been successfully fabricated with the integrated insulated copper bars, and parts are ready for final motor/EDU assembly	09/16/2022
2.1	Fabrication of MOSFET assemblies complete	The discrete MOSFET package has been successfully silver sintered to the copper heat sink, with parts ready for final EDU assembly	08/2/2022

★ Phase I Go/No-Go Decision Point - Design of key technology completed and verified by analysis and configuration selected

Accomplishments

- **Task 1.1 - High Efficiency Stator Development**
  - Baseline electric drive unit (EDU) was reviewed and summarized for project comparison purposes (AAM Gen 5.0 EDU)
  - Additional EDU systems benchmarked including the Jaguar I-PACE and Tesla Model 3
  - Preliminary HRE-free 3-In-1 EDU specification drafted with 2 design versions
    - Design A – High power, Design B – High Torque
    - Will be used as basis for design of the high-speed motor to meet program goals
    - EDU specification based at the vehicle level of performance utilizing Tesla Model 3 as donor vehicle platform
  - Performance specification includes requirements meeting program goals of power density >12kW/liter, system cost <$7/kW, and operating voltage >600Vdc
  - List of 22 potential lamination materials and associated suppliers developed for design consideration within the development of the high-speed motor
  - Initial feasibility assessment of the stator over molding was completed, with promising results

Benchmarking of production EDUs and a preliminary design specification for the project were completed

Accomplishments

Baseline EDU and Benchmark Data Summary

PERFORMACE SUMMARY					
MANUFACTURER	AAM	AAM	AAM	TESLA	
MODEL	I-PACE	Gen 5 Baseline	DOE Target	Model 3	
EDU INTEGRATION	2-in-1	3-in-1	3-in-1	3-in-1	
INVERTER TYPE	Si IGBT	SiC MOSFET	SiC MOSFET	SiC MOSFET	
MOTOR TOPOLOGY	PM	AC Induction	AC Induction	PM	
NOMINAL DC BUS VOLTAGE	350	350	650*	350	Vdc
EDU PEAK POWER	147	155	180	211	kW
MAX OUTPUT TORQUE	3146	3150	3269	3669	Nm (Axle)
EDU MASS	93.4	72	63	91	kg
EDU VOLUME	30.8	23.3	21.6	37.8	L
MOTOR-INVERTER VOLUME	17.1	11.8	10.1	18.8	Estimate
POWER DENSITY (Motor & Inverter)	8.6	13.1	17.8*	11.2	kW/liter
ESTIMATED COST/kW	[redacted]	[redacted]	$6.50*	[redacted]	Target

*These metrics meet the DOE goals

- Benchmarked EDUs
  - Jaguar I-PACE
  - Tesla Model 3 (Rear)
- Baseline EDU
  - AAM Gen 5.0
- DOE Target EDU
  - Voltage = 650Vdc
  - Power Density = 17.8 kW/L
  - Cost Target = $6.50/kW

DOE target design projected to meet project goal metrics. Substantial improvement over benchmarked production EDUs.

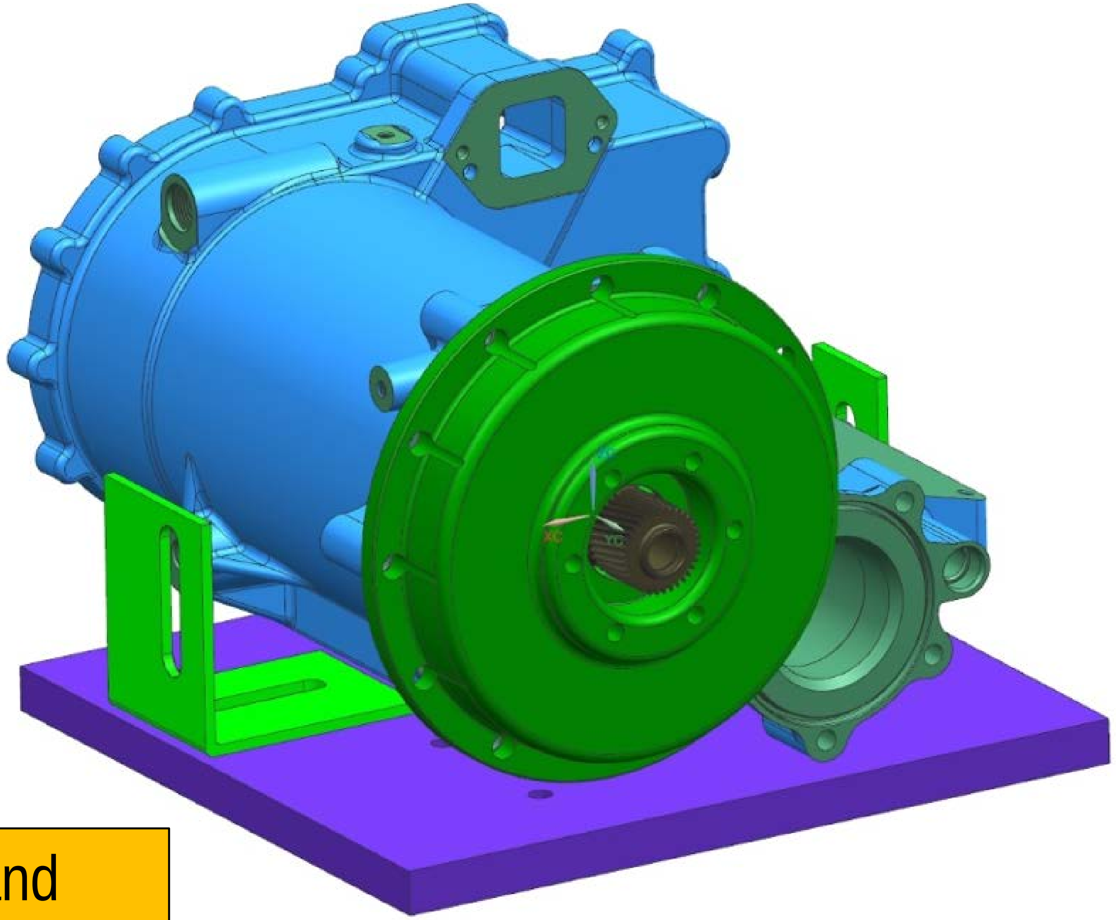
Accomplishments

- Task 1.2 - High Speed Induction Motor Development
  - An initial electromagnetic (EM) design for a 30k RPM motor was developed from the baseline Gen 5.0 EDU. Preliminary plots were generated for torque-speed and efficiency
  - Investigative work into the use of insulated copper rotor bars in the induction motor was started by contacting suppliers. Initial samples of coated rotor bars were provided for material analysis in AAM's materials lab
  - Initial work has started on the mechanical design of the motor only EDU. The design is being developed such that the same motor housing can be re-used in the full 3-In-1 assembly

Improved power density can be achieved by pushing the motor speed up to 30k RPM. Performance will be evaluated on a motor only design platform.

Accomplishments

- Initial Motor-Only Design
  - Platform to test high speed motor design and efficiency improvements
  - Used baseline motor geometry as starting point
  - Allows for later attachment of gearbox and inverter for full EDU testing
  - Adaptor will provide interface from rotor pinion output to dyno load motor



Motor-only design platform established for testing and evaluation of improvements over baseline and to DOE targets of power density (>12kW/liter) and voltage (>600Vdc)

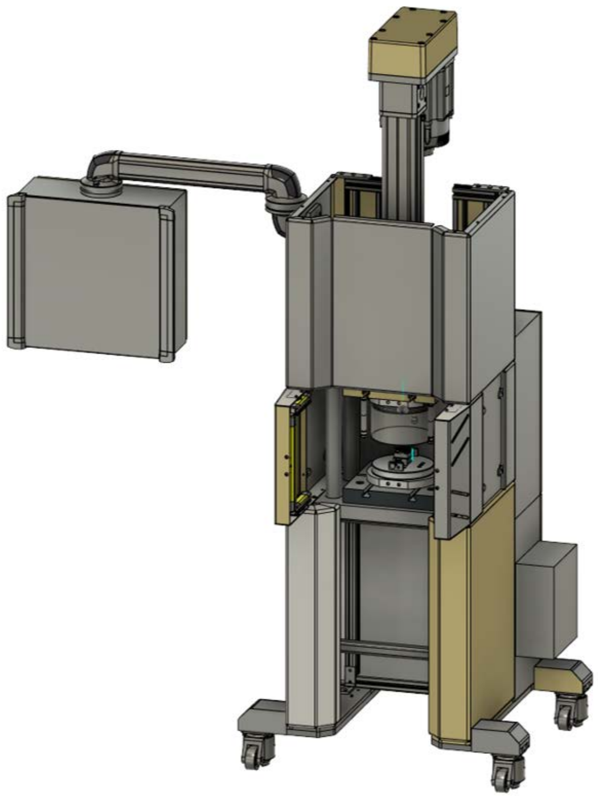
Accomplishments

- Task 1.3 - Advanced Packaging & Attachment Development of Discrete SiC MOSFETs
  - A survey of available literature was completed on the silver sintering process and how it can apply to this project
  - Suppliers for silver sintering material and equipment have been contacted to discuss collaboration opportunities and to quote equipment
  - Lists were developed based on literature review and discussions with suppliers for materials, equipment, parameters to investigate, and methods to evaluate parts
  - A preliminary mechanical design for an enclosed sintering process development fixture and press has been developed

Initial silver sintering foundational work for understanding and subsequent process development completed in support of high temperature WBG switching devices

Accomplishments

- Sintering Development Press and Fixture
  - Fixture design complete
  - Prototype press on order
- Identified Parameters to Investigate
  - Process temperature profile
  - Sintering pressure
  - Sinter paste silver particle size
  - Sinter paste silver percentage
  - Sinter paste organic materials
  - Part surface finish
  - Atmosphere
  - Part plating
  - Post-sinter treatment



Prototype sintering press will provide platform for process investigation and development within project

Response to Previous Year Reviewers' Comments

- This is the first year that the project has been reviewed

Collaboration and Coordination

Subrecipient

Electricore, Inc. (501c3 Non-Profit) is assisting AAM with program management and administration.

Electricore has a successful history of collaboration with the Departments of Energy, Defense, and Transportation in the development, demonstration, and deployment of advanced technologies. Electricore has managed over 100 multi-partnered research programs ultimately involving several hundred industry, university, and government entities.

Mr. Tom Gross, Electricore consultant, is serving as Project Advisor.

Remaining Challenges and Barriers

- Encapsulation development of the stator slots and windings using an injection molding process
  - Slot size vs. stator length could be a barrier
  - Over molding process may cause damage to magnet wire during material flow
- Optimized lamination material may provide excellent performance but may be too expensive
- Low-cost bearings for high-speed motor design at 30k RPM
- Insulative materials for power dense high voltage motor design (>600V) may increase motor size
- Insulative rotor bar material may not be suitable for high pressure die casting process
- Discrete MOSFET package may not withstand pressure needed for silver sintering process
- Standard MOSFET package material may not be compatible with silver sintering process

Proposed Future Research

- Future FY2021 & 2022 Focus (Budget Periods 1 & 2)
  - ★ – Complete 30k RPM electromagnetic (EM) design with >600Vdc supply
  - – Down select 3 candidate lamination materials for simulation analysis
  - – Determine best design and process for slot liner encapsulation and stator over molding
  - ★ – Complete the motor only mechanical design based on final EM design
  - ★ – Complete the full 3-In-1 mechanical design
  - – Investigate silver sintering of a discrete MOSFET device attachment by identifying gaps and solutions for a high-volume capable process
  - ★ – Build and test motor only unit according to the developed test plan
- Future research focus is according to DOE Assistance Agreement for Budget Periods 1 & 2 and related Statement of Project Objectives (SOPO)

★ Key Project Milestones

Any proposed future work is subject to change based on funding levels.

Summary

- **Objective**: To research, develop, and test a Heavy Rare Earth (HRE)-free 3-In-1 electric drive unit (EDU) that has class leading power density and cost. Key technologies to be developed will meet or exceed DOE targets of a cost ≤ $7/kilowatt, power density ≥ 12 kW/liter, and operating voltage ≥ 600 VDC.

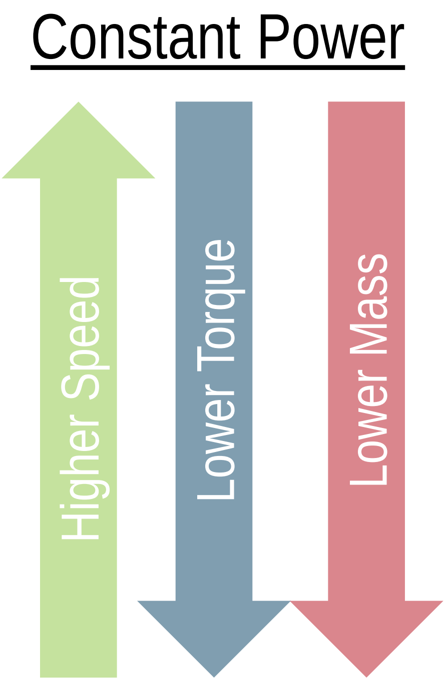
- **Relevance**: Successful development of the proposed technology will result in a substantial cost reduction for EDU systems in the market, and could enable cost and technology competitiveness for EDUs having no rare earth minerals.

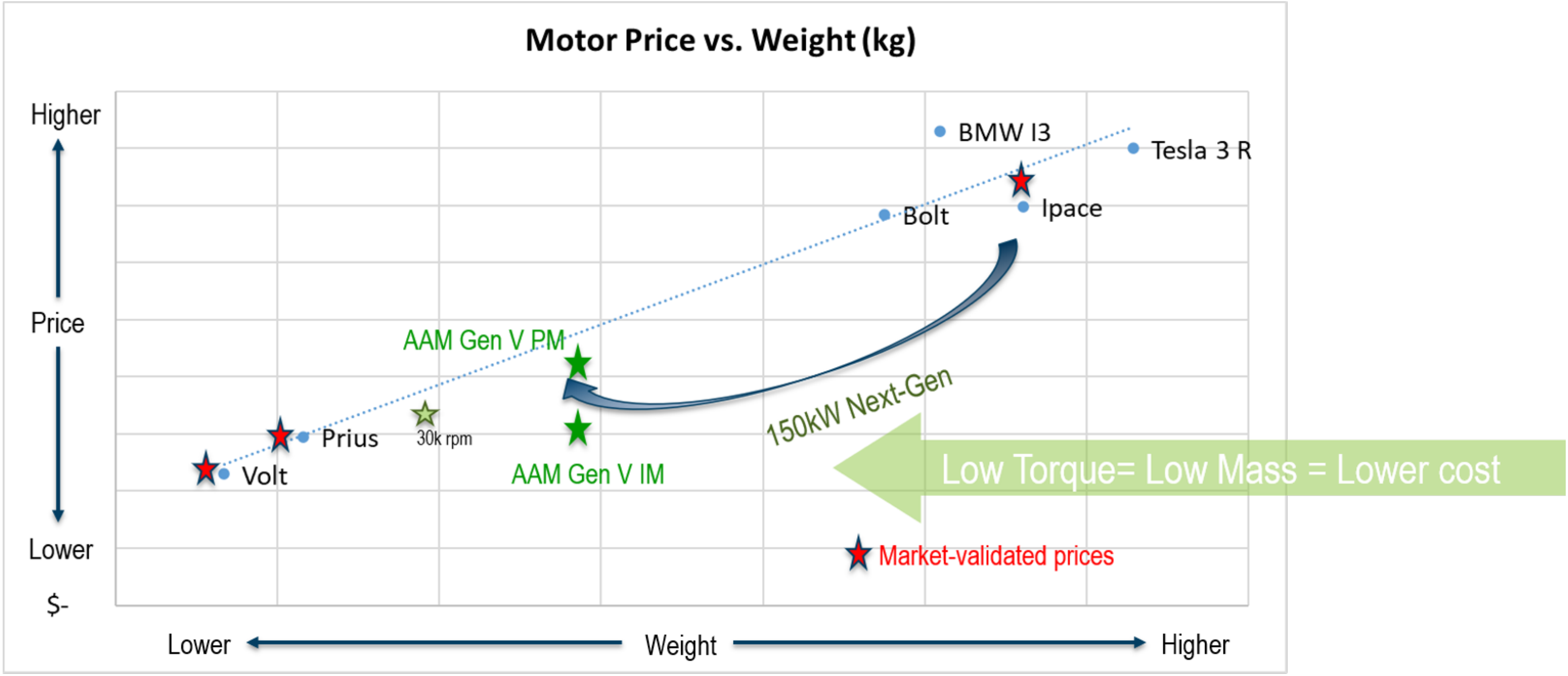
- **Approach**: Develop an EDU technology, with 6 specific improvement areas, to reduce the system cost of automotive traction drives by eliminating the use of HRE magnet materials, reducing motor material mass when compared with state-of-the-art designs, and improve performance of non HRE type motors.

- **Accomplishments**:
  - Benchmarked production EDUs and developed specification for a design to meet program targets
  - Identified list of high-performance lamination materials for down select, analysis, and implementation into the motor design
  - Investigated over molding process for stator slots and windings for improved thermal performance, with promising results
  - Started EM design for a 30k RPM motor to meet project specifications
  - Started mechanical design of motor only testing platform to evaluate motor performance to specification
  - Studied silver sintering literature and developed list of materials, equipment, parameters, and methods to evaluate for process development

Technical Back-Up Slides

Higher-speed Motors Reduce Cost





High speed motors can reduce weight and subsequently reduce motor cost

EDU Specification for Project

- Vehicle level specification for the EDU
- Tesla Model 3 used as donor platform
- 2 design options outlined
  - High Power
  - High Torque

Vehicle Level Specification - HRE Free 3N1 EDU			
Platform/PROGRAM	AAM DOE Design A	AAM DOE Design B	
EDU purpose	Standard Torque, High Pwr	High Torque, Medium Pwr	
Vehicle Donor Application	Model 3	Model 3	
EDU Placement	Front Axle	Rear Axle	
Vehicle Parameters			
TWC	4500	4500	lbs
GVWR	5400	5400	lbs
Max vehicle speed - forward	160.9	160.9	kph
Max vehicle speed - forward	100.0	100.0	mph
Tire	785	785	rev/mi
Radius of tire	0.326	0.326	m
Max grade at GVW (includes Park function)	> 30	> 30	%
Axle type and suspension layout	Independent	Independent	
Drive Unit mechanical parameters			
Peak Torque	144	192	Nm
Max wheel speed	1308	1308	rpm
Max rotor speed	30000	30000	rpm
gear reduction	22.93	22.93	
peak power	180	160	kW
Vmax power	108	96	kW
Peak Torque at axle	3269	4359	Nm
Thrust	2252	3003	lbs
System Design Parameters			
Minimum Operating Voltage @ max discharge	470	470	V DC
Nominal Operating Voltage @ OC	650	650	V DC
Maximum Operating Voltage @ max charge	750	750	V DC
motor winding turns per coil	TBD	TBD	TPC
Max Current	TBD	TBD	A rms

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