Multi-Functional Smart Structures For Smart Vehicles

2021 DOE Vehicle Technologies Office Annual Merit Review

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Project ID# mat197

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Overview

Timeline

- Project start: Oct 1st, 2020
- Project end: Dec 31st, 2023
- Percent Complete: 20%

Barriers & Targets

- Barrier: Lightweight structures that satisfy both structural requirements while offering multi-functionality in a reduced design space
- Target: Enhance the performance of lightweight fiber-reinforced composite with tailored smart preforms for sensing and strength

Budget

- Total project budget: $11,365,173
  - Total recipient share: $3,864,159
  - Total federal share with ORNL: $7,501,014
  - Total federal share, minus ORNL: $5,157,264
- Authorized total spending to date (BP1)
  - $1,704,987

Partners

- Oak Ridge National Laboratory
- Purdue University
- Michigan State University
- Yanfeng Global Automotive Interiors

Relevance

Overall Objectives

Develop a new class of multi-functional composite materials and processing technologies to produce lightweight fully integrated smart structures and surfaces

VTO's Mission

Support research, development (R&D), and deployment of efficient and sustainable transportation technologies that will improve energy efficiency, fuel economy, and enable America to use less petroleum.

- Polymer composites have delivered significant mass reduction when compared to metallic solutions
- However, the lower intrinsic stiffness often precludes stiffness driven applications with limited available design space as performance targets cannot be met
- This project is leveraging novel materials and processing methods to demonstrate feasibility for more weight efficient designs with closed sections and localized reinforcements
- A concept design for an instrument panel cross car beam is underway, targeting a 40% mass reduction compared to a steel counterpart at a cost premium of <$3/lb
- High volume (<3min cycle time) automated processes are being developed to enable materials handing and integration of embedded sensors and electronics
- These new materials and processing methods show promise to have application to a broad range of automotive applications thus magnifying the impact on the ability to achieve long-term improvements in fuel economy and/or battery electric vehicle range

Budget Period 1 Milestones and Gateway

Milestone (Project Month)	Lead	Description
0.1 Project Management	Ford	Project Management and Planning
1.1.1 Concept Development (M1)	Ford	Compile attribute/functional requirements for cross car beam and establish initial design concepts.
1.1.3 Design Sections (M9)	Ford	Transfer design sections to water assist and sensor integration teams. Complete (2) manufacturing feasibility assessment cycles.
1.1.4 Performance targets (M9)	Purdue	Establish cost and performance targets. Develop framework for realistic manufacturing alternatives based on performance and cost targets for the selected application.
1.2.1 Conductive composites compounding (M6)	ORNL	Identify at least four carbon-based conductive fillers (CBF) and complete their procurement, down select and compounding of three different CBF with PA6 or PA66.
1.2.2.2 Conductive composites characterization (M12)	ORNL	Demonstrate two or three manufacturing techniques to prepare conductive composites (CC), Complete characterization of CC for their electrical conductivity and mechanical properties (tensile, flexural, impact).
1.3.1.1 Design freeze (M8)	Ford	Complete design freeze and build of tooling to be fabricated for manufacturing feasibility studies.
1.3.1.2 WAIM process tryout (M9)	Ford	Mold 30 tryout parts on Functional Demonstrator Tool to determine manufacturing feasibility of proposed hollow sections.
1.4.1 Tape production (M6)	Purdue	Produce 100m of tape <25mm wide at < 1 mm thickness for the down-selected fiber and polymer system and further adapt for compatibility with M-TOW, QEE-TECH® and molding cells.
1.4.2.1 Feeding adaptation (M12)	Purdue	Re-designed and adapted feeding and consolidation system of the M-TOW-line allowing direct embedment of functional ducts/system into the structural M-TOW. M-TOW targets: diameter 6-12mm, >50 v/o fiber content and at a line speed of 0.5-1.0 m/min

1.5.1.1 Function identification (M6)	Ford	Identify functions in cross car beam and complete design of a 3D demonstrator (~150 x 150 x 50 mm) for integrated sensors/circuits/electronics
1.5.2 Prototype tool (M12)	Ford	Fabricate prototype tooling, form/mold 30 demonstrator components and complete functional electrical testing (resistance, continuity, sensor function) of integrated sensors/circuits/electronics.
1.6.1.2 Attachment concept (M9)	ORNL	Design concepts for attachment points on cross car beam – 3 concepts with 80% load transfer to discontinuous and continuous composite with 30% weight saving compared to stamped steel hard point.
1.7.1 Technology down selection (M8)	Yanfeng	Down select to 1 design concept for attachment points on cross car beam with 80% load transfer to discontinuous and continuous composite with 30% weight saving compared to stamped hard point.
1.7.1.2 EOAT studies (M9)	Yanfeng	Complete EOAT studies and establish a material handling strategy for inserts and continuous fiber tows allowing 3 minute cycle time.
1.9.1.2 Sub-scale mold integration (M6)	ORNL	Complete design of sub-scale molds for sensor, hardware, tow placement and water assist work streams.
1.10.1.1 Infrastructure review (M6)	ORNL	Complete lab and Tier 1 infrastructure review to determine process sensing capability for AI model development.
1.11.1.1 Recycling baseline identification (M12)	ORNL	Identify suitable short fiber reinforced thermoplastic (SF-TP) material and prepare 5-10 injection molded samples. Prepare 6 tensile testing specimens (ASTM D638) and test them for tensile strength and elastic modulus measurements.
1.11.1.2 Short fiber recycled material testing (M15)	ORNL	Prepare recycled short fiber reinforced thermoplastic samples via mechanical shredding/grinding and injection molding. Prepare at least 6 tensile testing samples (ASTM D638) and document mechanical properties.

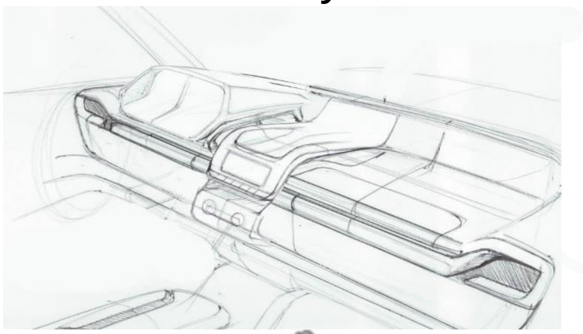
Conceptual Design Down Selection Complete	Go/No Go	Complete selection of cross car bean conceptual design and associated business case indicating potential to achieve a production cycle time of < 3 minutes and a ≥40% mass savings compared to steel.

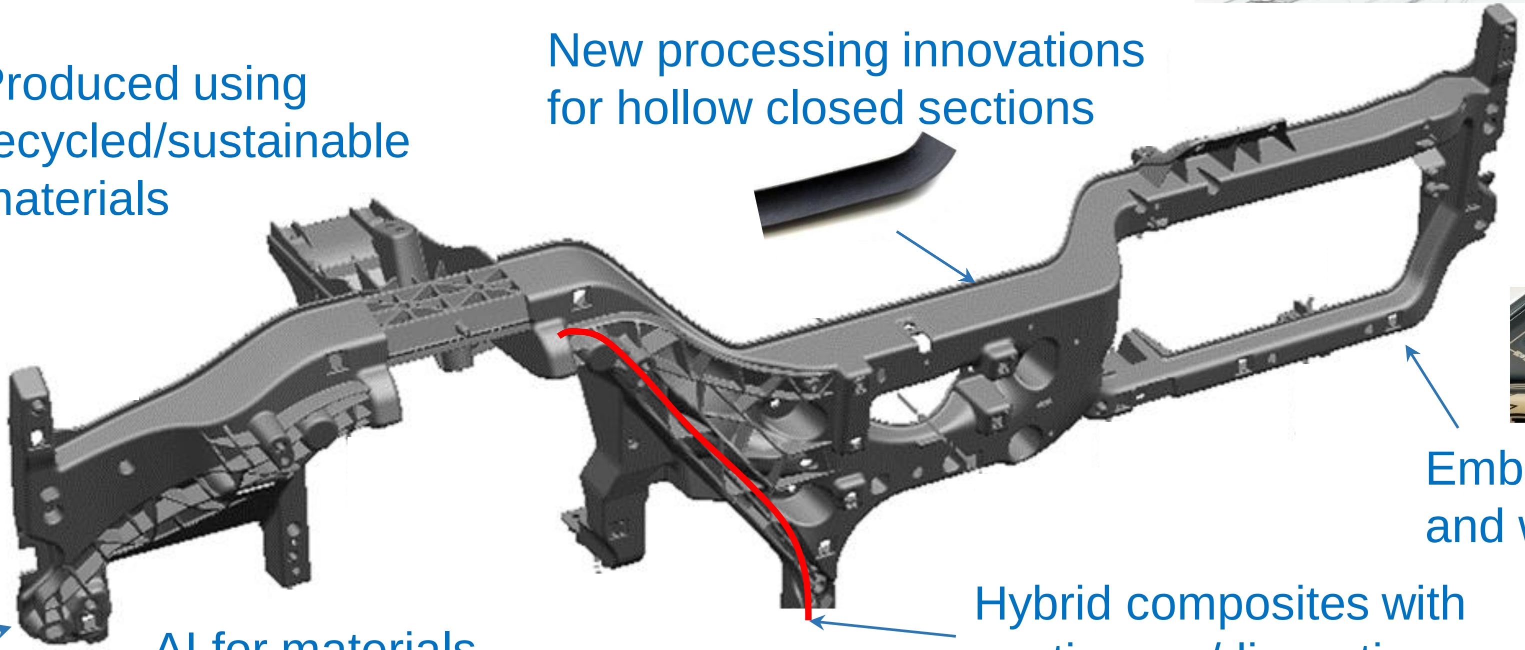
★ Complete
★ On-Track
★ Delayed but contained in BP1

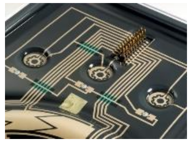
Approach: Multi-Functional Smart Materials

- While mass reduction is an important attribute, new functionalities need to be developed for polymer composites to compete effectively
- Concept instrument panel cross car beam incorporates advances in both material and processing to deliver a new customer experience to the vehicle interior.
- New functionality delivers more efficient design solutions for next generation interiors.

Future Mobility Solutions







Electrically and thermally conducting polymers (2D Fillers: e.g. graphene)

Produced using recycled/sustainable materials

New processing innovations for hollow closed sections

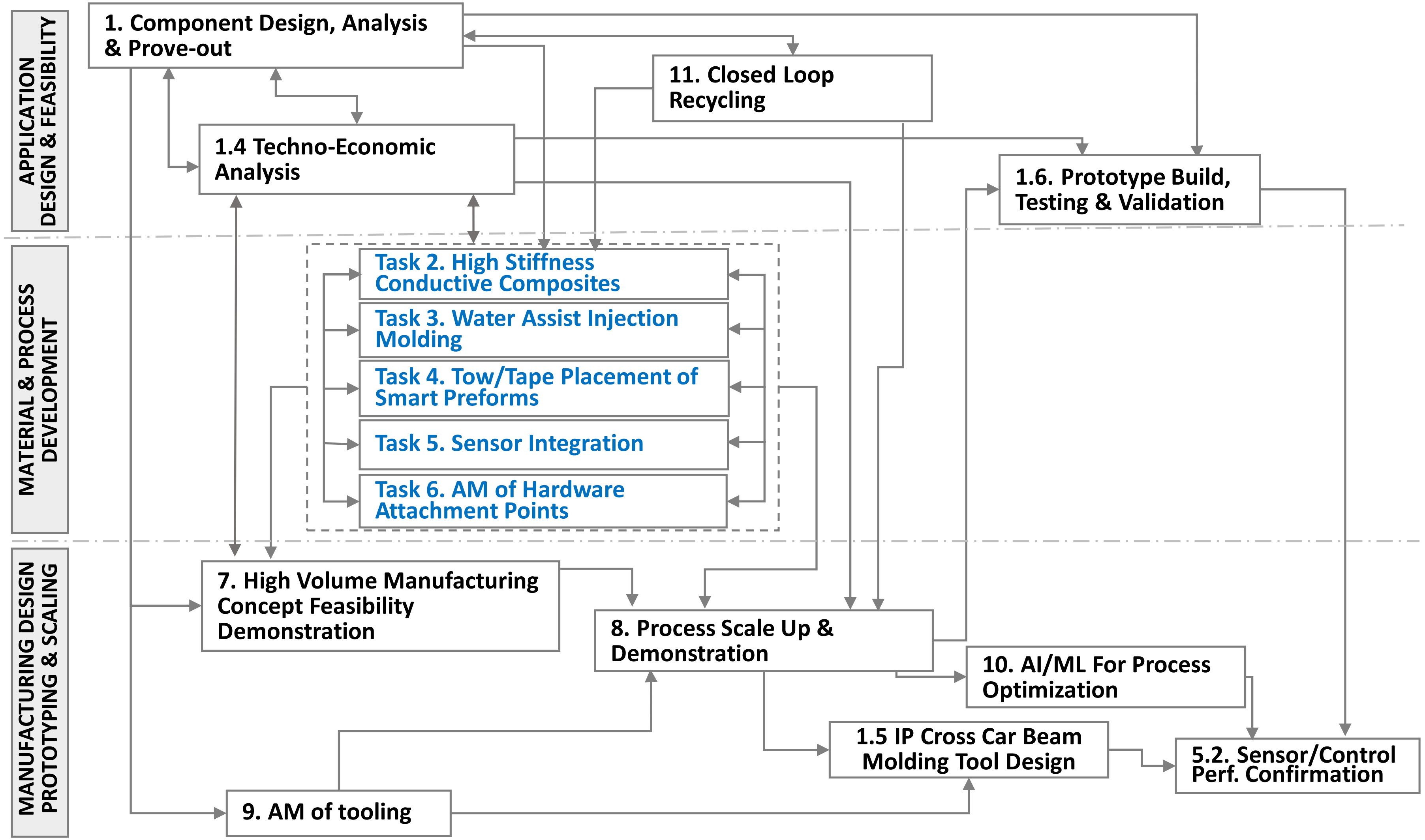
Embedded sensors and wiring

Hybrid composites with continuous/discontinuous fibers

Integration of AM attachment points

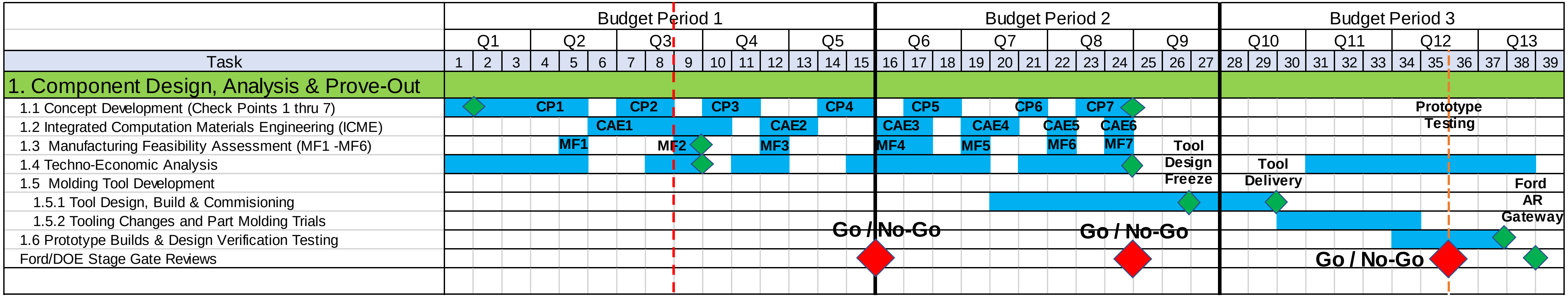
AI for materials discovery/process optimization

Project Structure



Vehicle Research & Technology

Task 1: Design Workstream Timing Plan

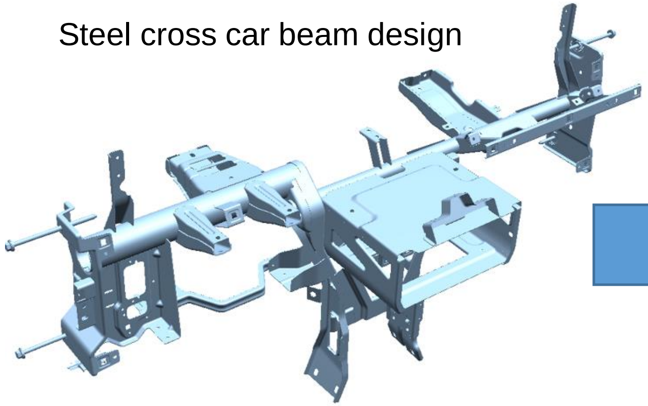


Design & Development Process (Budget Period 1)

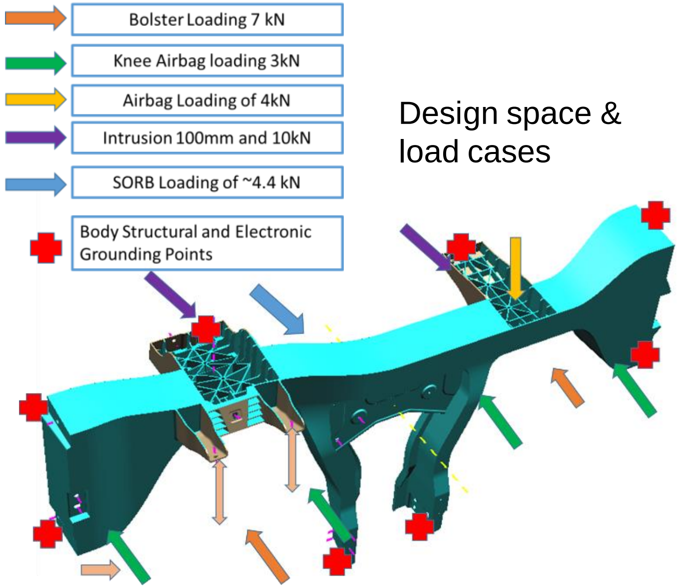
- The Design workstream is the lead activity with all other working groups acting as dependents
- Periodic check points (CPx) are built into the design process to incorporate results from supporting work streams
- Structural and manufacturing simulation analysis will be performed to ensure target functional requirements are achieved
- A manufacturing feasibility assessment of proposed design features and sensing technologies will be conducted to build confidence before formal inclusion on the final concept design
- A techno economic analysis will be conducted to allow evaluation of candidate designs

Task 1 Accomplishments: Cross Car Beam Requirements / Initial Concept

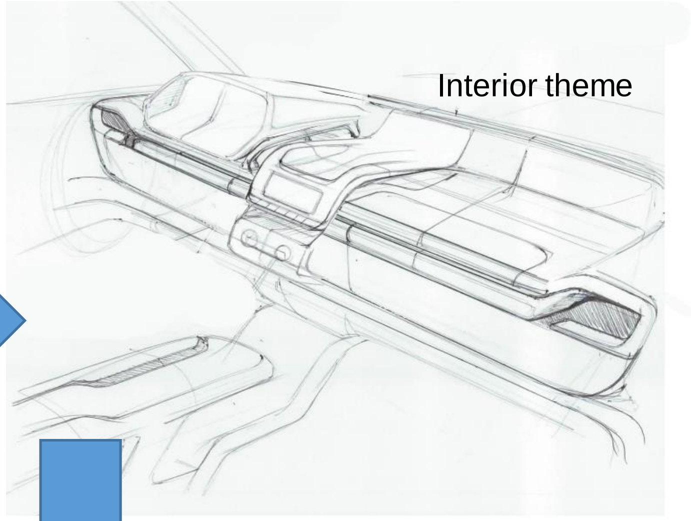
Steel cross car beam design



Design space & load cases

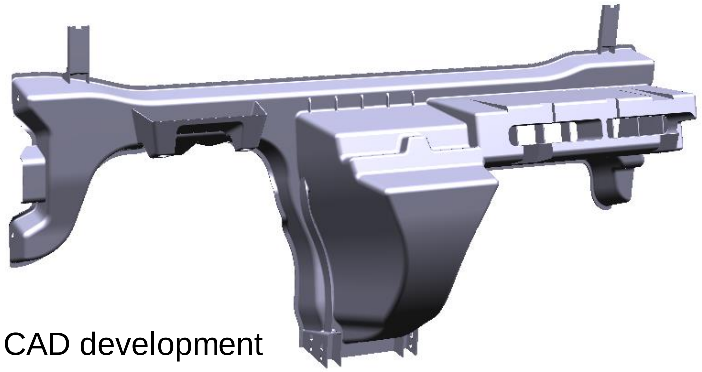


Interior theme



<u>Structural Requirements & Integrated Technologies</u>

1) Energy Management Pathways (For Tow/WAIM)
2) Vehicle Sensing / Health Monitoring
3) Thermal Management
4) Capacitive/Force Switching and Embedded Sensing
5) Class A Surface Integration
6) AM Attachment Locations
7) Bulk Material Properties



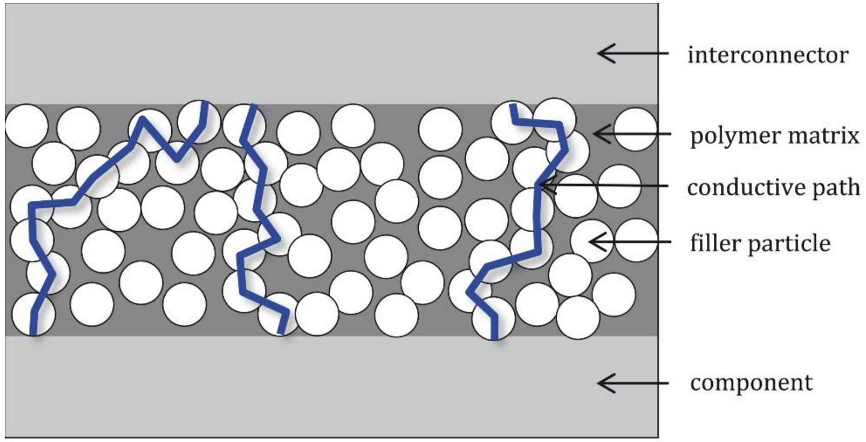
CAD development

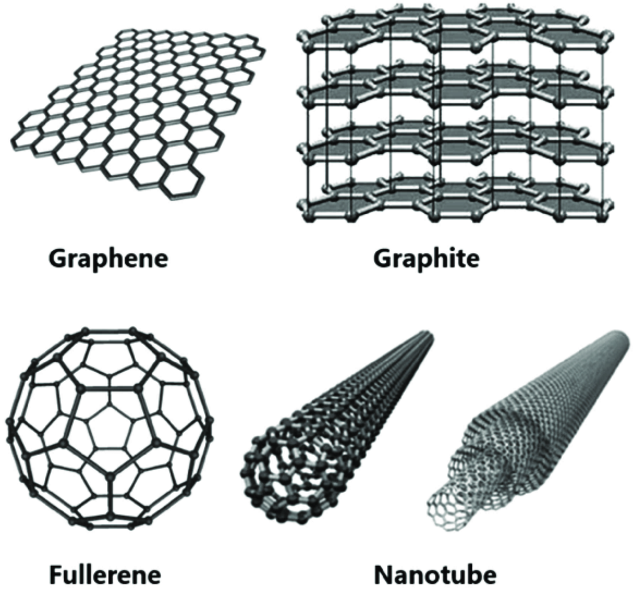
Completed Tasks:

- CAD model to meshing for CAE
- 1st check point for business case
- 2D Sketch (4th round)
- 3D Surface (1st round)

Task 2 Accomplishments: Materials Workstream

- Team identified 4 carbon-based conductive nanofillers:
  - Carbon nanotube (CNT)
  - Carbon nanofiber (CNF)
  - Graphene-oxide (GO)
  - MXene (MX)
- Team identified 5 reinforcement materials:
  - 50% short GF
  - 50% long GF
  - 40% CF
  - 25% CF/15% BF
  - 20% CF/10% BF
- Candidate nanofillers and reinforcements have been sourced and compounding completed using a base PA66 polymer.
- Thermal, conductivity and mechanical testing due to commence in May 2021.





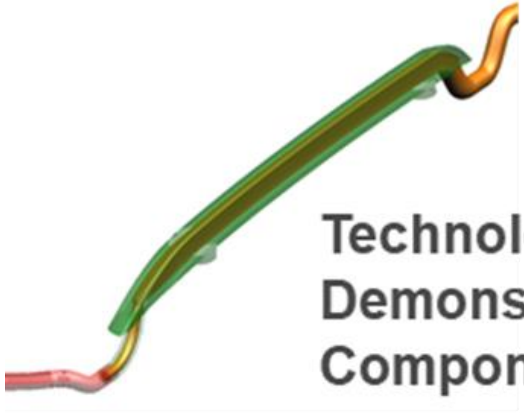
Task 3 Accomplishments: Water Assist Injection Molding (WAIM)

Design

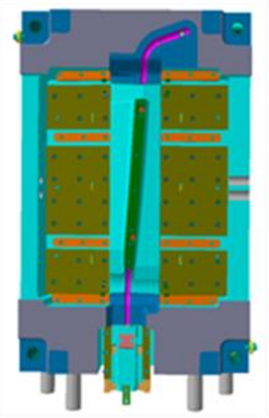
- Initial “closed section” channels incorporated into the cross car beam design
- Demonstrator tooling design complete for manufacturing feasibility studies
- Tool build completed and received on May 12th, 2021

Processing

- Water assist injection equipment installed and commissioned on site, March 25, 2021
- Commissioning trials completed on March 30, 2021
- Representative molding materials (per Task 2) received for Q2 processing trials.



Technology Demonstrator Component



Technology Demonstrator Injection Mold

Injection molding cell

Component cross section

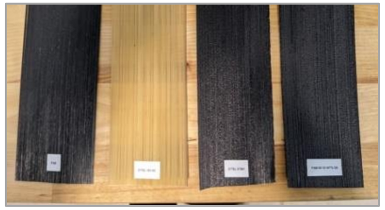
Task 4 Accomplishments: Tow/Tape Placement of Continuous Fibers

Budget Period 1 Accomplishments

Composite Tape Production:

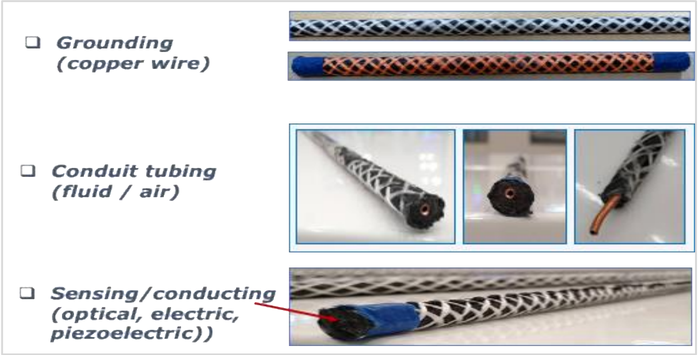
a) The laboratory's TAPE LINE has been redesigned and adjusted to fabricate continuous carbon and glass fiber Polyamide (PA) pre-pregs at industrial rates.

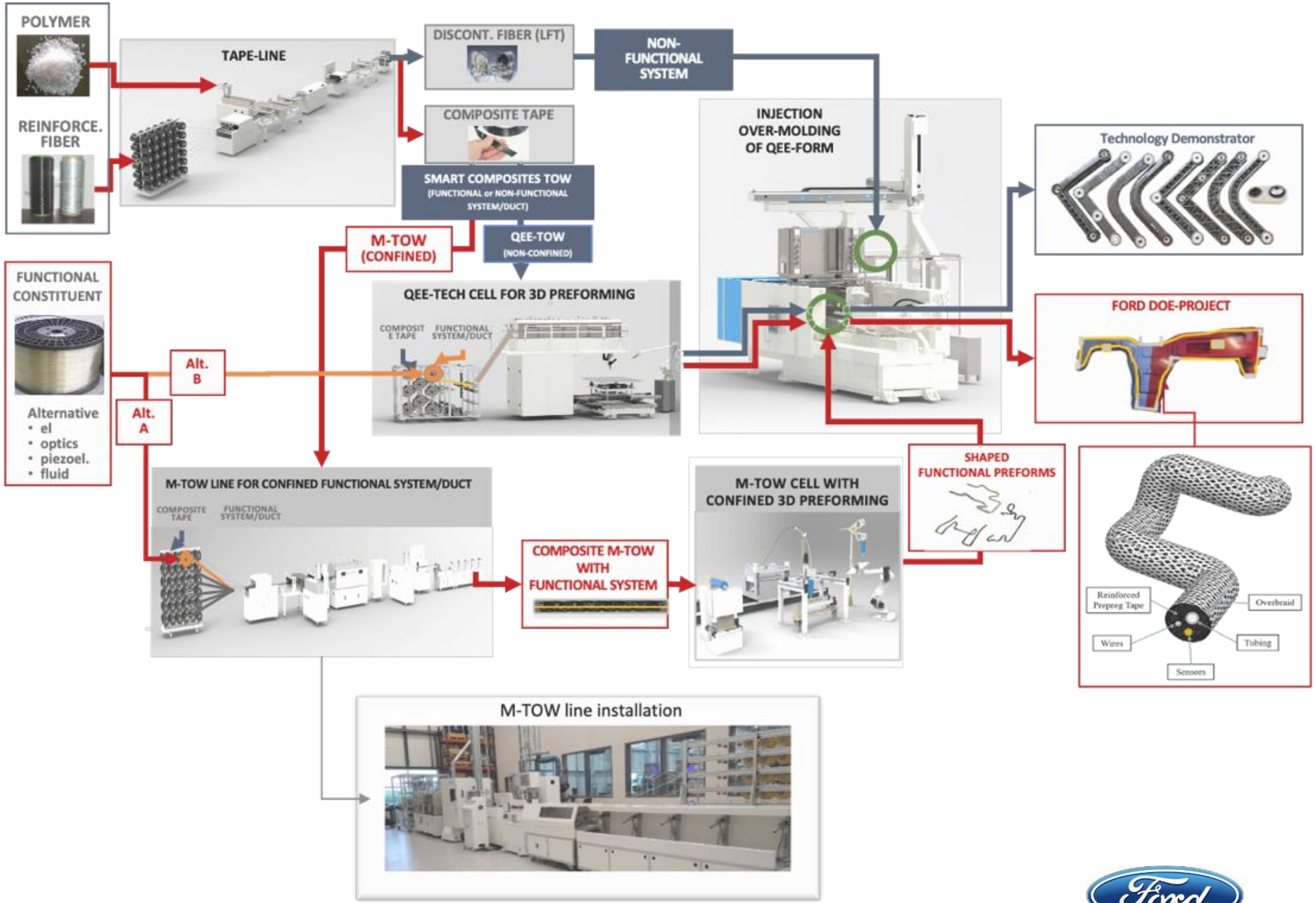
b) Production trials with surrogate fibers has been conducted in support of milestone 1.4.1



Functional Preform Production

The M-TOW LINE has been designed enabling preform fabrication with embedded functional systems for sensing, conducting and fluid transfer.





Task 5 Accomplishments: Sensor Integration

Substrate materials and conductive inks have been examined for testing

- Conductive inks: silver (nanoparticle, particle-free), copper, carbon
- Film substrates: PET, PCl, PI, PA66

Location for sensing functions on the class A surface of the cross car beam have been identified

- Interactive functionality/switching for customer input
- Representative 3D geometry for prototype tooling and testing
- Preliminary injection molding trials conducted using printed circuits to understand survivability with higher temperature PAGF15 engineering polymers.
- Initial trials have utilized a flat panel injection molding tool (125 x 125 mm).

Flat panel over-molding studies of printed circuits

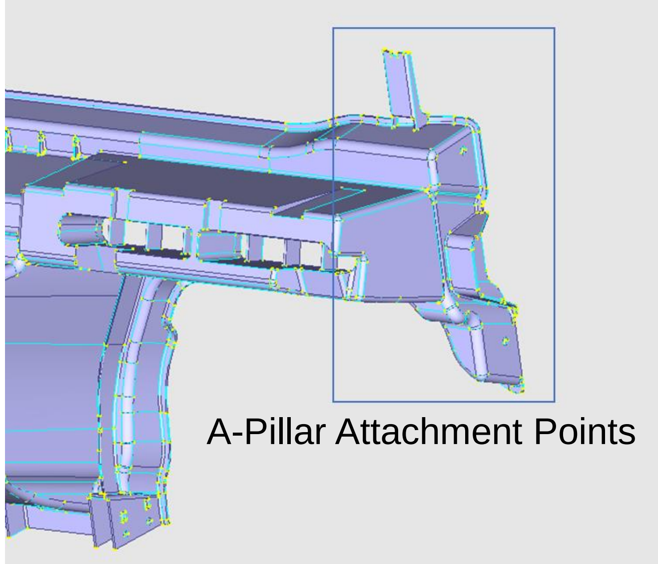
Trial Conclusions:

- Single layer capacitive touch circuitry appears to be compatible
- Force sensing resistor technology is not directly compatible with mold-behind IM processes
- Polyamide 6 could potentially be used directly as a mold-behind material
- Formulation of specific inks and films will be required to ensure compatibility with the back molding material
- Tooling for representative 3D geometry is now being designed in support of design feasibility assessments

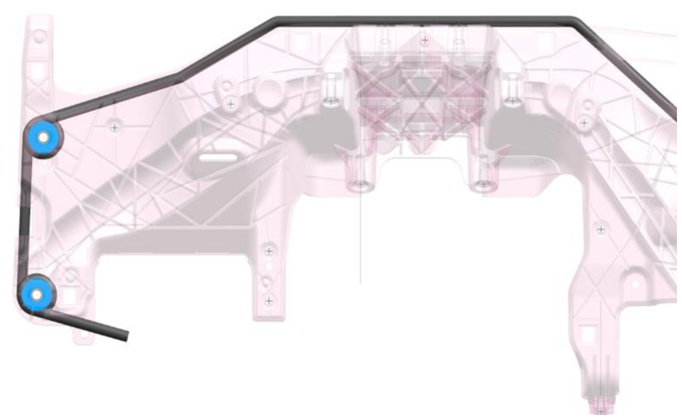
Task 6 & 7 Accomplishments: AM Attachment & Manufacturing Feasibility

Task 6: AM Hardware Attachment Points

- ORNL team working with Purdue and Yanfeng to determine an attachment strategy for integration of tow materials
- Task 1 Design workstream to complete initial concept of geometry at A Pillar body attachments
- Current candidate AM processes include DED – EBM – SLM – Binder Jet
- A final decision will be based on the attachment material, surface roughness , attachment size, etc



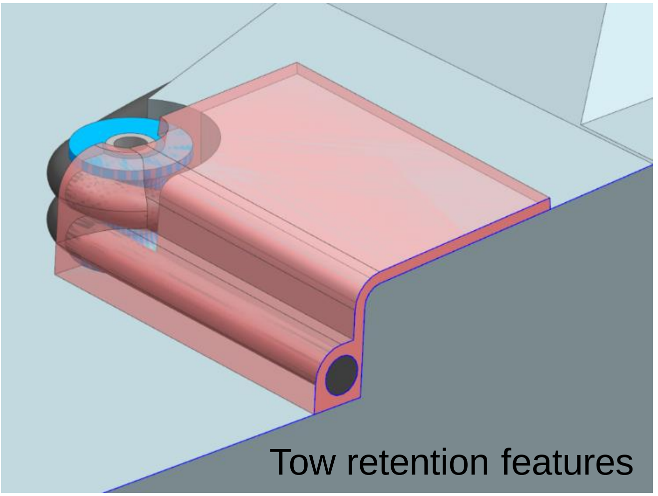
A-Pillar Attachment Points



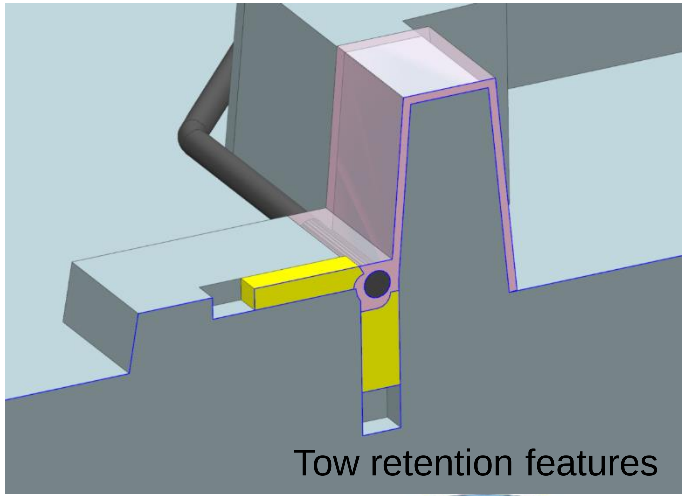
Example tow routing on 3D component

Task 7: High Vol. Manuf. Concept Feasibility

- Completed an initial evaluation of methods to locate tow(s) in injection molding tooling
- Developed multiple concepts to hold the tow in place in various geometric situations
- Conducted Pugh analysis to determine the most effective methods
- Created designs to reflect how those methods would package in a surrogate tool design



Tow retention features



Tow retention features

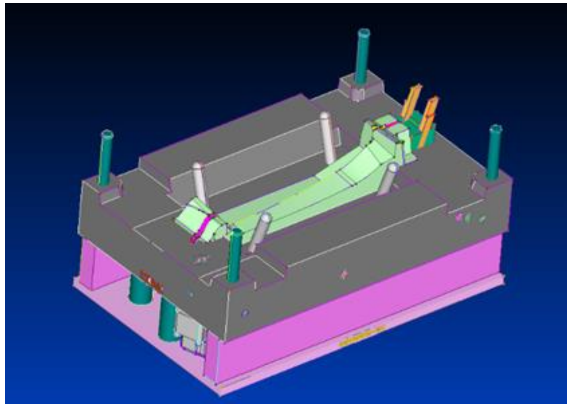
Task 9 & 10 Accomplishments: AM Segmented Tooling / AI-ML Process Optimization

Task 9: Additively Manufactured Segmented Tooling

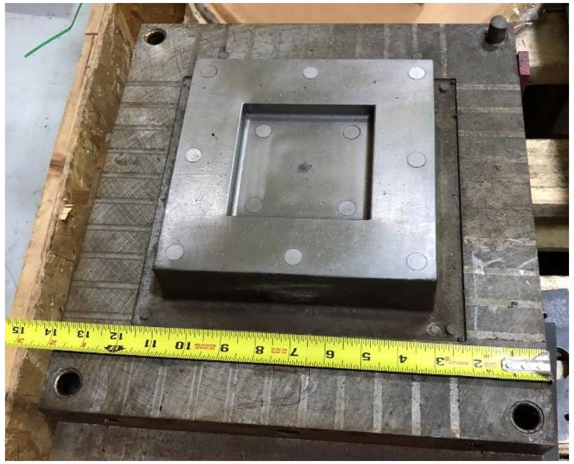
- The ORNL team has been working with Task 3 and Task 5 workstreams to identify tooling needs for planned manufacturing studies.
- A selection of existing master unit die (MUD) bases has been secured to reduce the size of potential AM tooling inserts.
- Currently evaluating the possibilities for printing inserts to the water assist demonstrator tool to allow variants in the channel cross section to be evaluated.
- ORNL is working with Ford and Yanfeng to develop tooling in support of the embedded sensor over-molding studies
- A proposed turnaround time of 6-7 weeks has been established for powder bed fusion (PBF) and Direct Energy Deposition (DED) processes
- A final decision on an initial set of AM tooling in support of the project experimental program will be made in June 2021.

Task 10: AI/ML Process Optimization

- Per milestone 1.10.1.1, a review of data collection and process monitoring methods has been completed for operations at Yanfeng
- The current data infrastructure captures and tracks the information associated with the injection molding machine
- Data analytics algorithms and tools are in place to extract information that can help qualify and optimize the process and the resulted molded parts.



Water assist demonstrator tooling CAD



Master Unit Die base

Collaboration and Coordination

Yanfeng Global Automotive Interiors (Sub) | Michigan State University (Sub) | Ford (Prime) | Purdue University (Sub) | Oak Ridge National Laboratory (Sub)

RASIC Chart: Multi-Functional Smart Structures For Smart Vehicles

R: Responsible: The Institute/Company Responsible for this task
A: Approve: The company/institue giving the approval
S: Supporting: The Company/Institute giving support for the competion of the task
I: Informed: The Compaby/Institute to inform about this task
C:Consulted: The company/institute that can act as expert in regard to the task

	Michigan State University	Purdue University	Oak Ridge National Lab	Ford Motor Company	Yanfeng
Task 0. Program Management				R	
Task 1. Component Design, Analysis & Prove-Out	I	S	S	R, A	S
Task 2. Formulation/Compounding of novel materials	I	I	R	S, A	R
Task 3. Water-Assist Injection Molding (WAIM) Process Development	S	I	S	R	S
Task 4. Tow/Tape Placement of Continuous Fiber	I	R	S	S	S
Task 5. Sensor Integration	I	S	S	R	S
Task 6. Additve Manufactured Hardware Attachment Points	S	S	R	S	S
Task 7. High Volume Manufacturing Concept Feasibility Demonstration (sub-scale)	S	S	S	S	R
Task 8. Process Scale Up & Demonstration	S	S	S	S, A	R
Task 9. Additive Manufacturing of Segmented Tooling	I	S	R	S	I
Task 10. Artificial Intelligence/Machine Learning For Process Optimization		I	R	I	S
Task 11. Closed Loop Recycling		I	R	S	S

All partners are represented within active working groups. Weekly alignment meetings are held to ensure effective coordination across all facets of the cross car beam design and development process

Remaining Challenges and Barriers

- Only early stage design work has been completed, leaving a significant amount of development required in order to meet mass savings and other functional objectives. The team is working towards validation of a formalized concept by the end of 2021. This will be featured as part of the Budget Period 1 gateway review. However, further refinements would still be required before a final prototype design freeze occurs in 2022.
- Determination of thermal and electrical conductivity is still outstanding as it relates to grounding requirements of electronics and the proposed elimination of supplementary wiring harnesses.
- Studies utilizing water assist injection molding have demonstrated feasibility of creating hollow sections. However, processing the size and complexity of the channels in the cross car beam presents new challenges. This is further compounded by the high thermal conductivity and rheological behavior of these highly filled fiber reinforced polymers.
- A proof of concept has been demonstrated for integration of sensing and conductive pathways in continuous tows/tapes. Further work is required to assess robustness of these “Smart Preforms” when incorporated into a high volume injection molding process.
- The relatively high processing temperatures of polyamide 66 creates survivability concerns during over-molding of sensors and embedded electronics. Further work is required to develop strategies for managing thermal exposure.
- Final validation requires full scale production demonstration featuring automated unit cell operations to manage material handling strategies for all over-molded features (e.g. sensors, smart preforms, AM attachment points).

Proposed Future Research

Budget Period 1 (Oct '20 – Dec '21): Concept Design & Development

- Design themes and CAD surface models will be subject to multiple iterations before converging upon a final concept at the end of Budget Period 1.
- Throughout this phase of work, technology and manufacturing feasibility assessments will be needed before incorporating results from parallel workstreams into the design. Furthermore, development of unit cell operations are required to manage material handling and over-molding sequences for a high volume production process.
- A Go/No-Go gateway review at the end of Budget Period 1 will also be supported by a techno-economic analysis to measure commercial viability of the concept design before scale up of operations in Budget Period 2.

Budget Period 2 (Jan '22 – Dec '22): Materials & Process Optimization

- The team will further refine the cross car beam design based on manufacturing feasibility trials and material and process optimization. Unit cell operations for integration of all over-molded structural inserts and sensors will be demonstrated. A completed CAD design for the cross-car beam will be prepared to enable fabrication of full scale prototype tooling and molding cell automation.

Budget Period 3 (Jan '23 – Dec '23): Prototype Validation & Testing

- The team will build prototype tooling to manufacture cross car beams for testing and validation. Materials and processing optimization will continue. Full scale injection molding will be demonstrated. The ability to fixture inserts and continuous fiber into the injection mold and retain them through the injection process will be demonstrated.

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

Summary

Highlights:

- The team has developed a vehicle interior theme that integrates a multi-functional structure within an instrument panel cross car beam
- The design volume has been established and requirements set allowing design concepts to evolve and work within dependent work streams to progress
- To date, surface CAD has been generated leading to generation of CAE models for structural analysis
- Down selection, procurement and compounding studies have been completed for candidate fibers and conductive fillers
- In parallel to design activities, facility commissioning has been completed for both water assist injection molding and production of continuous tow/tape reinforcements
- Design of a sub scale demonstrator part for water assist injection molding studies has been completed in addition to subsequent fabrication of corresponding tooling
- Methods for material handling and tooling retention are underway to support integration of all over-molded features

Outlook

- Design of the multi-functional cross car beam structure is progressing as planned. This is supported by each of the dependent workstreams that are now fully operational. Early on in the program some delays were experienced due to COVID restrictions and limited availability of design resources. However, these issues have been resolved and overall project timing remains on track.